The Sudbury Ores: Their Mineralogy and Origin

by

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PREFACE

In this volume the writer has attempted to bring together the results of some thirty years of part-time research on various aspects of the great Sudbury ore deposits, carried out in association with several generations of his students whose names, listed below, are unfortunately too numerous to include as co-authors. Although they may thus appear to be "silent partners" in the undertaking, specific references to their individual contributions, which have been very real, will be found throughout the paper. As every teacher directing research soon realizes, the part played by his students is an invaluable one, not only by virtue of their discovery of new facts, but also by the clarifying influence of prolonged discussions, the recognition and elimination of woolly thinking and faulty hypotheses, and by the many fruitful suggestions which inevitably emerge to be tested by further study or experiment. The volume is divided into three parts, the reasons for which will become apparent.

Throughout most of the investigation the mineralogical and chemical features of the ores were the main concern. The fortunate appointment of Dr. R. L. Stanton as a post-doctorate National Research Council Fellow allowed a fairly complete review of this phase of the work in 1957–8. The results of this are given largely in Part II under the joint authorship of Hawley and Stanton. In this section the various classifications of the ores and their relations to the rocks in which they are found are considered, the descriptive mineralogy of the ores is detailed and illustrated, and the distribution of metals and minerals throughout the field is indicated.

Such studies, however, have serious limitations when one comes to their interpretation unless there is available a well documented and authenticated geological succession of events into which they can be integrated. Probably only those familiar with the region are aware of the confused state of the published geological literature of Sudbury and the many unrefuted ideas which have either been discarded for some years or seriously questioned by field geologists. It was thus imperative that the geological problems existing in the area be reviewed to establish as clearly as possible the premises on which a theory of origin of the ores could be based. This has been particularly aided by recent advances in dating techniques, by further detailed mapping by the Ontario Department of Mines, by a very significant paper on the Frood-Stobie deposit and two Guide Books on the area, and to some extent by certain thesis studies. Part I is accordingly devoted chiefly to a consideration of the geological problems and premises to portray the geological setting. Part II is a factual study of the ores and minerals as noted. Part III is the writer's interpretation of the data presented. The latter begins with a summary of the history of events leading to and following the deposition of the ores. This has given rise to a dual classification of the processes involved—those which are truly magmatic and those which simply represent very minor post-magmatic ore effects produced in their long subsequent Precambrian history. The evidence for both is considered in some detail.

In such a contribution as this it naturally falls to the writer to assume full responsibility for the ideas advanced and especially for the appraisal of the geological history. The contributions of his co-workers and in fact of all who have written at one time or another on these outstanding deposits are however acknowledged as forming the foundation on which the final conclusions are based.

RESEARCH CONTRIBUTORS

As students	G. A. Harcourt	1932–33
	H. F. Zurbrigg	1932–33
	G. L. Colgrove	1939–40
	A. M. Clarke	1945–46
	D. F. Hewitt	1946–47
	V. A. Haw	1947–48
	C. L. Lewis	1949–50
	Y. Rimsaite	1950–53
	W. O. J. Groeneveld Meijer	1953–54
	E. C. Speers (*deceased*)	1954–56
	R. M. Ginn	1955–56
	J. F. Sadler	1957–58
	Ian Nichol	1957–58
	A. Y. Smith	1959–60
	A. J. Naldrett	1960–61
Others	Dr. R. L. Stanton	
	Dr. C. E. Michener	
	Dr. A. R. Graham	

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ABSTRACT

A comprehensive study of the mineralogy of the famous Sudbury ores is applied to the problem of their origin. A critical review of the many confusing and controversial geological problems of the region, however, has been required to establish premises on which a theory can be soundly based. Following this, the actual study is presented covering the nature of the ores, their detailed mineralogy and chemistry, microscopic relations of ore to rock-forming minerals, and distribution of metals and minerals. An interpretation of the history and origin of the ores, based on both geological and mineralogical evidence, is then given.

What may be termed the older classical view of the geological history of the area, after Coleman, Collins, and Sudbury field geologists, with minor modifications, is favoured. The ore-bearing nickel irruptive, clearly pre-Keweenawan in age, is considered as having been intruded as a single body much in the form it now shows, following, for the most part, a pronounced unconformity, pre-Animikean (?) in age, below which are highly altered, granitized and brecciated pre-Huronian volcanics and sediments with rare remnants of lower Huronian sediments unconformably above them. Extensive brecciation during extreme diatreme activity is considered as a prelude to the unique volcanic activity giving rise to the lower part of the Whitewater series, within the Sudbury basin, the Onaping tuffs and breccias (glowing avalanche deposits) and associated sediments which lie above the irruptive, are altered by it, and structurally appear unconformable to formations below. An Animikean rather than early Precambrian age for the Whitewater is suggested.

Post-irruptive events include two or more orogenies, (Penokean and Grenville), a period of faulting and fracturing and late Pb-Zn mineralization, minor intrusion of post-norite granite, and later (Keweenawan) trap and diabase, events locally modifying the ores.

Various classifications of ore types are given including a new one, named an "immiscible-silicate-sulphide" ore in which silicate blebs are dispersed in sulphides, the counterpart of some disseminated ores in quartz diorite or norite.

Detailed descriptions of over 60 metallic and non-metallic minerals are given showing chemical variations, trace element content and textural relations. Many metallic minerals (sulphides, arsenides and others) are recognized as of different generations and many participate in ex-solution intergrowths as well as peculiar pseudo-eutectic textures. Available data on distribution of the common metals, platinum group metals and minerals, gold and silver, cobalt and selenium, as well as bismuth, and others are given and rare but important instances of zoning noted.

Interpretation of the complex history of the ores is based on observed textural relations of the minerals, studies of synthetic sulphides and arsenides, and on the similarity of textures produced synthetically to those found in the ores. Comparisons are also drawn with other natural occurrences and with the mode of crystallization of sulphide-oxide-silicate systems showing liquid immiscibility.

Both mineralogical and geological evidence show that the ores are *magmatic* in origin and were derived from the nearby nickel irruptive magma which possibly had a quartz diorite composition and was about saturated with sulphides when intruded. As shown by disseminated sulphides in norite and quartz diorite

(Creighton, Frood), and by the disseminated silicate blebs in sulphide grading into massive ore, the sulphides were segregated as immiscible liquids, some crystallizing *in situ* at the base or along flatter dips of the intrusion, some being injected to other favourable sites, but never far from the thermal influence of the norite contact. The "upside-down" zoning of the differentiated deposit at Frood in quartz diorite which projects downward from the now eroded main irruptive above, is further conclusive proof, augmented by the behaviour of cobalt in various sulphides and the high temperature character of many of the ore minerals.

Superimposed on the primary ores are several post-magmatic ore effects. These include late-stage pseudo-eutectic intergrowths of arsenides and sulphides, remobilization of normal ore to a peculiar type by post-norite granite or granitization, late lead-zinc-marcasite mineralization (secondary hydrothermal), and effects due to Keweenawan trap and diabase dykes as well as minor supergene alterations. These are of scientific interest but quantitatively are unimportant.

THE SUDBURY ORES:
THEIR MINERALOGY AND ORIGIN

PART I

THE GEOLOGICAL SETTING

A. INTRODUCTION AND ACKNOWLEDGEMENTS

In marked contrast to accounts available on some very much smaller deposits, no comprehensive mineralogical study of the famous Sudbury nickel-copper ores has appeared since reports by Barlow (1904), Coleman (1905–1913), Knight (1917) and Wandke & Hoffman (1924). There are several reasons for this. One is certainly the high quality of earlier descriptions, as witness the fact that very few new mineral species have been identified in them since that time. Another is perhaps the apparent great similarity of most of the deposits, their very abundance, and in some years past the lack of incentive to establish mineralogical guides for the exploration for new ore bodies. In reality the ores do differ in certain respects from place to place and give interesting clues to events in their past. They have, of course, been studied in great detail by those engaged in their exploitation. Their great size and number, however, make it an almost impossible task for the casual investigator to study all in close detail, but it is hoped the present sampling is reasonably representative.

Much of the research on which this volume is based has been carried out in our mineralogical and chemical laboratories, but some has involved critical field studies by both graduate students and the writers. These, as well as stimulating discussions with many field geologists have led to some familarity with the complexities of the Sudbury geology. The laboratory investigations carried on periodically since 1930, have been made on collections of ores and rock suites at Queen's University. Some of these date back to the early part of the century and were begun by W. G. Miller, William Nicol and C. W. Dickson. Other collections have been acquired more recently both through students and the kindness of mining companies operating in the area. Improvements in analytical techniques in recent years have aided in several studies of various mineral assemblages from individual deposits and formations. The important contributions of graduate students taking part in these, and of Dr. R. L. Stanton in reviewing earlier research and in making additional studies

on new material have been referred to in the Preface and will be noted later in appropriate places.

