H. M. A. Rice

5

CANADA

DEPARTMENT OF MINES AND RESOURCES

MINES AND GEOLOGY BRANCH

GEOLOGICAL SURVEY BULLETIN

No. 3

PROBLEMS OF SUDBURY GEOLOGY, ONTARIO

BY

H. C. Cooke

OTTAWA
EDMOND CLOUTIER
PRINTER TO THE KING'S MOST EXCELLENT MAJESTY
1946

Price, 25 cents

CANADA

DEPARTMENT OF MINES AND RESOURCES

MINES AND GEOLOGY BRANCH

GEOLOGICAL SURVEY BULLETIN

No. 3

PROBLEMS OF SUDBURY GEOLOGY, ONTARIO

BY

H. C. Cooke

OTTAWA
EDMOND CLOUTIER
PRINTER TO THE KING'S MOST EXCELLENT MAJESTY
1946

Price, 25 cents

CONTENTS

CHAPTER IV

CHAPTER V

CHAPTER VI

Illustrations

PREFACE

Few mining districts in the world have attracted more sustained attention during the past 50 years than that of Sudbury, Ontario. Interest has, of course, centred on its mining activities, which supply some 90 per cent of the world's nickel besides a large tonnage of copper, important amounts of silver and gold, and Canada's only production of platinum and allied metals. To the geologist, as well, the region has provided problems of outstanding structural, stratigraphic, and petrographic interest, many of them either directly or indirectly concerned with the genesis and disposition of the nickeliferous deposits. Gratifying progress has been made towards the solution of some of these problems; others have proved more elusive, and final decisions may be long delayed.

The present report is concerned with the interpretation of certain features bearing on the sequence of events that contributed to the deposition, structural arrangement, and lithology of the successive sedimentary series laid down in this region in Precambrian time, and with the various volcanic and intrusive rocks with which these are associated. It presents significant new structural data, and results in some considerable rearrangement of the sedimentary and igneous successions. The report carries a bibliography of earlier related publications, and follows in some detail the progress of geological research since the discovery of the Sudbury ores. Field studies on which the author's conclusions are based were undertaken in 1938 and 1939, but subsequent diversion of effort during the war years has delayed their publication. Two geological maps, those of the Chelmsford and Falconbridge areas, within which most of the author's investigations were conducted, are being prepared for separate publication on a scale of 1 inch to 1 mile.

GEORGE HANSON,
Chief Geologist, Geological Survey

OTTAWA, August 28, 1945

PROBLEMS OF SUDBURY GEOLOGY, ONTARIO

CHAPTER I

INTRODUCTION

General Statement

The late Dr. W. H. Collins, Director of the Geological Survey, devoted such time as could be spared from administrative duties during the later years of his life to the revision of the geology of the Sudbury district, Ontario. This he intended to be the capstone of the great work to which his life had been devoted, namely the mapping and correlation of the Huronian formations throughout the region from Cobalt to Sault Ste. Marie. At Sudbury he had completed the preliminary mapping of the Espanola, Copper Cliff, Falconbridge, and Chelmsford areas, together with a detailed study of the internal and external relations of the great Sudbury norite irruptive, when death claimed him in January 1937. He had published the results of his study of the norite irruptive (31-34) [1], and had dealt with some special problems of Sudbury geology (35), but had prepared no comprehensive report on the area, doubtless because many details of structure and succession had to be studied further before such a report could be written.

After his death it was found that the manuscript of the Copper Cliff and Espanola maps had been compiled, and they were, accordingly, published. It was then decided to have a field officer check the manuscript mapping of the two remaining sheets and prepare them also for publication, at the same time continuing the study of the problems of the district. The writer was selected for this purpose.

Before entering the field, a close scrutiny both of the published and unpublished maps made it evident that there were problems remaining to be solved before the structure and succession could be thoroughly understood. After entering the field, unexpected and unsuspected facts were found that seemed likely to alter previous conceptions as to the Precambrian succession. The investigation of these problems is not yet completed; but as the onset of war caused the work intended for 1940 and later years to be indefinitely postponed, it seems desirable to report on the results to date. This report is not intended to be a discussion of the geology of one or more particular map-areas; it is intended rather to supplement Collins' classic report on the geology of the north shore of Lake Huron (29), and should be read in conjunction with it. It deals purely with a number of problems that arose, with their suggested solutions, and with observations that supplement the original information given by Collins on the various formations of the district. The report deals wholly with the geology and structure of the various sedimentary and igneous rocks. No attempt was made to study the great norite irruptive, except as regards its contact relations with other rocks. No examination of the ores has been made, outside of an effort to determine their age.

Working with Collins' published maps and manuscripts, on which most of the outcrops and geologic boundaries are laid down with great accuracy, the writer was able to devote all his attention to the geological problems, and to go at once to critical areas where exposures that might offer solutions of

---

[1] Numbers in brackets refer to the numbered papers listed in Chapter VI, Bibliography, pp. 75-77.

them could be found. Work was further facilitated by the open character of the country, due partly to logging and forest fires, and partly to the killing of all vegetation by sulphur fumes before the present smelter stacks were erected. Thus, with a minimum of work and time, a very large number of pertinent facts were obtained.

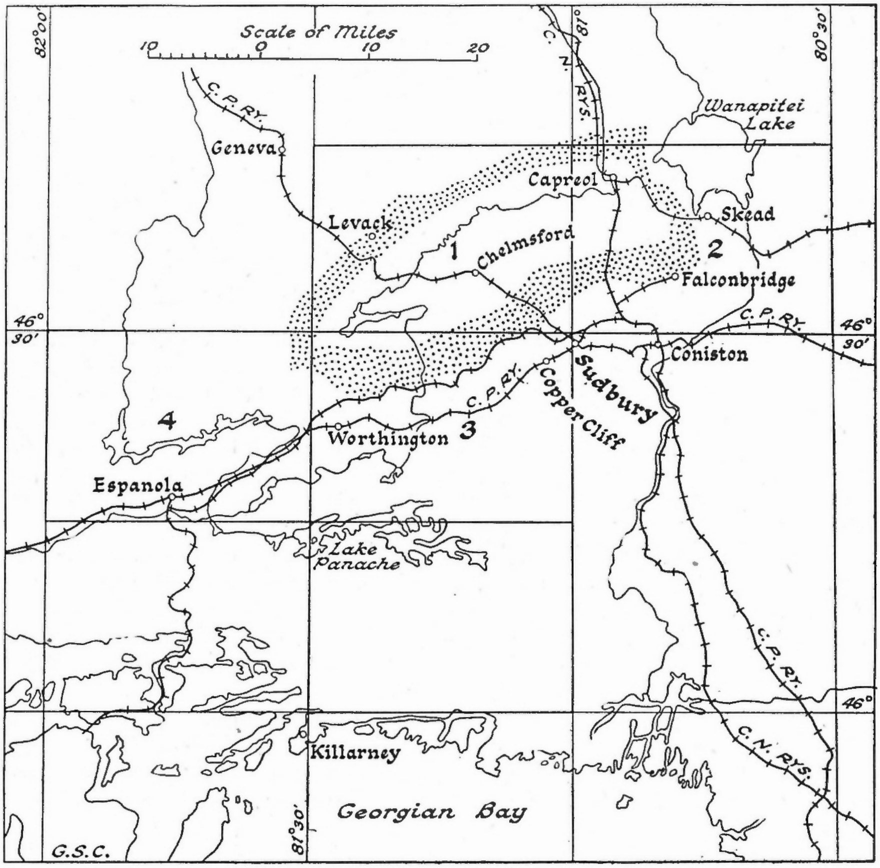

Figure 1. Index map of Sudbury district, to show principal map-areas referred to in text, and their positions relative to the norite irruptive. 1, Chelmsford sheet; 2, Falconbridge sheet; 3, Copper Cliff sheet; 4, Espanola sheet. Area of norite irruptive stippled.

The positions of the various map-areas here mentioned are indicated on Figure 1. In addition, a great deal of attention was paid to the Coniston area in the unmapped corner between Wanapitei and Copper Cliff areas. Street and Scadding townships, in the eastern part of Wanapitei area, were mapped in 1938 by H. W. Fairbairn for the Ontario Department of Mines, and his results are incorporated in the map of Falconbridge area[1].

The writer was ably assisted in 1938 by Mr. D. R. E. Whitmore, and in 1939 by Messrs. Whitmore, Don Mackenzie, and Gaetan Michaud. The writer expresses his thanks to the officials of the International Nickel Company and Falconbridge Nickel Mines, all of whom did everything in their power to facilitate his work.

---

[1] Maps of the Falconbridge and Chelmsford areas are being issued separately from this report by the Geological Survey, and incorporate the conclusions drawn by the present writer.

PREVIOUS WORK

The first general mapping of Sudbury district was that of Robert Bell (6), who in the 3 years 1888-90 covered an area 72 by 48 miles, with the Sudbury basin in the centre. In this preliminary work, undertaken while the district was heavily forested and almost entirely without roads, Bell mapped with considerable accuracy the sandstones, slates, and volcanic breccias of what is now termed the Whitewater series, and separated the other rocks into three main groups, the Huronian rocks, the granites, and the greenstones. The latter comprised mainly what are now known as the norite and Nipissing gabbro. Bell did not distinguish clearly between the micropegmatite of the norite irruptive and the other granitic rocks of the region, and hence missed the fact that he was dealing with a single basin-shaped intrusive mass; his map does show clearly, however, the basin shape of the Whitewater sediments.

T. L. Walker, Bell's assistant in 1890, became chemist at the Murray mine in 1891, and made detailed petrographic studies of the rocks of the district. In 1897 he presented the results (72) in the form of an inaugural dissertation to the University of Leipzig, as part of the requirements for the degree of Ph.D. In this he advanced evidence to indicate that the norite irruptive consists of a lower part, which for the first time was identified as norite, and an upper, acid part that he called micropegmatitic granite; and that the contact between the two is gradational. He noted further that the norite and micropegmatite of the northern and southern "ranges" face in opposite directions, with the micropegmatite always next to the elliptical area of sediments. He advanced the idea that the arrangements were due to differentiation in place of bodies of magma, without, however, inferring that the two "ranges" were parts of a single body; and he was the first to suggest that the Sudbury copper-nickel ores settled out of these bodies of magma.

In 1901-2 A. E. Barlow studied and mapped a section along the south boundary of the norite irruptive and made fairly detailed examinations of many of the working properties. His report (3) affords an excellent history of mining operations in the region, with a review of the literature on the subject. Barlow strongly supported the view that the ores were formed primarily by gravitative differentiation from the norite magma, and adduced much evidence favouring it; although he also admitted considerable rearrangement by later solutions and vapours.

In the years 1902-4 A. P. Coleman made his classic study. In his first map and report (14) he showed that the north and south "ranges" are only parts of a continuous elliptical ring. This ring he interpreted as the exposed rim of a single basin-shaped sheet 37 miles long, 17 miles wide, and about 1½ miles thick, the hollow of which is filled by the sedimentary series first mapped by Bell, and now termed the Whitewater series. He found that the gradation from norite to micropegmatite, described by Walker, exists around the entire basin, with the norite everywhere forming the outer or lower part. From the study of all the ore deposits he developed apparently convincing support for the concept suggested by Walker, and elaborated by Barlow, that the ores separated out of the cooling igneous mass into depressions at its base and into fissures beneath it (offsets); though the main process was admittedly modified by the later action of solutions or vapours.

Later, Coleman gave more detailed study to the other rocks of the region (19). He referred the banded gneisses southeast of Wanapitei River to the Grenville series; placed the Copper Cliff "arkose", the McKim greywacke, and the Wanapitei (afterwards Mississagi) quartzite in the Sudbury series, the age of which he considered pre-Huronian; and separated the areas of conglomerate now known as the Ramsay Lake and Bruce conglomerates and assigned them to the basal Huronian. It is clear that he considered these conglomerates to be correlative with others to the west and northeast, which have subsequently been recognized as the Cobalt conglomerate; and that it was this correlation that necessitated his conclusions that the Ramsay Lake and Bruce conglomerates must be much later than the folded rocks with which they are associated. Finally, he referred the Whitewater sediments to the Animikie or Upper Huronian.

For the next 15 years little geological work was done in the district, and that little was devoted mainly to the differentiation of the norite irruptive and its relations to the ores. C. W. Knight (54, 55), from chemical analyses of specimens collected at regular intervals across the intrusive, showed that there is no regular gradation in composition from one edge to the other, but that, on the contrary, a fairly sharp change occurs about the middle; he also emphasized the fact that the sulphides have almost invariably replaced the fine-grained matrix of crush-breccias, leaving the larger rock fragments unreplaced; and that these larger fragments include pieces of norite. He was thus among the first to adduce evidence indicating that the ores might be much later than the norite, instead of settling out of it.

In 1924 T. C. Phemister spent the summer studying sections across the norite irruptive and examining the relations of the norite to the ores. His conclusions (61) on both were much the same as Knight's; and he added to our knowledge the important fact that the norite and micropegmatite are each of fairly uniform composition, and are separated by a very narrow contact or transition zone. The abruptness of the change led him to conclude that the two rocks are separate intrusions, rather than differentiates of a single magma as previous writers had thought. Petrographic resemblances and the lack of any sharp contact he explained by assuming that both had come from the same reservoir of magma, the micropegmatite being injected while the norite was still hot.

This attack led Coleman and Walker, along with E. S. Moore, to revisit Sudbury and review their earlier evidence. In so doing they made four traverses across the intrusive, collecting forty-nine specimens, all of which were chemically analysed. These analyses indicated that the break between the norite and the micropegmatite is more gradual than Phemister had inferred from his microscope work. The writers concluded (23) that there is, in their opinion, no reason for denying their earlier conclusion that the norite and micropegmatite are differentiates of a single body of magma. They also reaffirm their opinion that the ores separated from the same magma.

In 1925 W. H. Collins entered the Sudbury field. Prior to this time (1908-12) he had mapped and traced the Huronian formations throughout the Gowganda mining division and Onaping map-area; this work (26, 28), together with that simultaneously carried on by officers of the Ontario Department of Mines, completed the geology of a block extending from Cobalt to within a few miles of Sudbury district. At that time (1912) Collins endeavoured, by examination of a narrow strip, to carry through the correlation into Sudbury district, but with unsatisfactory results (25, p. 302; 27), as this hasty work led him to correlate the Ramsay Lake conglomerate with the Cobalt series, and the Mississagi quartzite with the Copper Cliff "arkose", conclusions that he later silently abandoned. It was not until some years later that the block between Onaping area and the eastern part of Sudbury district was mapped by T. T. Quirke (63).

Collins then turned his attention to the original Huronian area near Sault Ste. Marie, mapped between 1847 and 1858 mainly by Alexander Murray with some co-operation from Sir William Logan. The years 1914-17 were spent by him in this district, and in addition independent work was done in 1915 by T. T. Quirke, in 1922 by Pentti Eskola of the University of Helsingfors, and in 1923-24 by R. C. Emmons of the University of Wisconsin. The results are published in Memoir 143 of the Geological Survey (29).

Collins commenced work again in 1925 with the mapping of Espanola map-area (30), and between that year and 1935 mapped the entire Sudbury district, comprising the Espanola, Copper Cliff, Chelmsford, and Falconbridge map-areas (*See* Figure 1). Collins also studied in great detail the transition from norite to micropegmatite. His earlier work had firmly established the fact that there are two Huronian series north of Lake Huron, as Murray originally found; the upper he identified with the Cobalt series of Onaping district, and the lower he termed the Bruce series. For each of these series he established a definite and recognizable succession of formations.

By tracing the basal conglomerate of the Bruce series eastward from Thessalon to Sudbury, he was able to prove it identical with the formation previously termed by Coleman the Ramsay Lake conglomerate. The same work proved that the Mississagi quartzite of the districts farther west is continuous with Coleman's Wanapitei quartzite in Sudbury district. This work, therefore: (1) corrected Coleman's erroneous correlation of the Ramsay Lake conglomerate with the Cobalt conglomerate; (2) proved that the Ramsay Lake conglomerate and Wanapitei (or Mississagi) quartzite are conformable and parts of the Bruce series; and (3) broke up Coleman's pre-Huronian Sudbury series into two parts, the upper of which was of Lower Huronian age (Bruce series), whereas the remainder, comprising the McKim formation, the Copper Cliff "arkose", and certain lavas, was undoubtedly pre-Bruce. For reasons more fully developed in a later section of this report, Collins looked on these formations as pre-Huronian as well as pre-Bruce.

Collins' unpublished manuscript map of Falconbridge area shows, in addition, that he correctly identified certain bodies of conglomerate in Falconbridge and Dryden townships as the Bruce conglomerate, a formation overlying the Mississagi quartzite, whereas Coleman and others had considered them as Ramsay Lake conglomerate.

By this great undertaking, carried through to a successful conclusion, Collins finally completed the identification and correlation of the Huronian formations throughout northern Ontario; and thereby laid a firm foundation for Precambrian stratigraphy. Though much still remains to be done to fill the gaps untouched by him, his work has supplied the basic elements of structure without which no forward step could be made. Future writers will no doubt make minor changes in his correlations, or differ from him as to various rock relationships, but his work will remain the strong warp on which further results must be woven.

Collins' other principal work in Sudbury region was the intensive study of the norite irruptive and its relations to the surrounding rocks (31-34). His work led him to conclude that Walker, Coleman, and others of the same school were correct concerning the differentiation of the intrusive and the origin of the ores.

In 1929 A. G. Burrows, Provincial Geologist of Ontario, began work in the Sudbury field, and continued it until 1932. His death in 1933 interrupted his work before the results were ready for publication, but his map and a brief statement of some of his results were published (11) after his death by H. C. Rickaby, who had assisted in part of the field work and who succeeded to the position of Provincial Geologist.

Burrows studied in some detail the Copper Cliff formation, which Coleman had considered a recrystallized sediment and had termed "arkose". Burrows recognized that it exhibits the flow lines, spherulitic textures, and other features of a volcanic rock. A better name for it is, therefore, the Copper Cliff rhyolite, by which it will be known in this report.

Burrows also recognized the fact that the lavas and the various sedimentary formations lying to the south of the norite mass are parallel to and apparently conformable with one another. His detailed mapping not only proves the conformity, but shows that the lavas and sediments are interbedded. These relations apparently made it impossible to accept Collins' conclusions as to the Bruce age of the Ramsay Lake conglomerate and Wanapitei quartzite, although these were known to him; hence, he somewhat doubtfully classed the whole succession as Temiscamian (?).

Burrows also emphasizes a number of facts indicating that the sulphide ores are much later than the norite, rather than differentiates of it and concludes, very definitely, that they are not related to the norite in the manner supposed by Coleman and those that follow him.

In 1931 the International Nickel Company of Canada established a geological department of its own, under the capable direction of A. B. Yates. Besides making thorough studies of the relationships found in the various mines, the geological corps has completed a large-scale plane-table map of the entire margin of the norite irruptive and the rocks for a considerable distance from it. A recent paper by A. B. Yates (74) outlines the results of an intensive investigation of the composition of the norite, micropegmatite, and the transition zone between them. Further results, described in detail, demonstrate that the offsets, supposed by Coleman and others to be dykes protruding from the norite body, really are quartz diorite, a rock of very similar composition but of much later age. The sulphide ores are closely associated, in all instances, with these bodies of quartz diorite rather than with the norite.

RESULTS OF THIS INVESTIGATION

The work of the writer, which deals particularly with the sedimentary rocks of the district, clears up many of the discrepancies found in the earlier work. It has been established that a great fault lies at the base of the Copper Cliff rhyolite, and continues westward through the area of sediments previously considered as McKim formation. To the north of this fault lies the complex of interbedded sediments and lavas observed by both Collins and Burrows, and named by the writer the Stobie group. South of it are the Copper Cliff and McKim formations; and as all previous writers have noted, there is no visible unconformity between them and the basal beds of the Bruce series. The recognition of the distinct break between these formations and the beds of the Stobie group no longer makes it necessary to conclude, as Collins did, that the McKim is pre-Huronian; or, as Burrows did, that the entire succession, including the Bruce, is pre-Huronian. The McKim and Copper Cliff formations can now be placed naturally as parts of the Lower Huronian succession, locally developed beneath the Ramsay Lake conglomerate. The Stobie group is probably pre-Huronian.

In addition, the writer has discovered two remnants of pre-Huronian formations, which he terms the Hill and Coniston groups. Their position in the stratigraphic column is otherwise unknown, but the discovery of the Coniston group may have an important bearing on the problem, discussed by Collins and Quirke (64), of the disappearance of the Huronian.

The preceding discussion of the changing views as to the succession of the sedimentary rocks of the district may be clarified by showing, in parallel columns, the formations as the various writers have viewed them. For the sake of greater simplicity the igneous rocks are omitted.

Coleman	Burrows	Collins	Cooke
Post-Laurentian Animikie Whitewater series	Whitewater series	Late Precambrian Whitewater series	Keweenawan Whitewater series
Huronian Ramsay Lake and other conglomerates		Huronian Bruce series Serpent quartzite Espanola formation Bruce conglomerate Mississagi quartzite Ramsay Lake conglomerate	Lower Huronian Bruce series Serpent quartzite Espanola formation Bruce conglomerate Mississagi quartzite Ramsay Lake conglomerate McKim formation Copper Cliff rhyolite
Pre-Laurentian Sudbury series Wanapitei quartzite McKim greywacke Copper Cliff arkose Sudburite	Temiscamian (?) Sudbury series Wanapitei quartzite Ramsay Lake conglomerate McKim greywacke Copper Cliff arkose Greenstone-sediment complex	Pre-Huronian Sudbury series McKim formation	Pre-Huronian Stobie group, Coniston group, Hill group
Grenville series Rocks south of Coniston		Keewatin Copper Cliff formation Transition zone lavas McKim lavas	

The foregoing table also brings out the fact that both Collins and the writer place the Whitewater series in the stratigraphic sequence later than previous workers had done. Collins, in a paper published not long before his death (33, pp. 50-53), indicated that he had recognized the existence, at the base of the Whitewater series, of a great unconformity. One cannot read his statement without feeling that he intended, after fuller consideration, to enlarge on its implications. The writer's observations abundantly confirm this earlier work. The unconformity, fully described later, seems to represent a time interval sufficiently long for the erosion of some 30,000 feet of hard sediments. The recognition of a gap of such magnitude enforces several rather drastic revisions of previous conceptions of Precambrian succession.

CHAPTER II

SURFICIAL ROCKS

TABLE OF FORMATIONS

Quaternary	Sands, gravels, lacustrine silts	
	PRECAMBRIAN	
Keweenawan	Olivine diabase (equigranular dykes) Trap (dykes) Killarney, Murray, and Creighton granites Norite and micropegmatite	
	Whitewater series	Chelmsford sandstone Onwatin slate Onaping tuffs and lavas
	Period of erosion	
Upper Huronian (Animikie)	Olivine diabase (porphyritic dykes) Birch Lake granite (?) Nipissing diabase[1]	
	Intense folding; possibly granitic intrusion	
Middle Huronian	Cobalt series:	Gowganda formation
Lower Huronian	Bruce series	Serpent quartzite Espanola formation Bruce conglomerate Mississagi quartzite Ramsay Lake conglomerate McKim formation Copper Cliff rhyolite
	Granite intrusion; probably folding	
Pre-Huronian	Stobie group: conglomerate, quartzite, greywacke, basic lavas Hill group: greywacke Coniston[2] group: conglomerate, quartzite, basic greywacke	

CONISTON GROUP

It has been known for many years that the strongly folded but otherwise relatively unmetamorphosed Huronian strata south and east of Sudbury, Ontario, are in contact on the south with a complex comprising granite, granite-gneiss, and intensely metamorphosed sediments. Coleman (19) considered the granites to be Laurentian, and placed the sediments in the Grenville series. Later, Quirke and Collins (64) showed that the granites cut the Huronian

---

[1] Many bodies of gabbro and amphibolite cut the Stobie series, and may be pre-Huronian in age, but as there is as yet no definite means of dating them they are provisionally grouped and mapped with the Nipissing diabase.

[2] Nothing is known of the age relations of the Coniston series to the Hill group or the Stobie group.

strata, and are, therefore, probably Killarnean in age; and, south of the area under consideration, in the region east of Panache Lake, Quirke found intensely metamorphosed remnants of sediments that, he showed, might be parts of the Bruce and Cobalt series caught up in the granite. In fact, he looked on the granite itself as formed in large part by the remelting of Huronian sediments. Still later, Collins (35) recognized that the rocks south of Coniston, here termed the Coniston group, are older than the Bruce series, and he correlated them with the Sudbury series. It is evident, therefore, that a correct determination of the nature and age of these rocks will have an important bearing on the problem of the "disappearance of the Huronian".

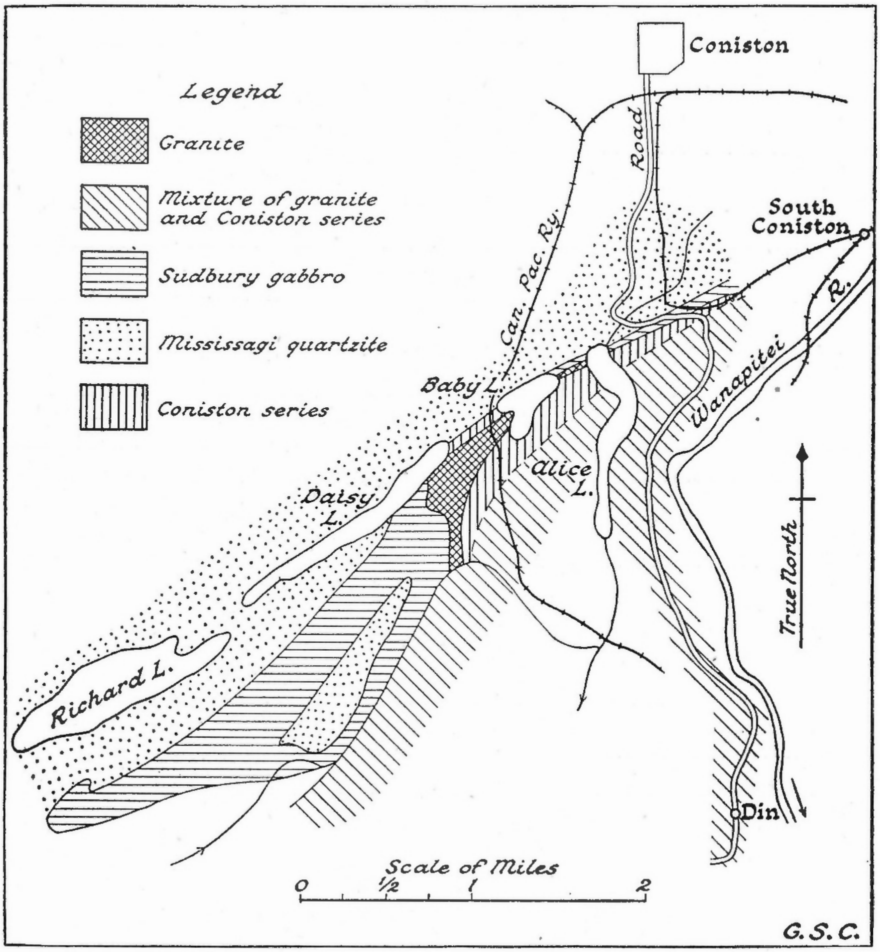

Figure 2. Sketch of areal relations of rock formations south and southwest of Coniston.

The writer's studies of these strata have convinced him that they have no resemblance to those of the McKim formation, or to the Mississagi quartzites, and that they cannot have been formed by the metamorphism of either. It is, therefore, suggested that the new name, Coniston group, be given to them, as the best exposures are near Coniston village.

