A PETROGRAPHIC STUDY OF THE COPPER CLIFF OFFSET IN THE SUDBURY DISTRICT

A

Thesis

Submitted to the Department of Geological Science
of McGill University in partial fulfillment
of the requirements for degree of
Master of Science

by

WILLIAM H. SLAGHT

McGill University April 20th, 1951.

TABLE OF CONTENTS

Pages

PETROGRAPHY (continued)

ILLUSTRATIONS

INTRODUCTION

Since the discovery of the famous deposits of the Sudbury district, the surrounding area (part of the Temiskaming sub-province of the Canadian shield) has received considerable attention, including systematic and detailed geological mapping, and intensive prospecting throughout the district.

In the geology of the area, three different problems are presented. These are: (1) the structural and time relationships of the norite - micropegmatite, the granites of the southern nickel range, the rock of the offsets; (2) the character of the norite-micropegmatite itself; (3) the genesis of the nickeliferous pyrrhotite ore bodies.

In this paper the relationship of the norite and the quartz diorite of the Copper Cliff offset will be discussed. It is important to work out both the correct relationships and the age of the quartz diorite because, as all recent workers now agree, the sulfide ore bodies are genetically related to this rock.

The quartz diorite is "offset rock", so called by Coleman,(1903), because many of the dykes seemed to be extensions or offsets from the main norite mass. Evidence favouring the offset rocks as part of the norite has been set forth also by Burrows and Rickaby, (1934), and Collins (1934, P. 169).

On the other hand, evidence for regarding the offset rocks as a separate and much later intrusion has been assembled by Yates (1938).

Recent studies in the Sudbury area by Cooke, (1946, P. 69), led him to support Yates' conclusions. Cooke considers the quartz diorite to be a separate intrusion, post-dating the norite and the Creighton and Murray granites.

The writer has undertaken, as a thesis problem, a petrographic study of the Copper Cliff offset, in an effort to obtain further information about the relationship of the quartz diorite to the main norite mass. During the field seasons of 1949 - 50, the writer spent approximately three months with International Nickel geological parties in the vicinity of the Sudbury basin. For one week in the fall of 1950 observations on field relationships were made and specimens collected in the Copper Cliff area for use in this study. During the academic year 1950 - 51, thirty-five thin sections from the Copper Cliff, Foy, Worthington offsets, and the main norite mass, were studied. In addition four specimens from the Copper Cliff offset were crushed, screened, and the minerals separated by means of heavy liquids to enable the writer to study the minerals by oil immersion methods.

ACKNOWLEDGMENT

The author is indebted to Dr. A. L. McAllister for his assistance in the field - study and in the collection of specimens, and also to the Geological Department of the International Nickel Company, Limited, for assistance in compiling and permission to use necessary data. Helpful criticism and supervision by Dr. J. S. Stevenson proved invaluable, both during the actual study and in the preparation of the manuscript.

Fig. 1.

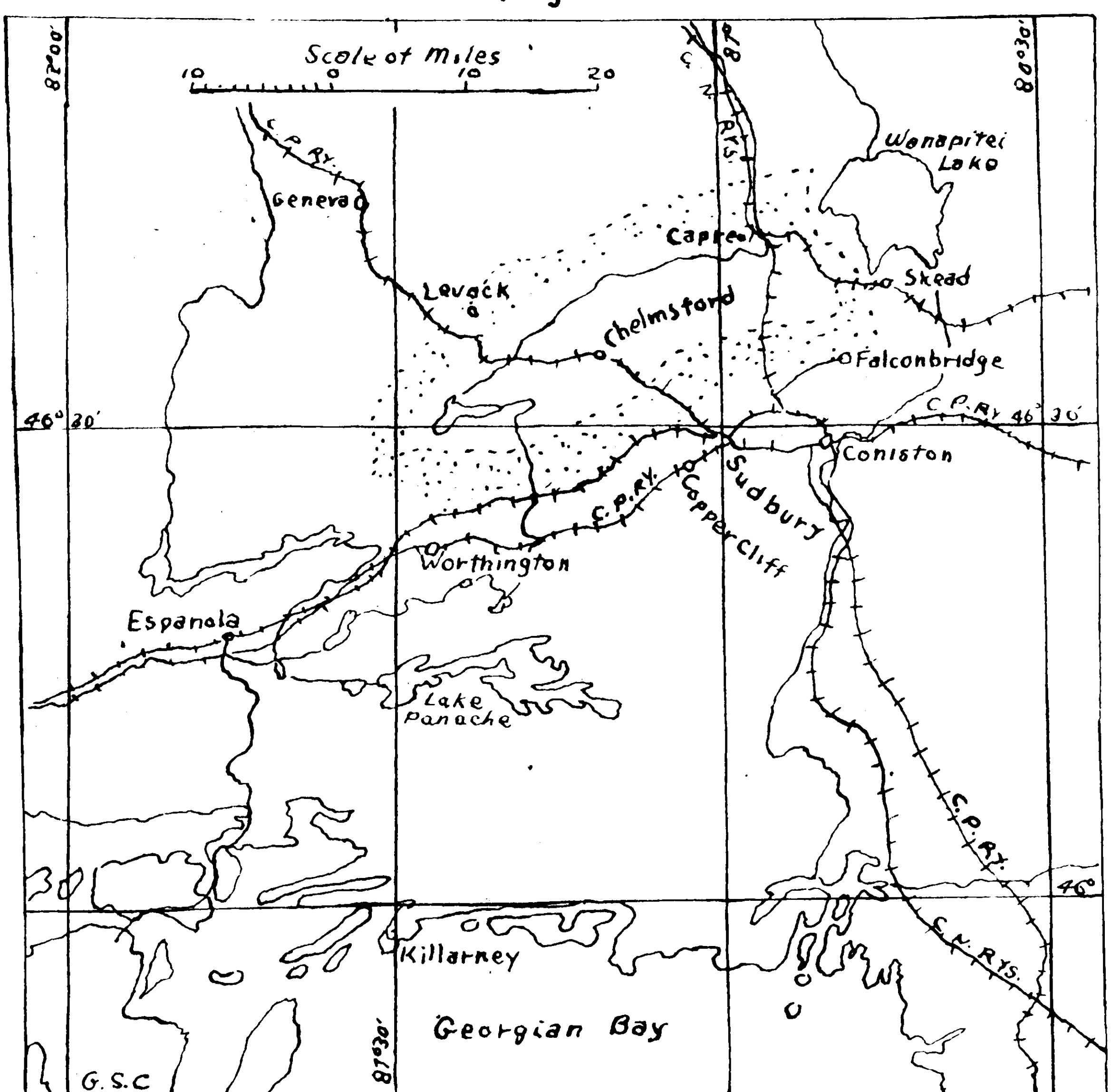


Figure 1. Index map of Sudbury Copper Cliff district, Area of norite irruptive stippled.