In addition, a large volume of work carried out by the late M. A. Peacock and his students at the University of Toronto has become available, and Dr. C. E. Michener has most kindly placed his valuable unpublished doctorate thesis on *Minerals associated with large sulphide bodies of the Sudbury type* at our disposal. This has proved most helpful in affording an independent check on many of our observations and interpretations.

The study bears heavily on the metallic constituents but touches briefly on associated non-metallic minerals and wall rocks. Dr. A. R. Graham, Falconbridge Nickel Mines, Limited, has allowed the use of his detailed study of alterations in silicified areas at Falconbridge. Further studies of this type, however, are needed elsewhere, as well as of the *x*-ray crystallography and sulphur isotopes of the various sulphides. While spectrochemical studies of the major minerals have been made and are reported herein, investigations of this type might be expanded, especially with newer instrumentation. Syntheses of several of the common ore minerals and their intergrowths have been made from time to time in our laboratories as well as by Kullerud and others in the Geophysical Laboratory, Washington, and are of great value in elucidating the textures observed in natural occurrences. Platinum metal tellurides and a few arsenides and bismuthides have also been synthesized particularly to check their possible occurrence in the ores. With such a large volume of material at hand it has seemed worthwhile to bring it together at this time, though no pretence is made that the study is in any sense complete.

The cordial co-operation of both International Nickel Company of Canada, Limited, and Falconbridge Nickel Mines, Limited, over many years both with our students and ourselves has been deeply appreciated. Without such assistance both in augmenting our collections and in visiting various mining areas, many of our theses studies would not have been possible. In more recent years we have been similarly indebted to officers of the Ontario Department of Mines, especially Dr. J. E. Thomson. To several generations of field geologists active in the district, we also wish to express our gratitude for many hours of patient guidance through the maze of problems exhibited and for much of the challenging inspiration needed to pursue our investigations, a feeling somewhat similarly recorded by Dr. W. H. Collins about a quarter of a century ago.

Most of our research has been made possible by grants-in-aid from the Ontario Research Foundation, the Geological Survey of Canada, the National Research Council, and the McLaughlin Science Research Fund of Queen's University, all of which are gratefully acknowledged. For a considerable volume of analytical work by spectrographic, chemical and x-ray methods we are greatly indebted to Messrs. J. G. MacDonald and Frank Dunphy. Thanks are also due Dr. Gunnar Kullerud for permission to use his diagrams of the Fe-Ni-S system.

B. GEOLOGICAL PROBLEMS AND PREMISES

1. General Statement

It has long been evident that the greatest of our Precambrian ore deposits lie in areas of great geological complexity. This is especially true of the Sudbury district where, even after some 70 years, geologists are still debating the origin and ages of both rock formations and the ores themselves. There are few regions which can match it for seemingly contradictory evidence leading often to diametrically opposed conclusions and hypotheses. As Collins (1934) once said, it "furnishes a most interesting case of the painfully slow, caterpillar-like . . . way in which we grope . . . to an understanding of big and intricate geological bodies." There is of course no reflection on the work of the host of geologists who have participated. New data obtained with new tools are simply casting more light on the many events culminating in and following the deposition of these important ores.

The broader features of the geology of the district are well known. They were remarkably well portrayed by Coleman some fifty years ago and his mapping was astonishingly accurate, even considering the stage of development of the area at that time. Although some of his interpretations have required adjustment, it may yet prove that his main thesis of the magmatic character of the ores and their intimate association with the noritic intrusive, offers, with what amount to really minor modifications, a much more satisfactory explanation of the ores than any other.

Somewhat divergent views by Dickson, Gregory and later by Knight both as to the dyke-like character of the nickel intrusive and the hydrothermal features of some ores have remained unresolved except for interesting suggestions by Phemister (1925). The classical study of the north shore of Lake Huron and the Sudbury region by Collins & Quirke in the period 1925–1938, and later partial studies by Burrows & Rickaby (1934) and by Cooke (1946) added new details and ideas on both the regional geology and structure, while Yates (1948) presented still different interpretations of the rocks and the events more intimately associated with the ores.

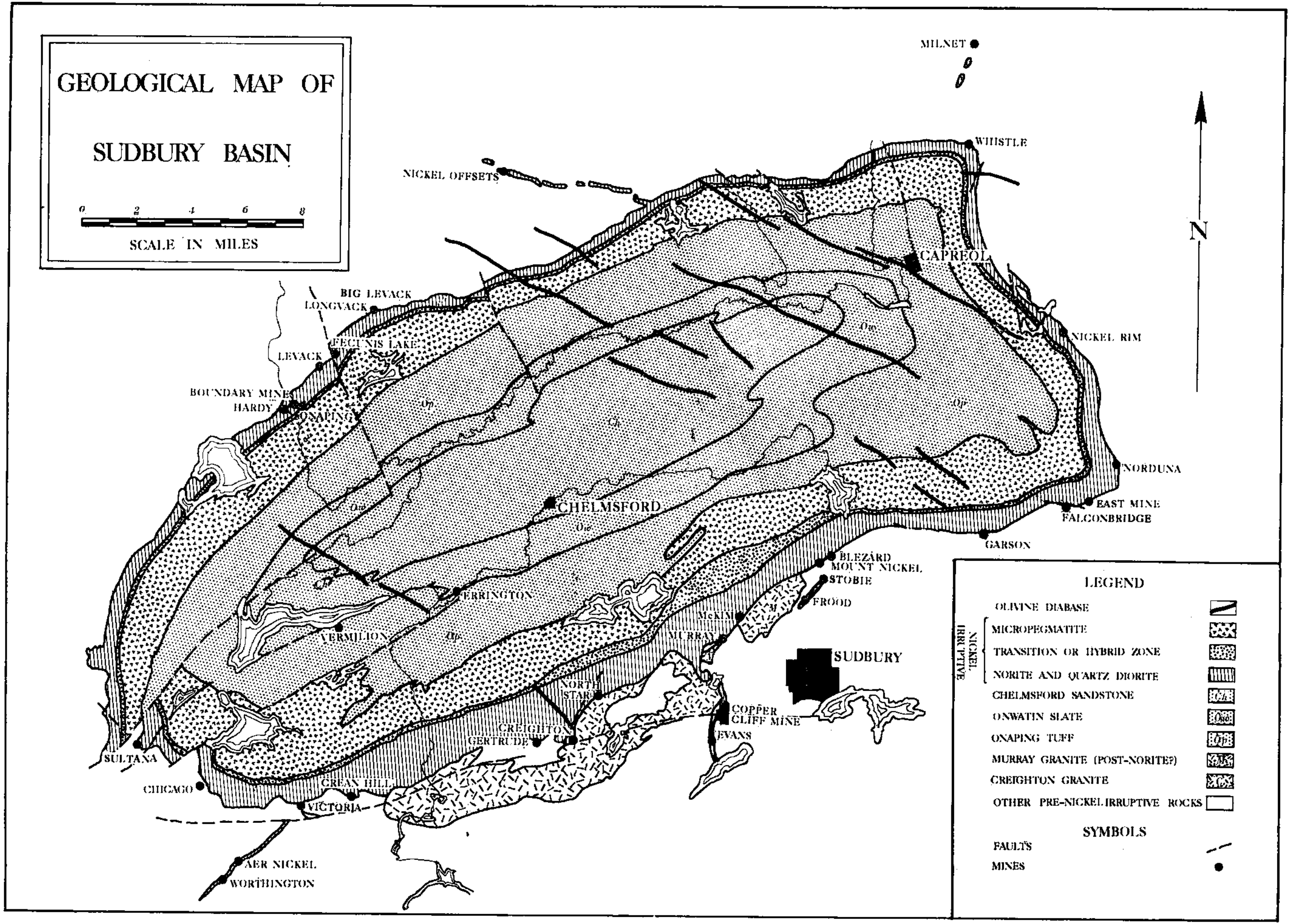

FIG. 1. Index map of the Sudbury Area showing the Sudbury irruptive and location of major deposits.

All of these were predicated on prevailing views of the major divisions of Precambrian history. With the advent of new dating techniques, our whole concept of Precambrian time has been tremendously enlarged and we know now that the history of this region embraces a time interval of well over 1000 million years, at least three major orogenies, and five or six periods of extensive intrusive activity. Within the last ten years, too, detailed mapping of what they regard as key areas has led Thomson, aided by Williams and Phemister, to present some very different concepts as to the sequence of events, although the full significance of these on the genesis of the ores has still to be indicated. Within this same interval it is apparent that Sudbury field geologists with their intimate and growing knowledge of critical areas, found reason to revise some of Yates' interpretations as to the timing of intrusions and brecciation, reverting essentially to the sequence of events envisaged by Coleman, though in a newer context. This is clearly indicated in Guide Books published by them (1953, 1957) and by the more detailed account of the geology at the Frood-Stobie Mine (Zurbrigg *et al.*, 1957).