The least metamorphosed beds of the group are found about 1½ miles south of Coniston, and form a band ranging in width from nil to a few hundred yards, extending west to Daisy Lake, a distance of about 2 miles. On the south the band is intruded and granitized by a great mass of Killarney granite. Large and small masses of the more or less granitized rocks of the group were found in the granite as far south as Wanup, as far west as Wavy Lake, and eastward beyond Wanapitei Village. These, however, were merely the limits of the writer's examination.

South of Coniston the rocks of the group are found on the south side of the valley through which runs the railway from Coniston to South Coniston. The valley at its narrowest is only about 300 feet wide, and on the north side, to be presently described, are the Mississagi quartzites. The most northerly beds of the Coniston group here are thin-bedded cherts with an exposed width of about 70 feet. South of them lie about 60 feet of dark basic beds interbanded with more thin-bedded cherts. South of this in turn is the Killarney granite. To the west, between Baby and Daisy Lakes, the width of chert beds is some hundreds of feet.

Although both the cherts and the basic beds have undoubtedly suffered recrystallization, the thinness, uniformity in width, and perfect parallelism of the banding combine to render it difficult to conclude that the banding is other than original bedding.

The chert bands range in thickness from $\frac{1}{40}$ inch to 3 or 4 inches, but many of the thicker bands are made up of a multitude of thin parallel laminæ. In the thinner bedded parts, the rock is white or reddish with a cherty texture; the layers are interbanded with thinner layers of fine-grained, somewhat softer, dark material of more slaty appearance and hardness. The thicker beds, those up to 3 or 4 inches, appear a little coarser in hand specimen, more like a very fine quartzite. In grain, in thickness, and in the character of the lamination, these beds are entirely unlike either the Mississagi quartzite of any strata seen in the McKim formation. It is interesting to note that they do seem to resemble the published descriptions of the so-called "iron formation" of the Grenville series in southeastern Ontario [1].

The microscope shows the chert to be an unusual rock, made up of parallel plates of quartz separated by narrow bands of white mica and colourless chlorite. The cross-sections of the quartz plates, as seen in thin section,have dimensionssuch as 0·12 × 0·02 mm. This quartz-mica groundmass surrounds approximately equidimensional crystals of albite and microcline, up to 0·2 mm. in diameter. The feldspars constitute between 5 and 10 per cent of the thin section, are fresh, and display little sign of strain; and the directed texture of the groundmass either passes around them or tends to do so. Some large micas are also present, which appear to have been crushed. It is inferred from the above facts that the feldspars, and perhaps also the large micas, were introduced by granitizing solutions from the nearby granites.

The writer has no explanation to offer of the extraordinary texture of this "chert". The parallelism of the fibrous or platy texture with the bedding seems to indicate that it was not an original chalcedonic fibrosity, as such would usually lie at right angles to the bedding. It has probably been produced by recrystallization of the siliceous beds under pressures exerted at right angles to the fibres.

---

[1] Miller, W. G., and Knight, C. W.: The Pre-Cambrian Geology of Southeastern Ontario; Ont. Bur. Mines, Rept. 22, pt. 2, pp. 25-26, 43-44 (1914)

The thicker beds of more granular appearance seem to owe that appearance to more extensive granitization and recrystallization. Only a little more than half the rock is quartz, in grains and elongate crystals of all sizes up to 1·5 mm., arranged in crudely parallel bands about 0·4 mm. wide. The remainder is fresh potash feldspar with a few crystals of mica. The feldspar in places occurs in strings of more or less widely separated crystals; in other places it forms bands. The nature of the feldspar and its freshness suggest that it was introduced by solutions from the granite, which at the same time may have recrystallized the quartz into larger grains.

The basic beds south of the cherty beds are 4 to 10 feet in thickness, and are separated in places by a few inches or feet of the cherty beds. The basic beds are hard rocks, so dark grey as to be almost black; some of them weather to rusty tints. Examined closely, they are seen to be made up of fairly regular laminæ, the more basic of which are one-fortieth to one-twentieth inch thick, the less basic about one-eighth inch. The microscope shows the rock composed entirely of minerals formed from the original constituents by recrystallization. The principal minerals are a green, strongly pleochroic hornblende, brown biotite, and a plagioclase about Ab_{85} in composition; considerable pistacite, a little magnetite, and one crystal of garnet were also observed. The above-mentioned minerals are found in all the bands, but the proportions vary from one band to another.

The width of the basic beds together with the small amount of inter-banded chert totals about 60 feet, beyond which sill-like masses of granite begin to appear in the sediments. These range from a fraction of an inch to many feet in thickness, and their appearance is accompanied by greatly increased granitization and recrystallization of the sedimentary beds. It was interesting to note that in many instances the granitizing solutions appear to have followed certain beds very closely, producing hybrids containing numerous large (2 mm.) metacrysts of feldspar, but without destroying the original bedding. If the beds are traced along the strike the metacrysts become fewer and smaller as the granite is left behind.

All these strata strike about north 75 degrees east, and dip south at angles ranging between 45 and 60 degrees. Cleavage-bedding relationships observed on the thin slaty layers between the cherty beds indicate that the beds face south. This conclusion was confirmed by the discovery of two drag-folds that plunge 30 degrees to the west and indicate upward movement of the south side.

Relations to the Bruce Series

On the north side of the 300-foot valley, as previously stated, the Mississagi quartzite outcrops as a prominent hill (Figure 2). This hill is cut off by a creek valley from the main ridge to the north, but exposures across the creek valley are almost continuous. On the hills exposures are magnificent, because fumes from the Coniston smelter have killed all vegetation, and years of exposure to the elements have removed most of the soil.

North of the creek the Mississagi quartzite has its normal aspect. It lies on edge, in beds a foot or more thick, separated on the weathered surface by shallow grooves eroded along the softer, slightly more argillaceous layers that separate the beds of purer quartzite. These beds strike north 50 degrees east, dip vertically, and face toward the northwest, as indicated both by excellent crossbedding and by the slaty cleavage of one or two softer beds.

Approximately the same relations are maintained to the creek. At the crossing of the railway and the creek several corroborative determinations were made. A change is seen, however, on the quartzite hill within the bend of the railway. Looking at the west end of this hill from a distance, the dip of the strata is seen to change from steeply northwest to steeply southeast, as in a tightly folded anticline. A closer examination, however, proves that the change of dip is caused, not by folding into an anticline, but by overturning of the almost vertical beds. After intensive search two places were found, both near the south side of the hill, where both the bedding and the cross-bedding are excellently preserved, and there can be no doubt that the strata continue to face toward the northwest. The strike in this part is north 30 degrees east, the dip about 80 degrees southeast.

The determination of the correct attitude on this hill is rendered peculiarly difficult by the intense shearing and jointing of the quartzite. This, it may be remarked, is found everywhere near its contact with the Coniston series, and in many places over large widths. Bands 2 or 3 inches wide of dark schist that in general parallel the bedding, but also cross it at small angles, cut the quartzite at intervals of a foot or so, and obliterate most of the original bedding planes so completely that most observations on crossbedding are valueless, because the relation of the crossbeds to the original bedding planes cannot be seen. Consequently, although crossbedding can be observed here in many places, only two could be found where the determinations therefrom are not open to question.

The bands of dark schist strike in general about north 30 degrees east, and poorly developed cleavage relationships observed in several places indicate that the east side moved upward relative to the west side. The conclusion is supported by the discovery, at the west end of the hill, of two faults. One of these strikes north and dips 50 degrees east, the other strikes north 20 degrees west and dips 60 degrees east. In both cases characteristic beds cut by the fault can be identified, and in each case the east side is thrust upward over the west side for a distance of 2 or 3 feet.

The Mississagi quartzites, therefore, not only strike more northerly than the beds of the Coniston group, but they face north whereas those of the Coniston group face south. Consequently, either the valley is the axis of an anticline, or the locus of a fault. If it were the axis of an anticline, the beds on the south should be Mississagi quartzite or some metamorphic equivalent of them; but it is evident from the descriptions that they are not. No known part of the Mississagi formation could give rise by metamorphic action to the mixture of cherty and basic beds found in the Coniston group. The contact must, therefore, be a fault of some sort, presumably fairly large, as it has brought together two such dissimilar formations.

Traced west (Figure 2) the fault contact passes across the north ends of Alice and Baby Lakes, and along the old portage into Daisy Lake. This portage lies in a valley that is almost bare rock without a vestige of vegetation; and rock can be seen almost to the actual contact, which lies in a creek valley and is covered by a 10-foot strip of gravel and boulders. For 10 to 20 feet south of this strip the Coniston sediments are intensely fractured and the fractures filled with quartz. On the north side the Mississagi quartzites, over a width of about 200 feet, are intensely smashed and sheared; and the strata have been twisted out of their normal strike, about north 60 degrees east, to lie as in Figure 3B. The existence of the fault may, therefore, be considered established.

A pronounced depression follows the contact between the rocks of the Bruce series and the complex of granites and ancient sediments for at least 16 miles to the northeast; and as the rocks along the edges of this depression continue to be more or less sheared, there can be little doubt that the depression is underlain by the fault. To the west the fault is obliterated to some extent by intrusion of the Killarney granite, as will presently be described; but it has been found as far west as Wavy Lake, where a wide zone of crushing and shear strikes about north across a point that lies north of the fairly large island in the middle of the lake. As elsewhere, the fault separates Mississagi quartzites on the west from a mixture of granite and inclusions of the Coniston chert quartzite on the east.

Direction of Fault Movement

The distortion of the Mississagi beds, illustrated in Figure 3B, can have been produced only by a movement of which the horizontal component was right hand; i.e., the beds north of the fault moved eastward, those to the south relatively west. Also, as the Coniston group does not correspond in its make-up to any group of known rocks younger than the Mississagi, it may be presumed to be older; and if this inference is correct, the south side must have moved up as well as west.

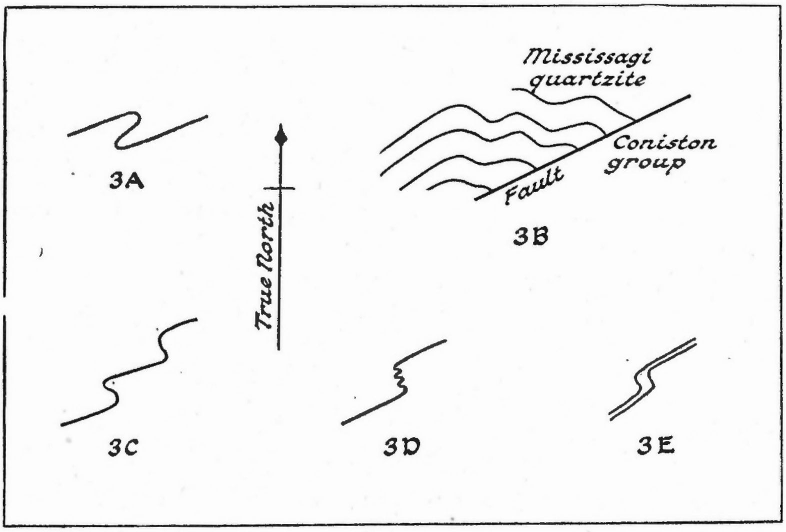

Figure 3. Structure of beds in vicinity of the Coniston-Mississagi contact.

In the Coniston group near the eastern end of the band, there are some drag-folds with almost vertical plunges, shaped thus in plan (Figure 3A). Such folds, again, must have been produced by an almost horizontal movement in which the beds to the south moved west, relatively.

Age of the Fault

As the Mississagi quartzite is faulted against the Coniston, the fault is obviously post-Mississagi in age.

The fault valley between the Mississagi quartzite and the Coniston group is underlain, in part at least, by a wide dyke of much chloritized gabbro. It appears on the north side of the valley at the south edge of the quartzite hill, and near Alice Lake in the valley bottom and on the south side. It also appears west of Alice Lake. The gabbro is chilled against the Mississagi quartzite, and is cut by pegmatitic stringers, presumably from the Killarney granite. It is, therefore, presumably a dyke of Nipissing gabbro. The manner in which the gabbro follows the fault suggests that it was injected along it. It was found, however, to be sheared locally along the line of the fault; so that probably there was fault movement both before and after the gabbro was injected. The two may be considered as having formed during the same period of crustal disturbance. This was, as will later be shown, the post-Middle Huronian folding that deformed the Cobalt series and older rocks.

Relation of the Killarney Granite to the Fault

As the Killarney granite is much younger than the Sudbury gabbro, it might be inferred that it is also much younger than the fault; and in that case might cut across it and obliterate it. This was found to be so. On tracing the fault contact southwest, about 10 miles from the localities discussed, at the northeast corner of the lake in lot 10, con. I, Broder tp., the granite was found intruding the Mississagi quartzite and cutting across its bedding at small angles and without the smallest sign of shearing or other disturbance. Similar observations were made at points farther southwest. Evidently, here the granite has crossed the fault and invaded the Mississagi quartzites north of it.

It might here be noted, for the benefit of those inclined to argue that the Coniston group might have resulted from the metamorphism of Mississagi quartzite, that neither here nor at any other point where the granite invades the quartzite was any trace of such metamorphism visible. At the above locality in Broder township there is no metamorphism of the quartzite. At the west end of Wavy Lake the quartzite is, in one place, much granitized, but is not converted into anything resembling the Coniston rocks.

Later Movements Connected with the Intrusion of the Killarney Granite

South of the west end of Baby Lake, where the Coniston sediments begin to be intruded by granite, some exceedingly interesting relations were observed. The well-bedded basic sediments there are intruded by fairly numerous little pegmatite dykes, averaging $\frac{1}{4}$ to $\frac{1}{2}$ inch in width; these parallel the bedding perfectly. *Both bedding and dykes are twisted into a series of drag-folds with vertical axes*, as in Figure 3C. Such structures indicate strong horizontal left-hand drag, the south side moving east relative to the north side. In many instances the dykelets in the cross part of the drags are much crumpled, as in Figure 3D, a fact that at first sight seems to indicate that the flowage took place after the dykes were consolidated, so that the crumpling would be due to thinning of the sediments by flowage under pressure. More careful examination shows, however, that this is not true. Not only do the minerals of the dykes exhibit no indication whatever of crushing or shear, but the dykelets, at bends, are thickened as in Figure 3E. The writer takes this to mean that the deformative movements took place while the pegmatite magma was actually being injected; the little cross folds, at right angles to the direction of main pressure, could be opened wider and receive more magma than the sections with a normal strike.

A cross-section of the mixture of granites and sediments between this point and Dill station, some 3 miles to the southeast, shows similar structures throughout. Wherever sediments are found they are recognizable as more or less granitized basic types; and everywhere they are dragged into folds indicating northeastward movement of the rocks to the south.

The railway crossing the strike between Baby and Daisy Lakes passes through a succession of deep rock cuts, in which many subordinate faults can be seen both north and south of the Mississagi-Coniston contact. All of these faults dip south, usually at angles of 60 to 70 degrees, and display various evidences of upthrust from the south. A few display two sets of striæ, the older dipping east at low angles, the later dipping west about 50 degrees. It will be recalled that in the earlier fault the north side moved relatively east and down, and the movement was mainly horizontal. The older set of striæ above could, therefore, correspond to the earlier fault movement. The later set may, similarly, be credited to the later movement associated with the granite intrusion, suggesting the south side moved upward as well as east.

Regardless, however, of the dubious evidence of the fault striæ, it may be pointed out that upward movement of the south side in the later movement should be expected, because of the upthrusting pressures of the invading batholiths of Killarney granite.

Conclusions and Inferences

The Coniston group has been subjected to a double movement. In the earlier, it was faulted against the Mississagi; the fault strikes east-northeast, and the Coniston rocks on the south moved west and up, relative to the Mississagi on the north. The horizontal component seems to have been much greater than the vertical, but no accurate means of measuring either has been found. At a later date granite was intruded, in places cutting across the fault and destroying it. The injection accompanied a second great movement, the direction of which was opposite to that of the first, that is, the south side moved east and up. Possibly the movement was due to pressures developed below and to the west by the injection of a large batholith.

Both movements, it will be observed, have resulted in the uplift of the rocks to the south relative to those on the north; so that the Coniston series must be older than the Mississagi quartzites. Presumably, therefore, it represents a pre-Huronian series; its entire lack of petrographic resemblance to either the McKim formation or the Copper Cliff rhyolite renders correlation with either very dubious. It is interesting to note, further, that the Coniston group has no resemblance to any pre-Huronian rocks yet known, except possibly one of the members of the Grenville series, thereby suggesting that the subdivision of the pre-Huronian may be more complex than there has yet been reason to believe.

The discovery of these rocks and their relations has a direct bearing on the conclusions announced by Quirke and Collins in "The Disappearance of the Huronian". In that work these authors decide that certain remnants of sediments found in the granite here and there between Killarney village and Delamere township (Figure 4) are remnants of Huronian formations. They base this conclusion, very soundly, on the fact that the petrographic character of these much metamorphosed remnants is such that they could have been formed from the different members of the Huronian system; and that where two or more members are found, their succession is the same as in the unmetamorphosed Huronian succession.

It will be observed that the remnants they describe lie only about 24 miles south of the contact described in this report. The writer made a cross-section from the contact to Wanup station, a distance of 6 miles, and within that distance all remnants of sediments belong indubitably to the Coniston group, and all dip to the south. Throughout that distance, again, there is continuous evidence of upthrust from the south.

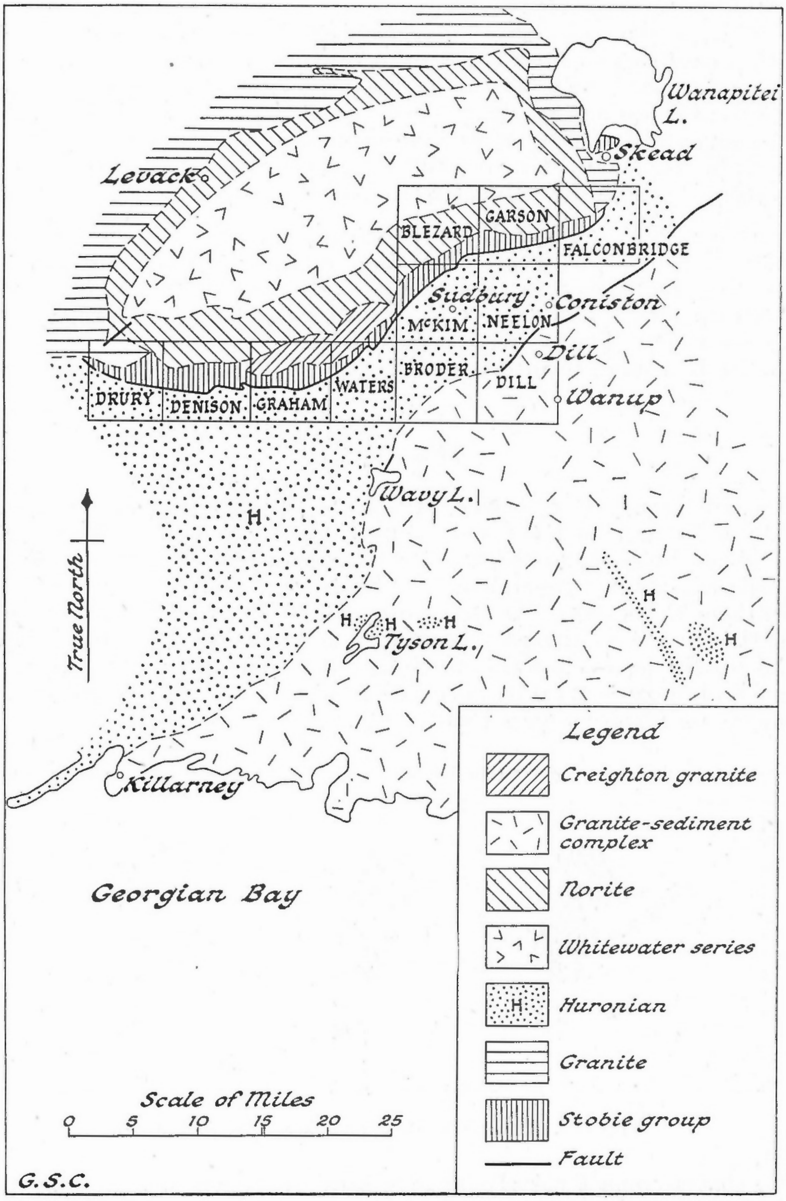

Figure 4. Areas of supposed Huronian remnants in the Killarney granite northeast of Killarney.

These two factors oppose one another, in considering what may have happened in the remaining 18 miles to the sedimentary remnants described by Quirke. If the southerly dip is continued, it is quite possible that within that distance some stratigraphically overlying series may come in, and that series could well be of Huronian age. On the other hand, the continuing uplift on the south, due apparently to batholithic injection from below, by tilting the whole region upward from a hinge line at the Coniston-Mississagi contact would cause the Coniston group to continue much farther to the south than it normally would, and might even eliminate entirely the younger strata. Only further study of this interesting section can discover what has actually happened; in the meantime it would seem best to regard Quirke's conclusions as tentative, and possibly subject to revision.

Attention may be drawn, however, to the fact that the west-southwest movement of the Coniston group during the first faulting must have become overthrusting farther west, where the contact swings nearly north-south; so that strata now found east of the contact must be stratigraphically below those to the west. The overthrusting need not have been sufficient, of course, to eliminate Huronian formations entirely.

HILL GROUP

The Hill group is so named because it forms a prominent ridge on the west side of Wanapitei Lake, extending from somewhat south of the extreme south end of the lake northward for three-quarters of a mile. The mass is wedge-shaped, about one-eighth mile wide at its south end and narrowing to a point on the north. At the south end it is cut off by intrusive granite. The southern part of the east boundary is a normal unconformable contact with the Stobie series, but the northern part is a fault. It is suspected that the west boundary is a fault, occupied in part by a dyke of gabbro; but this boundary is uniformly covered with drift.

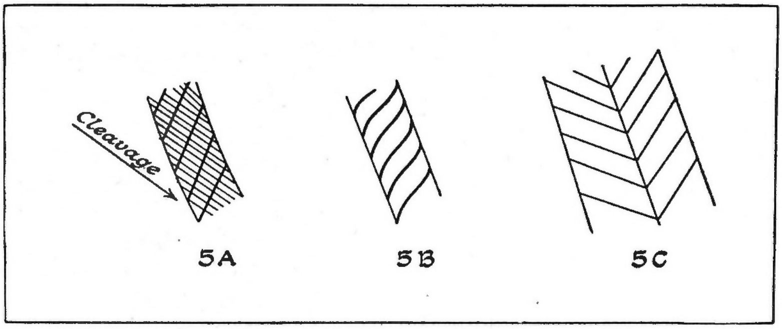

Figure 5. Structures in greywacke of the Hill group.

The strata consist mainly of very hard, very fine-grained, siliceous greywacke, interspersed in places with softer, slatier beds. The beds are mostly an inch or two thick, and very uniform throughout in grain and composition. They stand nearly vertically, striking nearly north in the northern part of the mass, but swinging to north 35 degrees west near the granite contact on the south. Fresh surfaces of the siliceous greywackes are dark bluish grey, and the slaty beds somewhat darker.

The siliceous greywackes are characterized by an extraordinary structure, which, for lack of a better name, the writer terms "herringbone structure". Individual beds are crossed, at about 45 degrees to the bedding planes, by a series of closely spaced, narrow, dark bands. It is difficult to avoid the conclusion that this alternation of darker and lighter bands is due to original bedding; and one is, therefore, inclined to look upon it as crossbedding. When closely studied, however, these bands are seen never to tail off to parallel a bedding plane, as true crossbeds do, but they invariably come up to the bedding plane at a large angle, and there end. In a fairly large number of places, also, these bands actually cross bedding planes, to pass uninterrupted through two or more beds; so that whatever their origin, they must have been formed after the beds were deposited. In one place slaty cleavage was observed to cross them (*See* Figure 5A), and in several places, instead of being straight, they are bent (Figure 5B). The difficulty of interpreting the meaning and origin of these bands is increased by the fact that the direction of banding is not always the same, but in places is reversed, thus giving a true herringbone structure (*See* Figure 5C).

Under the microscope the greywacke is seen to be composed of a large proportion of fine-grained chlorite — nearly 50 per cent in the specimen examined — some 20 to 25 per cent of quartz, and the remainder mainly partly altered albite-oligoclase. The grain averages 0·05 millimetres. Lighter bands contain much more quartz, darker bands much more chlorite. There is no clean-cut division between bands, as might be expected if they had been beds, but the boundaries are indeterminate, and the bands rather crooked. These features seem to confirm the conclusion that the bands are not original depositional structures.

The Hill series is cut by the Wanapitei granite that intrudes the Stobie series and is older than the norite irruptive. Its relations to the Keewatin series are not known. It is older at least than the Upper Stobie group, as will be indicated in the description of the latter.

The suggestion is advanced that the Hill series may possibly be correlative with the Coniston series. The thin, hard beds of the Hill series suggest, in general make-up, the cherty beds of the Coniston; and the difference in composition might be due to varying distance from the sources of supply of sediment.

STOBIE GROUP

The name Stobie group is applied by the writer to a succession of lavas and sedimentary rocks that lie between the norite irruptive on the north and the McKim and Copper Cliff formations on the south. The name "Stobie" seems a suitable one as James Stobie was one of the earlier prospectors of the district and discoverer of the Stobie mine, which lies in these rocks.

This group of rocks forms a band approximately 36 miles long, ranging in width from ½ mile to 2½ miles. It is in contact on the north with the norite sill, which intrudes it, but extends both east and west somewhat beyond the end of the sill; in two places along this contact granites have been injected between the sill and the rocks of the Stobie group. On the south, a great fault brings the group into contact with the McKim and Copper Cliff formations. The variations in width that the band displays are due to the fact that both edges have been thus cut off.

Besides this band, a small mass of rocks considered to be part of the group is found around the south end of Lake Wanapitei. It is about 2 miles long and a mile wide. In addition, numerous inclusions of these rocks may be seen for several miles in the granite south of Lake Wanapitei; and also in the granite around Levack.

The group is divided tentatively into two sub-groups, possibly separated by an unconformity. The one, which may be termed the Lower Stobie, constitutes the part of the band west of Sudbury, and the inclusions in granite around Levack. Both the Upper and Lower Stobie are found in the main band northeast of Sudbury. The mass at the south end of Lake Wanapitei, and the inclusions in the granite east of the end of the norite sill, are all Upper Stobie.

The Lower Stobie consists of basic lavas at the base, and these pass by alternation of lavas and sedimentary bands into a succession of quartzites and greywackes. The Upper Stobie consists of a conglomerate at the base distinguished by its extraordinarily high content of quartz pebbles. The conglomerate is overlain by, and to some extent interbedded with, very thick beds of quartzite. These are succeeded in turn by greywackes that, presumably, contained a good deal of clay, as they are now filled with large, secondary staurolites. One or two flows of basic lava occur in the uppermost horizons. No relations between the Upper and Lower Stobie could be observed in the main band, except the fact that the Upper lies stratigraphically above the Lower. A principal reason for supposing that a break may occur between them is that on Lake Wanapitei the basal beds of the Upper Stobie lie directly on the Hill group, and the Lower Stobie is apparently absent. Such relations must be due to unconformity or overlap.

Lower Stobie

The Lower Stobie is roughly divisible into two parts. The northern or lower part consists of lavas, mainly basic, with subordinate amounts of sediments. In the southern or upper part these proportions are reversed. The exposed widths of the lower part range from ½ mile to 1½ miles, those of the upper part from nil to a mile or slightly more. These variations in width, like those of the whole band, are caused by the intrusion of the norite and granite on the north, and by the faulting on the south. The contact of the two parts is a zone, ranging in width from a few feet to half a mile, within which sedimentary beds and lava flows alternate.