Location of Map Area

LOCATION

Sudbury, the chief town of the Sudbury nickel area of Ontario is about 35 miles north of Georgian Bay, Lake Huron. It is on the trans-continental line of the Canadian Pacific Railway, 439 miles westward from Montreal. It is also served by the Canadian National Railway, the distance from Toronto being 267 miles. About 3 miles to the west of Sudbury is the town of Copper Cliff and the Copper Cliff offset.

The Sudbury basin lies between latitude 46° 45' - 46° 20', and between longitude 80° 45' - 81° 30'. The actual location of the Copper Cliff offset extends from Pump Lake, which lies 2¼ miles north of Copper Cliff, in lots 1 and 2, concession iv, of Snider township, south through the town of Copper Cliff, to the north shore of Kelley Lake, which is about 2½ miles south of Copper Cliff.

TOPOGRAPHY

The general character of the country may, perhaps, be best described as that of an uneven or undulating, rocky plain, with a gentle slope towards the south and southwest. In detail, the surface of the plain is far from uniform, consisting of a rapid succession of more or less parallel and disconnected rocky ridges, with a prevailing north-east and southwest trend. The intervening valleys are usually occupied by swamps, lakes or river courses. The average elevation of the district varies from 800 to 1,100 feet above sea-level. The present topography has been the result of prolonged denudation and erosion, assisted to a considerable extent, by subsequent glacial action. This action is apparent everywhere both in the exposed rock surfaces in which glacial grooves and striae are preserved and in the well-rounded hills smoothed by the scouring action of the vast glacier. Although the country is exceedingly rough and uneven, there are no prominent hill features, the high elevations seldom being more than 150 feet above the neighbouring valleys, while elevations of 25 to 100 feet are far more common. To the northwest of this hilly tract, the land becomes tolerably level, forming a plain with an average elevation of nearly 880 feet above sea-level. This flat belt has a general width of about 6 miles, and stretches from the vicinity of Vermilion Lake almost to Wanapitei Lake, a distance of over 30 miles. Evidently this whole area is underlain by slates and feldspathic sandstones, largely concealed by a thick mantle of drift through which protrude occasional low, rounded hummocks, which alone give evidence of the underlying material.

The influence exerted by the underlying rock on the general contour of the ground is well exemplified everywhere throughout this district. The harder igneous and quartzite rocks, because of greater resistance to processes of weathering and erosion, form the higher ridges, while the less resistant slates, sandstones, and schists, make up most of the intervening lower ground. The area covered by the main mass or belt of norite is likewise one of low relief in contrast with the other igneous rocks. The district is not as abundantly supplied with lakes as are many other areas of the Canadian Shield.

The drainage of this district is by three streams, the Wanapitei, Spanish, and Vermilion rivers, all of which eventually drain into Georgian Bay and Lake Huron.

The district is unsuitable for agriculture and must rely on the development of its mineral resources. As the proximity of the mines furnishes a good market, every arable flat is under cultivation.

HISTORY

Nickel ore was first discovered in the Sudbury district in 1856, by Murray who obtained it near the present Creighton mine where Salter, an early land surveyor, had noted marked disturbances of the compass. Dr. Sterry Hunt, on analyzing the ore, found nickel and copper. No further discoveries of nickel ores were made until the construction of the Canadian Pacific Railway in 1883, when the ore body of the Murray mine was uncovered. In the following year the Stobie, Copper Cliff and other deposits were found.

The first geological map of the Sudbury district accompanied a report by Robert Bell in which he presented the results of his field work during the years 1888 - 90 and which was published by the Geological Survey of Canada in 1891. Bell clearly recognized the basin-structure of the sedimentary and volcanic rocks of the whitewater series, but he classified the norite and micropegmatite as coarse, grey diabase and red hornblende granite. These rocks were considered sills in the volcanic series but neither their continuity around the basin nor the close association of the granite and diabase was recognized.

In 1897, T. L. Walker, one of Robert Bell's assistants, published a paper pointing out the close association of the salic and mafic phases of the intrusive. He gave the name "norite" to the mafic phase and "micropegmatite-granite" to the salic phase, and concluded that the two were products of differentiation from the same magma. Although his map shows the intrusive in its true relation to the basin rocks, the continuity around the basin was still not recognized.

During the next seven years, A. E. Barlow, developing more fully the idea of differentiation, pointed out the continuity of the intrusive. His report was published in 1904 by the Geological Survey of Canada, while A. P. Coleman's field work was in progress. In a preliminary report published by the Ontario Bureau of Mines in 1903, Coleman described the continuity of the intrusive and pointed out the possibility of a structure conformable with that of the overlying volcanics and sediments. He fully developed the differentiation theory and applied it to the ores as well as to the rocks. The final results of Coleman's work were published in 1905, along with the map of the district.

C. W. Knight, in a paper published in 1923, pointed out that there was no uniform gradation from norite to micropegmatite but rather a sharp change which took place over a relatively narrow belt separating essentially uniform norite from the salic micropegmatite. T. C. Phemister, (1925), elaborating on this fact, offered the explanation that these two were probably derived from the same magma differentiated at depth and were intruded side by side, the micropegmatite somewhat later than norite.

W. H. Collins began his critical study of the intrusive in 1928, and the results of his work were published in a series of four papers, Collins (1934, 1935, 1936, 1937). He mapped and fully described a striking transition zone between the norite and the micropegmatite and concluded that the two resulted from the differentiation of the same magma but that they separated while still in liquid phase.

In 1938-39, H. C. Cooke did geological mapping in the Sudbury area and his work was published in 1946 - (Cooke 1946).

Since 1931, the International Nickel Company of Canada has employed a large, permanent staff of geologists, at present under the direction of F. Zurbrigg and Dr. C. M. Michener. This staff has not confined its attention merely to the mapping of ore occurrences but has investigated in detail many other geological features of the district.

REGIONAL GEOLOGY

In order to get a clear understanding of the Sudbury district, we must consider its relation to an extensive petrographical province, extending over 600 miles from the upper end of Lake Superior, easterly along the shores of Lake Superior and Lake Huron, through Sudbury and Cobalt and on into the province of Quebec.

Basic intrusive rocks of similar age and composition occur at intervals along the entire length of this belt. Metals are associated with these basic intrusives although not always in sufficient amounts to make ore. Notably there are: the great copper mines of Michigan, the many small pyrrhotite deposits between Sault Ste Marie and Sudbury; the nickel and copper mines of Sudbury; the silver and cobalt mines of Cobalt. All these deposits are associated with a quartz diabase type of rock known in different places as the Duluth gabbro, the Sudbury norite, and the Nysissing diabase. Sudbury is only one unit in this belt.

The Sudbury intrusive occupies a major discontinuity in the old pre-Cambrian series. North of the intrusive, in an extensive complex, are the granite, granite gneiss, and highly granitized sediments, the ages of which are not definitely known. To the south is an older succession of volcanic, metamorphic, and sedimentary rocks, highly folded and faulted, striking in general east-northeast with steep dips mainly to the north.