A complete critical review of the general geology of the region is much beyond the scope of this paper, but it is imperative that some effort be be made to evaluate widely divergent expressions of opinion on those phases most intimately related to the period of ore formation in order to clarify the premises on which any theory of origin must rest. There are however few events in the complicated history of the area which are not involved in one way or another. In attempting such an evaluation we have consciously striven to avoid letting our conclusions based on mineralogical data unduly influence decisions on geological relations, but it is inevitable that the two eventually must be completely reconciled. This review will be made rather arbitrarily by discussing first, the relevant geological features displayed outside the oval shaped nickeliferous intrusive (or irruptive),[1] those occurring within the basin, the intrusive itself, and finally, the late Precambrian features imposed on the area as a whole. Some familiarity of the reader with the general geology of the region is assumed. A tentative table of formations and events, modified after Thomson (1956–60) and Fairbairn (1960), will assist in following the discussion.*

[1]Coleman (1905) referred to the norite-micropegmatite as the "eruptive," but this was later changed to "irruptive" by Collins, the term used more recently by Thomson. The latter will be followed here, as it is useful to have one name for the layered body.

*According to the new time classification given by Lowdon (1961) the following changes should be made in Table 1. Early Precambrian = Archaean, Middle Precambrian = Lower Proterozoic, ending with the Hudsonian orogeny, and the formations of Late Precambrian are correlated with the Middle Proterozoic. No members of the Late Proterozoic are known in this area.

TABLE 1. TENTATIVE TABLE OF PRECAMBRIAN EVENTS AND FORMATIONS SUDBURY DISTRICT
(modified after Thomson & Fairbairn)*

	System	Group	Formation outside Sudbury Basin	Formation inside Sudbury Basin	Orogeny and orogenic events
LATE PRECAMBRIAN	Keweenawan		Olivine diabase and trap dykes(1020 m.y.)	Olivine diabase dykes	Grenville (1000–900 m.y.) Development of metamorphic complex south of Grenville front, faulting and intrusion basic dykes, brecciation of trap
			(Late galena-sphalerite mineralization) (1200 m.y.)	?	——? Faulting and late mineralization with sphalerite, pyrite marcasite ("Secondary hydrothermal")
MIDDLE PRECAMBRIAN	Huronian		Aplite and minor granite (part of Murray, Creighton ?) Local remobilization of ore		Penokean—post-norite brecciation; intrusions moderate folding, faulting of Huronian formations. 1600 m.y. (partly obscured by later Grenville orogeny (?)
			Sudbury irruptive micropegmatite—norite, quartz diorite; Magmatic copper nickel ores. ($\gg$1700 m.y.)?	Sudbury irruptive micropegmatite and associated dykes	
					Initial sagging of Sudbury Basin
		Whitewater (=Animkean?)		Chelmsford-Arkose greywacke Onwatin slate (?) Onaping volcanics—tuffs, breccias	

*See Lowdon, J. A. (1961) for new time classification.

	System	Group	Formation outside Sudbury Basin	Formation inside Sudbury Basin	Orogeny and orogenic events
			Common Sudbury breccia		Pre-norite brecciation and faulting
			Erosion interval (?)	Erosion interval (?)	Erosion interval (?)
			Gabbro (Nipissing diabase) (≫ 1800 m.y.) ?		Pre-gabbro brecciation
			INTRUSIVE CONTACT		
		Cobalt	Gowganda formation—conglomerate, argillite, quartzite, limestone	Quartzite (?)	
			Unconformity		Erosion interval
	Huronian (Middle and Lower	Bruce	Mississagi formation quartzite, conglomerate (uraniferous)	Quartzite (?)	
			GREAT UNCONFORMITY	?	Great erosion interval
EARLY PRECAMBRIAN	Pre-Huronian		Granites Murray (in part) Creighton Birch Lake Wanapitei (2060 m.y.)		Algoman (or Kenoran) (folding and intrusions)
			INTRUSIVE CONTACT		
		(Whitewater ?)		Chelmsford Onwatin Onaping {volcanics, tuffs, breccias} (?)	
			Copper Cliff rhyolite (Intrusive Contact)		
			Wanapitei quartzite	(? Quartzite)	
		Sudbury	Ramsey Lake conglomerates		
			McKim greywacke		
		Keewatin type	Stobie (Elsie Mt.) acid and basic volcanics and interbedded sediments		

2. Features Outside the Nickel Irruptive

Surrounding the nickel irruptive which forms the rim of the Sudbury basin, is a great variety of rocks, almost every unit of which has presented a problem of one type or another. Extending southward for some miles is an apparently conformable series of steeply dipping and southward facing meta-volcanics and interbanded sediments. These continue part-way along the eastern rim while the northeastern, northern and western borders are largely bounded by granite and granite gneiss. Five to ten miles south-east of the basin is the "Grenville Front."

(*a*) stratigraphy and intrusives

Problems in the rocks south of the norite have been ones of stratigraphy and correlation, the nature and origin of the Copper Cliff rhyolite, and the ages of the intrusive granites, particularly at Creighton and Murray. The oldest Precambrian (Pre-Huronian) Stobie series adjoining the norite consists dominantly of basic volcanics (Elsie Mountain), minor rhyolite, rhyolite breccia and interbedded greywacke. This is followed southward by the Copper Cliff "rhyolite" and the McKim formation which Phemister (1956) feels is essentially the same as the greywacke on the north. This formation contains quartzites with argillaceous partings and is noted by Phemister as also having a basic flow and a rhyolitic flow breccia. In turn this formation is succeeced by conglomerate (Ramsey Lake) and massive quartzites (Wanapitei). Though formerly correlated in part with the Keewatin and Sudburian (=Timiskaming) and in part with the Lower Huronian, recent mapping by Thomson and associates (1960) suggest they are a continuous succession, all facing south and of Pre-Huronian age, overlain unconformably, both at the southwest corner and the eastern end of the basin, by infolded and, in places, faulted, uraniferous basal conglomerates and quartzites of the Lower Huronian (Mississagi). Scattered outliers of the latter formations occur at the southwest corner of the irruptive, in granitic areas to the west and north, and overlie older sediments on the east side of the basin though in places, in faulted contact with them. Further detailed work on the south side of the irruptive appears necessary to ensure that the uraniferous Lower Huronian does not grade laterally into the non-uraniferous Ramsey Lake conglomerate and overlying quartzites, as relations may be obscured by faulting and Thomson most recently has left the area south of the Murray fault, where this conglomerate occurs, as "unclassified Precambrian." The distribution of the uraniferous conglomerates, however, indicates clearly that Huronian sedimentation at least took place on all but perhaps the south side of the basin. As there seems no marked difference between such sediments at both east and west ends there seems no good reason why they may not have extended completely around the basin. On the south side, if they are not represented by the Ramsey Lake formation and Wanapitei quartzites, more complete erosion would easily account for their absence, especially as this area is believed to have suffered considerable uplift and thrust faulting during the Grenville orogeny. If this is so, the question remains as to whether or not the Lower Huronian also covered the area now occupied by the irruptive and Whitewater formations within the basin, but from which they would necessarily have been largely removed by erosion in pre-Whitewater time. Alternatively, both the Bruce and Cobalt groups may never have been deposited over the basin area, if for some reason it remained a high land or island in the Huronian seas. The solution to this problem depends of course on the final interpretation of the age of the formations within the basin and the structures which produced it and need not further concern us here.

South of the irruptive detailed mapping by Phemister (1956) of the much-debated Copper Cliff rhyolite lying between the older, dominantly volcanic rocks on the north and the McKim greywacke on the south has led to the interpretation of this as a hypabyssal intrusive, dated recently by Fairbairn as 2200 million years. A relation between this intrusive and the Onaping volcanics within the basin has been suggested, which could only hold if the latter are of Keewatin type and age.

Intrusive also into this Pre-Huronian system are the intriguing coarser-grained granite stocks at Creighton, Pump Lake and Murray, as well as the unquestionably younger, prolific post-Cobalt gabbros and diorites (Nipissing diabase)[2]; the nickel irruptive and offsets, post-norite granite (?) and aplite, and still younger trap and olivine diabase dykes of Keweenawan (1020 m.y.) age.

(*b*) THE GRANITE PROBLEM

Since it has been contended by one author (Sullivan, 1957) that post-norite granites have somehow been responsible for the development of the ores along the contact, on the one hand, and by another (Yates, 1948) that they have intervened at least between the intrusion of the norite and "offset" quartz diorites, (a view not shared by later field geologists) it is of particular importance to establish their age. Along the south range, from both the Creighton and Murray granite stocks, granite or granite-like dykes appear to extend continuously northward into norite.