The bulk of the lava is basic, about the composition of andesite, but in the parts where the lavas begin to be interbedded with sediments more acid types, about the composition of trachytes, also appear. Close to the norite contact, the lava has commonly been too much metamorphosed to retain any original structures it may have had; but outside of this zone, perhaps one-quarter to one-half mile in width, the original textures and structures are present. Many flows exhibit beautifully developed pillow structures; others are highly amygdaloidal in the upper parts. Changes of grain from bottom to top were observed in a few instances. All of these features, together with crossbedding of interbedded sediments in a few places, indicate that the tops of the flows face toward the south. The strike is in general about parallel to that of the band, the dip nearly vertical.

The interbanding of lavas and sediments in the transition zone is well displayed in lot 10, con. III, Garson tp.; in lot 12, con. III, Graham tp.; in lots 3 and 4, con. IV, Drury tp.; and in many other places. For the most part the interbanded sediments are impure quartzites grading into greywackes, but in the Graham township locality some of them are white quartzites contrasting sharply with the dark lavas in which they lie. In McKim township, from Frood southwest for more than 3 miles, the transition zone is more than half a mile wide, and lavas, some fairly acid, constitute about one-third of that width.

The sedimentary part of the Lower Stobie is best developed in Drury and the western half of Denison townships, less well northeast of Sudbury. Between these two sections only a thin selvage of sediments, ranging in width from 200 to 1,200 feet, remains between the lavas to the north and the fault on the south.

In Drury and Denison townships the sediments have a considerable range in composition. The bulk of them are greywackes, some moderately siliceous, others comparatively basic. They form beds an inch to several inches in thickness, many of which are heavily impregnated with pyrrhotite. Interbanded with them are a good many beds, 2 to 6 feet thick, of muddy dark green rocks obviously composed largely of chlorite and epidote. Some of them contain whitish lumps that may have been fragments. Their interbanding with greywackes, and the presence not far away of thin flows of basic lava, combine to suggest that they were basic ash rocks.

In a few places, as on the east shore of Ethel Lake, beds of fairly pure quartzite appear. In that locality the quartzites somewhat resemble the Mississagi quartzite, but differ from it in being more rill-marked, less cross-bedded, and interbanded with thick beds of basic greywacke.

An interesting member of this series is found in lot 12, con. III, Denison tp., extending west more than 3 miles. This is a body of "quartzite" nearly 2,000 feet in maximum width; it has been mapped by Collins (Map 292A, Copper Cliff sheet) as Mississagi quartzite. Its relations were studied in the south end of lot 4, con. IV, Drury tp., and on the west end of the high, bare ridge straddling concession line III-IV in lot 3, Drury township. The last locality exhibits continuous outcrop over a width of some 1,500 feet.

In lot 4 outcrops are not continuous; but if it be considered safe to project the strikes of existing outcrops for approximately 700 feet, the relations indicate that a band of "quartzite" about 100 feet wide lies between two flows of moderately acid lava. The flow to the north is about 100 feet thick, and grades from a massive texture on the north side to finer grained, flow-textured material on the south; it, therefore, faces toward the south. The flow to the south is somewhat more basic, and has pronounced flow textures. The "quartzite" band is white and massive, without a trace of bedding. All strikes are north 70 degrees east; dips are vertical.

To the south of the southern lava flow other bands of lava were found interbanded with fine-grained, thin-bedded sediments that may be waterlaid tuffs. These can be followed eastward through lot 3 to where they are in contact on the south with the main body of "quartzite" previously mentioned.

The latter is a white or light grey rock of uniformly fine to medium grain, composed mainly of quartz. The extraordinary feature is, that though it is magnificently exposed over a width of some 1,500 feet as a bare, rain-washed ridge, not one bedding plane can anywhere be distinguished, nor is there any change in grain or composition to suggest that bedding exists. In a few places clean-cut straight lines separate darker and lighter parts; and as these have about the same direction as the regional strike they were at first taken for bedding planes. They can rarely be followed more than a score or two of feet, however, before they fade and disappear. Further, in one place two of them were seen to cross at an angle of about 20 degrees, so that they cannot both be bedding planes.

Near the north side, or base, of the "quartzite" mass much of the quartz was observed to occur in long narrow grains measuring, roughly, one-half inch in length by one-twentieth inch in width. On very clean surfaces these can be seen surrounded by a greenish matrix that looks like sericitized feldspar. The laths of quartz are parallel to the base of the band. No such texture could be formed in a sedimentary rock.

The description makes it evident that this rock has no resemblance whatever to the well-bedded, strongly crossbedded Mississagi quartzite; and its stratigraphic position apparently directly superposed on the lavas to the north is also against such a conclusion.

The origin of such a rock is an interesting matter for speculation. The entire lack of bedding seems to preclude any ordinary sedimentary process; even wind-blown sands exhibit bedding of a sort; yet if it were a true quartzite, its purity would demand long continued sorting by water action. The extraordinary texture of the basal parts suggests growth of crystals by recrystallization, though why they should assume such long narrow shapes is a puzzle. The writer would suggest that the rock was originally a rather fine tuff, perhaps of rhyolitic composition, which was silicified and cemented by volcanic vapours soon after deposition.

Northeast of Sudbury the sedimentary rocks considered to be Lower Stobie form a band only a quarter mile or so in width between the lavas to the north and the Upper Stobie to the south. They are impure sandy greywackes, interspersed with what appear to be ash beds. In lot 10, con. III, Garson tp., interbanding of sediments and flows can be observed at the contact; but in con. II, Blezard tp., approximately at the boundary between lots 1 and 2, prospectors have stripped the contact for about 300 feet across widths of 15 to 20 feet. There the lavas may be seen to end abruptly in conformable contact with the sediments, and the only interbedding observed was near the west end of the trench where a flow about 6 feet thick is separated by some 2 inches of sediment from the next flow to the north.

A very large number of structural observations was obtained on the sediments of the Lower Stobie group. Rill-marks and crossbedding can be found in the coarser, more quartzitic beds; the siltier beds are marked in many places by changes of grain from coarser and more siliceous material at the bottom to softer, finer, more argillaceous material at the top. There are few outcrops of any size that do not yield, on careful study, a determination of the direction in which the beds face. The writer can state positively, therefore, that the Lower Stobie sediments everywhere face toward the south. The lavas, it has already been stated, also face south wherever determinations were obtained.

The strike of the beds is in general parallel to that of the band, but by no means uniformly so. More correctly it may be said that the strike swings, to be more southerly than that of the band in parts, more northerly in others. Southeast of Ethel Lake, Denison township, for example, the strike suddenly swings to nearly due southeast, and maintains that direction for nearly a mile. The dip is commonly 70 to 80 degrees south, but in a few places the strata are slightly overturned and dip north at high angles.

Upper Stobie

The rocks here classed as Upper Stobie are found northeast of Sudbury, and in the fault block east of the south end of Wanapitei Lake. Inclusions of them are also numerous in the granite mass east of the norite irruptive.

Northeast of Sudbury the rocks of the Upper Stobie group overlie the sediments of the Lower Stobie, but there has been so much brecciation, recrystallization, and other disturbance that it was found impossible to determine whether the contacts are unconformable or not.

The base of the Upper Stobie group in this area is a series of conglomerate beds. These appear for the first time at the Stobie mine, and extend east-northeast from there to a point about half a mile west of the Kirkwood mine. The conglomerates form beds ranging from a few inches to 5 or 6 feet thick, and are interbedded with and overlain by beds of massive, bluish grey quartzite. The combined thickness of the conglomerate and quartzite rarely exceeds a few hundred feet, except in Blezard township, concession I, lot 4, where it appears to be considerably greater. The conglomerate and quartzite are overlain by a thick succession of dark, argillaceous, thin-bedded greywackes. These are strongly recrystallized, and in many places contain much staurolite. A little lava occurs in the uppermost horizons.

The conglomerates are unlike any others in the district in that most of the pebbles are of quartz. Beds in which less than half of the pebbles are quartz are rare, and in many beds nearly all the pebbles are quartz. Other pebbles are of greyish grits or sandstones, possibly derived from the underlying sandy greywackes; a pinkish, very fine-grained, hard rock, perhaps rhyolite; soft schists or slates; and some chloritic pebbles, which may have been derived from altered basic lavas.

The pebbles average 1 or 2 inches in diameter, but cobbles up to 5 or 6 inches in length and 3 or 4 inches in thickness may be observed. About the middle of lot 4, con. I, Blezard tp., some beds display magnificent imbricated structures, with the flat pebbles overlapping like shingles. These indicate that the conglomerates were formed by stream action. At one point where the beds strike north 80 degrees east, the long axes of the pebbles strike north 40 degrees east. The beds face toward the south, as indicated by excellent crossbedding in the overlying quartzites. The current of the stream, therefore, flowed from the east.

The conglomerate beds farther south in lot 4 are of a different type from those seen elsewhere. Many of them are not more than coarse grits, filled with little fragments of quartz up to the size of peas. In others the pebbles are a little larger, up to that of beans. In all these beds quartz fragments are very numerous, in places so much so as to be crowded together.

The quartzites are massive, bluish grey rocks, forming beds up to 6 feet thick. They are fairly uniform in composition and grain, and are not much crossbedded, though sufficient crossbedding can usually be found for purposes of structural determination. Thin sections show that they are fairly thoroughly recrystallized to new quartz grains with interlocking edges, fresh feldspar about oligoclase-andesine in composition, and small amounts of biotite and magnetite.

The greywacke overlying the quartzite is completely recrystallized, presumably by the heat of the numerous intrusions added to the pressures of folding. The bedding, however, looked at on a large scale, still remains beautifully preserved, although when closely examined the bedding planes are seen to be destroyed by the growth of secondary minerals across them. Thin sections show the rock now composed almost wholly of quartz and mica, with a little feldspar and magnetite. Biotite, partly altered to chlorite, forms large crystals and crystal aggregates, and fine-grained white mica, probably secondary after feldspar, serves as a matrix for the quartz crystals. Darker beds contain more of the biotite, lighter beds more of the quartz and white mica. Staurolite is extensively developed in places. In the north end of lot 3, con. I, Blezard tp., staurolite crystals 1 to 2 inches in length are numerous; and just southwest of the junction of road and railroad in lot 8, con. V, McKim tp., they attain lengths of 4 or 5 inches. A photograph of the latter occurrence is shown in the Ontario Department of Mines Report, vol. 43, pt. 2, p. 17.

A little lava is found in the upper horizons of the Upper Stobie group. Two flows of about the composition of andesite, and beautifully pillowed, can be traced about 2½ miles from lot 1, con. I, Blezard tp., into lot 8, con. II, Garson tp.

The structure of these beds was carefully studied. In spite of the metamorphism they have suffered, opportunities for excellent structural observations were numerous. The quartzite beds in many places display good crossbedding. Almost everywhere the greywacke beds show the characteristic change from more siliceous at the bottom to more clayey at the top, and secondary staurolite, where present, reflects the change in composition by being more plentifully developed in the upper parts of each bed. The pillow structures of the lava flows afford many excellent determinations of attitude. All these determinations indicate that the tops of the beds everywhere face south. This, coupled with the similar determinations made on the beds of the Lower Stobie, leaves no doubt as to the relative stratigraphic position of the two.

At the south end of Wanapitei Lake a body of similar sediments extends eastward from the west shore about 2 miles and has a north-south dimension of 1 mile. It is correlated with the Upper Stobie group because: (1) a recurrence of these rocks might be expected, to form the north limb of the anticline of which the previously described beds form the south limb; (2) the succession of beds is the same — at the base a few hundred feet of conglomerate and quartzite, followed by a great thickness of thin-bedded greywacke with a little lava in the uppermost horizons; and (3) the composition of the conglomerate and quartzite is the same, except for such differences as might have been caused by metamorphism. The conglomerate is made up largely of quartz pebbles, and the quartzite occurs in the same thick bluish grey beds, with little crossbedding.

These strong similarities justify, in the writer's opinion, the correlation here made with the Upper Stobie of the Stobie-Kirkwood area. However, the Lake Wanapitei beds are on the whole less metamorphosed than those farther south, and also display a few local peculiarities, so that a few remarks on their petrology should be made.

Although the basal conglomerate is, in most places, exactly like that of the Stobie-Kirkwood area, that is, composed largely of quartz pebbles, with a few of greyish grit, rhyolite (?), schist or slate, and chloritic rock, a different type is found on the east shore of Wanapitei Lake about half a mile from the south end. There, rounded, pebble-like bodies of red and grey granite are also present. No granite pebbles are found except in this small locality, and similar granites intrude the series within 200 or 300 feet of the spot; hence, it was concluded that the granite "pebbles" were formed by injection and are not true pebbles at all.

The quartzites are massive, bluish grey rocks, much less metamorphosed than in the Stobie-Kirkwood area. Thin sections of the flat-lying beds on the west shore consist of some 60 per cent of quartz in rounded grains set in a matrix of grains and small fragments of feldspar largely converted into sericite. There is no trace of the recrystallization noted to the south.

The greywackes are soft dark rocks, siliceous enough to make them somewhat harder than ordinary slates. They weather commonly to a reddish brown. On the east shore of the lake they display good bedding, and overlie the conglomerate-quartzite member with perfect conformity; but farther east they are much broken by movements, into breccias with fragments ranging from chunks several feet in diameter to bits an inch or two across. Some masses along the line of the Canadian National Railway about a quarter mile east of Skead Station have been so finely broken that almost all remnants of original structure are lost.

The structure of the Wanapitei remnant is that of a compound syncline, plunging east at a low angle. On the south it is in contact with intrusive granite; on the east and north it is bounded by large faults that have brought it into contact with the Espanola formation and the Serpent quartzite; and on the west it is in contact with the Hill series. The granite mass south of it is full of large and small, but recognizable, inclusions of the greywackes; and in the northeast corner of lot 7, con. V, Falconbridge tp., an inclusion of brecciated slate and quartzite, several hundred feet in length, may be seen on an east-facing hillside. It would seem, therefore, that before the granite intrusion the series must have extended at least 3 miles south of its present south boundary near Skead Station.

The contact of the Stobie and Hill series is well exposed in a number of places on the west shore of Wanapitei Lake. The Hill series rises from the lake as a steep-sided ridge; and the Stobie series flanks the side of it close to lake level, and can be studied at times of low water. Most of the contacts lie on a fault, of which the east side has moved vertically downward, thereby dragging the Stobie strata into approximate parallelism with the Hill beds. The fault is of the scissors type, however, strongest on the north and decreasing southwards to zero; so that at the southernmost outcrop the undisturbed contact may be seen. At this point the contact is a near-vertical surface almost parallel with the lake shore. On the west side of it lie the Hill beds, with their northward strike and near-vertical dip. On the east side the conglomerates and quartzites of the Stobie series lie almost flat, with a gentle northward dip of 8 or 10 degrees. The contact is wave-washed and perfectly clean, making it possible to determine, positively, that there has been no movement or fracturing along it. Evidently, therefore, the Stobie series at this point was laid down in a steep-walled valley cut in the Hill series, a valley like that of the present lake.

Relations of the Upper to the Lower Stobie

It was not found possible to determine directly the relations between the Upper and Lower Stobie. Not only are the contacts none too well exposed, but they have been more or less obscured by intense folding, and faults, though rarely definitely determinable, are undoubtedly numerous. Many bands in which brecciation has been intense (38) cross the contact; and large areas have suffered amphibolitization, as will presently be described. It was, therefore, found impossible to determine whether the Upper Stobie bevels across the bedding of the Lower Stobie. Certainly there is little if any apparent difference in strike and dip.

Nevertheless, a number of features indicate indirectly that an unconformity or disconformity is probably present. The extraordinarily quartzose composition of the Upper Stobie conglomerate, as well as the conglomerate itself, implies a sharp change in the conditions of deposition. The conglomerate contains an occasional pebble of grit, of rhyolite (?), and of material like basic lava, all of which could have been derived from the Lower Stobie. The thickness of the sedimentary member of the Lower Stobie is very much greater west of Sudbury than to the northeast, which may indicate that some of it was eroded before the Upper Stobie was laid down. Finally, on Lake Wanapitei the Lower Stobie is missing[1], and the Upper Stobie rests directly, with right-angled unconformity, on the Hill group. Such relations would seem explicable only by unconformity or by overlap.

Amphibolitization of the Stobie Group

Large parts of the Stobie group have been converted into coarse black amphibolite, particularly in the section extending from Copper Cliff to Garson. The block of so-called "Keewatin" rock mapped by Collins (Copper Cliff sheet) to the west of Creighton is also largely or wholly amphibolite.

The problem of amphibolitization is not a simple one. Certain large dyke-like bodies of coarse amphibolite appear to be truly intrusive, as they display chilled edges at their contacts against sediments or other rocks. It is possible that they are intrusives that have been amphibolitized after intrusion, the chilled edges retaining a finer grain than the rest, but although careful search was made, no evidence of such a history could be found. Petrographically and texturally identical with these are bodies of amphibolite, large and small, formed by the amphibolitization of the Stobie lavas and sediments. A very large, irregular mass of amphibolite formed in this way is found in lots 1 and 2, cons. I and II, Blezard tp., and around its borders every stage of alternation to amphibolite may be observed. Of particular interest was the alteration of pillow lava to amphibolite, observed toward the east side of lot 1, con. I. The pillow structure is retained to quite an advanced stage of alteration, by reason of the interpillow bands being replaced by hornblende finer in grain than that which replaces the body of the pillow; thus affording the singular spectacle of very basic, very coarse-grained rock exhibiting characteristically shaped pillows. In the earlier stages of alteration the interpillow material is a fine-grained mixture of mica and chlorite, with fairly numerous needles of hornblende about one-eighth inch long; the interior of the pillows contains much the same minerals, but the proportion of hornblende is larger and its grain much coarser.

On the west side of the hornblendite mass, in lot 2, concession I, the alteration of sediments to hornblendite may be observed. The bedding of the greywackes is preserved to an advanced stage of alteration, giving the hornblendite a banded structure. Near the north end of the lot some of the conglomerate of the Upper Stobie has been amphibolitized, and it is striking to see the pebbles of white quartz remaining practically unaltered, surrounded by a matrix of black amphibole.

A large, bare ridge of basalt or andesite in the northwest corner of lot 11, con. IV, McKim tp., exhibits very well the beginnings of amphibolitization, and was closely studied in the field. As a first step the rock seems to have been much jointed or sliced. Four sets of these joints were measured. The two commonest are: strike north 30 degrees east, dip 55 degrees northwest;

---

[1] Unless it may underlie and be completely hidden by the flat-lying Upper Stobie.

and strike north 45 west, dip nearly vertical. Two other sets, with much fewer joints, are: strike north 10 degrees east, dip 60 degrees east; and almost horizontal. All these joints are filled with a fine-grained, black mineral, presumably hornblende; the black veins range in width from one-fortieth to one-tenth inch, occasionally wider; and in length from a few inches to several feet. They have irregular edges of the replacement type against the basalt. In many places a thin veinlet will expand suddenly to the size of a pea or bean, and these enlargements are always coarsely crystalline hornblende.

The second step in alteration seems to have been the soaking of the rock between the joints, through inter-grain spaces, with the hornblendic juice. Interaction of this juice with the rock material produced, first minute, then large, crystals of hornblende in the rock body away from any vein.

In the latest stages of alteration, the amphibolite fluid became pegmatitic, possibly through deposition of most of its amphibole and consequent concentration of the more acid constituents. This final fluid deposited hornblende, with individual crystals up to one-quarter inch in diameter; and associated with this hornblende is considerable interstitial pinkish mineral, presumably feldspar, and some quartz. The pegmatitic material forms irregular nodules an inch or two in length, without well-defined boundaries, and also crooked, vein-like masses ranging in width from one-quarter inch to an inch, and in length from 3 or 4 inches to perhaps 15 inches. In some places, also, the pegmatitic juice seems to have reacted actively with the basalt, yielding a rock shot through with grains and short crooked threads of white or pinkish mineral, whereas the remainder is mostly hornblende in medium-sized crystals, but perhaps contains still a good deal of little-altered basalt.

It is rare, however, either to find surfaces clean and smooth enough to make complete observations, or places where alteration has not gone so far as to obscure the preliminary processes. More commonly, the rocks affected are converted to featureless masses of coarse hornblende, and the observer is lucky if around the edges he can find sufficient evidence to indicate that the mass is the result of replacement rather than intrusion.

The causes of amphibolitization in this region are as yet entirely unknown, though possibly very detailed mapping and study might reveal them. In a general way it appears related in some way to the norite, for it becomes more intense as the norite is approached, and seems confined to a zone less than 1½ miles wide along the norite boundary. Such a contention is difficult to support, however, because of the erratic distribution. The amphibolite formed by alteration of sediments or lavas is confined largely to the section between Stobie and Garson, and even within that zone its distribution is highly erratic. It does not seem related to any zones of crushing or fracturing, so far as the writer was able to learn; though undoubtedly the evidence of such metamorphism would be largely destroyed during the alteration to amphibole.

Sudburite. Close to the norite boundary amphibolite has been itself altered to a dark grey, equigranular rock that weathers pale brown. This rock has been termed sudburite by Robert Thomson (70). It is composed of about 40 per cent of fresh greyish pyroxene in grains averaging ½ mm. or less; about 50 per cent of plagioclase, $Ab_{35}\ An_{65}$; and the remaining 10 per cent of magnetite. All the minerals are very fresh. Thomson states that the pyroxene includes both orthorhombic and monoclinic varieties.

The relation of this material to the amphibolite is very difficult to determine. Apparently the fluids causing alteration soaked all through the rock, altering the finer parts but leaving the large crystals of hornblende and the solid veinlets unreplaced. The result is a brownish rock filled with hornblende crystals and cut by numerous hornblende veinlets. Thomson reflects this uncertainty when he describes hornblende crystals as embayed, and speaks of hornblende cores within later pyroxenes, yet is evidently inclined to consider the amphibolite as forming by alteration of sudburite. However, in con. II, Blezard tp., near the north end of the line between lots 1 and 2, places can be seen where the brownish sudburite forms irregularly tabular masses, 2 or 3 feet wide, cutting through the surrounding amphibolite. Plates and irregular lumps of the dark green rock are completely surrounded by the sudburite; and the contacts, though fairly sharp, are toothed, irregular, and distinctly of the replacement type. The occurrences leave no doubt that the sudburite is a product of the alteration of amphibolite.

The sudburite is confined to a zone less than 1,000 feet wide, measured from the outer boundary of the norite, and alteration is really intense for only a few hundred feet from it. Its origin, like that of the amphibolite, is still unknown.

Correlation of the Stobie Group

Previous writers have classified these rocks in various ways. Coleman (19, p. 275; 14, pp. 80-81) referred the whole group to the Sudbury series, and applied the special name "sudburite" to the lava parts. He says, "It (the "sudburite") seems to have been an early differentiation from the norite magma which finally spread out along the same plane". Collins, in his legend for the Espancla and Copper Cliff sheets, termed the lava parts of the Lower Stobie "Keewatin", and mapped the sedimentary parts either as McKim formation or as "transition rocks", which were described in the legend as "the transition zone between Keewatin and Sudbury series, which consists of repeated alternations of volcanic and sedimentary materials and represents diminution and final replacement of Keewatin volcanism by Sudburian sedimentation". Collins thus recognized the gradational passage between the Lower Stobie lavas and sediments; but his non-recognition of the great fault that bounds the Stobie on the south led him to correlate the Stobie sediments with the McKim formation, and thus to infer a "transition" more extensive than actually exists.

Burrows and Rickaby (11), in their work of 1929-32, mapped these rocks in considerable detail, and also recognized the conformity of the Stobie sediments and lavas. They state "In places the lavas are interformational with some of the sediments, consequently it is difficult to assign different ages to the two types of rock . . . The greenstones have been followed . . . for many miles, their formational arrangement with the sediments being everywhere visible; consequently, whichever age is assigned to the greenstones would of necessity include a number of the sediments also".

However, as Burrows likewise did not recognize the profound fault separating the Stobie series from the overlying rocks, he, therefore, logically classified the lavas and associated sediments with the Sudbury series.

In fairness to these writers, however, it should be emphasized that their main preoccupation was the differentiation of the norite-micropegmatite irruptive and the genetic relations of the orebodies so closely associated with it. Those were the great problems, the proper solution of which was of immense importance to the mining industry; and lesser problems of purely geological interest necessarily received scant attention. In reality, the present study represents the first attempt to scan these ancient sediments and lavas in detail.

The writer hesitates to attempt any correlation of the Lower Stobie. Its lavas, possibly by reason of recrystallization and amphibolitization, seem fresher in most places than the ordinary greenstones of the Shield directly to the north; and many flows contain amygdules in enormous numbers, a feature again not common in the Shield. The association of lavas and sediments it presents is unlike the Keewatin at the north end of Lake Wanapitei. One must go northwest for hundreds of miles, nearly to the Manitoba boundary, to find a sediment-lava association in the so-called Keewatin such as is found at Sudbury. The writer is doubtful, therefore, about classifying these rocks as "Keewatin", although the weight of the evidence at present indicates them to be pre-Huronian.

The position of the Upper Stobie is equally uncertain. It is a possibility — the writer cannot call it a probability — that the Upper Stobie may represent the basal part of the Bruce series, developed below the Copper Cliff rhyolite and cut off by the great fault that bounds the Stobie groups on the south. One small piece of evidence, described later in the discussion of the relations at the base of the Copper Cliff rhyolite, suggests this; and, if true, it would of course explain the right-angled unconformity with the Hill group. If not true, the Upper Stobie presumably falls somewhere into the pre-Huronian, with its position in the time scale as yet undetermined.

Some support is given to the latter view by the fact that the Upper Stobie is intruded by the Wanapitei granite, which has commonly been considered pre-Huronian as it has not been found cutting the Bruce or Cobalt series either in the locality under consideration or northwest of Lake Wanapitei. Certainly the Wanapitei granite is not one of the Killarnean types found farther to the south and east, as it is cut by the norite irruptive. However, this evidence can hardly be considered conclusive.

THE GREAT FAULT

In preceding pages the writer has stated that the Stobie group is separated from rocks to the south by a great fault. As this fault has not been recognized by earlier workers, the evidence for it will be presented in full.

The reasons for its non-recognition up to this time are threefold. The first, and undoubtedly the main, cause was the preoccupation of earlier geologists with the greater problems of the origin of the orebodies, the differentiation of the great norite irruptive, and the Huronian succession. A large part of the work of two summers has been devoted, by the writer, to the study of the structure of the rocks on both sides of the fault. At an earlier date this would hardly have been justifiable, with larger problems clamouring for solution. Second, without a careful structural study the fault is difficult to recognize. Almost everywhere it has been obscured by brecciation that involved great bands of all the rocks of the region, except the late olivine diabase and trap dykes. Bands of breccia formed with particular ease wherever earlier faulting created zones of weakness; and, except in two localities, these brecciated zones obscure the fault. Third, the existence, on both sides of the fault, of more or less metamorphosed sedimentary rocks of somewhat similar appearance led later workers to accept, without further study, Coleman's early classification by which all strata were lumped together.