TABLE OF FORMATIONS

Pleistocene

Olivine Diabase Dykes

Trap Dykes

Murray Granite

Creighton Granite

Norite and Quartz Diorite

Sudbury Gabbro

Whitewater Series:	chelmsford Sandstone Onaping Slate Onaping Tuff Trout Lake Conglomerate
Bruce Series:	Mississagi Quartzite Ramsay Lake Conglomerate Unconformity
Sudbury Series:	Frood formation basic flows Copper Cliff formation rhyolite McKim formation greywacke, quartzite, tuffs.
Keewatin:	Snider formation - quartzite Elsie Mountain Greenstone andesitic and basaltic flows.

Keewatin

The oldest rocks of the district are the highly altered; impure quartzites of the Snider formation and the basic extrusives of the Elsie Mountain greenstone formation. The andesitic and basaltic flows of the Elsie Mountain formation make up the greater part of the Keewatin. It is essentially a series of thin flows with some interstratified thin beds of arkose. The formation is extremely variable in thickness. This is due partly to the inherent irregularities in any volcanic series and partly to folding. Flow, amygdaloidal, and pillow structures are well preserved even where the rock is completely altered mineralogically. Narrow beds of coarse arkose, grit and quartzite occur throughout the Elsie Mountain formation, it is quite possible that the sediments of the Snider formation represent merely a local thickening of these beds.

Most of the sediments associated with the greenstone, which is the oldest rock in the area, lie adjacent to the granite and norite on the south side. They include light-coloured, bedded, sericitic rocks, with conspicuously altered crystals of staurolite varying in size from very minute grains to crystals several inches in length.

Sudbury Series

The Sudbury series, lying stratigraphically above the Keewatin, is a thick series of interbedded volcanics and impure sediments. This series is divided into three formations, the Frood, the Copper Cliff, and the McKim formations, (Yates 1938). There is a transition from basic lavas at the base of the Frood formation, to more acidic types upward while at the top is a thick series of acid lavas which in the field have been called the Copper Cliff rhyolite. Another striking transition occurs from lavas upward to sediments. The McKim formation is almost entirely made up of greywacke in the lower parts, with more quartzitic beds near the top. Some of the lower members of the McKim are probably tuffaceous.

The Unconformity

In some places there exists a major unconformity between the top of the Sudbury series and the bottom of the Huronian, usually marked by a characteristic conglomerate. In this immediate area, the top of the McKim, particularly toward the west, contains impure quartzite beds that are difficult to distinguish lithologically from the lower quartzite beds of the Mississagi. Certainly west, north, and east of the Sudbury district there exists such an unconformity.

The Huronian

The Huronian system is represented in this district almost entirely by the Mississagi quartzite, a great thickness of grey-to-white quartzite beds with many narrow beds of impure arkose, greywacke, and argillite. A conglomerate occurs at the base of the formation. Upper members of the Bruce series are missing from the immediate area, but appear again toward the east, and the whole series, although folded, has a north to northeast strike with steep dips. The members of the middle Huronian (Cobalt series), apparently missing entirely in the immediate area, do appear to the southwest where they lie unconformably on the Bruce series with steep dips, and to the northeast where the dips are flat and the lower members concealed.

Whitewater Series

Lying wholly within the basin and surrounded by the Sudbury intrusive, is a group of rocks, the whitewater series, which has been divided into four formations: the chelmsford sandstone; the Onwatin slate; the Onaping tuff; the Trout Lake conglomerate. Actually the rocks, mainly volcanic tuffs and agglomerates, appear to be a gradation from a coarse agglomerate and breccia near the bottom, to an impure and bedded tuff near the top. Sheared and of a slaty structure, they are only gently folded. The actual age of the whitewater series is still indefinitely known, however, it has been tentatively classed as upper Huronian and as Keweenawan.

Intrusives

Several periods of granite intrusions and regional granitization, as well as several ages of basic intrusives, are presented in the Sudbury district.

Algoman

The oldest granite in the immediate vicinity is a coarse, uniformly grained, pink variety, which is certainly of later age than the

Snider series of the Keewatin but is pre-norite. Placed between the Sudbury series and the lower Huronian it presumably represents the later archean granite known as algoman.

Keweenawan

Sudbury Gabbro: Gabbro appears in prominent ridges just south and east of Sudbury. The rock extends from the west end of Kelly Lake in a northeasterly direction into Falconbridge township. Coleman, (1905), has referred to this rock as the Sudbury gabbro. South of Sudbury there is evidence of a sill-like structure, namely the gabbro dipping to the southeast under greywacke.

The gabbro has a greyish-green weathering surface, in medium-to-coarse-grained in texture, and always shows evidence of being an intrusive with no indication of pillow or amygdaloidal texture, such as occurs in the greenstone near the nickel irruptive. This rock has some semblance to the norite, but is always green-weathering.