[2]An age determined for these by Fairbairn is 1800 m.y. Ginn (1960) reports ages of micas considered as metamorphic products of the diabases, of ±1425 m.y.

Yet the Creighton mass is clearly cut by the Copper Cliff offset of quartz diorite which extends southward from a funnel-like projection of norite and is now generally considered as either as altered equivalent or a definite phase of the norite. To explain the anomaly Collins (1936) suggested remobilization and injection of granitic material during and slightly after the intrusion of norite. Yates, believing the quartz diorite a distinct intrusive and later than the norite, rejected Collins' idea and considered the granite intrusive into the norite, and the quartz diorite intrusive into the granite. Both from discussions with geologists in the field and some personal observations, it appears that the quartz diorite though often a mappable unit is certainly in many places gradational from "norite," so Yates' view, as has been recognized for some time, is no longer tenable. Moreover, the composite nature of both the Creighton and Murray granites as "largely pre-nickel-intrusive in age with some post-nickel intrusive granite . . . " has also been indicated (Guide Book, Sudbury Area, 1957). For details we are indebted to Speers who examined these bodies and associated granitic dykes in very great detail, distinguishing as many as six different types of granitic rocks in the former. As his well documented report was not completely published prior to his untimely death, and as the data are pertinent in this discussion, a summary of his findings is included here.

The bulk of the Creighton mass is composed of gneissic and massive, coarsely porphyritic granite while other varieties are less extensive and dyke-like in character. That the two major types are pre-norite and pre-quartz-diorite is indicated by (1) the norite and quartz-diorite in places have fine grained margins against coarse granite; (2) no dykes of exactly these types have been found in the more basic rocks; (3) the granite is extensively brecciated while adjacent norite is not; and (4) the norite has imposed a metamorphism on the matrix of the brecciated granite as indicated by the development of pyroxene and a coarser grain which decrease with distance from the contact.

Four types of granitic dykes cut the Creighton mass and each other: a black "porphyry," a grey granitic type, a variable, grey to pink type, and pink pegmatitic dykes. The first three of these also cut the norite and quartz diorite while the fourth seems confined to the main granite stock. Of these the black "porphyry" most resembles the porphyritic granite save for its dark matrix. It is found along the margin of the norite and extends as dykes from the granite into the norite for varying distances, and in places for as much as 2500 feet. It contains inclusions of the granite, angular near the contact, rounded farther away, and fragments of individual feldspars with crushed corners, identical to those in the porphyritic granite. Within the granite they grade or in places pass more abruptly into typical "breccia dykes" of granite by increase in the number of enclosed fragments. Within the norite they truncate sulphide zones and are post-sulphide in age. They are interpreted as injection "porphyritic" breccias, forced into the norite along fractures or shear zones, the matrix of which has suffered recrystallization and metasomatic replacement as evidenced by the development of unfractured oligoclase, considerable scapolite, carbonate, epidote and fine biotite.

The gray "granite" dykes have a distinct metamorphic texture and a composition essentially the same as the matrix of the black "porphyries." They also form the matrix for injection "breccia dykes" with abundant greenstone inclusions, but in places are so free of fragments they have the appearance of magmatic granite dykes. They are the type which locally appear to granitize the norite. The fifth type, gray to pink "granite," differs from the fourth, chiefly in its content of poikilitic microcline and pinkish colour. Both cut the norite, quartz-diorite, and sulphides, and all four types showing this relation are regarded as injections of brecciated granitic material[3] which has undergone varying degrees of recrystallization and metasomatic replacement, rather than dykes of truly magmatic fluids. In essence this is a modification of Collins' hypothesis and we accept the pre-norite age for the main granite from which the granite-like dykes have been formed.

The Murray and the similar, smaller granite east of Pump Lake have long been considered post-norite, again on the basis of continuous granite dykes extending northward into the norite. Though outcrops are not everywhere continuous this relation is amply confirmed by surface and underground maps of mining properties along this contact. On the other hand dykes also extend southward to the great Frood breccia zone where they are themselves broken and brecciated. The continuation of these have never been found cutting the quartz diorite which intrudes the breccia (Zurbrigg *et al.*, p. 343, 1957), although extensions are known still farther south beyond it. Such relations can only be explained by the occurrence of two ages of granite.

Speers' detailed study of the Murray body and dykes appears to confirm this. The bulk of the Murray granite he considers older than the norite. This is extensively brecciated and has certain distinctive differences compared with an unbrecciated or less brecciated granite zone, 30–600 feet wide along the norite contact, from which the dykes, which vary within themselves, extend northward. Somewhat similar material is found within the older phase but it has not been possible to show in detail their precise relations. The older granite is a pink, medium grained

[3]Fairbairn *et al.* (1960) assigns an age of 1.6–1.7 b.y. to this period of brecciation, apparently post-norite.

equigranular rock consisting dominantly of microcline perthite molded around quartz, irregular grains of oligoclase (An 28), minor subhedral albite, brown biotite, titanite, epidote and zircon (hyacinth). It is relatively free of foreign inclusions compared to the dykes. Two types of breccia occur within it, one with a fine grained dark matrix, similar to the common Sudbury breccia found elsewhere (see below), the other with a sand-coloured matrix which is the product of either recrystallization or granitization of the dark type. Both the granite dykes in norite, the sand-coloured granitic matrix and small granitic dykelets bridging dark matrix contain graphically intergrown quartz and microcline, considerable myrmekite, green biotite and/or blocky amphibole. Grain size is usually irregular and proportions of minerals in different dykes vary from place to place.

What appear to be inclusions of the older granite in the unbrecciated northern border zone and also within the norite have been noted, and in the latter case have been altered largely to plagioclase. That the older granite is pre-norite is also substantiated by Zurbrigg (1957) in his descriptions and maps of the Frood-Stobie and by Fairbairn's recent age determinations. There is thus no question that both an older and a younger granite are present. How much of the younger granite is magmatic and how much is metasomatic, like that appearing in the matrix of breccias in the main body to the south, is not known. It seems possible the younger material may represent an end stage in the emplacement of the norite-micropegmatite, though it should be borne in mind an orogenic disturbance recorded by Fairbairn *et al.* (1960) is noted in the older body at 1.2–1.3 b.y. When it is possible to map the younger body in detail (with associated post-norite dykes) a new name should obviously be assigned, reserving "Murray" for the pre-norite body as used at present by Sudbury geologists. That the younger granite is of some significance with respect to certain ores will be indicated later in discussing the granite-norite contact here and a peculiar pyrite-pentlandite ore body found within the granite of the McKim mine.

Turning westward now to the southwest corner of the basin we find the Birch Lake granite adjoining the norite and swinging north and northeasterly along the northern contact of the irruptive. Collins logically suggested that this much larger body of batholithic dimensions, was very probably connected with the Creighton mass by virtue of their similarity, relatively short distance apart, and a smaller satellite between. Cut by the Foy offset (quartz-diorite) to the north, in Bowell and Foy townships, the Birch Lake granite bears the same relation to this rock as does the Creighton. Accepting the equivalence of the quartz-diorite and norite (see further below), the Birch Lake granite is pre-norite.[4] Both recent age determinations in Drury township (1900 m.y.) and the occurrence of outliers of uraniferous lower Huronian conglomerate lying unconformably on it (Thomson, 1961), confirm its pre-Huronian age. It is to be noted, however, that in the Agnew Lake area, (S.W.) Thomson recently states there is some evidence for a post-Huronian granite as well.

At this point we might interject that though all three granites are considered pre-nickel irruptive and pre-ore, they are not necessarily of identical age. The Creighton and Birch Lake, containing in places, abundant greenstone inclusions, may be in part products of granitization, though the porphyritic varieties seem clearly magmatic. The similarity of the two, noted above, is confirmed to some extent by detailed studies by Ginn (1958) of the trace elements and heavy minerals in each. The Creighton and Birch Lake granites both contain a low content of magnetite and the malacon variety of zircon in contrast to the Murray granite which has nearly 1 per cent magnetite and a hyacinth type of zircon. The Creighton mass contains acicular apatite, rarely euhedral, fluorite equal in amount to the zircon and apatite combined, and a higher amount of vanadium and chromium than either of the others. Sphene is present in the Murray and Birch Lake while garnet (and minor allanite, Ginn, 1960) was only found in the latter. The Creighton and Murray contain similar traces of Cu, Ni and Co and more Cu and Ni than the Birch Lake. Each mass thus has its own characteristics but it is difficult to indicate precisely how these have been acquired.

Still other granitic rocks occur on the east side of the norite. These are described by Thomson (1960, 1961) as hornblende syenite and "massive pink granite grading into syenite and aplite" (the Wanapitei granite) and are placed as pre-Huronian and pre-"norite."