It was obvious, however, to any close student of the literature, that there was something very unusual about the structure of Sudbury district and the conclusions regarding the rock succession. Elsewhere in the Precambrian, known Huronian strata overlie pre-Huronian formations with profound, almost right-angled unconformity; but at Sudbury the Huronian beds and those classed by earlier workers as pre-Huronian are parallel. How could the pre-Huronian of this region have escaped the widespread deformation that elsewhere ended the Archæan era? This thought at once cast doubt on the accuracy of the conclusions reached at Sudbury. What, then, were the alternatives? One was that the supposed pre-Huronian beds were not Archæan but, though older than the Bruce series, were members of the Huronian system. Another was that some important feature, such as a fault, existed but escaped the notice of earlier observers. It is true that beds laid down on a surface eroded on folded rocks will parallel the older beds at the crests of folds, but such parallelism could not be expected to continue for miles as it does at Sudbury. From the start, therefore, the writer directed his work toward the solution of this problem.

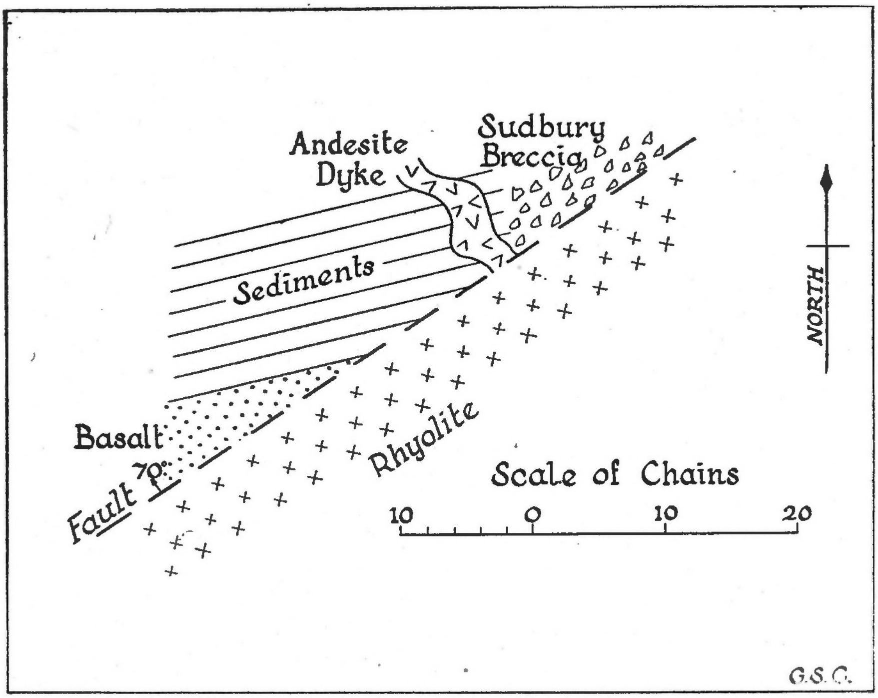

Figure 6. Fault contact relations of Copper Cliff rhyolite and older rocks, lot 10, con. IV, McKim tp., west of road.

Study of the contacts between the Ramsay Lake conglomerate and the McKim formation showed that, as other writers have concluded, there is no apparent unconformity; and the same is true of the contact between the McKim formation and the underlying Copper Cliff rhyolite. The evidence for these conclusions is given in subsequent pages. At the base of the rhyolite, however, it was evident that some great disturbance had occurred; and it was the writer's good fortune, after brief search, to find one of the two localities in the district where, as it proved, the fault is both well exposed and not masked by later brecciation.

The locality is the north side of the Copper Cliff rhyolite, in lots 9, 10, and 11, con. IV, McKim tp. The road from Sudbury to the Murray mine runs northwesterly through the middle of lot 10, making the place easily accessible. Both east and west of the road the fault is exposed in many places as a strong sheared zone striking north 55 degrees east and dipping about 70 degrees northwest. East of the road the rocks north of the fault are a basalt flow in conformable contact with sediments. The contact between them strikes north 75 degrees east, so that it runs into the fault, which can thus be seen to bevel these older strata at a small angle. Somewhat farther east an irregular basic dyke, about the composition of andesite, crosses the bedding of the sediments as far as the fault, where it likewise is abruptly truncated. The sheared zone marking the fault ranges from about a foot in width between basalt and rhyolite to several feet between sediments and rhyolite.

Evidence indicating the direction of fault movement was not plentiful, even in this well-exposed section. After considerable search two places were found west of the road, in lots 10 and 11, where the relation of the fault cleavage to the dip of the fault indicates upward movement of the north side; and one place where some thin beds of sediment have been dragged so as to indicate that the north side also moved eastward. This scanty evidence, if correct, indicates that the rocks north of the fault are older than those to the south; but there are no data, beyond their greater metamorphism, to indicate how much older they may be, and in view of the fact that the norite or the ore-bearing solutions may have had strong metamorphosing effects, such evidence is rather unsatisfactory.

For about 3 miles to the northeast, the fault is masked by later brecciation, but in lot 3, con. I, Blezard tp., the band of breccia is only a few feet wide, and it can be seen that the lavas of the Upper Stobie group strike nearly at right angles to the rhyolite contact, which cuts west across them and the sediments. About 1½ miles east of this, again, in lot 12, con. I, Garson tp., the rhyolite contact again bevels a contact between lavas and sediments of the Stobie group. A few feet of the actual contact can be seen in one place; it is an intensely sheared zone at least 6 feet wide.

To the west of the locality first described, the fault is not well exposed, but it appears to follow the northern contact of the Copper Cliff rhyolite closely. In the south end of lot 3, con. IV, Graham tp., the rhyolite comes to an end, possibly cut off by the faulting; and the Lower Stobie group is thenceforward in direct faulted contact with the McKim formation. This section affords some of the best evidence of faulting.

From the end of the rhyolite in lot 3 to the middle of the west side of lot 6, con. III, Graham tp., the contact follows a belt of swamp at the bottom of a moderately deep valley. At the west side of lot 6, it swings abruptly northwest for about 900 feet, and in this course truncates squarely the nose of an east-plunging anticline in the McKim formation (Figure 7). In the next three-quarters mile the contact has several sudden changes of direction; but, finally, about the middle of the north end of lot 8, concession III, it assumes a slightly curving westward course. In this section the original fault, which may be seen in a number of places, is again masked by later breccia forming a band some 40 feet or so in width. The rocks to the north of the breccia zone are rather badly metamorphosed lavas of the Stobie group; those to the south are McKim greywackes. The latter, by numerous excellent determinations from rill-marks and changes of grain, face *north*, whereas along most other sections of the contact they face south.

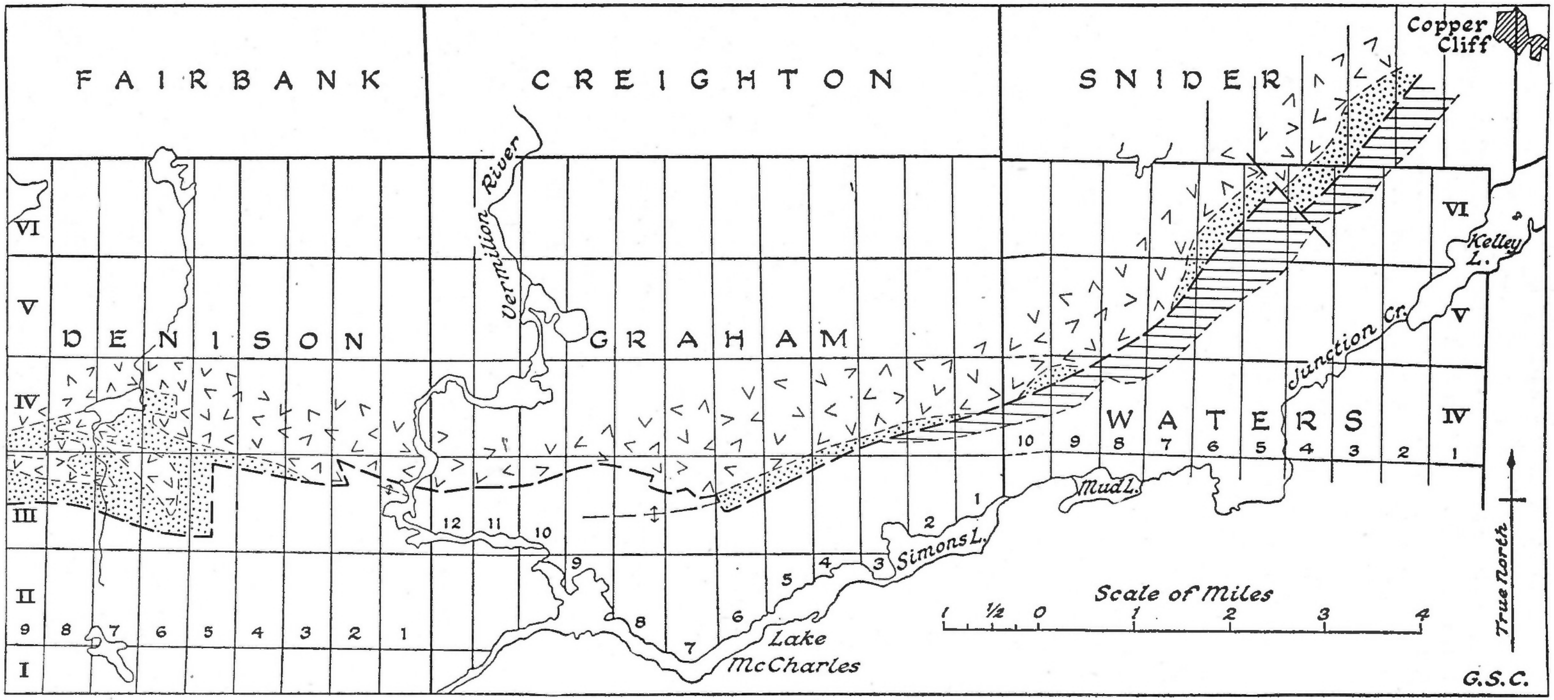

Figure 7. The great fault separating the Stobie group and Bruce series, in Waters, Graham, and Denison townships. Stobie lavas shown by angle pattern; Stobie sediments by stipple; Copper Cliff rhyolite by horizontal lines. McKim greywacke, represented by no symbol, lies south of the fault in Graham and Denison townships, and south of Copper Cliff rhyolite in Waters township.

Where the Stobie-McKim contact crosses Vermilion River, in lot 1, con. III, Denison tp., an anticlinal axis in the McKim can be seen just south of the contact, on the west side of the river. The McKim is cut off, however, just north of this axis, and its place is taken by the rocks of the Stobie group.

It is obvious that only faulting can account for the features described, and faulting, at that, with large vertical movement. It must be assumed tentatively that the north side of the fault rose, as the rocks on that side have always been considered the older, and the small available amount of direct evidence points to the same conclusions. The fault also had a horizontal movement, the south side moving west. Direct evidence for this is better than that for the vertical movement, for in several places evidences of drag were observed and all point to the same conclusion.

West of Vermilion River the region is more heavily covered by drift and forest, and good evidence of faulting proved difficult to obtain. It was observed in several places, however, that the Stobie contact continues to be the locus of strong brecciation. The contact passes out of the west side of the Copper Cliff map-area near the south end of lot 6, con. IV, Drury tp., and has not been traced farther.

THE "SUDBURY SERIES"

The term Sudbury series, as originally used by Coleman (18, 19), included most of the surficial rocks of the region except the Ramsay Lake and Bruce conglomerates. The latter he considered Huronian in age, the other rocks pre-Huronian. Burrows (11) also termed all the surficial rocks Sudbury series, and went farther than Coleman by including with it the Ramsay Lake conglomerate, because he proved it to be conformably interbedded between the McKim and Mississagi formations; and he tentatively assigned it to the Temiscamian (?). Collins' investigations (29) indicated the Ramsay Lake conglomerate to be the base of the Bruce or Lower Huronian series; and as he looked on the lavas of the region, comprising the Copper Cliff rhyolite and what are here termed the Stobie lavas, as Keewatin, he was obliged to confine the term Sudbury series to the McKim formation, with which he included most of the Stobie sediments.

The writer considers that there is now no justification for retaining the term at all. Evidence to be presented will indicate that the McKim and Copper Cliff formations lie conformably beneath the Bruce series, and should hence be classed as a local part of it; whereas the new name Stobie group has been applied to that part of the old Sudbury series that lies north of the great fault.

BRUCE SERIES

Copper Cliff Rhyolite

The Copper Cliff rhyolite outcrops to the south of the Stobie group as a gently curving band about 17 miles long and, for the most part, a little less than half a mile wide. Owing to its hardness, the formation is usually a strong ridge. Along its northern, faulted contact with the Stobie group the rhyolite is everywhere more or less sheared or brecciated, and it seems likely that its disappearance at either end is due to faulting.

For the most part the rock is massive, dull pink, and rather coarse-grained for a rhyolite; it looks much like a rather fine-grained granite poor in ferromagnesian minerals. In places it is beautifully and evenly banded in layers 1 or 2 inches wide, and it was presumably structures such as these that caused Coleman to term it "arkose" (19, p. 212). Such banding as the writer has seen, however, never extends far without bending into sharp curves, which, if due to folding, would be accompanied by intense deformation and shearing. As evidence of such is entirely absent, the banding is interpreted as an original flow structure. On very clean surfaces it can be seen that much of the rock is a breccia, with sharp-angled fragments, some of them partly remelted, in a matrix of similar or slightly different composition. Toward the southeast or upper side of the formation there are many thin beds of amygdaloidal rhyolite and breccia; and the impression gained from cross-sectioning the formation is that the period of extrusion started with the ejection of thick masses of viscous lava, much of which brecciated as it moved, and ended with a succession of volcanic explosions and small flows that did not extend far from the vents.

Under the microscope the rhyolite characteristically has a grain of about 0·15 mm., though larger crystals are present. Quartz constitutes 35 to 50 per cent, or even more, and most of the remainder is fresh feldspar, about $Ab_{85}An_{15}$ in composition, with 2 or 3 per cent of biotite and, in places, some muscovite. Burrows states (11, p. 21) that orthoclase and microcline are present, but the writer did not identify any in the thin sections examined. One thin section of more basic material that forms the matrix of a coarse breccia contains no quartz, about 20 or 25 per cent biotite, and the rest mainly fresh feldspar, about $Ab_{60}An_{40}$. This material has a grain of about 1 mm.

The contact between the rhyolite and the overlying McKim greywacke is best exposed and most accessible at two places in lot 6, con. V, McKim tp. One of these is approximately at the northeast corner of the lot, the other about 500 feet to the southwest. At the latter, the flows and sediments strike north 40 degrees east and have a vertical dip. The rocks are beautifully exposed on a clean cliff face that crosses the bedding at an angle of about 45 degrees. For about 100 feet northwest from the contact the rhyolite is a series of flows ranging from 1 foot to 25 or 30 feet in thickness. Some of them are fine-grained and massive, others highly vesicular, and still others are breccias of rounded and angular fragments of rhyolite and other materials in a matrix of fine, flow-textured lava. Close to the contact there are some 2-inch bands of material that may be flow-textured lava or tuff.

At this point, unfortunately, there has been injected a dyke or sill of rhyolite 3 or 4 feet wide. Its intrusive nature is proved by the fact that apophyses a few inches long run off from it across the bedding of the overlying sediments. The latter are dark, thin-bedded argillites or greywackes, and are about 4 feet thick. East of them again is a rhyolite flow about 2 feet thick, then about 20 feet of sediments with the varve-like bedding characteristic of the McKim greywacke. All these beds seem perfectly conformable, and the varve-like bedding indicates that the beds face southeast.

About 500 feet northeast of this exposure even better relations are visible. As before, the upper 100 feet or so of the rhyolite consists of thin flows, many of which weather as if their upper or southeastern sides are highly amygdaloidal. These are followed without break by the dark, varved greywackes, and with them are interbedded: (*a*) two or three bands, one 4 feet wide, of coarse rhyolite agglomerate in which the rhyolite fragments attain diameters of 6 to 8 inches; (*b*) at least one thin highly amygdaloidal rhyolite flow, 3 or 4 inches thick. All of these volcanic strata thin to the northward along the strike and pinch out.

It can hardly be doubted, therefore, that there is perfect conformity between the McKim greywacke and the Copper Cliff rhyolite. The evidence indicates that after sedimentation began there were still a few sporadic outbursts of volcanism. It is even possible that the more argillitic parts of the McKim formation represent showers of fine volcanic ash, and that this accounts for the extraordinary varve-like bedding peculiar to it.

Before leaving the discussion of the Copper Cliff rhyolite, it may be noted that in a few places in the volcanic part of the Stobie series there are flows of petrographically quite similar rhyolite. Both Burrows and Collins, considering the Copper Cliff as merely one unit of a series as they did, naturally mapped these flows as Copper Cliff. This can no longer be done, if the writer's conclusions as to the stratigraphy are accepted. Again, southwest of Crean Hill mine, Denison township, Collins has mapped two bodies of fine-grained granitic intrusive rock as Copper Cliff; and in the area northeast of the Stobie mine there are some dykes and sill-like masses of similar rock. It is quite possible that all these bodies are intrusive equivalents of the Copper Cliff rhyolite, but there is as yet no means of proving it. They may equally be ascribed to the Killarnean period of granite injection.

Relations to the Stobie Group. Along most of its length the Copper Cliff rhyolite is faulted against the Stobie group. The evidence for the faulting has already been given at length and is so complete that no doubt as to the relations can remain.. This being so, it was extremely puzzling to discover one locality, close to the extreme eastern end of the rhyolite, where, over a length of some 30 feet, the contact is apparently unfaulted and conformable.

Near the west side of lot 11, con. I, Garson tp., the upper beds of the Stobie group are coarse, impure quartzites striking north 60 degrees east, dipping vertically, and facing southeast. Immediately above them, and apparently in perfect conformity, is a dark, fine-grained, massive, micaceous rock, entirely without flow lines or other indications of deformation. Its general appearance suggests a volcanic mud. This band is about 25 feet wide, and the length of contact exposed is somewhat less. On its north side the band contains a few irregular lumps of vesicular rhyolite, up to 6 inches in diameter, that seem to be volcanic bombs. Toward the south side the supposed bombs increase both in size and number, attaining lengths of 2 or 3 feet and constituting about one-third of the rock. The edges of the "bombs" are extremely irregular, with numerous large and small protuberances and intervening depressions; not at all the type of outline found in the fragments of a breccia formed by movement. A drift-filled gully about 20 feet wide separates this peculiar rock from the massive rhyolite to the south.

This outcrop, therefore, suggests that the extrusion of the Copper Cliff rhyolite began with explosive activity, forming mud and bombs that were deposited conformably on the Stobie group. On the other hand, if the drift-filled gully just mentioned be the locus of the otherwise omnipresent fault between the Stobie group and the Copper Cliff rhyolite, then the only alternative appears to be that the bomb-filled bed represents an episode of volcanic activity within the Stobie, and that its presence thus at the contact is purely fortuitous.

McKim Formation

The McKim formation forms a band ½ mile or less to 2 miles wide, between the Copper Cliff rhyolite on the north and the Ramsay Lake conglomerate on the south. Its easternmost outcrop, where it passes under drift, is in lot 7, con. II, Garson tp., and the writer has traced it west to lot 4, con. III, Drury tp., a distance of 30 miles. It undoubtedly extends farther. Coleman (19, p. 213) estimated its thickness as at least 7,000 feet, a figure that is perhaps as good as any, considering the immense amount of faulting, crumpling, and brecciation to which it has been subjected.

The bulk of the formation is made up of two types of beds. The first is beautifully stratified, dark grey-green argillite that notably resembles the varved clays and silts of glacial lakes. It is made up of regular layers ranging from ½ inch to 2 inches in thickness, though a few attain widths up to 4 inches. Somewhat more than half of each layer looks like coarse silt, and in it a few sand grains can be seen. Tested with the knife, this part is distinctly harder than the remainder of the layer, which is finer grained as well as softer, and was presumably nearer pure clay in composition. It is assumed that the latter is the original top of the varve-like layer; and structure determinations made on this assumption check with those made by other methods.

The other type of sediment consists of medium to coarse, impure quartzite and greywacke, in massive beds for the most part 2 to 4 feet thick, but attaining in extreme cases thicknesses of 12 to 15 feet. Some of these beds contain no quartz, but are now recrystallized to mixtures of feldspar and mica with an average grain of 0·1 mm. or more. Others do contain some quartz, and a few are fairly pure quartzite. It is not uncommon to find a concentration of coarse quartz grains, up to the size of small peas, at the bottom of a bed of this type; and in such cases the large grains tend to be concentrated in rill channels cut an inch or two into the underlying beds. Such rill markings are very common in this formation, particularly where a thick sandy bed overlies thin-bedded silts, and are an excellent means of determining the structure.

In addition to the two main types, a few beds of coarse rhyolite tuff and ash are found near the base of the formation. Some of them, though ranging from perhaps a foot to several feet in thickness, display a regular change of grain from coarse at bottom to moderately fine at the top, implying that they were formed by single showers of ash falling into water.

In general, the massive, sandy beds seem to be concentrated in the stratigraphically lower parts of the formation, and the thinner, varve-like beds in the upper parts; but this arrangement is not fixed, and beds of both types are found throughout.

It is obvious that the McKim formation was deposited under subaerial conditions, as the numerous rill-marks and the occasional crossbedding show. Probably the varve-like beds were, therefore, laid down in rather shallow ponds, a conclusion supported by the occasional occurrence in them of very delicate crossbedding and a wavy structure of the bedding planes suggesting ripple-marks. Possibly also the varved bedding indicates cold or glacial conditions, as evidence presented later indicates.

At Sudbury and Copper Cliff the varved beds contain numerous metacrysts of staurolite (now decomposed to quartz and mica) about the size of large grains of rice. These are more numerous and larger in the clayey upper part of a bed than in the silty lower part, and thereby lend a pseudo-coarseness to the former that is the reverse of their original character. It was also observed that the metacrysts become larger and much more numerous as large bodies of the Nipissing gabbro are approached, so that their development is due to the heat of these intrusives. In Graham township, ranges II and III, where no gabbro is near at hand, the varved beds contain no metacrysts, and as a consequence are so much fresher in appearance that the writer devoted considerable time to checking the possibility of their representing a different formation.

The structure of the McKim is, in general, that of a homocline facing south or southeast. There is a fairly large drag-fold in the southwest corner of lot 7, con. III, McKim tp.; the axis of an anticline runs through the middle of lots 7, 8, and 9, con. III, Graham tp., but was not traced farther; and the axis of another anticline is visible on the west bank of Vermilion River, close to the boundary of the Stobie group; but for the most part the beds face uniformly south or southeast from the Copper Cliff rhyolite or the faulted contact with the Stobie series to their contact with the Ramsay Lake conglomerate.

Relations to the Ramsay Lake Conglomerate. The relations of the Ramsay Lake conglomerate to the McKim formation have been a subject of discussion for many years. Coleman (19) considered the conglomerate as unconformable on the McKim and on the Mississagi quartzite, both of which he placed in the Sudbury series; his conclusions, it is clear from his reports, were due to the insufficiency of the areal work at that time, which caused him to lump into one age group formations that we now know to be of three different ages, namely the Ramsay Lake, Bruce, and Gowganda conglomerates. Burrows (11) later stated that he had found no unconformity, and he, therefore, classed the Ramsay Lake conglomerate as part of the Sudbury series, along with the McKim and Mississagi formations. Collins acknowledges that no unconformity is visible in Sudbury district, but, having found the conglomerate at the base of the Huronian throughout the rest of the North Shore region, he was reluctant to consider the possibility of older Huronian formations elsewhere; in addition, he did not differentiate the Stobie sediments from the McKim, and hence could not reconcile the interbedding of "McKim" sediments and ancient, Keewatin-like lavas with the conclusion that the McKim is but little older than the Ramsay Lake.

The field work of 1938-39 has removed this difficulty by showing that the interbedded sediments and lavas, here termed the Stobie group, form no part of the McKim formation. The writer concurs with Burrows in the conclusion that the Copper Cliff, McKim, Ramsay Lake, and Mississagi formations constitute a conformable series; and as Collins has proved conclusively that the last two are parts of the Bruce series, of Huronian age, the first two must likewise be older parts of the same series. Their limited distribution is undoubtedly due to limitation of the original basin of deposition.

The relations between the McKim formation and the Ramsay Lake conglomerate are well exposed in lot 7, con. II, McKim tp.; in lot 7, con. IV, Waters tp.; and in lot 6, con. II, Graham tp. At the first of these localities, about 200 feet northeast of the road, the Ramsay Lake conglomerate rises as a low cliff 5 or 6 feet high, facing northwest. At its base the contact with the McKim is well exposed for a length of about 70 feet. A few feet below the contact the McKim is the usual dark, even-bedded, siliceous greywacke, in beds 2 to 7 inches thick, but just below the contact these give place to very fine-grained sediments in beds $\frac{1}{8}$ to $\frac{1}{4}$ inch thick. The conglomerate, a coarse quartz grit carrying moderately numerous quartz pebbles an inch or two in diameter and a few larger ones of granite, does not cut across the thin underlying beds or contain any fragments of them. In one place a granite boulder measuring 4 by $4\frac{1}{2}$ inches is embedded in the thin-bedded strata 18 inches stratigraphically below the base of the main conglomerate horizon. The thin beds above it are not broken as if the boulder had sunk through soft muds, but on the contrary the thin beds rise to pass smoothly over the boulder, so that they were clearly deposited after it came into position.

In lot 6, con. II, Graham tp., the contact is especially well exposed. The McKim here is the thick-bedded, sandy greywacke interbanded here and there with a few feet of the usual thin-bedded types. About 20 feet from the base of the main conglomerate band they become more siliceous, and have widths of 4 or 5 inches. Among them appear, about 6 feet below the main conglomerate, two pebbly beds, one 4 inches thick, the other 10 inches. These contain numerous pebbles about an inch in diameter of quartz, granite, and some unidentified materials. About 2 feet below the main conglomerate band, conglomeratic stringers ½ to 1 inch wide are interbanded with the greywackes. At this locality, therefore, it is quite clear that there is no sudden change of sedimentation, but that for a time deposition of greywacke alternated with deposition of conglomerate.

In lot 7, con. IV, Waters tp., the situation is similar. Forty or 50 feet below the main band of conglomerate the McKim consists of the usual thin-bedded siliceous greywackes. The beds nearer the conglomerate are more siliceous, and can be termed quartzites. Toward the northeast end of the hill these beds alternate repeatedly with thin beds of conglomerate as the main contact is approached. Toward the southwest end of the hill one bed of fine-grained quartzite was observed to contain a single boulder of granite measuring 6 inches long and 3 inches wide; and a 2-foot bed of siliceous slate contains a boulder of granite nearly 3 feet long and 1½ feet wide.

These descriptions make it evident that there is no unconformity at the base of the Ramsay Lake conglomerate, but that conditions of sedimentation changed gradually to permit of deposition of conglomerate rather than siliceous greywacke. It is evident that the change was not a sudden one, as there was alternation of conglomerates and greywackes near the contact, and from the thickness of the alternating beds this must have gone on for a considerable time.

Ramsay Lake Conglomerate

The Ramsay Lake conglomerate forms a band about one-eighth mile wide, or less, between the McKim greywacke on the north or northwest and the Mississagi quartzite on the south or southeast. In Copper Cliff area it is well exposed, and outcrops as a reasonably continuous band, somewhat broken by faulting, in Denison and Louise townships, but in Falconbridge area exposures are rather poor. One small area of outcrop occurs in lot 11, con. V, and others in lots 8 and 9, con. VI, Neelon tp., and in the adjoining part of Garson township. A drift-covered gap of more than 6 miles separates the last outcrop mentioned from the next, in lot 6, con. IV, Falconbridge tp. Beyond this point no outcrops of the formation have been found, except for a few discovered by H. W. Fairbairn in the southeast corner of Scadding township and one in the northeast corner of Street township.