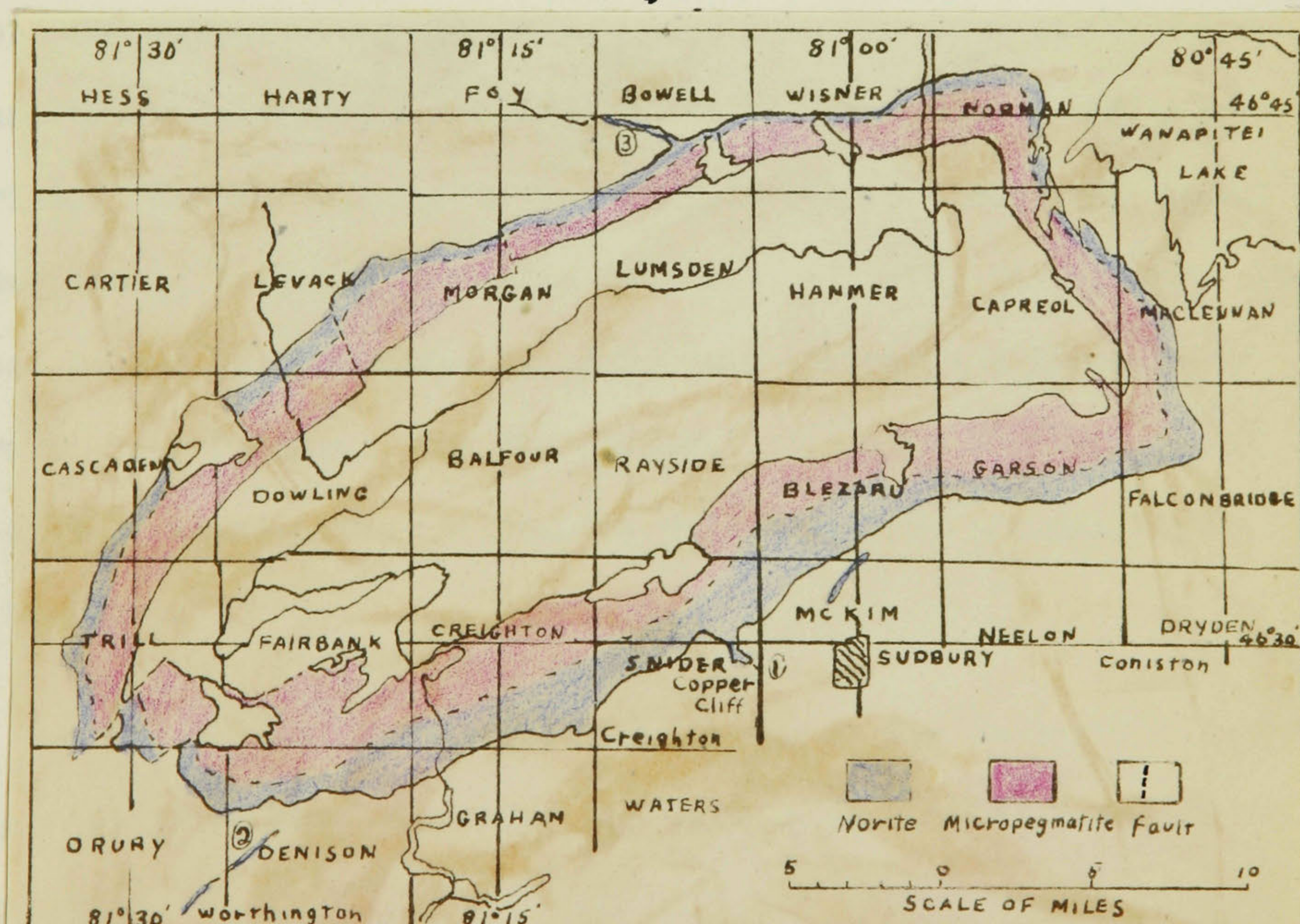
The Norite

Much has been written about the norite, mainly to explain the differentiation into a basic lower and more acidic upper part. Many hypotheses have been presented, these discuss such processes as, liquid immiscibility, crystal settling, fractional crystallization; some have required two separate intrusions, the norite first, followed by the micropegmatite.

The norite is a coarse-grained, equigranular rock. In colour it is various shades of gray, generally dark along the most productive part of the southern nickel range, passing insensibly into the pale grey or flesh-coloured micropegmatite towards the inner and upper edge. The width of the band is quite variable, ranges from 2.5 to 3.6 miles in the south range and averages about 3 miles.

Perhaps one of the most noticeable differences between the norite and the micropegmatite in the field is the difference in the nature of their contacts with country rocks. In general, the norite is in sharp contact with the rocks on the outer rim of the basin, whereas the micropegmatite veins and pervades the overlying Trout Lake conglomerate.

Fig. 2.



After G.S.C.

Location Map for

1. Copper Cliff offset ; 2 Worthington offset ; 3 Foy offset

Quartz Diorite

Several dykes which occur in the adjacent rock near the outer edge of the norite have been considered apophyses from the norite. These have been named the Frood, Copper Cliff, Worthington, and Foy. The following characteristics are common: quartz diorite composition; dyke like form; spotted rusty weathering surface due to the presence of sulfides, an associated ore deposit. The offset rock in all of these dykes is so similar that specimens from different offsets cannot be distinguished.

The Frood offset forms a ridge running parallel to the norite from a point just below the Frood mine to the Stobie mine. The Copper Cliff offset extends from the norite mass at Pump Lake, south to Kelley Lake. The offset joins the norite in a bay, and from field observations, there is no definite boundary between the norite and quartz diorite. The Worthington offset extends from a small lake on lot 3, concession 1, of Drury township, in a northeasterly direction to the center of lot 9, concession 4, of Denison township, a distance of approximately 5 miles. The Foy offset lies in the northern nickel range and extends west-northwest from the main irruptive through Bowell and Foy townships.

The age of the offsets relative to the norite is uncertain, some geologists think they are older and some think they are younger than the norite.

Granite

The granites include two varieties, the Creighton and the Murray granites, both of which intrude the older sediments and associated greenstones.

The largest mass is called the Creighton granite. In some places it is directly in contact with the norite. The granite of this mass appears to consist of a number of types. It is principally represented by a pinkish porphyritic phase, but there is also a fine-grained red variety and a gneissic variety. There is some difference of opinion as to relative ages of the norite and the main mass of Creighton granite as has been discussed before in regards to the age of the quartz diorite.

A biotite granite, known as the Murray granite, is more uniform than the Creighton and its relation with the norite more definite. Numerous apophyses of the Murray granite penetrate the norite one mile northeast of Murray mine.

There is conflicting evidence as to the relationship of the norite and granite as a whole. Coleman, (1905), believes that most of the granite is older, while Knight, (1923), and Phemister, (1925), claim the contrary. Yates,(1938), considers the Murray and Creighton granites within the district to be post norite for the most part. Smaller areas of older granite which occur within the Creighton confuse the relationships. This probably accounts for the contradictory age relationships.

Trap Dykes

Following the intrusion of the norite and quartz diorite there appears to have been a little igneous activity that found expression in the intrusion of trap dykes. These are fine-grained uralitic diabases, striking east to west, that cut the norite, the Murray and Creighton granites and the quartz diorite. All are cut by the dykes of late equigranular olivine diabase.

Olivine Diabase Dykes

The last important intrusion of Keweenawan times was that of a series of olivine diabase dykes. This olivine diabase is a medium-to-coarse-grained, equigranular rock that weathers to a warm-brown tint. The dykes generally strike from 20° to 40° north of west and can be traced for many miles.

STRUCTURE OF THE SUDBURY BASIN

The irruptive outcrops as an annular body and encloses within it the sediments of the whitewater series. On the west, north, and east, the outer edge of the irruptive dips inward at moderate angles; the south edge has steeper dips inward which is in part due to faulting. The whitewater sediments within the ring have a general synclinal structure, with very low dips prevailing through the central parts. These facts have led to a general agreement among geologists that the shape of the intrusive, and of the sediments within it, is that of a canoe-shaped, rather gentle syncline, approximately 37 miles long and

17 miles.

Most hypotheses require the emplacement of the norite in the form of a horizontal sheet and differentiation in place with subsequent down-folding or collapse.

Yates, (1948), maintains that there is no validity for the hypothesis that the norite was intruded as a horizontal sheet. He believes also, that there is no good evidence of intense folding or movement after the emplacement of the norite, and certainly nothing to suggest that the basin structure was developed after intrusion. He believes that a large Pre-existing syncline, controlled the position and shape of the norite.

PETROGRAPHY

From a petrographic study of the Copper Cliff offset, it has been found that all the rock is gabbro diorite. A basic core of quartz gabbro extends south from the main irruptive for a mile. The quartz gabbro grades into quartz diorite on the east, west, and to the south. The name "quartz gabbro" is given to rock that has labradorite feldspar and the name "quartz diorite" is given to rock that has andesine feldspar. These two rock types will be described in detail and will be compared to rock in the main irruptive mass and in other offset dykes.