Fewer details are available on the granitic gneisses and granite along the northerly contact of the irruptive where, according to Mitchell & Mutch (1957) at the Hardy mine, mafic and granitic gneisses grade into grey granite or occur as fragments in it to form a granite breccia. Pegmatite dykes in the granite contain some chalcopyrite. Gneiss and granite also occur abundantly in an extensive breccia zone, the Levack breccia, along the norite (quartz diorite) contact. This breccia has a coarse matrix close to the norite but finer, farther away. While the gneisses seem clearly products of granitization of pre-existing more basic rocks, there is the further problem of determining just what these were originally, and why

[4]Ginn, R. M. (1960) studied the Birch Lake "granite" in some detail in Porter Township, shows it is intruded by Nipissing gabbro, and obtained K/A age of 2150 m.y. ($\pm$100 m.y.). He classifies the Birch Lake mass as quartz monzonite.

rocks within the irruptive, if pre-Huronian, were not also similarly affected.

In addition to the granite rocks discussed above, throughout the norite of both north and south ranges are abundant, usually narrow dykes of aplite. These usually lie about at right angles to the outer norite contact but always die out before they reach the actual contact or neighbouring ore. Farther within the norite they may parallel the contact. They are clearly post-norite. In places they are mineralized with pyrite and calcite and have been considered as pre-ore (Mitchell & Mutch) but this seems doubtful and their exact source has not been determined.

(*c*) THE SUDBURY BRECCIAS

Ranking in interest, both geologically and economically along with the nickel ores and the nickel irruptive are the Sudbury breccias of great variety and probably several ages, so extensively developed around the periphery of the basin and for some miles beyond. Had these been amenable to detailed mapping in their entirety as was the irruptive itself, they would have illustrated this unique characteristic of the Sudbury area, as in fact they do, and left a more lasting impression on all who have studied the area. They have of course been noted by early workers including Coleman and Collins and have been the subject of local studies by Yates (1938), by Fairbairn & Robson (1941), Cooke (1946) and Thomson (1957). At Frood-Stobie, Zurbrigg *et al.* (1957) have illustrated the character of the most outstanding breccia in the area and indicate its age as post (Murray) granite and pre-quartz diorite. A comprehensive investigation was also made by Speers over a three year period, but only a part of his research has been published (1957).

Although there are many examples of "normal" types of breccia in the area, such as volcanic and fault breccias in highly deformed brittle rocks, those referred to here have been known as "crush" breccias or the "common Sudbury breccia" and are characterized usually by a fine-grained dark matrix. The great majority, as shown by Speers, are pre-norite, but rather rare examples exist of post-norite age, and even these appear to be remobilized, pre-norite breccias forcibly injected into the norite in a few places on both the south and north ranges. Outside the irruptive they pervade all the pre-norite rocks—volcanic, sedimentary, granitic and gneissic. For the most part they are missing in the formations within the basin[5] and in the norite-micropegmatite itself, except where

[5]One exception here is possibly the breccia at the base of the Onaping formation, interpreted recently by Stevenson (1961) as a tectonically-transported quartzite breccia (see p. 18 below).

engulfed by it along the outer border to form "inclusion norite"[6] or quartz-diorite breccia. Their general distribution around the basin has been illustrated by Speers (1957), the most outstanding example being the great Frood breccia zone extending for many miles.

Though described in some detail by several authors, a short summary will not be amiss here. Many breccia zones are linear, following or slightly truncating contacts of different formations and great "fault" zones, up to a mile in width, as at Frood, but showing little lateral displacement. Others border the cross-cutting Foy, Worthington and Copper Cliff offsets and are partly engulfed by the quartz-diorite in these. Many are highly irregular in form, "repeatedly branching" and ramifying through their host rocks in every direction. They consist of sub-angular to rounded inclusions of all sizes, some as large as 2600 feet by 400 feet, dominantly of adjacent or nearby host rocks, against which they commonly present sharp, clean contacts. In places also, erratics are present which must have travelled some distance. These are set in fine grained matrices which vary in colour and composition both with the character of the dominant rock types present and their comminuted fragments, and with the intensity of metamorphism, including some metasomatism and even granitization, which has been imposed upon them, especially in proximity to the norite contact. Thus, in those with a dark matrix speckled quartz with fine opaque sulphides or oxides, fine biotite, or white mica have developed, and in others, poikilitic and porphyroblastic oligoclase, scapolite, clinopyroxene, amphiboles, epidote, and even granophyre and microline appear, but show a definite zonal relation to the norite, the intensity of the metamorphism, decreasing away from the contact. Details are contained in Speers' well documented thesis and need not be repeated here. Compared with the host rocks, the matrices appear enriched in places in soda, in others in potash, and also in V, Cr, Mn, Co, Ni, Mn, Mo, Pb and also in free carbon (up to 0.57 per cent). Most, on the whole, are surprisingly low in water which is reflected by the amount of micaceous minerals present.

Though perhaps formed over a considerable period of time, as noted above, the bulk of the breccias are considered pre-norite and pre-quartz-diorite in age.[7] Like other age relations at Sudbury, even this has been

[6]This is the view of Speers. At Falconbridge, D. R. Lochhead (personal communication) restricts this term to norite with sub-angular feldspathic inclusions, and "quartz diorite breccia" to that phase of the norite with foreign inclusions. Inclusions in both phases may also have been acquired from sources other than the Sudbury breccia.

[7]Peculiarly this age (>1700 m.y.) has not been confirmed as a period of orogenic disturbance in the Sudbury area, possibly due to the imprint of two subsequent orogenies. See also Zurbrigg *et al.* (1957).

much debated. Their relation to the extensive Sudbury gabbro (Nipissing diabase) is somewhat less clear and depends on whether they are all of one age or not. There is no question that some breccias cut and inject the gabbros, and gabbro fragments abound in some breccias along such bodies. In other cases some gabbros have been observed by several, intruded into "crush breccia" zones, so, unless the period of gabbroic intrusions overlapped the brecciation, some pre-gabbro brecciation must have occurred. The apparent absence of such breccias in the Onaping-Chelmsford (Whitewater) group of pre-norite-micropegmatite rocks within the Sudbury basin is as difficult to explain as is the absence of granites of any size, if these groups are the equivalent of the oldest rocks outside the basin, when one considers the distribution of the breccias on all sides.

The origin of the Sudbury breccias is of particular interest because of the ores some of them contain. This has recently been reviewed by Thomson, (1957), and clearly must have involved tremendous widespread crackling and heaving of the various rock types, including even granites and gneisses, around the periphery of the basin, with the opening and closing of fractures, perhaps many times, aiding, no doubt, in the further comminution of rock fragments to smaller sizes. Absence of large scale fault movements is indicated by continuity of the stratigraphy and lack of shearing, though movement within the breccia zones is obvious from the disorientation and rounding of fragments, the presence of erratics from some distance away, flow structures in some of the matrices and injection in places of nothing but matrix in the narrow tapering ends of many fractures. That water or water vapour may have played an important part in rendering the fine matrix and enclosed fragments fluid seems most probable. The relative dearth of hydrous silicates in many places may be due to the low temperature at which such a fluid was formed originally, or perhaps more logically to the fact that in places, near the later intrusive rocks, a high temperature metamorphism (in the extreme up to the pyroxene-hornfels stage) was later imposed. In essence, as Thomson notes, they may represent "abortive diatremes." This, however, hardly settles the question and we may ask what exactly caused such an extreme case of "diatreme" activity, whether or not "fluidization" . . . "from juvenile fluids" as noted by Reynolds, was a factor in the comminution of fragments, their movement and injection. Thomson suggests the breccias "are more closely related to local intrusions which could be the source of the gas fluxing as they worked their way upward . . .," referring to the widespread gabbro intrusions on the south and southeast of the basin. Against this, however, may be noted the rarity of such breccias in more remote areas where gabbros are present, and the apparent dearth of gabbros along the north rim of the basin. The uniqueness of the Sudbury breccias throughout the district has been emphasized. A second unique feature in this Precambrian area, at least on the scale developed here, is undoubtedly the occurrence around the inner rim of the nickel irruptive, in addition to quartzite breccias noted by Stevenson,[8] of great thicknesses of the unsorted Onaping tuff-breccias, interpreted by Thomson and Williams as glowing avalanche deposits which they believe arose from "elongate rhyolite domes of the Pelean type" and andesitic feeder dykes. Whatever their true character and actual source they give clear evidence of intense and violent explosive volcanic activity. Speers, accepting a younger Precambrian age for the Whitewater (after Collins and other Sudbury geologists, see Guide Book, Sudbury Area, 1957), logically related these two unique features both of which are pre-norite. If the nickel irruptive is removed as in pre-irruptive time, the volcanics would then lie in fairly close juxtaposition to the areas of most intense brecciation. Speers further found a rather striking similarity in many trace elements in the Onaping and Sudbury breccia matrices, including up to half of one per cent free carbon, though he cautiously avoided placing too much significance on this, as both such porous rocks might have acquired various trace elements later. Any such relationship, however, depends on the relative age of the volcanics.