The structure of the Mississagi quartzite south of the main conglomerate band is that of a much faulted synclinorium, and block faulting has brought up to the present surface two large blocks of Ramsay Lake conglomerate in Waters township, one in lots 2 and 3, concession IV, the other in lots 5 and 6, concession III. The second mass is shown on the Copper Cliff map as a plate about 2 miles long. Faulting is also responsible for the appearance of a block of conglomerate and McKim greywacke nearly 5 miles long and more than a mile wide, in the north end of Louise township.

On the south side of the synclinorium, a local anticline, whose crest has been eroded into the valley of Long Lake, brings the conglomerate to the surface toward the northeast end of the lake; and outcrops of it may be seen on the shore in lot 10, con. III, Broder tp., and again in lots 6 and 7, concession IV. A band of the conglomerate also follows the extreme south side of the synclinorium for about 2 miles from the north end of lot 7, con. II, Broder tp., to the middle of lot 3, concession III. Farther east and west it is cut off by intrusive igneous rocks.

The conglomerate is, for the most part, a rather coarse grit carrying a few small and rather widely scattered pebbles, though there are places where pebbles are numerous and a few where the rock is crowded with them. Many of the smaller pebbles are quartz, but the larger are almost all granite, with a very few of other unidentified materials. No pebble or boulder of the McKim greywacke has yet been found in the conglomerate. The matrix is quartzite, generally but not invariably impure, and its characteristic feature is the presence of glistening fragments of quartz about as big as peas. In places these are narrow shards, so sharp-angled and plate-like that they have obviously undergone little wear by transporting agencies. This is best seen at the southwest end of lot 7, con. IV, Waters tp. The conglomeratic grit generally forms massive beds, ranging in thickness from 4 or 5 feet to perhaps 100 feet or more. Within these beds there is rarely any trace of subordinate stratification, although occasionally a lens of slightly differing grain may yield a strike and dip observation.

Huge boulders are scattered here and there throughout the conglomerate, entirely without reference to the character of the enclosing beds. In the northeast corner of lot 6, con. II, Graham tp., one such boulder at the corner of a cliff measured 4 by 2 by 1½ feet, and two others nearby were almost as large. In Louise township, lot 12, concession VI, three boulders lying fairly close together each ranged from 4 to 5 feet long and from 2 to 3 feet thick. West of the Sudbury district (as noted by Collins, 29, p. 40) the conglomerate carries boulders up to 5 feet in diameter. In no place is the matrix near such boulders any different from that farther away; the boulder seems to have been dropped at random into the grit. Many of the boulders are fairly well rounded, about half of them are subangular, and a few have one or more fairly sharp corners. Some have flat or flatly rounded sides, suggestive of soling.

Comparison with other Conglomerates. The Ramsay Lake conglomerate is readily distinguishable in most of its outcrops from all other conglomerates of the region. The Upper Stobie conglomerate has a far higher percentage of quartz pebbles, and lacks the gritty matrix with its numerous fragments of quartz. The Bruce conglomerate, which overlies the Mississagi quartzite, has a greater variety of pebbles and, in most places, a larger proportion of pebbles to matrix; and the matrix, instead of being a siliceous grit, is a basic, fine-grained greywacke with rather numerous sand grains. The Gowganda conglomerate at the base of the Cobalt series is crowded with a great variety of pebbles, and the matrix is a very fine-grained greywacke, which, under the microscope, is seen to consist of finely pulverized and undecayed rock material.

Lack of recognition of these differences has caused, in the past, much misunderstanding of the stratigraphy. Coleman classed together bodies of the three conglomerates above mentioned, and the undoubted unconformity of the two younger, particularly the Gowganda, on the formations he classed as Sudbury series, was the cause of his conclusion that the true Ramsay Lake is likewise unconformable on it. Although Burrows recognized the correct relations of the Ramsay Lake conglomerate around Sudbury to the other formations, he then confused with it certain large bodies of the Bruce conglomerate in Falconbridge and Dryden townships, and thereby fell into error in his mapping. Both Burrows and Lawson (56, p. 375) confused with it certain bodies of autoclastic breccia, later to be described; and this confusion led Lawson to maintain that the whole accepted succession is upside down. Only Collins, of all who have described the region, recognized the proper stratigraphic position and petrography of this formation, and thereby mapped it without error.

Except in Sudbury district, the conglomerate has not been described or mapped as a separate formation, but has merely been referred to as the conglomeratic phase at the base of the Mississagi quartzite. Collins, however, traced it east from the original Huronian district near Thessalon, and says (35, pp. 1677-78):

> "A conglomerate that lies at the base of the Bruce (Lower Huronian) series was traced into continuity with the Ramsay Lake conglomerate. This conglomerate extends, with only short gaps due to drift-cover, lakes, or faults, all the way from Thessalon eastward to Sudbury. It lies in profound unconformity upon the Keewatin green schists and the granite gneiss of the pre-Huronian, consisting from place to place of the decomposition products of whichever of these two groups of rocks lies immediately beneath. This conglomerate grades conformably upward into the next formation of the Bruce series, the Mississagi quartzite, a thick feldspathic quartzite. Eastward toward Sudbury, where the belt of Sudbury series is reached, this basal conglomerate consistently maintains a position between the Sudbury series (McKim greywacke) on one side and the Mississagi quartzite and succeeding formations of the Bruce series on the other, continuous into the Ramsay Lake conglomerate at Sudbury".

Origin of the Ramsay Lake Conglomerate. The nature of the Ramsay Lake conglomerate suggests some interesting speculations as to its origin. The only agencies capable of moving the very large boulders found in the conglomerate are glacial ice, torrential streams, or floating ice cakes. The composition of the rest of the conglomerate, however, is not that of morainic material, nor is it such as would be laid down by a torrential stream. The only remaining agency is, therefore, floating ice, and the erratic distribution of the boulders, their wide range of size, and their presence here and there in the fine-grained, directly underlying beds of the McKim formation, all combine to attest the correctness of the conclusion.

Floating ice, however, implies a body of water deep enough to float ice cakes capable of supporting a ton or more of rock. Some of the boulders observed weigh about a ton, and one occurrence is such as to suggest that three of them must have been dropped by one ice cake. On the other hand, the water body cannot have been very deep, as the coarse grit, with grains up to the size of peas, must have required fairly strong waves or currents to spread it.

Some of the pebbles and boulders in the conglomerate are well rounded, as if subjected to long wear; yet others display a degree of angularity that obviously indicates little wear. The little fragments of quartz in the grit are, in many places, sharp plate-like shards that have obviously undergone little wear. On the other hand the grit, though by no means pure silica, is nevertheless pure enough to demand, apparently, long weathering and the removal of the clay constituents by water action.

To the writer the only possibility combining all these seemingly contradictory features is that of glaciation of a deeply weathered granite surface. Moderately deep, thorough weathering of a granite would convert the feldspars and ferromagnesian minerals to clayey products, whereas the quartz grains and quartz veins would be unaffected except by solution. In this mass there would remain a few kernels of unweathered granite, with rounded and subangular shapes. If such material were pushed into a shallow sea by an advancing glacier, wave action might quickly carry off the clayey parts, leaving the sands and quartz crystals to be spread rapidly over the shoal areas near shore. Many quartz grains might be broken to form sharp-angled fragments, but the material would be deposited too rapidly for such fragments to be rounded off. The boulders, scoured by wave action of their weathered envelopes, would be frozen into shore ice that, carried away at intervals on a rising tide, would float away and drop its load where it melted.

Mississagi Quartzite

In earlier studies of the Sudbury district the Mississagi quartzite was termed the Wanapitei quartzite, by which name it is still occasionally known; but Collins (35, pp. 1677-78), tracing the formation from the west, found the Wanapitei quartzite continuous into the Mississagi quartzite, and altered the name accordingly, as the term Mississagi is the older.

In Falconbridge map-area the formation consists almost wholly of quartzites, which range from very pure white or greenish varieties to the more ordinary feldspathic types. The purer quartzites are found near the centre of the principal syncline, and, therefore, in the upper horizons of the series. Farther west, according to Collins, the quartzites are interbedded with conglomeratic and argillitic lenses, but in the Sudbury district no conglomerates were seen above the basal Ramsay Lake conglomerate, and argillitic beds are thin or lacking.

The quartzites are light grey rocks, weathering to light grey and white. The grain is mostly fine and fairly uniform. The beds in general average from 6 to 12 inches in thickness, although some, particularly the purer varieties, may attain thicknesses of 10 to 15 feet. Crossbedding is so invariably present, at least in the area studied, that it becomes a characteristic of the series. The crossbeds are extremely narrow, so that they appear on the weathered surface as a series of lines, but are almost or quite impossible to detect on fresh surfaces. In Falconbridge area the crossbedding is always in the same direction, that is, if the beds are brought back, in imagination, to a flat position, the crossbeds always face toward the south or somewhat west of south, indicating that the currents bringing in the sediment came from the north or east of north. This conclusion suggests, first, that the source of the quartzites was to the north, a matter previously in doubt; and, second, that the thickening of the Mississagi quartzites to the east and south, which was pointed out by Collins, must have been due to sinking of the bottom of the geosyncline of deposition in that direction.

The structure of the Mississagi quartzite is that of a broad syncline, with steep dips, about 85 degrees, on the flanks and low dips in the centre. The syncline plunges east-northeast at an angle of 10 degrees or less. In the middle of Wanapitei area, where the north limb is complete and no intrusives are present, it is about 2¼ miles from the centre of the syncline to its northern boundary, which would correspond to a thickness of about 12,000 feet if the steep dips were maintained throughout. The width of the limb has, however, been increased by drag-folding, and over about three-quarters mile from the centre of the syncline the dips are comparatively low, so that an estimated thickness of about 9,000 feet is probably correct within 500 feet or so. This checks fairly closely with Collins' determination of 10,000 to 12,000 feet "throughout the southern area (of Mississagi quartzite)" (29, p. 44).

The quartzite, which appears to form a simple syncline in the middle part of Falconbridge area, widens toward the southwest and becomes a compound syncline complicated by faulting. A section across it due south of Sudbury showed at least two subordinate anticlines in the synclinorium; and probably the wider part in the Whitefish Lake Indian Reserve has a still more complex structure. The Ramsay Lake conglomerate, which should normally be found along the south side of the synclinorium, is seen only for about 2 miles in Broder township. Elsewhere it is cut off by a strong fault, already described (pages 14, 15), and by intrusions of granite that followed the fault and in places cut across it to lie in direct contact with the quartzite. This fault has affected the quartzite profoundly in many places. Wide bands of it near the southern contact have been broken up by a multitude of sub-parallel fissures spaced a few inches or a foot apart; shearing along these has produced bands of dark schist half an inch to an inch in width. All available evidences indicate a movement of the south side upward and to the west.

Infaulted Blocks. Near the south side of Falconbridge area, on both sides of the Dryden-Neelon township boundary, block faulting and overthrust have caused some interesting relations between the Mississagi quartzite and the Nipissing gabbro.

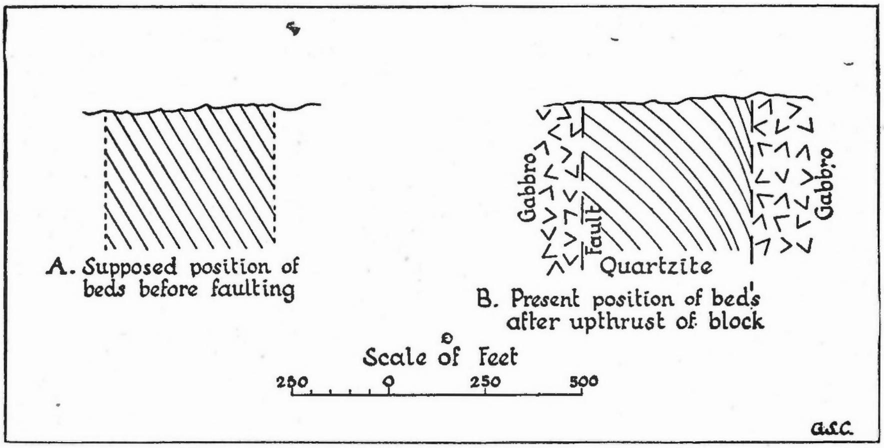

Figure 8. Cross-section of quartzite block upthrust into gabbro dyke in lot 2, con. V, Neelon tp.

In lot 2, con. V, Neelon tp., two plates of quartzite strike north across the gabbro body and are separated by a mass of gabbro about 1,000 feet wide. The eastern plate is about 700 feet wide, the western less than 200; and both at the south ends run into a drift-covered stream valley. Mapping done by Burrows (11) south of Wanapitei area shows only one band following this valley southwest; so that either the narrow band is pinched off or the two coalesce beneath the drift.

These bands are unbroken bodies of hard white quartzite. The gabbro at their edges has been badly brecciated over widths of 20 to 25 feet. The eastern slice of quartzite is well exposed across its entire width. Its beds strike north, but the dip, which is 45 degrees east on the west side, becomes gradually steeper toward the east until at the eastern edge it is vertical and in places slightly overturned. If a slice of quartzite with an original eastward dip of about 60 degrees had been block-faulted up, the drag on the walls during the upward movement might produce the relations observed (Figure 8).

The inference thus made from the changing dip was checked by direct observations. A band of schist was found in the breccia of the well-exposed east side, and the relations of the cleavage planes to the general strike indicate that the quartzite moved relatively up and north. A drag-fold with an amplitude of about 4 feet was also found near the south end of the outcrop, which likewise showed that the quartzite moved relatively up. Part of the bottom of the drag-fold is exposed, permitting the plunge to be measured as 15 degrees to the north; so that, as the slaty cleavage also indicated, some northward movement accompanied the upward movement of the quartzite slice.

The narrower western slice is much less well exposed, as it outcrops on a steep hillside and is largely covered with talus, but it displays similar dip relations. The dip changes from 25 degrees east on the western side to 50 degrees east near the eastern side; so that, like the other, it probably came into its present position by upfaulting.

Half a mile or so east of these occurrences, straddling the Neelon-Dryden boundary, a wedge-shaped mass of quartzite runs northwest into the gabbro, and is separated by some 1,200 feet of gabbro from a similar but shorter wedge of quartzite running southeast into the gabbro. Drag-fold and cleavage relations indicate that these two bodies moved toward each other. The one to the northwest consists of isolated flat plates of quartzite, some not more than 6 or 7 feet thick, surrounded on all sides by gabbro; and the relations obtained indicate that these are the brecciated remnant of a body of quartzite thrust over the gabbro from the northwest. The triangular mass 1,200 feet to the southeast exhibits similar evidence of overthrust from the southeast. A dyke-like body of breccia connects the two.

In the north end of lot 12, con. IV, Dryden tp., another U-shaped mass of quartzite runs eastward into the gabbro. Slaty cleavage and drag-folds along the edges of this mass again prove that it moved eastward and up into its present position; that is, it was overthrust from the west.

Some 400 feet north of the last occurrence, in the south end of lot 12, con. V, Dryden tp., and the adjoining part of lot 1, con. V, Neelon tp., a plate of somewhat brecciated quartzite 1,000 feet wide cuts almost east and west completely across the gabbro body. Good evidence was not obtained here as to the direction of movement, but there can be little doubt, from the brecciation of the quartzite and the way it cuts across the gabbro, that it has likewise been brought into position by faulting.

The west-facing concave contact of gabbro and quartzite in lot 11, con. IV, Dryden tp., is also a fault. Evidence at this point indicates that the quartzite is upthrust against the gabbro, and also moved relatively south.

The writer is inclined to correlate these fault movements with the Late Precambrian disturbances that produced the Sudbury breccias, described in a later section.

Relations to the Killarney Granite. Excellent contacts between the Mississagi quartzite and the Killarney granite were observed on the lake shore in the northeast corner of lot 10, con. I, Broder tp., and on the west shore of Wavy Lake in the Whitefish Lake Indian Reserve. In the first locality the contact is visible for a length of about 10 feet; the granite parallels the bedding of the quartzite in a general way, but its boundary is wavy, with vertical distances from crest to trough of about 3 inches; and these waves cut across the thin bedding of the quartzite. This is, however, the only evidence of intrusion; the granite sends no stringers into the quartzite, and exerts no perceptible metamorphic effects.

The relations on Wavy Lake are very different, for the quartzite there has been intensely metamorphosed by the granite. The rock mapped by Collins (Map 292A, Copper Cliff sheet) as quartzite on the west shore of the south arm is really an interbanded mixture of granite sills and quartzite bands; and the quartzite has been granitized to a greater or less extent, with development of micas and feldspars and additions of silica. All traces of the usual crossbedding are destroyed. Traced northward along the shore for about a mile, the granite sills become fewer and then disappear; concomitantly the quartzite gradually becomes less and less granitized and passes into the normal crossbedded type.

Bruce Conglomerate

The Bruce conglomerate, originally called the Lower Slate conglomerate by Logan and Murray, is made up of very numerous subangular to rounded boulders in a dark, gritty matrix. The boulders are mostly 3 or 4 inches in diameter, although a few larger ones up to 2 or 3 feet in length are present. They consist of granite and gneiss, various basic rocks that look as if they are derived from the Keewatin, and a few of glassy quartzite. The gritty matrix is made up of grains of quartz and feldspar averaging about 1 mm. in diameter in a finer matrix of the same minerals with chlorite, sericite, and other decomposition products. The quartz grains characteristically display black, glassy fracture surfaces. The matrix differs from that of the Cobalt conglomerate in containing a higher percentage of the coarse gritty particles, as if there had been a certain amount of washing out of the finer clay-like components.

West of Sudbury district, according to Collins (29, p. 45), the conglomerate is interbanded with some beds of silt and silty quartzite. In Wanapitei map-area, however, the materials interbanded with or directly overlying the conglomerate are fairly pure pink or white quartzites, well bedded but differing from the Mississagi quartzites in their entire lack of crossbedding. One of these bands, in con. I, lot 8, Falconbridge tp., is 250 feet wide. The beds dip about 60 degrees southeast, so that the thickness is about 215 feet.

Several masses of the conglomerate run through the middle of Dryden and Falconbridge townships in a north-northeast direction. All the contacts of these with the Mississagi quartzite are faults, so that apparently the conglomerate bodies are down-faulted blocks. On this account no reliable estimate of thickness could be made.

In the southern part of Copper Cliff area Collins has mapped large bodies of Bruce conglomerate, but the only one examined by the writer lies at the southwest end of Long Lake. Its presence there seemed difficult to understand, as Long Lake lies on the axis of a pronounced anticline, which, near the northeast end of the lake, brings the Ramsay Lake conglomerate to the surface. Several thousand feet of Mississagi quartzite might, therefore, have been expected to outcrop between this axis and the nearest outcrop of Bruce conglomerate. The conglomerate mass proved to be a down-faulted plate, bounded on both sides by zones of intense crushing and shear.

The Bruce conglomerate, according to Collins (29), overlies the Mississagi quartzite conformably with a fairly sharp transition, and grades upward, by increase of the silty constituents, within a few feet into the silty limestone member named by Collins the Bruce limestone.

Espanola Formation

Above the Bruce conglomerate Collins (29) distinguished the Bruce limestone, a formation 150 to 250 feet thick of which the upper and lower thirds are thin-bedded, silty greywacke and the middle third limestone beds alternating with thin, siliceous layers; the Espanola greywacke, a silty, thin-bedded rock very like the Bruce limestone member, but with the limy beds reduced to the thickness of films; and the Espanola limestone, a formation containing limestone beds from a few inches to a couple of feet thick in the middle part, and grading both up and down into the thin-bedded silts. The thickness of the Espanola greywacke ranged from 250 to 400 feet, that of the Espanola limestone from nil to 75 feet. The Espanola limestone beds weather to a brick-red colour, those of the Bruce limestone to a dull grey.

Fairbairn, in the eastern part of Falconbridge area (38), lumped these three formations under the name of Espanola, though he distinguished in mapping between a lower limestone part (Bruce limestone) and an upper greywacke part (Espanola greywacke). Apparently he did not find the Espanola limestone, or at least distinguish it.

In the part of Falconbridge area examined by the writer, only a small remnant of the Espanola greywacke was found just east of Skead Village. It was identified as such because the band, projected eastward along the strike, appears again in the area examined by Fairbairn (38) and its relations to formations above and below are there evident.

The outcrop near Skead is a well-bedded greywacke in bands about an inch thick. They strike slightly south of east, and dip north at about 25 degrees. Some of the beds exhibit a pronounced decrease in grain from bottom to top. On the south the contact with the Upper Stobie group is a strong fault, marked by intense shearing over a zone several feet wide. Vein material carrying gold values has been introduced into the sheared zone, and the fault is, consequently, well exposed in a number of trenches dug to explore the zone. On the north the rock is overlain by drift.

Serpent Quartzite

The Serpent quartzite, according to Collins (29, pp. 55-6), overlies the Espanola formation conformably and is at least 1,100 feet thick and may be much thicker. The lower part is very thinly laminated, fine-grained, and greenish white; this passes upward into a somewhat purer quartzite, dead white in colour, and with a peculiar close-grained texture suggesting unglazed porcelain. The thin lamination is likewise preserved, but is less easy to detect except on weathered surfaces where it is expressed by a slight corrugation.

Outcrops of what appears to be the Serpent quartzite are found in Falconbridge map-area between Skead and Wanapitei Lake. About 1,000 feet north of the outcrop of Espanola greywacke described in the preceding section, a knoll about 700 feet in diameter consists of a very fine-grained, greenish, impure quartzite in thin beds that dip northward at angles of less than 10 degrees. The bedding is so thin that in places it approaches lamination, and no crossbedding is evident. Beds of slate up to an inch in thickness were observed in one or two places.

The stratigraphic position of these beds, which must overlie the Espanola greywacke if no fault lies between the two outcrops, and their likeness to the Serpent formation as described by Collins, appear to justify the correlation here given them.

The area north of this outcrop to Wanapitei Lake is entirely overlain by gravel except for some scattered outcrops of diabase along a large dyke. On the shore of the lake, however, there are further outcrops of a peculiar quartzite. The beds range in thickness from 2 inches to 3 feet, strike about north, and have eastward dips of 15 to 25 degrees, though in some places even lower. At the sawmill on the bay about the middle of the map-area a drag-fold plunges northward at an angle of about 10 degrees. Crossbedding is beautifully developed in these rocks, with layers of large clean quartz grains alternating with fine-grained, silty layers. The beds weather to various tints of light grey and greenish grey.

These quartzites have been mapped as Mississagi by Quirke (63) and others studying the area, but their crossbedding and general appearance are entirely unlike the Mississagi elsewhere in Wanapitei area. Their dips, however, suggest that they probably overlie the beds identified as Serpent farther south; and this, coupled with their general unlikeness to the Mississagi, inclines the writer to classify them as upper beds of the Serpent formation.

Quartzites identified as probably Serpent underlie most of lots 1 and 2, con. V, and lots 1-3, con. VI, Falconbridge tp.; lots 1-4, con. I, and lots 1-3, con. II, MacLennan tp.; and adjoining parts of Street and Scadding townships. Outcrops are rather scattered and poorly exposed. The general strike in this area is northwest, and the dips steep to vertical.

WHITEWATER SERIES

The Whitewater series is an elliptical body of sediments, tuffs, and lavas approximately 33 miles long and 10 miles wide. It lies entirely within the annular ring-shaped outcrop of the norite-micropegmatite irruptive, which isolates it completely from all the other sediments of the region. The hard micropegmatite and the rhyolite agglomerate and tuff at the base of the Whitewater form a high ridge surrounding the low flat lands underlain by the upper Whitewater formations; and this topography has given rise to the name, the Sudbury Basin, by which it is generally known.

The Whitewater series is made up of three formations, the Onaping formation at the base, consisting largely of volcanic agglomerates and tuffs, with some flows; the Onwatin slate; and the Chelmsford sandstone at the top.

A very complete and beautifully illustrated account of the series has already been given by Burrows and Rickaby (10), so that for purposes of completeness only a bare outline will be given here, together with a few descriptions of features not recorded by them.

Onaping Formation

The Onaping lavas and tuffs have been estimated by Coleman to have a thickness of 4,100 feet or more (17, p. 22). The base of the formation rests now on micropegmatite, which has intruded and somewhat metamorphosed it. The basal member is a very coarse agglomerate (termed by Coleman the Trout Lake conglomerate) composed of bouldery fragments up to 6 or 8 inches in diameter. Away from the micropegmatite the fragmental materials, in general, become gradually finer in grain, until they pass into very fine-grained tuffs almost indistinguishable from the overlying Onwatin slate. The fragmental rocks are interbanded with a number of flows of acid lava, approaching rhyolite in composition, many of which display beautifully developed amygdaloidal or spherulitic textures, slaggy tops, or flow breccias. The relative volume of the lavas is not large, however.

Burrows has called attention to the almost entire lack of stratification in this formation, and concluded, therefore, that it could not have been laid down in water. The writer would modify his statement somewhat. Although it is certainly true that even the fine tuffs display little or no evidence of fine stratification, a separation of the formation into thick beds, ranging from 1 or 2 feet to 50 or more, is distinctly evident. The planes separating the beds are straight, and those in the same locality are closely parallel, so that there can be little doubt of their being true bedding planes. Flow contacts, where obtained, are also parallel to the supposed bedding planes of the tuffs.

Small masses of white or slightly pinkish quartzite have been found in the tuffs near the micropegmatite border; some of the localities are in lot 6, con. IV, Blezard tp., and in lots 2, 3, and 5, con. VI, Garson tp. Various workers in the region have toyed with the idea that these might be fragments of Mississagi quartzite caught up during the injection of the norite and hoisted to their present position. Investigation, however, has shown that they have no resemblance to the Mississagi quartzite. Some of the bodies, though 15 or 20 feet thick, display no bedding whatsoever, and others have a vaguely defined parallel banding that may represent bedding, but is at least doubtful. In structure, the masses form tabular sheets that parallel in strike and dip the agglomerates with which they are associated. One band about 6 inches thick was observed to lie between two bands of rhyolite flow-breccia.

Whatever the origin of this rock, therefore, it is clearly an interbedded part of the Whitewater series, and not fragments of the Mississagi quartzite. Its origin is at present purely a matter of speculation. It may be a true quartzite, as its composition and appearance suggest, but against this is its entire lack of bedding and its presence in an assemblage otherwise entirely volcanic. All the masses are found fairly close to the micropegmatite boundary; and this fact inclines the writer to believe that they were probably originally fine-grained acid tuffs that have been silicified by vapours or solutions emanating from the intrusive.

The Onaping formation, as Burrows points out, ranges from very coarse agglomerate carrying boulders up to 3 feet in diameter in the parts next the micropegmatite, through gradually finer and finer varieties, to very fine tuffs next the overlying Onwatin formation.

Onwatin Formation

The Onwatin consists of dark grey to black, well-bedded rocks, the beds for the most part only fractions of an inch in thickness. A secondary cleavage is generally superimposed. The rock is very similar in appearance to the finer tuffs of the Onaping formation, except that it lacks minute fragments of lava; and its chemical composition, as given by Burrows, is that of a leached tuff. Probably, therefore, the slate is fine, tuffaceous material that has been deposited in water. However, all contacts between the tuffs and the slate are drift covered, so that the structural relations of the two are unknown.

Analyses made by the Ontario Department of Mines laboratory show that the slate has a carbon content ranging, for four specimens analysed, from 0·3 to 3·35 per cent (10, p. 28). Veins of anthraxolite are found in it, and a small deposit of the mineral has been opened in the northwest corner of lot 10, con. I, Balfour tp. It is probable, as Coleman concluded in 1912, that the slate was originally an oil-shale, and that heat and pressure first drove part of the bituminous material into fissures to form the anthraxolite veins, and then volatilized the remaining hydrocarbons to leave only a residue of pure carbon.