Quartz Gabbro

In hand specimens of the unaltered rock, the quartz gabbro is a medium-grained rock, grey to grey-black in colour. In altered phases, the rock may be green or because of biotite, brownish green. Blebs of sulfides are evident and in places sedimentary inclusions are observed. The rock appears to be essentially composed of white to grey-black feldspar laths, of grains of biotite, and of other mafic minerals.

The texture is hypidiomorphic granular to subophitic. The mineral composition is as follows:

	Plagioclase feldspar	48 - 52 per cent
	Amphibole	25 - 30 per cent
Essential Minerals	Quartz	7 - 8 per cent
	Biotite	10 - 12 per cent
	Chlorite	
	Pyroxene core	
	Apatite	0.5 per cent
Accessory Minerals	opaque oxides (Magnetite, Ilmenite)	1 - 1.5 per cent
	Sulfides -	Trace of (pyrrhotite, chalcopyrite, pyrite)

Mineralogy: - The pyroxene in this rock occurs as core, with schiller-like structure, altered completely or around the edges to amphibole. No accurate determinations can be made on the pyroxene but the structure is characteristic of both hypersthene and diallage.

The amphibole is seen to develop from alteration of pyroxene. From the sections studied, it appears that two varieties of amphibole are present. One variety has the following optical properties: biaxial negative; 2V 70°; maximum extinction angle measured $Z \wedge c = 18°$; length slow; pleochroic; absorption Z blue green Y light green X pale yellow.

The other variety forms by alteration after diallage and has optical properties as follows: it is biaxial negative; 2V maximum 75°; maximum extinction angle measured $Z \wedge c = 26°$; strong pleochroism; absorption Z deep bluish green Y deep green X light, bluish green; length slow; birefringence moderate to low.

Further evidence for the existence of two varieties of amphibole was found by means of microscopic examination of minerals in immersion oils, the minerals having been separated from crushed rock. There is a definite variation in the refractive indices: Nx 1.590 - 1.631; Ny 1.605 - 1. 643; Nz 1.622 - 1. 653.

The change in optical properties indicates a gradation of the amphibole in the quartz gabbro between actinolite and green hornblende. The amphibole termed actinolite often lacks the needle-like shape that is so characteristic of actinolite. In general, the amphibole is usually shapeless and has no regular terminations.

The amount of biotite in the sections of quartz gabbro is variable, but could be considered an abundant mineral, particularly in specimens which are partly altered. The biotite is a dark-brown variety. It shows marked pleochroism and absorption with X light brown Y brown Z dark brown. The biotite shows good bird's eye structure. The crystals may be flaky or shreddy when associated with the amphibole. In every slide some of the flakes show pleochroic halos which are probably around radioactive minerals such as zircon. Many of the flakes show bleached edges.

In a few slides there are two types of chlorite. The chlorite alters from amphibole and biotite and is variable in amount, ranging from nil to four per cent. Most of the chlorite shows parallel extinction; is biaxial positive; has a 2V maximum 40°; elongation positive; low relief; refractive indices greater than Canada balsam; shows an anomalous blue colour. This chlorite is penninite.

In several slides there occurred serpentinized chlorite that has the following properties: biaxial negative; low birefringence; greenish grey colour; refractive indices in the vicinity of Canada balsam; parallel extinction; these indicate the mineral antigorite (Plate 1, Fig. 1,2).

The amount of quartz in these sections averages from 5 to 8 per cent. It occurs in irregular masses, and is interstitial to the other minerals. In many slides the quartz corrodes and embays the feldspar and in some other sections corrodes and embays the amphibole.

In some parts of the rock where the quartz has intergrown with the feldspar granophyric texture is developed. The intergrowth of quartz and feldspar is often found radiating from well-defined crystals of plagioclase feldspar. A microscopic examination of crushed material showed the grains of quartz and feldspar to be composite. From a few index determinations the feldspars of the intergrowth were found to range from potash to An25 - that is oligioclase. The potash feldspar has refractive indices less than Canada balsam.

The plagioclase feldspars, as a rule, are fairly fresh in appearance. The feldspar in these sections ranges from An55 and An46 - that is albite rich Labradorite. These determinations were made by measuring extinction angles on combined Carlsbad-albite twinning.

The microscopic examination of selected material in immersion liquids shows that the extinction angles and indices of refraction of the feldspars vary somewhat: Nx 1.551 - 1.554; Ny 1.552 - 1.559; Nz 1.555 - 1.564. The indices of refraction indicate that the feldspar in these sections range An44 to An55 - albite rich Labradorite.

The feldspar occurs in broad, subhedral laths. In all slides studied the plagioclase has well developed albite and Carlsbad twinning and some zoning is present. Where checks were made on zoned feldspars the center of the crystals showed refractive indices higher than the outer rim. The maximum extinction angle in the center measured $\perp Z, X \wedge 001 = -20^{\circ}$ - An50, this is labradorite. The minimum extinction angle in the outer rim measured $\perp Z, X \wedge 001 = -10^{\circ}$ An35, this is oligoclase. This shows a variation in zoned plagioclase between labradorite at the core and oligoclase at the rim.

In the central portion of the zoned crystals and also along cleavage and twinning plane intersections of some of the lathlike crystals, the feldspars have, in part, altered to epidote, clinozoisite, sericite, and sometimes to calcite. Owing to its dusty-brown colour the feldspar is very striking when viewed under plane light.

Because of its high relief the epidote is very conspicuous, it shows parallel extinction in longitudinal sections. It is colourless under plane light and in plane polarized light shows large variation in inferference colour from high first order to lower third order. It occurs as small granular to more or less distinct crystals.

The most abundant alteration product is a colourless non-pleochroic mineral that occurs in elongated crystals or columnar aggregates or bunches. It is anomalous deep blue to greyish blue. In most sections the extinction is parallel. This mineral that is found replacing plagioclase in part, is clinozoisite, which may occur as large knots in the feldspar, as well as in small aggregates evenly disseminated throughout. In several places around the edges of clinozoisite was found a light yellowish mineral of slightly lower refractive index, which may be zoisite.

Sericite and calcite are also present. As the carbonate was in very fine grains an accurate optical determination was impossible.

In all the slides examined apatite is present as a prominent accessory mineral. Its amount varies greatly in a single specimen but averages 0.5 per cent. There is no definite relationship between the size of the apatite grains and the texture of the rock.

The opaque oxides include titaniferous magnetite and ilmenite. This was determined by separating the heavy minerals by the heavy liquid method and later by removing the magnetite by magnetic separation.

The magnetite when viewed microscopically showed evidence of alteration to leucoxene. On removal of the magnetite, an opaque oxide remained with the heavy minerals. The oxide which has the opaque white alteration product, leucoxene, on its surface and boarders is ilmenite. In thin section it is difficult to differentiate between these two oxides as they both alter to leucoxene.