Whether the forces leading to the injection of the nickel irruptive itself may be related to the widespread brecciation is also a question difficult to resolve. A spatial relation does exist between them as shown by footwall breccias of various types, quartz-diorite breccias and irregular bands or tongues of breccia which seem to have been caught up in the norite as at the Gertrude, Murray, and other places. The greatest breccia (Frood) is of course not right at the contact nor does it parallel the contact in dip. Until more precise details are available as to the form of the irruptive at depth and the structural history leading up to its emplacement, it seems futile to speculate further on the underlying causes of such widespread brecciation. The peculiar type of Onaping volcanism and the successive intrusions of gabbros and the nickel irruptive may well represent a significant sequence of events. It is recognized, of course, that in a region subjected to several orogenies breccias of many different ages may have formed and some of these may be virtually indistinguishable from the type referred to above.

[8]J. S. Stevenson (Abst. Royal Soc. Canada, June 1961) has recently confirmed the presence of quartzite and quartzite breccias along the south range at the base of the Onaping formation.

3. Features Within the Basin

Within the basin as elsewhere in the Sudbury district, the formations of the Whitewater Group present many amazing and puzzling features. Some of these bear somewhat on the manner of intrusion of the irruptive and hence on the mineralization.

Pre-irruptive in age, as shown by granophyric alteration of the basal formations in contact with the micropegmatite and by what Collins referred to as micropegmatite "offsets" in the roof of the irruptive, the group was first divided by Coleman into four formations, the Trout Lake "conglomerate," the Onaping volcanic breccias and tuffs, the Onwatin slate and the Chelmsford "sandstone," all of which were portrayed as having a rather simple synclinal structure.

Burrows & Rickaby (1929) concluded that the irregularly disposed Trout Lake "conglomerate" was a rhyolite breccia and essentially a part of the over-lying Onaping formation, a conclusion with which Collins (1934) and Cooke (1946) later concurred. More recent mapping by Thomson led to the view that most of the rhyolitic material of this formation represents Pelean domes and dyke feeders "from adjacent fissure swarms" along with associated andesitic flows, which were distributed "close to the present position of the nickel irruptive," and around the inner rim of the entire basin. "As volcanism continued the rapid accumulation of subaerial glowing avalanche deposits within the Basin (Onaping formation) quickly drained the magma chamber and caused large scale subsidence to form a volcanic-tectonic depression," (Sudbury Basin) (Thomson, 1956). Outside the basin volcanic activity was envisaged as giving rise to submarine lava flows, glowing avalanches and sediments to form the Stobie formation. The Whitewater group was thus considered the equivalent of the oldest volcanics and sediments outside the basin.

Still more recently Stevenson has given a contradictory opinion on the character and origin of the siliceous material at the base of the Onaping formation. On the basis of very close detailed mapping on the inner side of the south range he has shown this consists of a practically continuous formation of quartzite and quartzite breccia, considerably deformed, drag folded and sliced, particularly at the eastern end, and interprets the now isolated sections as "tectonically transported" quartzite breccia. Much of this formation has been albitized and altered to varying degrees along the micropegmatite contact, as noted earlier by others, so its composition in places may approach that of a rhyolite. The preservation of bedding and fine pebble layers in parts of the formation, however, confirms its original sedimentary character. The only known quartzites in the district lie outside the basin where there appear to be three. These are the pre-Huronian Wanapitei[9] quartzites, rare remnants of Lower Huronian Mississagi quartzites and those of the overlying Gowganda formation still farther away. To which group these quartzites belong has not been determined. Correlation with any one of them especially the Huronian would place the volcanic Onaping breccias and tuffs which overlie them and also contain quartzite fragments, as distinctly younger than the very early Precambrian Stobie volcanics lying just outside the basin.

The generally uniform distribution of the Onaping volcanics on all sides of the basin led Burrows & Rickaby to suggest a fissure feeder somewhere, but in addition, the Pelean type of rhyolite domes and dyke feeders described by Thomson along the north and north east rims may also represent vents for the so-called glowing avalanche deposits. Descriptions of Onaping volcanics have been so well given and illustrated by Burrows & Rickaby and by Thomson and Williams that further details need not be included here.

Lying above the Onaping and apparently of local distribution are peculiar carbonate, chert and argillite beds overlain in turn by the Onwatin slate. In the southwestern part of the basin the beds below the slate are hosts to the fine-grained copper, lead, zinc deposits of a non-nickeliferous variety, originally considered as a late stage of the nickel-copper mineralization, but believed by Thomson (1956–61) to have resulted from contemporaneous fumarolic activity. These strata pass inward and stratigraphically upward to the carbonaceous Onwatin slate and Chelmsford arkose-greywacke formed in the further subsiding "volcano-tectonic sink."

That the formational name Onwatin should be retained is strongly suggested by Sadler's (1958) study of drill core which indicates this slate has a thickness of at least 1000 feet and is a distinctly mappable unit even though faulting may have modified it to some extent. Drill core data also suggest the Onaping-Onwatin contact is, in places, a gradational one, and additional analyses of the slate confirm its similarity to and probable derivation from the finer grained portions of the Onaping formation.

In contrast is the overlying arkosic to greywacke Chelmsford formation with minor interbedded slatey layers and distinctive large calcareous and ferruginous oval concretions. Williams has suggested this was derived from more distant sources, from which one might infer it had formerly a much greater lateral extent.

[9]In Thomson's most recent paper *Extent of the Huronian System between Lake Timagami and Blind River, Ontario* (1961), he places the Whitewater as still pre-Huronian but above the Stobie and Wanapitei quartzite.

Intrusions in the basin are rare and minor in character though none-the-less significant. Some are granitic to syenitic, probably related to the micropegmatite; others occurring in slate are basic and usually highly altered and bear some resemblance to the Sudbury gabbro, though their sill-like character and local granophyric alteration suggested to Burrows & Rickaby a derivation from the norite-micropegmatite magma. Later Keweenawan olivine diabases cross-cut all other rocks, including the altered basic intrusives just described.

Structurally the basin rocks have undergone in places, intense folding and faulting, probably at different times and to some extent, certainly after the emplacement of the nickel irruptive. Thomson (1956) summarizes the structure of the Whitewater as "an elongated, basin-shaped, asymmetrical synclinorium, gently folded on the north, overturned on the south flank, and thrown into a complex system of minor folds in the interior." Some of the structures may be Penokean, others as late as the Grenville, but a synthesis of these must await more accurate dating of the formations involved and the true relations of the quartzite breccias, the Onaping volcanics and overlying sediments.

This is also important in assessing the significance of the distinctly different types of sulphide ores within and without the basin. Recent dating by Fairbairn, if correct, shows that neither the formations nor the nickel irruptive can any longer be considered Keweenawan and an age greater than 1700–1800 m.y. is indicated. While Thomson held that the Whitewater is the equivalent of the oldest Precambrian volcanics and sediments outside the basin and latterly that it is at least pre-Huronian, a younger, but still pre-Keweenawan age is considered possible by many. This is based primarily on what is still interpreted as the unconformable relation of the Whitewater to underlying pre-Huronian rocks, even though this is obscured by both the nickel irruptive lying between them, and overturning and faulting on the south limb of the basin, much of which may well be post-irruptive in age. Detailed mapping still seems to confirm the concentric outline of the formations and their original rather simple trough-like structure. The pre-Huronian basement rocks, on the other hand, are everywhere steeply dipping, extensively brecciated, granitized, and intruded by great bodies of granite and later gabbro. This condition obtains everywhere in the deepest mine workings where the norite dips inward at moderate angles. It must also have obtained at higher elevations in pre-irruptive time as shown by projections of the base of the irruptive and the less deformed Whitewater. The steeply outward dipping contact of the irruptive, as explained later, may be attributed to local faulting.

The quartzite and quartzite breccia at the base of the Onaping volcanics introduces a complication which cannot be settled until its age can be determined as pre- or Lower Huronian. There is, however, a great time gap of 300–500 m.y. between pre-Huronian rocks and the irruptive. Between the Huronian of the Lake Huron district and the Keweenawan, is the Animikean (Upper Huronian, 1700 m.y. Goldich *et al.*, 1961) in Michigan and Minnesota. If the Whitewater group is not pre-Huronian, the Animikean would seem to be the only logical place for it.

Against this it may be argued that elsewhere in the Lake Huron area no Animikean rocks are found above the Huronian, and volcanics are not common to the Animikean where it does occur.[10] Erosion of course could explain the first. The second, *per se*, hardly seems a valid objection, and one might equally well say, neither is there another Sudbury irruptive known in the Animikean.