Chelmsford Sandstone

The Chelmsford sandstone, which overlies the Onwatin slate, occupies the centre of Sudbury Basin, and is particularly well exposed west of Chelmsford. It is a rather dark-coloured arkose, the colour due to the presence of about one-quarter of 1 per cent of carbon. Beds observed by the writer range in thickness from one-quarter inch to a foot or two, and in grain from fine, almost silty material to fairly coarse grit. Coleman mentions beds up to 7 or 8 feet thick. A thin section of a finer grained bed — grain 0-2 mm. or slightly less — contained about 10 per cent quartz, the remainder, plagioclase feldspar and partly chloritized hornblende in about equal proportions, with a little black dirt. The hornblende appeared to be a product of recrystallization. Two thin sections from average beds had a grain of 0·3 to 0·4 mm., and were about half quartz, in rounded or angular grains, the remainder mainly plagioclase grains, with a good deal of blackish dirt and a few flakes of partly chloritized mica.

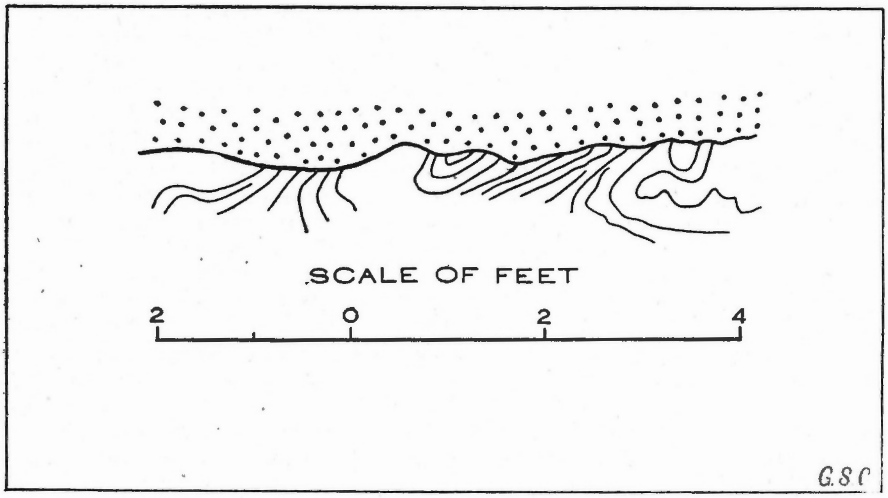

Figure 9. Crossbedding in Chelmsford sandstone, beneath a bed of coarse grit that lies on a rill-marked surface; east side of lot 6, con. III, Balfour tp., near road.

It is difficult to find places where the bedding is well displayed on weathered surfaces, but one such place was found near the west side of lot 6, on the north side of the road along concession line II-III, Balfour township. At this place the beds are 4 inches and less in thickness, strike north 65 degrees east, dip 10 to 15 degrees north, and are seen in cross-section on a cliff 3 or 4 feet high. All varieties of current action are displayed here. One rather fine-grained bed has a sort of swirling crossbedding abruptly truncated at the top by the base of a bed of coarse grit (Figure 9).

In another place, on the west side of the road in the south end of lot 1, con. II, Dowling tp., a prominent outcrop displays a block of silty sediments about 3 feet long and a foot or more in thickness entirely surrounded by coarse, gritty quartzite. The bedding of the silty material lies at a large angle to the normal bedding, and the sides of the block are cut by stringers of the grit that roughly parallel its edges. Apparently a stream that flowed fast enough to transport gritty sediment first cut a channel some feet in depth into the soft silts, and then undercut a bank so that a large block of silt slid down, turning on its side as it did so. Flakes of the silt an inch or so in thickness cracked away, allowing grit to enter the cracks; and the whole block was then engulfed in the grit before it could be broken up by the stream.

These data indicate that the Chelmsford sandstone was not laid down in standing water, but must have been a subaerial deposit of the alluvial fan type, with streamlets anastomosing over the surface.

The sandstone contains in places numerous rounded and irregular lumps that are clearly replacements, as the bedding, in lot 6, con. III, Balfour tp., can be seen to pass through them undisturbed. They weather to a more rusty colour than the rest of the rock, and also more rapidly than it does, so that they appear as shallow pits, about half an inch below the surrounding surfaces. The microscope shows them due to replacement of most of the rock constituents by an iron-bearing carbonate. Where replacement has been nearly complete, all the ferromagnesian mineral of the sandstone, all the black dirt, all the feldspar except an occasional grain, and even a little of the quartz have disappeared and their place is taken by carbonate. Where replacement is less perfect more of the feldspar remains, but the ferromagnesian minerals and the black dirt have gone. No evidence was obtained as to the origin of the carbonate, or how it entered the rock.

The structure of the sandstone, and that of the slate beneath, with which it is conformable, is that of a compound syncline. A cross-section just west of Larchwood shows two synclines separated by an anticline, with axis running about through Larchwood village and plunging 9 or 10 degrees northeast. Farther east there is probably more than one anticline; Coleman mentions finding four (14, p. 99), but describes them in such general terms that the reader cannot know whether they are separate folds or merely outcropping parts of one or two folds.

The synclinal structure of the centre of the basin has led all writers to assume a synclinal structure for the entire Whitewater series; and as there can be little doubt that the series is a conformable one, in spite of the fact that no contact between the tuffs and the slate has yet been seen, the assumption seems unassailable. At the same time, there is something peculiar and as yet unexplained about the structure. In the writer's few traverses across the Onaping tuffs he observed that strikes in many cases make a considerable angle with the micropegmatite contact, and that dips, even close to the contact, are steep or vertical, instead of sloping at a moderate angle toward the centre of the basin. Dips near the contact in lot 3, rge. VI, Garson tp., were even steeply south. Some detailed structural study of this peculiar situation seems desirable.

Age. The age of the Whitewater series is discussed in a later section of this report (pages 67-71). It is there shown that the series overlies a great unconformity representing a period of erosion that must have endured throughout Upper Huronian time. It is inferred, therefore, that the Whitewater series must have been laid down in Keweenawan time, a conclusion consonant with its highly volcanic character.

CHAPTER III

INTRUSIVE ROCKS

ACID INTRUSIVE ROCKS

Granites of at least two ages are found in Sudbury district, together with basic intrusives in considerable numbers and of various ages.

Wanapitei Granite

The older granite forms a large body between Wanapitei Lake and the norite to the west. At the south end of the lake the margin of the granite turns abruptly eastward and extends a tongue in that direction about 2½ miles. The granite is a medium-grained, equigranular rock that ranges in colour from pinkish to bright jasper-red, and in composition from almost a syenite to a fairly quartzose granite. Included fragments of country rock, which are numerous and many of them of great size, have been intensely metamorphosed and granitized by the intrusion.

The age of this granite is not closely known. It intrudes and metamorphoses the Hill and Stobie groups. Large recognizable remnants of the latter may be seen in it both westward to the norite boundary and southward almost to the southern margin of the granite, in con. V, Falconbridge tp. It also encloses certain remnants of old gabbro dykes. It is not in contact with any member of the Bruce series in the Falconbridge map-area. It is cut by numerous dykes of gabbro, supposedly the Nipissing diabase. It is also cut by the norite irruptive, and by dykes of the porphyritic olivine diabase. Apparently it continues past the northwest end of Wanapitei Lake, into a granite mass that underlies the Cobalt series (63). Thus the granite was probably injected at the close of Archæan time, a conclusion that, if correct, makes it pre-Bruce in age, but the conclusion is inferential and far from positively proved.

Levack Granite

The northwest side of the norite irruptive is bounded by a granite here called, for convenient reference, the Levack granite. Collins (33, p. 38; also Geol. Surv., Canada, Map 155A, Lake Huron sheet, 3d ed.) considered it as pre-Huronian gneiss, along with the Wanapitei granite. The writer has no facts bearing on its age, except that it is older than the Nipissing diabase, the Birch Lake granite, presently to be described, and, apparently, than the norite irruptive.

The rock is typically a pale grey to white granite carrying swarms of inclusions of varying size. The inclusions are mostly of a finely banded, grey, biotite gneiss, oriented in all directions, which from their banding and general appearance are considered to be of sedimentary origin. It is the writer's opinion that these are the recrystallized representatives of the Lower Stobie sediments. Less commonly, inclusions are found of basic hornblende-biotite gneiss and, rarely, of amphibolite. In these banding is poorly developed, and they may be included fragments of the Stobie lavas.

The granitic material closely associated with the inclusions is generally coarse and quite variable in grain. Its ferromagnesian constituent is usually biotite. Where inclusions are few, the grain is finer and more uniform in size, and the ferromagnesian constituent is largely hornblende. Both types are commonly gneissic. In many places the grey colour grades into pink, particularly near dykes or bodies of the Sudbury breccia, and where cut by bodies of the Birch Lake granite. The latter are found throughout the area mapped as older granite, in stringers and larger masses presumably satellitic to the larger mass to the northwest.

Birch Lake Granite

The Birch Lake granite, which was first separated, described, and mapped by Collins (33, pp. 34, 38), was also studied in some detail in 1939 by the writer's assistant, D. R. E. Whitmore. It occupies much of the northwest corner of Chelmsford map-area and, according to Collins, extends many miles farther southwest. It is a coarse, pink or red, biotite granite, many phases of which contain large phenocrysts of red feldspar. In places these are arranged so as to give the rock a trachytic texture. Around its borders it takes on a gneissic texture, though still remaining coarse and porphyritic; the gneissic texture parallels its contacts with the rocks it intrudes. Rather numerous little stringers of quartz, pegmatite, and aplite, all carrying hematite, characterize the rock. They appear to have been formed by magmatic vapours or solutions immediately after consolidation, and the reddish colour of the granite may be due to penetration by finely divided hematite.

The writer has made no petrographic study of this rock, but according to Carl Tolman[1], one of Collins' assistants who examined it, it is made up of quartz, albite, and microcline, with a very small amount of fine-grained biotite and accessory apatite, zircon, magnetite, and titanite. The general texture is granitic, but phases with large porphyritic feldspars are reasonably common. Tolman found that two types, a paler and a redder, are present; the latter contains a little more potash feldspar than the paler and is somewhat the younger of the two. Both rocks are very fresh, though the plagioclase is lightly sericitized and the biotite somewhat altered to chlorite. They display some evidence of strain; most of the quartz has undulatory extinction, and in places some of the quartz or feldspar crystals have been shattered.

The Birch Lake granite intrudes the Levack granite and gneiss both lit-par-lit and discordantly, and in places cuts it in a network of small stringers. The contact zone is more than a mile wide. According to Collins' latest determinations (Geol. Surv., Canada, Map 155A, Lake Huron sheet, 3d ed.), the Birch Lake granite extends southwest to the southwest corner of Espanola map-area, and intrudes the Bruce and Cobalt series in that area. It is nowhere in contact with norite, but Collins considers it as cut by the so-called "Foy offset" in Bowell and Foy townships. Whitmore's determinations indicate, however, that all the granite around the Foy offset is Levack granite; and in any case, the Foy offset itself appears to be quartz diorite rather than norite (74).

Whitmore's determinations indicate the Birch Lake granite to be cut by various dykes of gabbro. Some of these appear to be the ordinary Nipissing gabbro, others are the porphyritic olivine gabbro, and at least one is the equi-

---

[1] Manuscript report, Geological Survey, Canada.

granular olivine diabase. The first two, as will be shown later, appear to have been intruded during the period of folding at the close of Cobalt or Middle Huronian time. If, as Collins concluded, the Birch Lake granite intrudes the Cobalt series, its age is, therefore, determined rather narrowly. It must have been injected during the earlier part of the movement that folded the Cobalt series and older rocks.

Murray Granite

The Murray granite is a small mass about 3 miles long and a mile wide, in McKim and Blezard townships to the northeast of the Murray mine. A smaller mass, considered as Murray granite by Collins (33, p. 32), lies just east of Pump Lake, mainly in lot 1, con. IV, Snider tp. The rock is pink and equigranular, with an average grain of about 1 mm. It contains about 40 per cent of quartz and the rest feldspar, except for a few flakes or biotite and grains of magnetite. The feldspar is microcline and plagioclase, and two plagioclases appear to be present, one near albite in composition, the other basic oligoclase, about Ab_{65-70}. Here and there the rock is cut by narrow pegmatite stringers containing little or no ferromagnesian constituents.

The granite is mapped as being in contact with the norite for a distance of about 2 miles, but, in fact, over much of this distance a band of altered basic lava and amphibolite ranging from 4 to 50 feet in width separates the two. The lava is cut by numerous dykes of the granite, but in general they do not penetrate the norite. The writer found three places in a distance of about three-quarters mile, however, where dykes of the granite penetrate the norite; at one, the norite is intersected by a network of granite dykelets, which surround blocks of it. Other writers have described similar phenomena, so that there seems no reason to doubt that the granite is later than the norite.

The granite is cut toward its western end by two large dykes of equigranular olivine diabase, which cross it in a northwesterly direction. According to Yates (74, p. 168), dykes of the granite have been traced south, with only minor interruptions, through lot 7, con. VI, McKim tp., to the Frood breccia zone, where they are cut off and brecciated, and appear again on the south side of the zone. Admitting that the dykes are apophyses from the Murray granite, of which there seems little doubt, the age of the granite is thus closely delimited between the intrusion of the norite and the brecciation preceding the injection of the equigranular olivine diabases.

Creighton Granite

The Creighton granite is a crudely tabular mass about 12 miles long and 2 miles wide, extending from Copper Cliff southwest across Snider and Graham townships into Denison township. The bulk of the granite is a porphyritic rock characterized by squarish phenocrysts of potash feldspar up to an inch or more in diameter in a pink or grey, granitic matrix. The matrix is itself largely feldspar, with a little quartz and a variable amount of biotite. In places this rock grades into an equigranular variety with somewhat more quartz and less dark minerals. A third variety is a rather fine-grained, equigranular, reddish rock that forms dykes cutting the two coarser varieties or tends to follow gneissic textures where these are present. It is not unlike the Murray granite in appearance, though somewhat finer in grain, but it differs in composition. Quartz constitutes 35 to 40 per cent of it, and the rest is nearly all albite with a little microcline. Dark minerals are lacking.

Geologists studying the relations of the Creighton granite to the adjacent norite have been confused and puzzled by the apparently contradictory relations it presents. All agree that along the main contact the norite is penetrated by scores of granite dykes, most of which are of the coarse, porphyritic, Creighton type; but, on the other hand, a long dyke that seems to be the continuation of a funnel-shaped protrusion from the norite mass near Copper Cliff indubitably cuts through the porphyritic granite. Geologists hesitated to draw the natural and logical conclusion that the dyke is not a part of the norite, but a later intrusion, for three reasons: (1) the areal relations; the funnel-shaped mass protrudes southeast from the norite, and the dyke is apparently its direct continuation across Lady MacDonald Lake; (2) the chemical composition of the dyke material is almost identical with that of the norite, although the constituent minerals are different; (3) orebodies occur in the dyke, replacing the rock material. To conclude that the dyke was younger than the norite would imply that the ores are likewise much younger, and this would upset the then prevailing and apparently well attested theory that the ores separated by gravity from the molten norite.

The last and probably the best attempt to reconcile the conflicting data and thereby retain the prevailing theory of ore formation was made by W. H. Collins, who advanced the conception that though the granite was older than the norite, it had been so softened by the norite intrusion that it could be squeezed into fissures in the solidifying norite and thereby present the appearance of dyke intrusion. His discussion of the evidence pro and con is detailed and unbiased (33), and should be studied. Yates (74, p. 168), however, rather wrecked the plastic granite idea, by describing a locality, in lot 2, con. V, Denison tp., where a plate of greenstone intervenes between the granite and the norite; and a granite dyke can be traced from the main mass of granite across the greenstone slab into the norite.

The studies of the geological staff of the International Nickel Company, which has been working on the problem since 1931, now seem to indicate quite clearly that the orebodies are not differentiates of the norite mass, but were formed at a much later date, one, at Garson mine, after intrusion of the equigranular olivine diabase, the youngest igneous rock of the district. Drilling by the company has also shown that the dyke cutting the Creighton granite near Copper Cliff is not connected, at the surface, with the funnel-shaped protrusion of norite above mentioned. There is, therefore, little reason to doubt that the basic dyke is a later intrusion than the norite, and it is, accordingly, so considered here; and the Creighton granite itself is considered to be later than the norite.

Killarney Granite

The great mass of granite and granite-gneiss south of the Mississagi quartzite in Dill and Broder townships is mapped by W. H. Collins (Geol. Surv., Canada, Map 155A, Lake Huron sheet, 3d ed.) as areally continuous across to Killarney, Ontario, where he and Quirke determined it to be intrusive into rocks of the Cobalt series. As it intrudes the Mississagi quartzite and may be seen to invade the Nipissing diabase in the southwestern corner of lot 6, con. I, Neelon tp., there seems no reason to doubt Collins' correlation.

Quirke and Collins have described (64, pp. 42-4) the Killarney granite as a coarse-grained, massive, red rock containing a very small percentage of quartz. Salmon-coloured feldspar, almost exclusively orthoclase and microcline, with a minor quantity of oligoclase-albite, makes up the bulk of it.

About 5 per cent of biotite is present, with small amounts of muscovite, titanite, and black iron ore. The texture ranges from granitic to a coarse porphyritic variety containing square feldspar crystals half an inch across.

Age of the Killarney, Murray, and Creighton Granites

The Killarney, Murray, and Creighton granites display certain similarities. All are dominantly potassic granites, with small amounts only of the soda-lime feldspars; and the Killarney and Creighton granites are characterized by large phenocrysts of potash feldspars. None of the three is cut by either the Nipissing diabase or the porphyritic olivine diabase; and the Killarney granite has been definitely observed by Quirke (64, p. 29) to intrude and metamorphose these basic rocks. All of them are cut by dykes of the equigranular olivine diabase. The Killarney granite intrudes the Cobalt series, the other two the norite irruptive, which, as indicated later, appears to be of Keweenawan age. Until evidence to the contrary presents itself, therefore, the writer would group all three granites as belonging, closely, to the same period of batholithic injection, in late Keweenawan time.

Smaller Acid Intrusions

Southwest of Crean Hill mine, in lots 5-7, cons. IV and V, Denison tp., are two small masses of granite mapped by Collins (Map 292A, Copper Cliff sheet) as rhyolite. The rock is fine-to medium-grained, grey or slightly pinkish, and made up of quartz and feldspar with very little dark mineral. It is not unlike the Copper Cliff rhyolite in general appearance, but near the mine it cuts squarely across the bedding of sediments of the Lower Stobie group, which there strike north and dip almost vertically. Farther away it surrounds and includes fragments of the Lower Stobie lavas. Its identification as an intrusive rock thus seems indubitable, but as it is not in contact with anything but the Stobie group, its age relations are otherwise unknown.

Several small dykes and sills of fine-grained, acid rock have been found in the Stobie group, particularly in the section northeast of the Stobie mine. Except for the fact that they cut the Stobie, nothing is definitely known as to their age relations. A somewhat similar dyke was found in lot 9, con. IV, Dryden tp.; it is about 4 feet wide and cuts a body of Nipissing diabase, hence must be fairly late Precambrian in age.

BASIC INTRUSIVE ROCKS

The basic intrusives of Sudbury district, from the youngest to the oldest, are as follows:

Equigranular olivine diabase (dykes)
Fine-grained trap (dykes)
Quartz diorite (dykes)
Norite-micropegmatite irruptive (sill or laccolith)
Porphyritic olivine diabase (dykes)
Nipissing gabbro (dykes and sills)
Amphibolite (dykes)
Pre-Huronian gabbro (inclusions in Wanapitei granite)

Pre-Huronian Gabbro

The granite west and south of Wanapitei Lake contains here and there inclusions of gabbroic rock, some of considerable size. Their original composition must be inferred from the weathered surface, for the original minerals are now converted into secondary products, of which chlorite is the chief. Nothing is known as to the stratigraphic position of these gabbros, except that they are older than the Wanapitei granite.

Amphibolites

Various bodies of amphibolite are found within the Stobie group, and have already been described. Many are definitely replacements of lavas or sediments, but others appear to be true dykes. Whether or not they are dykes of gabbro that have been amphibolitized has not been determined.

A large dyke of the sort strikes northeast through the northwest corner of lot 9, con. IV, McKim tp. It has been mapped by Burrows (11) as an isolated mass of greenstone, but in fact is an extension of the larger mass of amphibolite mapped by him in lot 10. The body of the dyke is a coarse hornblendite made up of hornblende crystals about ¼ inch in diameter, but the edge, across a width of 10 feet or more, grades down into material that in composition and grain looks like ordinary basalt. The dense band was followed for several hundred feet, and nothing was observed to suggest that it is not an ordinary chilled edge.

A similar dyke-like mass with a chilled edge was found in the southeast corner of lot 7, con. VI, McKim tp.; a third, of large size, runs easterly through lots 2-5, con. VI, McKim tp.; and others were found in lots 3 and 4, con. I, Blezard tp.

Nipissing Diabase

The Nipissing diabase is a quartz gabbro that forms large sills and dykes in the Huronian and older rocks. The great bulk of the rock is concentrated in sill-like masses largely confined to areas of the Bruce series. They are numerous in both Copper Cliff and Falconbridge map-areas, and most of them are several miles in length. The largest is traceable from the middle of Waters township to the east side of Falconbridge township, a distance of 22 miles. Both to the east, in Scadding township, and to the southeast, south of Panache Lake, sills of them cut the Cobalt series, so that there is little reason to doubt Collins' correlation (29, p. 77) of them with the Nipissing diabase of Cobalt and Gowganda districts, in spite of the fact that they are more altered to secondary minerals. Between the western boundary of Scadding and Wanapitei Lake dykes and large masses of gabbro are fairly numerous in the Bruce series, and in the Wanapitei granite southeast of the lake, though none was actually observed to pass from the granite into the Bruce series, or vice versa. Outcrops are so scattered in this region, however, that this means little. Similar dykes are numerous in the Wanapitei granite west of the lake, and are identical in appearance with gabbro cutting the Bruce series. Toward the south end of the lake the gap between two such bodies of gabbro is less than half a mile wide, and, so far as could be determined, the gabbro that cuts the granite is identical with that cutting the Huronian sediments.

Individual gabbro sills vary considerably in width of outcrop. In some instances the variation is due to change of dip, without, so far as could be determined, any variation in thickness, but in others there is actual change of thickness. In a few places it could be observed how this takes place. The gabbro contact follows a bedding plane of the sediments for distances ranging from a few feet to hundreds of feet, then suddenly cuts across the bedding almost at right angles to another bedding plane, which it follows in turn. Presumably the break is along some pre-existing joint.

The Nipissing diabase is a dark greenish, equigranular, fairly coarse-grained quartz gabbro, quite different in appearance from the norite of the nickel irruptive, which has a greyish colour and a rather platy texture. Nevertheless, the quartz gabbro is itself a norite, as pointed out by Coleman (13, p. 296) and Barlow (13, pp. 68-70), as where fresh it carries faintly pleochroic hypersthene as well as augite or diallage. Collins correlated these rocks with the Nipissing diabase of Gowganda district, and pointed out (28, pp. 87-8; 29, pp. 77-82) that the latter gradually changes in composition between Gowganda and Sudbury. In the northern part of that region the gabbro sills carry no hypersthene whatever; at Florence Lake a sill was found which, though mainly quartz gabbro, contained parts with 5 to 10 per cent of hypersthene. Southwards toward Sudbury more and more hypersthene occurs in the gabbro until the noritic type predominates.

The relation of the gabbro to the norite irruptive was determined directly for the first time in 1938 by the writer while making a fairly detailed examination of the eastern edge of the norite mass. This edge is in contact with the Wanapitei granite, which is cut by a number of the gabbro dykes. The norite bevels the granite-gabbro contacts; both rocks for widths of a few feet to 100 feet or more are brecciated and the fragments surrounded, attacked, and partly digested by a sort of pegmatite. There can be no doubt, therefore, that the gabbro is older than the norite.

In the Falconbridge area, also, the gabbro is cut by dykes of porphyritic olivine diabase; hence it is likewise older than they. This relation is the same as that noted by Collins throughout Onaping region (26, p. 94).

A large dyke of the gabbro runs along the fault that separates the Coniston group from the Mississagi quartzite in Neelon, Dill, and Broder townships. Although it was not mapped, and thereby proved continuous, its presence in this position was noted in four places over an interval of 9 miles. At none of these places is the gabbro sheared or greatly fractured, hence it was concluded that it was injected into the fault after movement was completed. If the inference is correct, the gabbro is post-faulting in age. It is supported by an occurrence in lot 4, con. VI, Louise tp., where the east end of a mass of diabase cuts northward across a large fault that bounds a large mass of upfaulted McKim greywacke and Ramsay Lake conglomerate. The gabbro forms a bare ridge, and can be seen to be unsheared along the line of the fault.

The fault separating the Stobie group from the Bruce series is in most places a zone of breccia, and, as shown on a later page, the breccia is of fairly late Precambrian age. In many places most of the fragments in this breccia zone are of gabbro, and unbrecciated gabbro can be seen in a few places along its sides. The writer suggests that this fault was formed originally at about the same time as the Coniston fault and, like it, then formed a channel into which gabbro dykes were injected. In the northern fault, however, these were largely involved in the late Precambrian brecciation, which tended to follow pre-existing zones of weakness.

The larger bodies of gabbro contain rounded bodies of coarse pegmatitic material ranging from a few feet to about 100 feet in diameter. W. A. Jones has made a study (52) of some of them near Sudbury. The ordinary body is perhaps 8 or 10 feet in diameter, and is made up of crystals of hornblende an inch or two in length, in places more, in a matrix of very coarse, white plagioclase. The larger masses, which are relatively rare, may become highly siliceous in places, and composed mainly of quartz and feldspar. All grade at the edges into the normal gabbro.

Jones suggests that these masses were probably formed by interaction between the gabbro and included blocks of Mississagi quartzite, basing this conclusion on Collins' observations (29, p. 80) at Blind River; and undoubtedly such interaction might produce a rock of the kind. At Blind River, however, the light patches in the diabase range only from 1 to 6 feet in diameter, according to Collins, and many of them still contain cores of quartzite "in all stages of absorption from ragged vestiges to but slightly corroded blocks". No such cores have been found near Sudbury, however, and, in the writer's opinion, it rather exaggerates the gabbro's powers of interaction to suppose that a block of quartzite 100 feet long and 40 feet thick could, according to Jones, be so completely recrystallized and altered that no trace of the original rock can be recognized.

To the writer these acid spots appear no more than the coarse pegmatitic bodies found in almost any large mass of gabbro, and produced, presumably, by the tendencies of such products to segregate during crystallization. In support of this conclusion, the writer found the pegmatitic spots rather numerous in the upper horizons of the sills, where they might be expected, and practically lacking in the lower horizons. Again, near the southern, or upper, side of the sill, in lot 1, con. I, Denison tp., there is a large and very quartzose segregation much like the one described by Jones. In its most acid part there are a number of irregular miarolitic cavities an inch or more in length, into which project the ends of the quartz crystals of the surrounding rock, displaying good crystal faces. This occurrence would indicate a cooling magma well supplied with mineralizers, rather than the action of a gabbro magma on a block of cold quartzite.