Texture

The common texture is " hypidiomorphic granular", in which anhedral grains of amphibole, biotite, quartz, and of chlorite are found within a network of subhedral plagioclase laths.

Order of Crystallization

The order of crystallization of the principal minerals in the quartz gabbro is difficult to determine because of varying degrees of alteration. Shand, (1949, P. 114), states that there is no such thing as a constant order of crystallization, applicable to all magma or even to one magma under different physical conditions. The writer believes the sequence, in the quartz gabbro, from early to late to be as follows: 1) plagioclase; 2) pyroxene subsequently altered to amphibole and biotite; 3) quartz.

The plagioclase has well developed subhedral laths, which in many slides show evidence of having been corroded by later minerals, and appear to have crystallized early.

The original pyroxene probably followed closely after the feldspars, as in many places the amphibole, which is secondary after the pyroxene, is seen cutting plagioclase crystals. In some slides a subophitic texture is still evident.

The quartz and the granophyre are interstitial to the amphibole and to the feldspars and were the last of the principal components to crystallize.

Uralitic amphibole, chlorite, biotite, clinozoisite, epidote, sericite, and calcite, are secondary minerals and formed by either deuteric or hydrothermal alteration.

Among the accessories, the order of crystallization is not too clear. Apatite is found in quartz and in some feldspars. The opaque oxides show a preference for biotite and for amphibole to some extent.

Alteration of Quartz Gabbro

The hypersthene with schiller-like structure remains only as core within amphibole (Plate 2, Fig. 1). It is replaced by dark-green hornblende which usually begins at the outer margin of the crystal and works inward, replacing everything as it goes. This green hornblende is later converted to a mixture of fibrous, blue-green actinolite, and shreddy brown biotite. These appear to be the stable alteration products and are the common ferromagnesium constituents of the more altered phases of the rock.

In general, the feldspar resists alteration better than the ferric constituents of the rock (Plate 2, Fig.2). The first stage of alteration is the development of small veinlets of amphibole, sericite, and biotite along cracks and along grain boundaries. Clinozoisite, epidote, and sericite, the common alteration products of plagioclase, seem to form either in the central portion of zoned crystals or along cleavage and twinning plane intersections.

The alteration observed in sections from the quartz gabbro at first appears to be deuteric but upon closer examination it may be seen that there is vein-filling of the alteration products along fractures in the plagioclase laths. This strongly indicates hydrothermal alteration.

There is some evidence of brecciation in several slides and a few feldspar laths appear bent. These factors probably indicate a slight movement after crystallization. Such a movement could have been responsible for releasing pressure and allowing hydrothermal solutions to become active within the rock.

Quartz Diorite

In hand specimens of the unaltered rock, the quartz diorite varies from medium grained to fine grained rock in the southern part of the dyke. Typical quartz diorite is dark grey and faintly speckled with white feldspar particles. Whereas fine grained quartz diorite is almost black. The best field test for recognizing this rock is the presence of blebs of sulfides. Another criterion, also useful in field investigation is the occurrence of inclusions in some parts of the dyke. Specimens taken on either side of the core of quartz gabbro show blue quartz-eyes but south of Lady MacDonald Lake the quartz-eyes are not so prominent.

Under microscopic examination the essential minerals observed in the sections studied are:

Essential	Plagioclase feldspar	42 - 56 per cent
	Amphibole	23 - 32 per cent
	Quartz	6 - 15 per cent
	Biotite	7 - 14 per cent
Accessory	Apatite	.4 - .8 per cent
	Opaque oxides (Magnetite Ilmenite)	1 - 3 per cent
	Sulfides (Pyrite, pyrrhotite, chalcopyrite)	lesser amounts

Mineralogy: In several sections pyroxene occurs but only as cores with schiller-like structure in which the pyroxene is almost completely altered to amphibole as in the quartz gabbro.

The amphibole is seen to form from alteration of pyroxene (Plate 3, Fig.1). From the sections observed, it appears that two varieties of amphibole are present, green sodic hornblende and actinolite. That there is a gradational change between the two is again indicated by an increase in extinction angle measured $Z \wedge c$ and an increase in refractive index shown by means of oil immersion work, as well as a change in pleochroism and absorption.

The amphibole in the sections from the quartz diorite has the same characteristics as the amphibole observed in the sections of quartz gabbro with the one exception that only a few slides show evidence of the alteration from pyroxene to amphibole.

The biotite is the dark-brown variety, either flaky or shreddy when associated with the amphibole. In all sections some of the biotite flakes show pleochroic halos and have bleached edges.

The chlorite is of two varieties as determined again from optical properties, penninite and antigorite. In some of the slides the sequence of alteration - hornblende to actinolite to biotite - to chlorite can be traced (Plate 3, Fig. 2).

The amount of quartz in these sections averages from 6 to 13 per cent. It is found interstitial to other minerals and an intergrowth of quartz and feldspar is often found radiating from a well-defined crystal of plagioclase feldspar (Plate 4, Fig. 1). The quartz and feldspar are in a granophyric intergrowth, which is better developed in many sections of quartz diorite than in the quartz gabbro core. The quartz, where it is interstitial to other minerals, is found to corrode the feldspars.

The plagioclase feldspars, as a rule, are relatively unaltered. The feldspar in these sections by measuring extinction angles ranges from An40 to An50 - this is andesine. These determinations were made by measuring extinction angles on combined Carlsbad-albite twinning and extinction angles $\perp Z$ $X \wedge 001 = -20^{\circ}$, An47 - this is andesine.

The microscopic examination of selected material in immersion liquids shows the indices of refraction of the feldspar to vary somewhat; Nx 1.544 - 1.552; Ny 1.550 - 1.555; Nz 1.551 - 1. 560. The indices of refraction indicate that the feldspar in this rock type ranges An39 - An46 - this is andesine (albite rich).

The feldspar occurs in broad subhedral laths in the northern part of the offset (Plate 4, Fig. 2) and in long, slender, subhedral laths in the southern portion of the dyke. The plagioclase has well developed Carlsbad-albite twinning and some zoning. Where determinations were made on zoned feldspars the center of the crystal showed refractive indices higher than the outer rim. In the center the maximum extinction angle measured $\perp Z$ ($X \wedge 001$) is -21°, An48, in the outer rim the minimum extinction angle measured $\perp Z$ ($X \wedge 001$) is -10° An32. This shows a variation in zoned plagioclase between andesine at the core and oligoclase at the rim.

Alteration has taken place in the central parts of zoned plagioclase crystals or along cleavage and twinning plane intersections in some crystals. The alteration of the feldspar has resulted in the development of epidote, clinozoisite, sericite, and calcite. The dusty-brown colour that was observed in the feldspars from the quartz gabbro is still present in the feldspars from the quartz diorite, but becomes progressively less apparent in sections from more southern points on the dyke.

In all slides examined apatite is present as an accessory mineral.