On the contrary, though the sedimentary formations of the Whitewater differ from much of the Animikean of the Lake Superior region (slates and iron formation) they do resemble in certain respects the carbonaceous Thomson formation (Animikean slates and greywacke) in East Central Minnesota (Goldich *et al.*, 1961), and the Rove beds in Thunder Bay, in both of which calcareous concretions are developed over great distances. This is also a typical feature of the Chelmsford. Such lithological similarities may be of little significance but it can hardly be stated that the Chelmsford is unlike any other formation.

All of this bears on the emplacement of the nickel irruptive as will be discussed further below.

4. The Nickel Irruptive

The relation of the norite-micropegmatite, the irruptive, to the nickel-copper ores is so intimate that opinions on its origin and emplacement have had a vital bearing on theories of genesis of the ores. As a detailed study of this body was not a part of our investigation we shall merely record the different views as to the variations in its composition and structure, which are intertwined, and indicate those which we find most acceptable and with which we are able to integrate conclusions derived from the study of the ores themselves.

There are two main schools of thought. The one, by Coleman, Moore, & Walker and also Collins, considers the irruptive to have been intruded between the overlying Whitewater group of volcanics and sediments and the unconformable basement rocks below, as a single flat-lying sheet, differentiated in place by either crystallization or liquation (Collins) into

[10]James, H. L., (1958) notes two volcanic formations (basic flows and pillow lavas, in the upper half of what he now classifies as Animikean.

a basic norite and more acid micropegmatite, with contemporaneous segregation of immiscible sulphide liquids to the base, and subsequent subsidence of the central areas, aided by regional deformation, to bring it into its present position. The associated dyke-like, near vertical dipping, inclusion-ridden "offsets" represent fractures formed in the surrounding formations below the sheet, and filled or injected laterally or from above with magma which had acquired a quartz diorite composition, and sulphides with a more than normal volatile content. Sulphides which had segregated along the base of the irruptive, particularly in what were considered favourable embayments into footwall rocks, are thought to have remained liquid until deformation produced faults and brecciated zones along the footwall into which they spread. They were thus capable of migration and injection for some distance along favourable channels, controlled largely by the contact. Other effects of the norite include the development of a fine grained hornfels from adjacent basic lavas along the south range, a pyroxene-rich rock named "sudburite" by Coleman who had first classed it as an "older norite."

Wilson (1956), comparing the Sudbury body with the Bushveld complex and other lopoliths, noted similarities in their inward dipping surfaces and *layering* and suggested a funnel rather than a lens shape, concordant with the underlying formations only in places. This led to the further suggestion that deeper levels of the Sudbury intrusion are composed of ultra mafic members and his illustrations suggest the whole mass was fed from a central conduit or fissure. He thus significantly indicated at least that, with the layering dipping inward at more gentle angles than the footwall, the proportion of micropegmatite to norite as presently exposed, (on the south range 1 : 1, but on the north 3 : 1) is not necessarily a true representation of the facts and is entirely dependent on the section chosen, so that the true thickness may well be uniform on both sides. He further proposed that during intrusion of such a body great adjustments were necessary which resulted in development of the widespread Sudbury breccias. Later movements along faults he estimates caused the upthrusting of the south range by an amount of the order of 2–4 miles.

The opposing school (to Coleman *et al.*), represented early by Knight, Harker, Phemister, and latterly by Thomson, considers the irruptive a composite intrusion of first the basic norite (or gabbro, according to Phemister) followed quickly by the micropegmatite with formation of a variable hybrid zone between. Both petrographic and chemical evidence are cited to show the most basic and most acid portions are not at the very base and top respectively, that both norite and micropegmatite have fine grained contact phases, in places, and that the volume of the micropegmatite is much in excess of that to be expected from differentiation of an original gabbroic magma. A genetic relation between the two, however, is considered probable, and both may have stemmed from a layered magmatic reservoir at depth. With this concept, the need for the initial intrusion of the mass as a single flat-lying sheet, in order to differentiate, disappeared. Early structural observations by Knight and later by others, called attention to lack of evidence of post-intrusive folding and to the steep dips and dyke-like character (conformable in places) both at the southwest and southeast ends of the basin. This led eventually to the ring-dyke concept first enunciated by Knight and later by Thomson, who pictures the composite irruptive as intruded around the edges of a "ring-graben," following subsidence of the central basin, initiated by and subsequent to the outstanding Onaping volcanic activity, and possibly still further depressed or even modified as to dips by later orogenic disturbances.

For the past many years very detailed studies of the irruptive have been underway in the area and it would be presumptuous on our part to attempt to forecast the results. So little is really known about the actual configuration of the irruptive beyond about a mile of depth that theories here cannot but be speculative. There are, however, certain points that persist in current literature that need clarification or de-emphasis and it is essential that we state what seems the most acceptable view as to the general nature of the irruptive and its mode of emplacement, in the light of our own findings.

Reasons for the opposing interpretations are not hard to find. While the broad layering of the irruptive into more basic, intermediate and more siliceous bands has long been obvious, variations both in grain size and minerals within the bands are great and every casual investigator is aware of the difficulties besetting one in collecting truly noritic, and in places, even granophyric material. Within the "norite" very extensive areas have been altered either deuterically or by shearing to a rock which can only now be referred to as a quartz gabbro or diorite in which enrichment has occurred in secondary blue quartz, amphiboles and/or biotite. Away from such areas, however, there is no question that the rock is a *norite*, still showing fresh ortho- and clino-pyroxenes and basic feldspars. Similarly the intermediate, so-called "transition" or "hybrid" zone is seldom exactly the same in any two localities and differences cannot be solely explained by either differentiation by crystallization (Collins even suggested liquation) or hybridization and must have involved late-stage deuteric effects as well as deformation in places. While the upper, more siliceous layer of micropegmatite or granophyre seems more uniform, differences here may arise from the extent of granophyre developed in the overlying formations. Its gradational character from the norite, however, is suggested by the occurrence of some granophyric material in the norite itself. Thus it is that, with Collins, we feel there is little positive evidence that the irruptive consisted of two distinct intrusions. Some of the peculiarities in composition and grain size may reflect inflow of magma over a period of time, while others may be simply superimposed effects.

The most important evidence bearing on the question however, to our mind, is that noted by Wilson (1956) with respect to crystal layering within the irruptive. This seems to have been ignored by some later writers possibly because no specific occurrences were cited. Although we can not give precise details, we can report that in an address to geology and mining students, February 16, 1961, at Queen's University, H. F. Zurbrigg confirmed the fact that such crystal layering has actually been observed in at least two instances in the norite, and that where it has been possible to take measurements, the dip of the layering is flatter than the footwall.

The significance of this is readily apparent. As the crystal layering noted is a type formed by crystal settling, the shallower dip compared with the footwall contact should also obtain for the base of the most important layer, the micropegmatite. For this to occur the irruptive magma must have been introduced as one body, much in the form in which we see it today, and apparent variations in proportions of norite and micropegmatite, as noted by Wilson, and probably not real but a matter of geometry. The main argument for two intrusives may be thus eliminated.

Whether the magma was introduced in a lopolithic form, perhaps as a concavo-convex lens, or as a funnel shaped body as suggested by Wilson, we will not attempt to say. It undoubtedly extended some distance beyond its present limits, and as far as we can see was emplaced between a down-sagged rolling surface carved by erosion on the underlying basement of older Precambrian rocks and below the overlying quartzite breccias and the less deformed and metamorphosed Whitewater group. *For the most part* this surface dips moderately inward, but here and there, at the southeast and southwest corners, it changes sharply to a steeply outward dip, a change best explained by faulting after some differentiation had occurred, but before the norite was completely solidified, as suggested by Lochhead. Though the latter occurrences give the irruptive a more dyke like aspect, it must be emphasized, these are quantitatively minor features and must not be allowed to confuse the issue.

In retrospect, apparent "necessity" seems to have been "the mother of invention" time and again, in endeavours to explain the geology at

Sudbury. Thus Coleman at first considered the irruptive must have been intruded as a flat sheet in order to differentiate into micropegmatite, norite and ore, all of which were thought to have been subsequently folded or down warped. Later, the "ring dyke" and "multiple intrusive" hypotheses seem to have arisen as alternatives when it became apparent the irruptive had *not* been so folded and to explain both apparent discrepancies in proportions of supposed differentiation products and the apparent lack of an unconformity as the site of intrusion, the latter necessarily following from the classification of the Whitewater as part of the earliest Precambrian. New facts available and slightly modified older interpretations leave little necessity for either of the latter hypotheses.