Porphyritic Olivine Diabase

The porphyritic olivine diabase is a very fresh, almost black, fine-grained rock enclosing rather numerous white feldspar phenocrysts about ¼ to ½ inch in length. Generally the phenocrysts are of a squarish habit, but in some instances they are long prisms. The dykes are identical in appearance and relations with the olivine diabase of Onaping district (26, p. 94; 28, p. 101), and the writer considers them to be the same.

The writer has seen these dykes only in the Wanapitei granite, where they cut the granite and the Nipissing diabase, and hence are younger than both. Dykes stated by the writer's assistant, D. R. Whitmore, to be similar have been found by him cutting the Birch Lake granite north of Levack. For some unknown reason they do not appear in the Huronian sediments in Falconbridge map-area.

A large dyke of the porphyritic olivine diabase was found on the east side of Ella Lake, at the narrows just north of the Capreol-Norman line, where the east boundary of the norite mass runs along the shore a few feet from the water. The dyke strikes about north 70 degrees west, that is, at a large angle to the contact and the norite bevels across it and brecciates it in exactly the same way as it does the quartz gabbro. The norite is, therefore, later than the porphyritic olivine diabase.

Norite

The norite is a grey, coarse-grained, equigranular rock with a rather platy texture difficult to describe but quite characteristic when once seen in the field. The rock, together with its associated micropegmatite and other variations, has been described so thoroughly by various observers from 1897 on that the writer will enter into no description here. The following remarks are confined, rather, to certain of the geological relations observed.

The south boundary of the norite is a strong zone of shear, obviously a fault, from Falconbridge west to a point at least 2 miles-west of the old Kirkwood mine. In lot 12, con. III, Garson tp., it was inferred, from cleavage and drag-fold relationships, that the norite has moved west and up relative to the rocks on the south. How far this fault extends to the west is not known. To the east it seems to get stronger, and to split into several faults, giving rise to very complex relations.

At its east end the norite contact is not much disturbed by faulting, and the normal relations can be observed, as it is well exposed in several places. The general strike is north-northwest, and the average dip about 25 or 30 degrees to the west. If the contact is carefully observed, however, either on the ground or as mapped, it is seen to have considerable irregularity. The irregularity is both in strike and dip, and although in part due to faulting, much of it is not. At the old McVittie-Graham property, lot 11, con. IV, McLennan tp., a long section of the contact is particularly well exposed, and it displays all the irregularity commonly found at the base of a lava flow poured out on an irregular erosion surface. Detailed mapping of this part of the contact shows a horizontal variation of 600 to 700 feet within comparatively short distances along the strike. At an average dip of 25 degrees, the variation in the position of the contact, measured at right angles to its plane, would be from 250 to 300 feet.

The cause of these peculiarities is an interesting matter for speculation. Many geologists have supposed that the norite body was inserted along the contact between the flat-lying Whitewater series and the folded basement on which it lay. If this is true, then the present irregular contact is that old erosion surface, and its relief, at the place studied, was 250 to 300 feet.

The nature of the contact in this section rather supports the idea of intrusion along an old erosion plane. Igneous contacts, particulary of basic intrusives, are generally straight or gently curving lines, with abrupt bends where the intrusive found joints into which it could work. This contact has no likeness whatever to that normal type. Sharp-angled bends are few or lacking although the contact is highly irregular. There is also no evidence that the intrusive attacked or replaced the older rocks — another possible cause of irregularity.

Objectors may ask why the intrusive should have selected the precise contact for intrusion, and why remnants of the Whitewater series should not now be found here and there beneath the intrusive mass. It is difficult to see why this should not take place; all that can be said is that in the relatively small areas studied no such remnants were found.

Movements along this eastern contact appear to have been small, and confined to such adjustments as would necessarily take place during the later folding of the sill. In places the norite has been crushed and granulated across widths of about an inch, and the adjoining 5 or 6 feet of norite has been much jointed. The older rocks seem to have suffered more, for they are commonly much brecciated for several feet from the contact.

Quartz Diorite

Quartz diorite forms dykes that cut the Creighton granite and all older rocks, including the norite irruptive, and sill-like masses that spread out along the base of the norite mass. It is Coleman's "offset rock" (13, p. 279), so called because many of the dykes seemed to be protrusions or "offsets" from the main norite mass.

The quartz diorite is closely similar to the norite in chemical composition, but differs from it in mineral composition and texture. The grain is much finer than that of the norite, for the most part ranging from glassy to finely crystalline, though in the Copper Cliff offset a medium grain is attained. According to Collins' Rosiwal analyses (31, p. 163) the composition is: quartz, 11 to 12 per cent, in angular interspaces between the other constituents; zoned plagioclase, ranging from andesine to labradorite, 35 to 44 per cent; brown biotite, 5 to 14 per cent; hornblende, apparently primary, 27 to 38 per cent. Minor constituents are apatite, titanite, and from 1 to 5 per cent of titaniferous magnetite.

Evidence in favour of regarding the offset rocks as part of the norite has been set forth in great detail in the above-mentioned paper by Collins, to which the reader is referred. On the other hand, evidence for regarding the offset rocks as a separate and much later intrusion has been assembled with equal care by A. B. Yates (74).

The discussion of the correct relationships and the age of the quartz diorite is of importance because, as all recent workers now agree, the sulphide orebodies are closely associated with this rock. The question will be discussed briefly in the section on economic geology, but it may here be pointed out that if Coleman, Collins, and others of that school are correct in considering the quartz diorite as a phase of the norite, their hypothesis that the ores are differentiates of the norite can be maintained. On the other hand, if Yates is correct, that hypothesis falls to the ground as the ores must be much later than the norite. According to Yates' conclusions, the norite was intruded and cooled, the Creighton granite was intruded and cooled, and the quartz diorite was intruded and cooled before brecciation of the latter took place and the ores were introduced.

As the writer's work was not the study of the ores and their origin, he did not attempt to study this important problem further than to examine with some care certain critical outcrops around the Copper Cliff offset, the Murray mine, and the Foy offset. The relations visible in these areas support Yates' conclusions, and the writer sees no reason to doubt their accuracy. The quartz diorite is, therefore, here considered to be a separate intrusion post-dating the norite and the Creighton and Murray granites.

One of the most puzzling characteristics of the quartz diorite is its frequent occurrence as intrusive breccia, in which a matrix of very fine-grained quartz diorite surrounds and includes a great variety of foreign fragments. Dykes in norite include fragments of norite. Collins, who believed the quartz diorite dykes to be offshoots of the norite mass, explained the relations by seepage of fluid norite into fracture zones in the older rocks, but this explanation is no longer valid if the view be accepted that the quartz diorite is much younger than the norite. All the offsets are of this nature, except the Copper Cliff offset.

No one has yet advanced any good explanation of this extraordinary rock, hence the writer will venture the following suggestion. The general appearance of the quartz diorite breccia is similar to that of the Sudbury breccia described on a subsequent page, except that the matrix is igneous rather than fragmental. It may be supposed that the Sudbury breccia was formed, not in a single episode but in a succession of episodes. If a preliminary brecciation took place, quartz diorite magma might have arisen through the fissures thus formed, and would then include the fragments that had formed. During succeeding episodes of brecciation, the quartz diorite dykes could be themselves brecciated, as in places they are. Hypothetical as it is, this notion receives perhaps some slight support from the brecciation that undoubtedly preceded the injection of the pegmatite now to be described.

Pegmatite. Around the east end of the norite irruptive, for distances of a few feet for the most part, but in one place for 100 feet or more from the contact, the older rocks are brecciated and the interspaces between fragments filled with a white or pinkish pegmatite. As this material lies at the base of the norite, like the sills of quartz diorite, and appears unrelated either to the norite or to the older rocks; and as, further, it appears to be related to the sulphides somewhat like the quartz diorite, it seemed best to describe it at this point, to draw attention to a possible relationship.

The pegmatite was found in most places where the eastern contact is exposed. It is best seen near the north end of the lake in lot 11, con. IV, McLennan tp., where the country rock is a coarse gabbro that contrasts strongly with the pinkish pegmatite; but it was also seen and studied on Clear Lake, Ella Lake, and Waddell Lake.

In these places it may be observed that the pegmatite after its formation was cracked or somewhat granulated by small movements that permitted the entry of sulphides. The pegmatite is, therefore, pre-ore in age; and there may be some genetic connection between the two. The brecciated and pegmatitic zone at the base of the norite appears to have been particularly favourable for ore deposition, perhaps because this loosely cemented material refractured readily under slight stress, or perhaps because the norite formed an impermeable mass and rising solutions, therefore, followed its contact with older rocks. At any rate, the pegmatitic zone is strongly mineralized along most of its length and contains several small bodies of ore.

The pegmatite varies considerably in composition. Where fresh it is composed of a colourless, non-pleochroic hornblende, oligoclase albite about $Ab_{90}An_{10}$, and quartz. Much of the quartz is graphically intergrown with feldspar. The proportions of these minerals vary a good deal. Some sections carry about 25 per cent of quartz, a relatively small part of which is in graphic intergrowth with feldspar, whereas in others there is little quartz except that in graphic intergrowths. The feldspar is usually very fresh, but in some sections it contains rather numerous small flakes of white mica. The average grain of the pegmatite is about 0·4 mm.

In some sections this material, particularly the feldspar, is partly or largely replaced by crystals of feldspar averaging about ½ mm. in length. They are well crystallized, with well-developed albite twinning, and their composition is andesine, $Ab_{60-65}An_{40-35}$. This alteration is of special interest because examples are rather rare of a calcic plagioclase replacing a more sodic.

Trap

Following the intrusion of the quartz diorite, and about the time of the folding of the norite sill and the widespread brecciation of the rocks to the south, there appears to have been a little igneous activity that found expression in the intrusion of trap dykes. These are fine-grained, uralitic diabases, commonly striking east-west, that cut the norite, the Murray and Creighton granites, and the quartz diorite. Some of them cut the late breccia, others are broken by it. All are cut by the dykes of late equigranular olivine diabase, and by the ores.

The only published description of one of these dykes is that of Collins, who quotes (34, p. 19) an unpublished report by Phemister on the composition of a 40-foot dyke in lot 7, con. II, Shakespeare tp. This dyke consists of 52 per cent of green hornblende, 32 per cent albite, 7 per cent quartz, 2 per cent titanite, and 9 per cent of mica, epidote, and other secondary minerals. The silica content is 51·12 per cent.

Possibly of the same period of intrusion is a series of small, basic, intrusive bodies that form sill-like dykes in the Onwatin slate and Chelmsford sandstone. Most of them are so highly altered to carbonates and chlorite that little or none of the original mineral constituents can be recognized. Burrows, however, found a less altered example in the northeast corner of lot 3, con. II, Fairbank tp., and describes it as consisting mainly of a brownish augite, and hornblende apparently secondary after it, with minor amounts of oligoclase-andesine feldspar and quartz (10, p. 31).

Equigranular Olivine Diabase

The latest basic intrusive is an olivine diabase very different in appearance from the porphyritic variety. Previous writers have not distinguished the two types. This olivine diabase is a medium- to coarse-grained, equigranular rock that weathers to a warm brown tint. The older porphyritic variety contains numerous phenocrysts of very fresh white feldspar and weathers dead black.

The equigranular diabase is composed of labradorite, about 60 to 70 per cent; augite, 15 to 20 per cent; and olivine, 10 to 15 per cent. Accessory minerals are brown biotite, magnetite, and apatite. The minerals are mostly fresh, and the texture is ophitic. The rock weathers very rapidly, so that it is common to find the course of a dyke marked by a shallow gorge with steep or vertical walls. This weathering is due to mechanical disintegration, not chemical alteration. On steeply sloping surfaces it is common to find the rock broken down to a heap of rounded boulders and coarse reddish sand. An excellent photograph of such an occurrence is given by Collins (29, p. 153). Samples taken from one of the boulders just below the surface show no sign of decomposition, and even the sand, composed of feldspar and augite grains, is not greatly decayed.

In Sudbury district most of the dykes are wide, 50 to 100 feet or even more, and strike in a west-northwest direction. A few were found with other strikes. They cut all the rocks of the district, including the norite irruptive, the Whitewater series, and the Killarnean granites. According to Collins, they have not been found cutting the Ordovician strata along Lake Huron (29, p. 84). They are, therefore, considered to be of very late Precambrian age, though the possibility remains that they may be Cambrian.

The dykes have been observed to cut directly across zones of Sudbury breccia (*See* Chapter IV), but they are nowhere themselves brecciated. They are, therefore, later than the brecciation. Near the Garson mine a body of sulphide ore some 40 feet in width cuts across a dyke of the equigranular olivine diabase; hence it would appear that this body of ore, at least, was formed after the injection of the dyke.

CHAPTER IV

STRUCTURAL FEATURES OF SUDBURY DISTRICT

SUDBURY BRECCIA

Breccias are of common occurrence in the Sudbury area, and have a variety of origins. The granite area west and south of Wanapitei Lake is almost all a great intrusive breccia, as the granite contains numerous large and small fragments and roof pendants of the Stobie group and of an older gabbro; and the quartz gabbro, which intrudes the granite, in places includes numerous fragments of it. South of the Copper Cliff rhyolite there are a few bands of coarse rhyolite breccia, or agglomerate; and in various places there are small breccias obviously formed by faulting.

Apart from these types, which are common everywhere throughout the Precambrian Shield, there is a most unusual breccia in Sudbury district. It has such peculiar characteristics, and is present in such volume, that the writer believes it should be given a special name, and will, therefore, refer to it as the Sudbury breccia. Various writers have referred casually to the extensive brecciation in the district, but the peculiarties of the Sudbury breccia, and its bearing on ore deposition, appear to have been appreciated only by the geologists employed by the mining companies. Both Burrows (11) and Lawson (56) described bodies of this breccia as Ramsay Lake conglomerate, thereby obscuring further the understanding of this complex district. Detailed studies of the Sudbury breccia have recently been completed by H. W. Fairbairn (41, 42).

The breccia forms bands of very irregular shape that run across the district in a northeasterly direction, generally a few degrees more northerly than the strike of the formations. The bands are not straight, however, but may follow a contact for long distances, perhaps several miles, and then turn suddenly northward to cross the bedding at a large angle. Such behaviour is particularly common where the rock thus to be crossed is a hard, competent band such as the Copper Cliff rhyolite or a wide band of gabbro. In crossing the structure, the bands brecciate all the rocks of the district except the latest olivine gabbro, which was clearly younger than the brecciation, and the norite, which appears to have been too massive to be much broken by the brecciating forces.

The matrix of the breccia is always very fine-grained, and where suitably weathered usually exhibits lines of flowage. It clearly acted like a fluid under the forces causing brecciation, for besides forming the matrix to the fragments it ran into any available crevice, no matter how narrow. On good outcrops such matrix-filled cracks, many of them only an inch or two in width or even less, have been followed for some scores of feet. Commonly, where outcrops are good enough, it can be observed that such cracks surround large blocks of country rock, so that these may be looked on as huge fragments in the breccia, surrounded by a minimum of matrix.

The composition of the matrix varies with that of the rock brecciated. One thin section, from brecciated hornblendite in the Stobie group, was a mat of small laths of greenish hornblende, with very little of any other constituent. Another, from a breccia zone in the Mississagi quartzite, contained about 15 per cent of quartz, about the same amount of zoisite, much faintly green chlorite, and an unidentified colourless mineral with an index of refraction approximately 1·54 and a low birefringence. A. B. Yates (74) reports a very wide range of composition in the numerous thin sections studied by the geologists of the International Nickel Company, from almost pure quartz to types carrying large and varying amounts of augite, hornblende, biotite, feldspars, and other minerals. All these minerals are clearly secondary products of recrystallization.

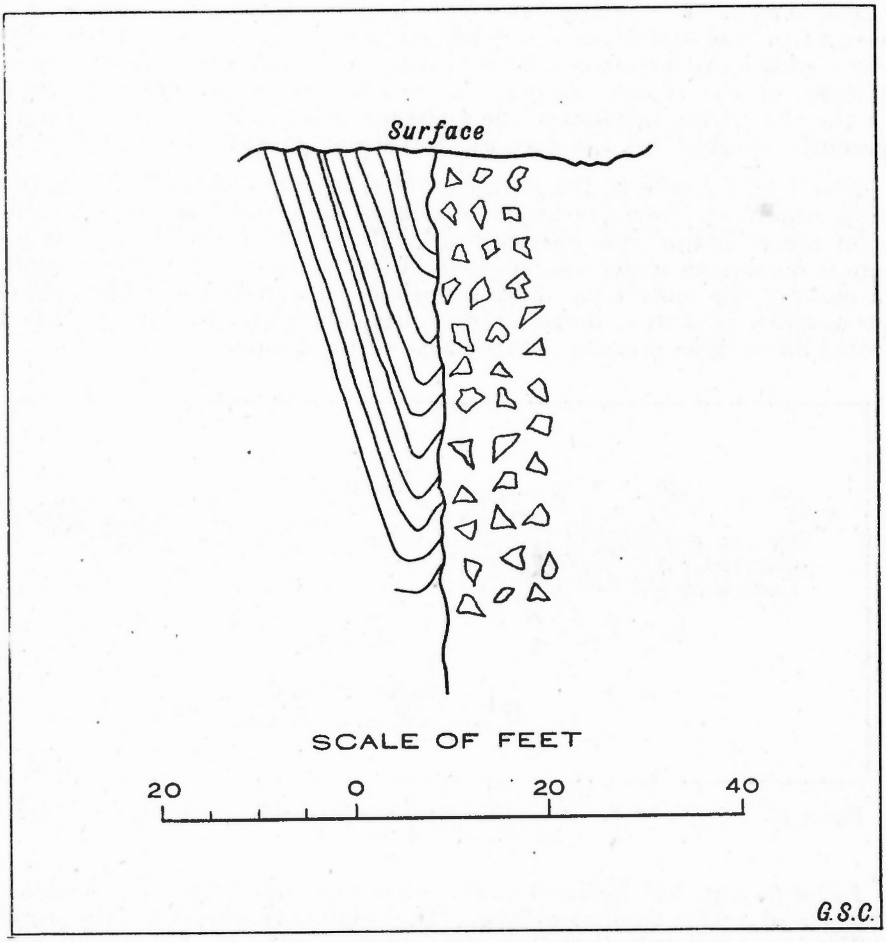

Figure 10. Vertical cross-section observed in southwest corner of lot 1, con. V, Neelon tp., showing upward drag of quartzite beds where cut by zone of breccia.

The fragments in the breccias range from angular to well rounded, but some degree of rounding is the rule. The majority are usually derived from the surrounding formation or formations, but some foreign fragments are nearly always present, and in many places such fragments are numerous.

The result is a rock of conglomeratic appearance, which one not thoroughly acquainted with the district is apt to mistake for a true conglomerate. Lawson (56, pp. 574-5) did this, and thereby fell into the error of concluding that "the conglomerate rests unconformably on the (Mississagi) quartzite, and (therefore) that it is the basal conglomerate of the formation called the Sudbury series".

The fragments in the breccia are of all sizes. The majority are, of course, relatively small, ranging from a few inches to a few feet in length, but larger fragments 50 to 75 feet long are not uncommon, and Yates (loc. cit.) reports one more than 2,600 feet long and 900 feet wide.

The unusualness of this breccia lies in the fact that it apparently flowed like a fluid magma under the stresses that prevailed, and it displays corresponding phenomena. In the southeast corner of lot 1, con. V, Neelon tp., the observer can look east from a bare hilltop to see well exposed on the side of a valley a good cross-section of a band of the breccia that approximately parallels the strike of the steeply dipping Mississagi quartzites. Near its junction with the breccia the bedding of the quartzite is bent sharply, as in Figure 10, apparently dragged by the upward movement of the fragmental material.

About half a mile to the southeast of this point "dykes" of breccia consisting wholly of quartzite fragments occur here and there in the gabbro. One of these "dykes" has an exposed length of 135 feet. At its north end, where it disappears under swamp, it is 14 feet wide, and it narrows gradually to a point at the south end. Southward along its strike the gabbro is sheared over a width of 3 or 4 inches. Obviously, therefore, the breccia has been injected like a dyke into the sheared zone of the gabbro.

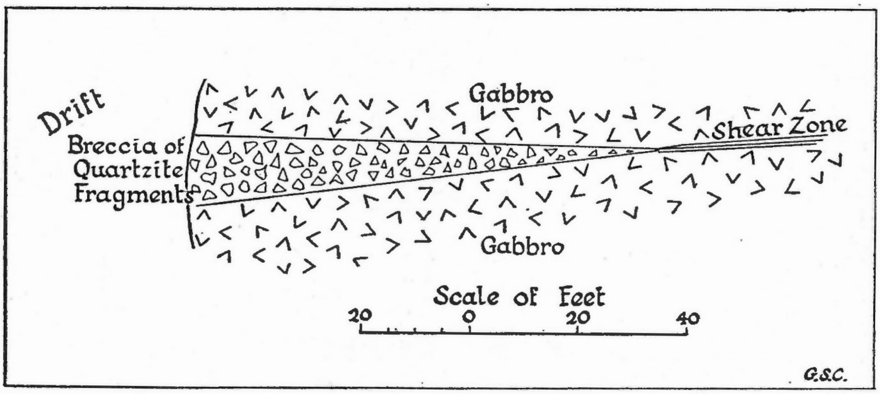

Figure 11. Breccia "dyke" of quartzite fragments injected into shear zone in gabbro, lot 12, con. V, Dryden tp.

In lot 6, con. VI, Neelon tp., there has been much brecciation along the south side of a wide band of gabbro. The fragments consist mostly of gabbro and Mississagi quartzite, but they also include a number of the easily recognizable Ramsay Lake conglomerate. One of the conglomerate fragments is 50 to 60 feet long and 15 to 20 feet wide. Fragments identified as McKim greywacke are also fairly common. This locality is more than three-quarters of a mile across the strike from the outcrop of the band of Ramsay Lake conglomerate; and as the beds have an almost vertical dip it is probably safe to say that the breccia zone could not have intersected the conglomerate stratum at a depth of less than 2,000 or 3,000 feet. To bring these fragments of conglomerate and McKim greywacke to their present position, therefore, implies an upward movement of the breccia materials of that amount.

Phenomena of this sort could only have been the result of intense and deep-seated compressive stresses. Probably also the area was domed upward by these stresses, putting the surface under tension so that cracks could open through which the breccia might rise. The cause of these compressive stresses is an interesting subject for speculation. Coleman (14, p. 13) supposed that they were due to the collapse of Sudbury district after the expulsion of the norite magma; though why collapse should take place when pressures in the deep-seated zone were high enough to drive out the enormous volumes of the norite irruptive is not explained. Be that as it may, Coleman's conclusions as to the time of ore formation demanded that the collapse and accompanying brecciation must have taken place during or immediately after intrusion of the irruptive. We now know that the Murray granite, the quartz diorite, and certain of the trap dykes are among the rocks brecciated, so that brecciation took place long after injection of the irruptive.

The only important post-norite period of deformation in this region was that during which the Whitewater series was folded, and the great norite sheet itself deformed into a syncline. It seems necessary, therefore, to assign the brecciation to this late Precambrian deformation. In this connection it may be noted that large faults cut the norite body in a number of places and displace it very considerably. It seems likely, therefore, that the faulting of the norite must have coincided roughly in time with the brecciation of the older rocks, because, as noted, the post-Whitewater deformation was the last important movement affecting the region.

General Structure and Correlation

In the following discussion the writer assumes throughout that the present subdivision of late Precambrian time into Lower Huronian, Middle Huronian, Upper Huronian or Animikie, and Keweenawan is correct. Should the subdivision later prove more complex than now suspected, the conclusions here expressed will have to be revised accordingly.

Figure 12, a geological map of the east end of Sudbury region, shows the manner in which the Bruce and Cobalt series form an arc a few miles to the east of the norite mass. The inside of the arc is occupied by older formations such as the Stobie group, Keewatin lavas, and the Wanapitei granite. Such areal relations are those of an east-plunging anticline; and the plunge thus inferred from the areal relations has been checked in many places by direct field observations.

It will be further observed that the Whitewater series and the underlying norite overlie the axis of this anticline, and together form a great syncline that, in this section, plunges to the west. The axis of the syncline is not directly over that of the anticline, but lies about 2 or 2½ miles northwest of it. In other words, there is approximately a right-angled unconformity between the Whitewater series and the older strata.

The mapping indicates that before Whitewater deposition began the Bruce, Cobalt, and older strata must have been folded into their present anticlinal structure, and then eroded so deeply as to expose the core of lavas and Stobie rocks at the centre. This involved the removal of: (*a*) the Cobalt series, for which Collins has indicated a maximum thickness of about 13,000 feet; (*b*) the Bruce series, with a maximum thickness of more than 21,000 feet; (*c*) at least 4,000 or 5,000 feet of the Stobie group; in all, more than 30,000 feet of strata, most of which were hard and resistant to erosion.

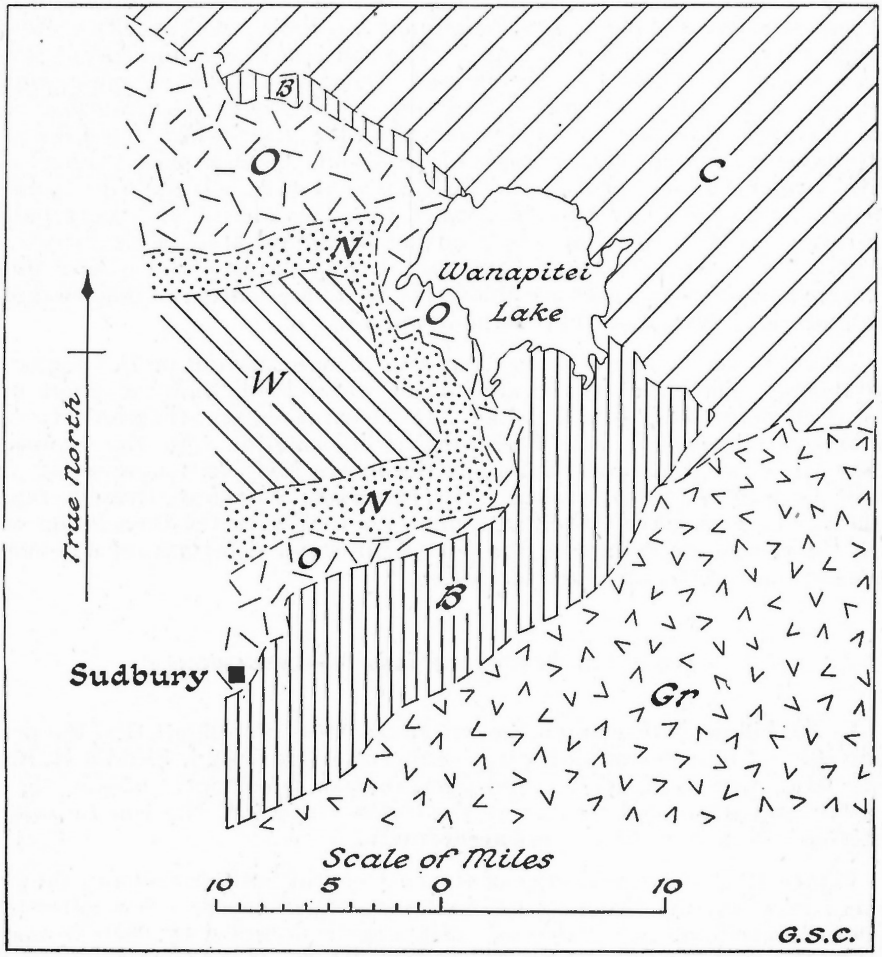

Figure 12. East end of Sudbury region, showing how Whitewater syncline overlies anticline in older rocks. W — Whitewater series; N — norite and micropegmatite; O — older, pre-Huronian rocks; B — Bruce series; C — Cobalt series; Gr — granite-intrusive into Bruce and Cobalt series.