Its amount varies greatly and averages 0.6 per cent. The opaque oxides include titaniferous magnetite and ilmenite. This was determined by the method described under quartz gabbro (p. 25). Minor amounts of pyrite, pyrrhotite, and chalcopyrite are also present.

Texture and Order of Crystallization.

The texture of the quartz diorite, especially south of Lady MacDonald Lake, does not appear to be quite as definite as in the quartz gabbro. The texture may be said to be indistinct because of alteration, which has obliterated much of the original texture. The texture may be termed intersertal Johannsen, (1939, P.47). The order of crystallization as accurately as can be determined appears to be the same as that for the quartz gabbro (P. 26).

Alteration

Pyroxene is present but only as grains with schiller-like structure. It is replaced by green hornblende, which is later converted to a mixture of fibrous, blue-green actinolite, and shreddy brown biotite.

In the quartz diorite, as in the quartz gabbro, the feldspars resist alteration better than the ferric constituents of the rock. The first stage of alteration is the development of small veins of amphibole, sericite, and biotite along cracks and grain boundaries. The alteration to epidote, clinozoisite, and sericite, begins in the basic core of zoned crystals and along cleavage and twinning plane intersections in crystals that do not show zoning.

The origin of the dusty-brown colour in the plagioclase of the quartz gabbro and quartz diorite is uncertain. According to Coleman, Moore, and Walker, (1929, pp. 11-16) this cloudy appearance in feldspars id characteristic of hypersthene rocks and is supposed to be due to very fine inclusions of ilmenite.

MacGregor A. G., (1931, pp. 524-538), after examining the evidence relating to clouded feldspars in the Baltimore gabbro has concluded that this cloudy appearance in feldspars is due to: a) faint brown patches of almost ultra-microscopic features; b) localized (patchy) grey cloudiness caused by concentrations of extremely minute opaque inclusions. MacGregor found the specks to be of two types: a) equidimensional; b) rod-like. The rod-like forms tend to occur in parallel sets, probably along crystallographic planes, the sets occurring at different levels.

Recent magnetic work around Murray mine has shown that the very dark feldspars are weakly magnetic, and it is suspected that the minute inclusions are magnetic.

Reynolds, D. L. and Bailey, (1936, pp. 341-342 and P. 270), regard the clouding of plagioclase feldspars as evidence that the rock has suffered contact metamorphism, that is, baking.

Henderson, G. H., (1937, pp. 65-67), finds that the clouding of feldspars forms two kinds of patterns. In the one, the fine particles are more or less evenly distributed throughout the grain and are probably mostly hematite or magnetite; in the other, they are concentrated along cleavages or within certain twinning bands and are probably kaolinite. The former were probably formed during the period of contact metamorphism, the latter is more probably the result of weathering and other later processes. Henderson believes as Mac Gregor (1931, pp. 524-538), that clouding by iron oxides commonly accompanies metamorphism and states that the least basic (outermost) part of zoned crystals do not as a rule become clouded.

Several men have made a comprehensive study of the components of saussurite. Catherein, (1878, pp. 248-249), the first to make a study of the components of saussurite, found that it was composed of a mixture of plagioclase, rarely orthoclase, and zoisite, with accessory actinolite, chlorite, and other minerals. He concluded that it was the product of metamorphism of feldspar through the replacement of silica and alkalies by lime, iron, and water. Reusch, 1928, showed that both epidote and zoisite occur in saussurite. Lehmann, (1884, pp. 197-198), determined the cause of saussuritization to be chemical re-formation and dynamometamorphism. Williams, (1890, pp. 58-60), after summarizing the opinions of others on the formation of saussurite, indicated that saussurite of the gabbro of Michigan consisted of zoisite and a clear matrix, perhaps albite. Phemister, (1926, pp. 653-656), would limit the term to a secondary aggregate of epidote, zoisite, and albite.

Saussurite, therefore, appears to consist of the three minerals, zoisite, clinozoisite, and epidote, or much more commonly of these three minerals combined with quartz, mica, albite, scapolite, actinolite, and other minerals.

Inclusions in the Copper Cliff Offset

Inclusions were found at several locations in the dyke, the main concentration being north of Lady MacDonald Lake, while others were found between this lake and No. Two mine.

The inclusions are of two types. In one type you find that the inclusions for the most part, vary in size from a half-inch to a foot in length and average three to four inches. On a weathered surface these inclusions are greyish and lighter in colour than the dyke rock, whereas on a fresh surface they have a siliceous, sugary appearance. From field investigations the inclusions do not appear to have any preferred orientation. In the other type, found just north of Lady MacDonald Lake near the west contact, there is a decided difference. These inclusions occur as feldspathic like blebs in the dyke rock (Plate 9, Fig. 1)

The inclusions first described, under a microscope, appear as fine grained, recrystallized aggregates of grains (Plate 5, Fig. 1). The mineral composition is as follows:

	Feldspar	75 - 80 per cent
	Biotite Chlorite	15 per cent
	Epidote Clinozoisite Sericite	3 per cent
Accessories	Opaque oxides Apatite Quartz	3 per cent

The biotite is of the dark-brown variety, is flaky, shows pleochroic halos and bleached edges. The other mafic mineral present is penninite (chlorite). These two minerals, with disseminated particles of opaque matter, give the dark colour to the rock.

The feldspar is the predominant constituent; with refractive indices greater than Canada balsam, and the optical sign negative. A measurement of extinction angles measured on Carlsbad-albite twinning the feldspar ranged between An38 - An20, this is oligoclase - andesine. Some of the feldspars are subhedral and show marked polysynthetic twinning. Other crystals of feldspar are anhedral and some show rude evidence of zoning. The alteration to epidote-clinozoisite-sericite is due to the break-down of the feldspar.

The description of these inclusions compares favourably with the description of the greywacke described by Barlow, (1904, P. 63), indicating that portions of the country rock were incorporated into the Sudbury irruptive.

The second type of inclusions under a microscope show evidence of recrystallization (Plate 5, Fig. 2). The texture is fine-grained allotriomorphic. The mineral composition is as follows:

Essential	Microcline Perthite Plagioclase	70 per cent
	Quartz	20 - 25 per cent
Accessories	Apatite Biotite	3 per cent

The microcline is easily distinguished by its characteristic cross-hatched appearance. The perthite might be termed a streaked perthite and could be due to ex-solution phenomena, or to replacement. There are lath-like feldspars that have refractive indices higher than the microcline and in several determinations the optical sign was both positive and negative. The extinction angle measured $\perp Z$ $(X \wedge 001)$ 13°, An15, the plagioclase is albite-oligoclase. Some of the feldspars are zoned and the centers are altered to clinozoisite, epidote, and sericite.

Myrmekite is present as an intergrowth of quartz and feldspar. Kranck, (1951 - Lecture notes), says the formation of myrmekite can be traced through three stages: quartz replacing feldspar; formation of microcline; late stage of albitization. This alteration may be responsible for the microcline and for the albite formed in these conclusions.