There remain, however, problems relating to the composition of the intrusive as a whole, and especially the derivation of the quartz diorite and, most important, of the associated ores. The bulk composition of the original intrusive must at least have been capable of supplying by differentiation the known volumes of norite, quartz diorite, micropegmatite, and we believe, the ores. In this admittedly poorly-layered intrusive no unmistakeable chilled margin appears to have been recognized as part of the original magma. If there is any such phase present it can only be represented by the *quartz diorite* and many arguments may be given to support this idea. The quartz diorite seems always confined to the basal part of the intrusive and the underlying offset dykes. It is clearly more siliceous and of finer grain than the norite; it has been found completely gradational into norite though in places the transition is rather sharp. As might be expected of a primary magma injected along an unconformity or into fractures, it almost everywhere contains abundant rounded fragments of footwall rocks, ranging from amphibolites and gabbros and the like on the south range to granite and gneiss on the north. Moreover the general similarity of its composition to an average calculated for the combined norite and micropegmatite, as noted by Collins, is in keeping with such an origin. That it formed rather early in the history of the irruptive, rather than later by normal differentiation after some norite had accumulated, is indicated not only by its usual basal position with respect to the norite, but by its occurrence in the underlying offsets such as Frood-Stobie. There and in other offsets it can be shown to be intimately related to the time during which magmatic sulphide liquids were separating and settling from the silicate phase, both by its common association with disseminated sulphide blebs and by the newly described occurrence at Frood-Stobie of rounded to club shaped inclusions of silicate (quartz diorite or gabbro, some reported to contain ortho-pyroxene) enclosed in a continuous sulphide groundmass, both occurrences being regarded as products of immiscible sulphide and silicate liquids, described in more detail below. Certainly at Frood-Stobie the quartz diorite must represent magma introduced from the main intrusion above. This is confirmed by the fact that it pinches out at depth and also as shown later, by the peculiar type of zoning exhibited by its ores. At the time this solidified it had already attained essentially a quartz diorite or gabbro composition, but it is not possible to say that this was its original state, as some modifications may have arisen from the associated ore fluids. This does not necessarily imply that all offsets are of the same type, though Collins was inclined to the view they were fed from above rather than below, on the basis that feeder dykes would have been swept clear of inclusions.

On the other hand, as noted by Yates, the quartz diorite resembles a "re-made" rock, and in places has been extensively altered and amphibolitized. It seems possible such a rock may have arisen from more basic material either by assimilation of acidic rock fragments prevalent in many breccias of the region which it would be expected to envelop along with more basic types now predominating in it, or, as noted above, by acquisition of silica and other volatiles acquired with the sulphide ores it so commonly contains.

Around the margins of the irruptive, and within the zone of observation available at present, as far as we are aware, there is at least no evidence supporting the very early crystallization of more basic silicates such as olivines or pyroxenes alone, to give ultrabasic layers. True these might have settled to much greater depths, but some indications of them might be expected both along shallower dipping contacts and in the downward projecting offsets. Whatever its bulk composition (and that of a quartz gabbro or diorite is favoured) it would appear to have been essentially saturated with sulphides so that before any appreciable crystallization occurred, immisicible sulphide liquids were able to settle vertically downward toward the footwall contact and into offset fractures to give segregations of massive sulphides which must have displaced any silicate liquid originally there. Above these ores, in places, are found the mixed silicate-sulphide ores and disseminated sulphide blebs in either quartz diorite or norite, as described in more detail below, especially along more gently dipping contacts which have not been controlled by faulting. Lack of such sulphides along some of the higher basement "ridges" or on the steeply dipping portions of the contact may simply reflect the downward draining of immiscible sulphide liquids to depressions or flatter dips below. From material gathered on several traverses, Harcourt (1933) determined the relative distribution of nickel across the irruptive and found the most basic portions contained the most nickel, present in fine scattered specks of nickeliferous pyrrhotite. In a similar study Stonehouse (1954) found that nickel decreased from ~200 ppm. to ~80 ppm. in a distance of about 500 feet from the contact. It may thus be suggested that the major segregation of the sulphide liquids, though by no means all of them, occurred prior to the crystallization differentiation of the remaining magma above into norite and eventually micropegmatite. Discussion of the history of such sulphide liquids to form many different types of ore is deferred to a later section, but the spatial and time relations of both disseminated ores and "immiscible silicate-sulphide" ores newly reported from Frood-Stobie, are accepted as prime facie evidence of their derivation from the irruptive magma.

In general, then, the irruptive is considered to have been intruded much as we find it today, along a somewhat rolling surface, dominantly dipping inward and locally outward, paralleling faults or underlying formations. Early separation of sulphide liquids by liquation, some of them mingling with the quartz gabbro (diorite) magma, is believed to have been followed by later crystallization differentiation to give the norite (with some sulphides) and micropegmatite layers. Post-irruptive orogenies, the Penokean and Grenville (Table I) have undoubtedly affected the intrusive, and great thrust faults which displace it and pass through the centre of the basin may have been responsible for the elevation of the southern range with respect to the north. Within the irruptive, faulting and uplift rather than folding would appear to have been the main result.

5. Post-Huronian and Late Precambrian Features

To the west along the north shore of Lake Huron, in Michigan, Wisconsin, and Minnesota, what are there dated as Huronian formations, including Animikean, were affected by the Penokean orogeny (1700 m.y.) accompanied by some granitic intrusions. Goldich *et al.* believe this extended eastward through Ontario and into Quebec. It seems possible the moderately folded Blind River–Elliot Lake syncline was developed at this time. In the Sudbury area and to the north of it, folding and faulting of remnants of the Lower Huronian are known, and may conceivably have affected the Whitewater and other rocks of the district, as well as the irruptive. Fairbairn has noted an orogenic effect including brecciation and an imprint on the Onwatin slate at 1680 m.y. Lack of any undisputed Animikean sediments in the area, and the effects of later orogenic disturbances at 1200 m.y. and particularly the Grenville at 1000 m.y., make it impossible at present to indicate with any certainty those structural features attributable to the Penokean. The same applies to such post-lower Huronian granites as may be present in both the Murray mine area and near Agnew Lake.

The disturbance indicated at 1200 m.y. is represented by the deep fractures mineralized in places with late galena and sphalerite which cut through many nickeliferous ores. No other features have yet been related to it.

That many of the structures, especially great fault zones in the Sudbury area, lying a relatively short distance northwest of the Grenville Front, are related at least in part to the Grenville orogeny is shown or suggested by the apparent displacement of parts of the Front on such faults (see Fig. 1 Thomson, March, 1961), by their northward overthrust character, and by the relation of late trap and diabase dykes to them. The great Cameron Creek (re-named Vermilion by Thomson) fault through the central part of the basin is regarded by Thomson as possibly the sole of a great series of thrusts from the south. That these orogenies would leave some imprint on the ores is certainly to be expected, and it is rather surprising that effects are not more obvious than they appear to be. It seems not improbable, however, that much of the apparently contradictory evidence of age relations of the rocks involved may be due in part to effects produced during this stage in their history.

The only late Precambrian rocks in the region, other than minor late granites consist of trap and olivine diabase dykes, both of which require description because of the relation to the ores.

Narrow trap dykes are found throughout the footwall formations, the breccias and the norite, and even penetrate the ore bodies at least for short distances (Knight). In both breccias and ore they are broken in places into isolated segments, suggesting a pre-breccia and pre-ore age, but most observers now agree that these are post-ore and account for their local fragmentation by subsequent deformation and flowage of surrounding material into the breaks. Similar trap dykes have been described recently by Phemister (1961) in the nearby Grenville metamorphic complex where their discontinuous nature is attributed to intrusion while shearing was active along the north easterly trending faults. If these dykes are all of one age the implication is clear that some Grenville orogenic effects have been superimposed on the ores.

The many W.N.W. trending olivine diabase dykes are the youngest Precambrian rocks of the district and are dated as Keweenawan. That some follow faults is well shown by Thomson's map of Falconbridge township (Map No. 1957–5) where they crosscut all other formations and even the north easterly trending faults with no deviation. Several of these dykes cut through ore deposits without any indication of displacement other than separation, and locally appear to have engulfed some sulphides, and in small fractures within the dykes, pyrite and pentlandite have been deposited. As will be detailed later the dykes have had little apparent effect on the ore except possibly slight redistribution of silver and lead.

In the foregoing an endeavour has been made to review the geological history of the region and to resolve some of the conflicting views. For a summary of this the reader is referred to Part III where the more pertinent features are dealt with as a prelude to our interpretation of the formation of the ores.

effects of two or more orogenies and many periods of intrusive activity. Finally, from a more practical standpoint, though by no means new and perhaps hardly required, we may emphasize what has long been common practice, that the search for ore in this area continue along the norite contact, particularly where changes in dip occur. There seems no reason why ores should not continue in suitable structures to depths well below mining limits, nor for that matter, why other offsets may not be present in footwall rocks, difficult though they would be to find beneath the irruptive cover.

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