Attention has already been called to the facts mentioned above by W. H. Collins, in a note (33, pp. 51-3) appended to a paper published by him about a year before his death. It is clear that Collins recognized the serious implications of the facts, as he states that "Introduction of a major unconformity below the Whitewater series would require some important revisions of current geological opinion", and suggests a number of questions that might arise.

It is probable that such deep and long-continued erosion would reduce the surface to a low relief, before deposition of the Whitewater series. This was also Collins' opinion, for he states: "So its (the nickel irruptive's) bounding formations, the complex of older rocks beneath and the Whitewater sediments above, must have had a nearly horizontal surface of contact before being spread apart by the irruptive magma". He goes on later to say: "It is even possible to deduce something about the topography of the floor under the Whitewater series by inspection of the upper and lower contacts of the nickel irruptive. These elliptical contact lines represent inclined, elliptical section lines in the floor. Their southern halves have been considerably deformed by faults and folds, but the northern halves seem to be much better preserved. These latter are gently sinuous lines, the irregularities of which presumably correspond with hills and valleys of the ancient surface on which the Whitewater series was deposited. The lower contact line represents such topographic features more faithfully than the upper contact, where the hot magma of the irruptive dissolved considerable portions of the overlying sediments. This lower contact indicates an ancient surface a good deal like the present peneplane of northeastern Ontario".

The writer's observations at the east end of the norite mass check perfectly with Collins' conclusions. These have already been described in detail.

Let us now compare the events of Sudbury region with the fairly well established geological column of the south shore of Lake Superior. The sedimentary sequence there, as known at present, is:

Gentle folding, with formation of Lake Superior syncline
Keweenawan deposition
Upper Huronian deposition
Folding and granite intrusion, in Gogebic district
Middle Huronian deposition
Lower Huronian deposition

It is generally considered that the original "Lower Huronian" of Thessalon district, the distribution of which over the north shore region was worked out by Collins, and which was named by him the Bruce series, is correlative with the formations of the south shore of Lake Superior later grouped under the name "Lower Huronian". The correlation is not very convincing; the thousands of feet of Mississagi quartzite are represented at Marquette by 150 to 700 feet of Mesnard quartzite; the Bruce conglomerate is entirely lacking at Marquette; the Bruce limestone, Espanola greywacke, and Espanola limestone, with a combined thickness of 450 to 700 feet, is represented at Marquette by the Kona dolomite, a dolomite interstratified with slate, greywacke, and quartzite, ranging from 200 to 700 feet thick; and the upper formation of the Bruce, the Serpent quartzite, 1,100 to 1,500 feet thick, is replaced at Marquette by the dark, sandy Wewe slate, the thickness of which is doubtful, but lies between 100 and 1,000 feet. However, these differences, though apparently considerable, can be explained as due to deeper water and greater distance of the Marquette area from the source of the sediments; and the disappearance of the Bruce conglomerate, Collins has shown, was probably due to cessation of deposition, as in the explored North Shore district it decreases westward from 500 feet near Sudbury to 20 feet near Echo Lake.

Assuming, therefore, the correctness of this correlation, the writer points out that whereas in Lake Superior district there are four sedimentary series of late Precambrian age, in Sudbury district there are only three; but, in addition, room must be made for a great interval of erosion after deposition of the Cobalt series. During this interval the Bruce and Cobalt series were closely folded, intruded by certain igneous rocks, and then very deeply eroded, with removal of more than 30,000 feet of hard strata. Such a sequence of events must have consumed approximately the equivalent of a geologic period, and the only place it will fit into the accepted classification is in Animikie (Upper Huronian) time.

If the preceding reasoning is valid, two consequences follow. The Cobalt series, the position of which has up to now been nebulous, must be considered as approximately contemporaneous with the Middle Huronian of the south shore; and the Whitewater series, which most writers have been inclined to term Animikie, is wedged upward into the Keweenawan — a conclusion rendered more plausible by the highly volcanic character of the series.

The rather perfect parallelism of the Lake Superior succession with the revised succession of Sudbury district is well brought out by the following table of events.

Lake Superior	*Sudbury*
	Intrusion: equigranular olivine diabase
	Intrusion of Killarney, Murray, and Creighton granites
Gentle folding: Lake Superior syncline	Gentle folding: Whitewater syncline
Intrusion: Logan sills, Duluth gabbro	Intrusion of norite-micropegmatite
Deposition: Keweenawan lavas, tuffs, and sediments	Deposition: Whitewater lavas, tuffs, and sediments
Erosional unconformity Deposition of Upper Huronian (Animikie) sediments Erosion of more than 2,000 feet of sediments and lavas, Gogebic distrct[1]	Erosion of 30,000 to 40,000 feet of sediments
Intrusion Presqu'ile granite[1], Gogebic district	Intrusion: Birch Lake granite
Close folding, Gogebic district[1]	Close folding, accompanied in later stages by intrusion: Nipissing diabase
Intrusion of gabbro, Gogebic district	
Deposition of Middle Huronian sediments	Deposition of Cobalt series
Erosional unconformity: Lower Huronian cut through in places and perhaps 2,000 feet or more removed	Erosional unconformity: 1,700 feet or more of sediments removed
Deposition of Lower Huronian sediments	Deposition of Bruce series

The conclusions drawn make it necessary to review the age of the Nipissing diabase, which, along with the porphyritic olivine diabase, has commonly been considered Keweenawan. It has been shown in the preceding pages that both these diabases are cut off abruptly at the lower edge of the norite; so that either (1) they formed a part of the base-levelled surface on which the Whitewater was deposited; or, (2) they were injected after the Whitewater was laid down, but before the norite was emplaced. If the latter were true, such dykes should now be found in the Whitewater series, but neither the writer nor any other student of the area has ever found any. The other alternative, that they formed a part of the base-levelled surface on which the Whitewater was laid down, is probably the true one.

As the dykes were peneplaned together with the strata by which they are surrounded, it may be presumed that they were injected at a relatively early date; and the common association of intrusive phenomena with folding suggests that they were probably injected during the post-Cobalt orogeny. Had the sills been intruded early in that orogeny, one would now expect to find evidences of slippage at the edges, caused by adjustments during the remainder of the folding. Such indications are entirely lacking, however, and hence it would seem that intrusion must have occurred near the end of the folding period.

---

[1] Allen, R. C., and Barrett, L. P.: Contributions to the Pre-Cambrian Geology of Northern Michigan and Wisconsin; Mich. Geol. and Biol. Surv., Pub. 18, Geol. Ser. 15 (1915).

This chain of reasoning, therefore, places the age of the Nipissing diabase, and of the slightly later porphyritic olivine diabase, approximately at the close of the Middle Huronian period, instead of Keweenawan as formerly thought. The only truly Keweenawan intrusives in the area are the norite-micropegmatite mass, the granites that intrude it, and the dykes of trap and equigranular olivine diabase. The age of the silver ores of Cobalt district, which are genetically associated with the Nipissing diabase, is thus referred to the post-Middle Huronian period of orogeny, instead of the Keweenawan.

AGE OF FAULTS

In preceding pages faults have been mentioned in many places, and they seem to fall into two great groups. The earlier group includes the great fault or set of faults separating the Huronian formations from the complex of Killarney granite and Coniston group of sediments to the south; the fault or faults separating the Stobie group from the Bruce series; and a number of other faults that have brought bodies of the Ramsay Lake or Bruce conglomerate into positions where without faulting they would not appear. Undoubtedly there are many other faults of this group, unrecognized because the rocks on both sides are alike.

Several cases have been described where these faults are occupied or crossed by dykes of Nipissing diabase, and the diabase is either unsheared or very slightly so. The conclusions reached as to the age of the diabase, therefore, date these faults as occurring earlier in the orogenic revolution that ended the Cobalt sedimentation.

A later period of faulting has broken and displaced the norite at its western end, together with the Whitewater sediments of Sudbury basin; has caused important ruptures along the southern edge of the norite irruptive; and has fractured the quartz diorite of the Creignton mine and elsewhere. Late Precambrian movements, possibly of the same date, were responsible for the blocks of Mississagi quartzite faulted into bodies of Nipissing diabase, as previously described. Possibly also to be correlated with these movements is the formation of the Sudbury breccia, which involved the trap dykes and all older rocks.

The only post-norite movement known is the gentle folding that gave synclinal shape to the Sudbury basin and the underlying sheet of norite-micropegmatite. It seems probable, therefore, that the late folding and faulting were both results of the same compressive stresses.

CHAPTER V

ECONOMIC GEOLOGY

The economic deposits of the region include the great nickel-copper deposits around the Sudbury basin, the lead-zinc deposits within it, and two small gold deposits, one of which, the Lebel Oro near the west end of Long Lake, is exhausted, and the other, near Skead, was abandoned after some development. The writer has made no especial study of any of these, and, consequently, no attempt at description will be made. The following remarks are confined to a discussion of the age and origin of the nickel-copper ores, insofar as his personal observations enable him to write.

The concept of origin, originally advanced by Walker and Barlow and strongly upheld by Coleman, was that the ores sank out of the cooling norite magma to be concentrated in bays along the base, and in cracks in the rocks of the basement on which the norite lay. This theory has recently been reviewed in detail by Collins, who, after considering all the evidence, pronounced in its favour. The extraordinary plausibility of the theory gave it widespread acceptance. It is well known that the norite irruptive is highly differentiated; every geologist learns in his first essays with the microscope that the most basic minerals are the first to separate from a crystallizing mass, so that, having separated, they can sink through the liquid from which they had just separated; and, to cap all, the orebodies actually are limited either to bays in the basement or to offsets at no great distance from the base. The whole position of the theory was thus apparently so impregnable that even geologists who carefully examined the situation have preferred to find other explanations for opposing facts rather than suggest that the theory may be incorrect; and those who have attacked the theory have merely taken the attitude that it does not explain all the orebodies, but that some must be accounted for by later rearrangements.

The patient and continuing studies of the geological staff of the International Nickel Company, particularly from 1931 to the present, have brought to light much evidence suggesting that this theory is incorrect, and that the ores did not originate until long after the norite-micropegmatite mass was completely solidified. They have pointed out, for example — and with this the writer's observations fully agree — that there is no visible gradual increase in sulphide content in the norite as the base is approached; and with the recognition of this fact one of the strongest arguments in favour of separation from the magma falls to the ground.

The chief obstacle in the way of a correct understanding of the geology of the ores has been the presence in the district of rocks of similar composition but widely separated ages. Coleman, for instance, grouped the Nipissing diabase with the norite, because of its hypersthene content; and although later workers separated them in mapping because of differences in general appearance it was not until 1938 that the writer proved the diabase definitely to be the older. Similarly, both Collins and the geologists of the International Nickel Company have recognized that the ores are associated with, and somewhat later than, quartz diorite, which was also classed by Coleman as norite. Both Collins and the Company geologists recognized that the quartz diorite forms dykes cutting the norite, but, as this would make the ores much later than the norite, Collins preferred to consider the quartz diorite merely as a basal part of the norite kept liquid by mineralizers until the remainder had solidified. To do this, as the quartz diorite cuts the Creighton granite, he had to go further and conclude that the dykes of Creighton granite cutting the norite proper are merely parts of it softened by the intrusion of the norite to a point where they could be pushed like putty into cracks of the solidifying laccolith.

In spite of the inherent improbability of Collins' conclusions, even the opponents of the segregation theory had to admit their possibility, until Yates, in 1938, described the occurrence of a dyke from the Creighton granite that cuts across a remnant of Keewatin greenstone to intrude the norite. It would be extremely difficult to suppose that such a dyke originated as Collins suggests; and, if not, the Creighton granite must be definitely later than the norite, and the ore, in turn later than the quartz diorite cutting the granite, must be very much later than the norite. The question was finally, and, it would seem, irrevocably settled, by the discovery in 1939 of a large body of ore in a fault that cuts through the dyke of equigranular olivine diabase east of the Garson mine. As this dyke has been traced through the norite, and is the latest intrusive of the region, no one can doubt that much ore, at least, is of very late Precambrian age.

The work of the International Nickel Company has shown that ore deposition is localized largely in zones of the Sudbury breccia and in faults of late Precambrian age. It seems not unlikely that both the brecciation and the faulting were products of a single general period of movement. In the Frood and Stobie mines the ore is all in breccia; and the same breccia zone extends southwest to cut the Copper Cliff offset and there form the pipe-like masses of ore of the Copper Cliff and No. 2 mines. In the Creighton, Garson, and Falconbridge mines there is much ore filling faults, as well as the normal breccia ore. However, there is much breccia in the district that contains no ore; and even where ore deposition has been active, as in the neighbourhood of Frood, great masses of breccia are entirely devoid of ore. The investigations of the geologists of the International Nickel Company, in fact, seem to indicate that ore in breccia is confined, or almost so, to places where quartz diorite dykes have been crushed and broken. Thus the great Frood orebody is centred around the crushed remains of a quartz diorite dyke; and the pipe-like orebody of No. 2 mine at Copper Cliff is found where the quartz diorite offset is crushed and brecciated. The conclusion seems indicated, improbable as it may appear, that the quartz diorite had some precipitating effect on the ore-bearing fluids.

The same conclusion is suggested by the fact that in many places quartz diorite that has not been crushed is heavily mineralized. Coleman refers to such instances when he says (14, p. 18): "Norite spotted with ore is sometimes found in bands a long distance from the nearest ore body and separated from the basic edge by rock free from ore". The bands thus mentioned are not bands of norite, as he considered, but dykes of mineralized quartz diorite, with knife-sharp contacts against the norite. One of them is to be easily seen near the Murray mine, about 50 feet from the road. Again, when Coleman states (loc. cit.) that "no long stretch of the lower edge of the norite is entirely devoid of ore", the reason is, commonly, that quartz diorite has spread out in sill-like masses in many places along the lower contact, and it is this rock, not the norite, that is mineralized. Collins states (34, p. 25): "Scattered observations indicate that the offset and intermediate rocks together form a zone of varying thickness at the outer edge (base) of the nickel irruptive along its southern side. It reaches a greatest thickness of three-eighths of a mile at the Creighton mine and may in other places thin out completely. Less is known about the north edge of the irruptive, but probably this basal zone is much thinner there". Collins, it is only fair to state, believed the quartz diorite to be only a phase of the norite, not a separate rock; but this does not vitiate his recognition of it as a petrographic entity, or his careful observations as to its distribution.

Collins, in considering the quartz diorite as a phase of the norite, endeavoured to explain the differing mineralogical composition as due to the action of the molten sulphides on the norite. He suggested, following Goodchild[1], that hydrogen and water generated from the cooling sulphides would cause the norite with which they were in contact to remain liquid longer than the rest of the intrusive, and later, presumably, caused the constituents to crystallize as hornblende, biotite, quartz, and andesine, instead of as the normal labradorite and pyroxenes of the norite. If this action took place at Sudbury, however, it should also take place wherever sulphides and norite are associated, but this is not the case[2]. In view of this fact, and of the other facts indicative of the age of the quartz diorite that have been detailed in the preceding pages, there seems little reason to doubt that the quartz diorite is really an individual rock type entirely different in age and origin from the norite.

The details of the various orebodies have not been studied by the writer, as they have already been described by many others. The fullest and most recent published descriptions are those of Knight (54) in the Report of the Ontario Nickel Commission published in 1917. Most of the properties, in operation when he studied them, were closed at the end of the last great war, so that only the surface outcrops can now he seen. Knight's descriptions clearly show, however, the dependence of ore occurrences on faulting and brecciation; and by numerous illustrations he proves indubitably that the ores are later than both the norite and the Creighton granite. At that time, unfortunately, the quartz diorite was not recognized as an individual rock type, so that his work does not bear on the relation of the ore to that rock.

---

[1] Goodchild, W. H.: The Evolution of Ore Deposits from Igneous Magmas; Min. Mag. (London), vol. 18, Jan.-June 1918.

[2] Horwood, H. C.: Magmatic Segregation and Mineralization at the B. C. Nickel Mine, Choate, B. C.; Trans. Roy. Soc., Canada, 3d ser., vol. 31, pp. 5-14 (1937).

CHAPTER VI

BIBLIOGRAPHY

1. Argall, P.: Nickel, the Occurrence, Geological Distribution and Genesis of Its Ore Deposits; Proc. Col. Sc. Soc. 4, pp. 395-421 (1891-3).
2. Barlow, A. E.: On the Nickel and Copper Deposits of Sudbury; Ottawa Naturalist, June 1891, pp. 1-20.
3. —— Report on the Origin, Geological Relations, and Composition of the Nickel and Copper Deposits of the Sudbury Mining District, Ontario; Geol. Surv., Canada, Ann. Rept., vol. XIV, N.S., pt. H, p. 236 (1904).
4. —— On the Origin and Relations of the Nickel and Copper Deposits of Sudbury, Ont.; Ec. Geol., vol. 1, pp. 454-66, 545-53 (1906).
5. Bateman, A. M.: Magmatic Ore Deposits, Sudbury, Ont.; Ec. Geol., vol. 12, pp. 391-426 (1917).
6. Bell, Robert: Report on the Sudbury Mining District; Geol. Surv., Canada, Ann. Rept., vol. V, N.S., pt. F, p. 54 (1891).
7. —— The Nickel and Copper Deposits of Sudbury District, Canada; Bull. Geol. Soc. Am., vol. 2, pp. 135-6 (1891).
8. Brackenbury, C.: Notes on the Rocks at Levack, Ont.; Ont. Bur. Mines, Rept. No. 23, pt. 1, pp. 194-201 (1914).
9. Browne, D. H.: Notes on the Origin of the Sudbury Ores; Ec. Geol., vol. 1, pp. 467-75 (1906).
10. Burrows, A. G., and Rickaby, H. C.: Sudbury Basin Area; Ont. Dept. Mines, Rept. No. 38, pt. 3 (1929).
11. —— Sudbury Nickel Field Restudied; Ont. Dept. Mines, Rept. No. 43, pt. 2 (1934).
12. Coleman, A. P.: The Rocks of Clear Lake near Sudbury; Can. Rec. Sc., vol. 5, pp. 343-6 (1892-3).
13. —— The Sudbury Nickel Deposits; Ont. Bur. Mines, Rept. No. 12, pp. 235-303 (1903).
14. —— The Sudbury Nickel Field; Ont. Bur. Mines, Rept. No. 14, pt. 3, pp. 188 (1905).
15. —— The Sudbury Laccolithic Sheet; Jour. Geol., vol. 15, pp. 759-82 (1907).
16. —— The Nickel Industry: With Special Reference to the Sudbury Region, Ontario; Dept. of Mines, Canada, Mines Branch Pub. No. 170 (1913).
17. —— The Sudbury Area; Twelfth Int. Geol. Cong., Guide Book No. 7, pp. 11-48 (1913).
18. —— The Sudbury Series and Its Bearing on Precambrian Classification; Congrès Geol. International, Compte-Rendu de la XIIe Session, Canada, pp. 387-398 (1913).
19. —— The Pre-Cambrian Rocks North of Lake Huron; Ont. Bur. Mines, Rept. No. 23, pt. 1, pp. 202-236 (1914).
20. —— The Origin of the Sudbury Nickel Deposits; Ec. Geol., vol. 10, pp. 390-3 (1915).
21. —— Geological Relations of the Sudbury Nickel Ores; Eng. Min. Jour., vol. 102, pp. 104-5 (1916).
22. —— Geology of the Sudbury Nickel Deposits; Ec. Geol., vol. 19, pp. 565-79 (1924).
23. Coleman, A. P., Moore, E. S., and Walker, T. L.: The Sudbury Nickel Intrusive; Univ. of Toronto Studies, Geol. Ser. No. 28, 1929.
24. Collins, J. H.: The Sudbury Copper Deposits; Quart. Jour. Geol. Soc., London, vol. 44, pp. 834-8 (1888).
25. Collins, W. H.: Geology of Onaping Sheet, Ontario; Geol. Surv., Canada, Sum. Rept. 1912.

26. Collins, W. H.: Geology of Gowganda Mining Division; Geol. Surv., Canada, Mem. 33, 1913.

27. —— Geology of a Portion of Sudbury Map-area South of Wanapitei Lake, Ontario; Geol. Surv., Canada, Sum. Rept. 1913, pp. 189-195.

28. —— Onaping Map-area; Geol. Surv., Canada, Mem. 95, 1917.

29. —— North Shore of Lake Huron; Geol. Surv., Canada, Mem. 143, 1925.

30. —— Southwestern Part of Sudbury Nickel Irruptive; Geol. Surv., Canada, Sum. Rept. 1928, pt. C.

31. —— The Life History of the Sudbury Nickel Irruptive, Part I; Trans. Roy. Soc., Canada, 3d. ser., sec. IV, vol. 28, pp. 123-177 (1934).

32. —— Idem., pt. 2, vol. 29, pp. 27-47 (1935).

33. —— Idem., pt. 3, vol. 30, pp. 29-53 (1936).

34. —— Idem., pt. 4, vol. 31, pp. 15-43 (1937).

35. —— Sudbury Series; Geol. Soc. Am., Bull. 47, pt. 2, pp. 1675-84 (1936).

Collins, W. H., and Quirke, T. T.: *See* Quirke.

36. Dixon, C. W.: The Ore Deposits of Sudbury, Ontario; Trans. Am. Inst. Min. Eng. (Albany meeting), vol. 34, 1903, 65 pp.

37. Dresser, M. A.: Some Quantitative Measurements of Minerals of the Sudbury Nickel Eruptive; Ec. Geol., vol. 12, pp. 563-80 (1917).

38. Fairbairn, H. W.: Geology of the Ashigami Lake Area; Ont. Dept. Mines, vol. 48, pt. 10, pp. 1-15 (1939).

39. —— Relations of the Sudbury Series to the Bruce Series in the Vicinity of Sudbury; Ont. Dept. Mines, Rept. 50, pt. 6, pp. 1-13 (1941).

40. —— The Bruce Series in Falconbridge and Dryden Townships; Ont. Dept. Mines, Rept. 50, pt. 6, pp. 14-17 (1941).

41. —— Breccias at Sudbury, Ontario; Jour. Geol., Rept. 50, pp. 1-33 (1942).

42. Fairbairn, H. W., and Robson, G. M.: Breccia at Sudbury; Ont. Dept. Mines, Rept. 50, pt. 6, pp. 18-33 (1941).

43. Foullon, Baron von: Ueber einige Nickelerzvorkommen; Jahr.d.k-k. geol. Reichsanstaltat, vol. 42, pp. 223-310 (Vienna, 1892).

44. Garnier, J.: Mines de nickel, cuivre, et platine du district de Sudbury, Canada; Mem. Soc. des Ing. Civils, Paris, 1891.

45. Goodchild, W. H.: Magmatic Ore-Deposits of Sudbury, Ont.; Ec. Geol., vol. 13, pp. 137-143 (1918).

46. Gregory, J. W.: The Sudbury Nickel Ores; Geol. Mag., vol. 4, p. 454 (1907). *Also* vol. 5, pp. 139-40 (1908).

47. Harker, A.: Differentiation in Intercrustal Magma Basins; Jour. Geol., vol. 24, pp. 555-8 (1916).

48. Hixon, W. W.: The Ore Deposits and Geology of the Sudbury District; Jour. Can. Min. Inst., vol. 9, pp. 223-35 (1906).

49. Hoffman, A., and Wandke, F.: A Study of the Sudbury Ore Deposits; Ec. Geol., vol. 19, pp. 169-204 (1924).

50. Hore, R. E.: Magmatic Origin of Sudbury Nickel-copper Deposits; Trans. Can. Min. Inst., vol. 5, pp. 528-51 (1902).

51. Howe, Ernest: Petrographic Notes on the Sudbury Nickel Deposits; Ec. Geol., vol. 9, pp. 505-22 (1914).

52. Jones, W. A.: Petrography of Rocks near Killarney, Ont.; Univ. of Toronto Studies No. 29, pp. 39-60 (1930).

53. —— A Study of Certain Xenoliths Occurring in Gabbro at Sudbury, Ontario; Univ. of Toronto Studies No. 29, pp. 61-73 (1930).

54. Knight, C. W.: Report of the Ontario Nickel Commission, pp. 110-115, 117-121 (1917).

55. —— The Chemical Composition of the Norite-micropegmatite, Sudbury, Ontario; Ec. Geol., vol. 18, pp. 592-4 (1923).

56. Lawson, A. C.: Some Huronian Problems; Geol. Soc. Am., Bull. 40, pp. 361-83 (1929).

57. Merritt, W. H.: The Minerals of Ontario and Their Development; Trans. Am. Inst. Min. Eng., vol. 17, pp. 293-300 (1888-9).

58. Moore, E. S.: Geological Structure of the Southwest Portion of the Sudbury Basin; Trans. Can. Inst. Min. Met., vol. 33, pp. 292-302 (1930).

59. Park, James: Sudbury Ore Deposits; Ec. Geol., vol. 20, pp. 500-4 (1925).

60. Penfield, S. L.: On Pentlandite from Sudbury, Ontario, Canada, with Remarks on Three Supposed New Species from the Same Region; Am. Jour. Sci., vol. 45, pp. 493-7 (1893).

61. Phemister, T. C.: Igneous Rocks of Sudbury and Their Relations to the Ore Deposits; Ont. Dept. Mines, Rept. No. 34, pt. 8, 1925.

62. Quirke, T. T.: Espanola District, Ont.; Geol. Surv., Canada, Mem. 102 (1917).

63. —— Wanapitei Lake Map-area; Geol. Surv., Canada, Sum. Rept. 1921, pt. D, pp. 34-50.

64. Quirke, T. T., and Collins, W. H.: The Disappearance of the Huronian; Geol. Surv., Canada, Mem. 160, 1930.

65. Roberts, H. M., and Longyear, R. D.: Genesis of the Sudbury Nickel-copper Ores as Indicated by Recent Explorations; Trans. Am. Inst. Min. Eng., vol. 59, pp. 27-67 (1918).

66. Silver, L. P.: The Sulphide Ore Bodies of the Sudbury Region; Jour. Can. Min. Inst., vol. 5, pp. 528-51 (1902).

67. Spurr, J. E.: Ore Deposition at the Creighton Nickel Mine; Ec. Geol., vol. 19, pp. 275-80 (1924).

68. Stewart, L.: The Creighton Mine of the Canadian Copper Company, Sudbury District, Ont.; Jour. Can. Min. Inst., vol. 11, pp. 567-85 (1908).

69. Thomson, Robert: Nickel Eruptive of Sudbury, Ontario; Pan-American Geol., vol. 63, pp. 248-64 (1935).

70. —— Sudburite, a Metamorphic Rock near Sudbury, Ont.; Jour. Geol., vol. 43, pp. 427-65 (1935).

71. Tolman, C. F., and Rogers, A. F.: A Study of the Magmatic Sulphide Ore; Leland Stanford Junior Univ. Pub., Univ. Ser. 1916.

72. Walker, T. L.: Geological and Petrographical Studies of the Sudbury Nickel District (Canada); Quart. Jour. Geol. Soc., London, vol. 53, pp. 40-66 (1897).

73. —— Magmatic Differentiation as Shown in the Nickel Intrusive at Sudbury; Univ. of Toronto Studies, Geol. Ser. No. 38, pp. 23-30 (1935).

74. Yates, A. B.: The Sudbury Intrusive; Trans. Roy. Soc., Canada, 3d ser., vol. 32, sec. IV, pp. 151-172 (1938).

75. Young, J. W.: The Sudbury Ore Deposits; Ec. Geol., vol. 19, pp. 677-81 (1924).