The mineralogical composition of the inclusions and the fact that the granular quartz shows a slightly preferred orientation seem to indicate that the inclusions may have originated from a granite gneiss.

Norite

Thin sections examined from various locations within the main eruptive sheet form a good basis for comparison with the rock types found in the Copper Cliff offset. In hand specimens the norite of the main intrusive is dark grey, and is coarse to medium grained. In it feldspars are visible, coarse biotite may also be apparent, and commonly, there are eyes of blue quartz. The main differences between the rock from the north side and that from the south area are both darkening of the feldspar and greater deformation in the latter. In altered phases the norite may be grey or green. Petrographically the rock may be classified according to alteration and textural differences.

A section from the Ministic Lake area showed a minimum amount of alteration. The mineral composition is as follows:

Plagioclase feldspar	49 per cent
Pyroxene	28 per cent
Amphibole	10 per cent
Quartz	11 per cent
Apatite	.4 per cent
Opaque oxides (Ilmenite Magnetite)	1.5 per cent
Minor amounts of: (Pyrite Pyrrhotite)	

Mineralogy: There are two varieties of pyroxene, one variety is hypersthene with the following properties: biaxial positive; $2V = 60^{\circ}$; faintly pleochroic; crystals stubby; parallel extinction.

The other pyroxene is diallage and is much more abundant than hypersthene. It is biaxial positive; 2V approximately 60°; $Z \wedge c$ maximum $= 40^{\circ}$; colourless under plane light. The optical angle is not diagnostic but the extinction $Z \wedge c$ furnishes fair criteria. For the most part the crystals are subhedral.

The amphibole is found as a reaction-rim around pyroxene crystals. It is impossible to make more definite determinations than that it is green and strongly pleochroic but it is highly probable that the amphibole is a uralitic green hornblende altering after pyroxene.

The quartz is partly interstitial and partly intergrown with feldspar in a granophyric intergrowth which is almost always found radiating from a well-defined crystal of plagioclase.

The plagioclase feldspar is consistently zoned (Plate 6, Fig. 1), and the composition in the core, determined by measuring the extinction angle $\perp Z$ $(X \wedge 010) = -23^{\circ}$ An46, is andesine; the composition in the rim, determined by measuring the extinction angle $\perp Z$ $(X \wedge 010) = -4^{\circ}$, An26, is oligoclase. The maximum extinction angle measured on combined Carlsbad-albite twinning gives a composition An50 - this is on the andesine labradorite border.

In this rock type the feldspars are beginning to lose their subhedral form and there is evidence of alteration to epidote, clinozoisite, and sericite in the more basic centers of the zoned feldspars. Under plane light the feldspars appear to be slightly cloudy as in the quartz gabbro and quartz diorite of the Copper Cliff offset.

A section from near the Little Stobie mine shows a maximum amount of alteration. The principal minerals observed in the section are :

Plagioclase feldspar	48.9 per cent
amphibole	25.0 per cent

	Pyroxene core	6.1 per cent
	Biotite	10.3 per cent
	Quartz	8.0 per cent
Accessories are:	Apatite	.5 per cent
	Ilmenite Magnetite	1.3 per cent
	Minor traces of pyrrhotite, chalcopyrite.	

Because of alteration the pyroxene in this slide is undeterminable. It exists as cores which have the diagnostic schiller structure of hypersthene (Plate 6, Fig.2).

The amphibole is recognized as being of two types, green hornblende and actinolite. The green hornblende has the following properties: optically negative; $2V = 60^{\circ}$, strongly pleochroic with absorption Z brown green Y pale green X pale, bluish green; maximum extinction $Z \wedge c = 25^{\circ}$, good prismatic cleavage. The actinolite differs from the green hornblende by the following properties: less pleochroic, extinction angle $Z \wedge c$ maximum $= 20^{\circ}$; associated with shreddy brown biotite.

The biotite is the brown variety, it shows pleochroism, and pleochroic halos are evident in some of the flakes.

The plagioclase feldspar appears relatively unaltered. The feldspar was determined by measuring extinction angles on Carlsbad-albite twinning, the average composition was here An48, this is andesine. On a measurement of extinction angle measured $\perp$ X ($Z \wedge 001$) $= -34^{\circ}$ - An47 this is andesine. The feldspars which occur as subhedral laths are broad and stubby. The quartz where interstitial is seen to embay and corrode feldspar. Little granophyre is present. There is some evidence of alteration in the centers of zoned feldspar crystals and along the intersection of twinning and cleavage planes in other crystals. This alteration is to epidote, clinozoisite, sericite, and calcite. Here, as in slides from the Copper Cliff offset, the feldspars show a dusty brown colour under plane light.

Texture

The common texture is "hypidiomorphic granular", in which anhedral grains of amphibole, biotite, quartz, and chlorite are found within a network of subhedral plagioclase laths. Where fresh pyroxenes are present the texture may in places be called subophitic.

Order of Crystallization

In some sections from the main intrusive the feldspars appear to have crystallized first but in several other sections the pyroxenes appear to have crystallized first. The quartz as interstitial filling and as intergrowth with feldspar in granophyric texture has the appearance of being formed by late magmatic processes. The oxides were probably formed early in crystallization of the magma although some may be of a secondary nature due to hydrothermal alteration. Amphibole is seen to alter from pyroxene.

Alteration

The rock examined from the main eruptive as well as the rock examined from the quartz gabbro and quartz diorite of the Copper Cliff offset, generally show a similar order of susceptibility to alteration. In some sections from the norite there is evidence of uralitic green hornblende forming at the expense of the pyroxene. The biotite, when present in such sections is primary rather than deuteric.

In sections from the south range for example, Little Stobie Mine area, and Murray Mine area, the pyroxene is altered to green hornblende. This alteration usually begins at the outer margin of the crystal, works inward, and replaces everything. The green hornblende is altered to a more or less fibrous blue-green amphibole which is actinolite. This alteration is similar to that in the quartz gabbro of the Copper Cliff offset. There is not as much shreddy biotite in this rock as in the offset rocks, but flaky biotite is unique. However there is some evidence to indicate progressive alteration from pyroxene to hornblende to actinolite to biotite, as in the offset rocks.

In the slides from the norite mass alteration of the feldspar proceeds more or less independently of the pyroxene alteration. In some sections there is slightly altered diallage and hypersthene and the feldspar is beginning to lose its subhedral character. In other sections the feldspar is only slightly altered to epidote, clinozoisite, and sericite, while the pyroxene forms only cores in amphibole, and in places there is only secondary amphibole. In rock of the southern part of the main eruptive there is very good evidence of secondary alteration products forming vein-like stringers which cut the feldspars along fractures.

Probably the different intensities of alteration and varying freshness of the rock are due to differences in the amount of shearing or crushing which allowed hydrothermal solutions to circulate more freely in some parts than in others.

Worthington Offset

The Worthington offset extends from lot 3, concession 1, Drury township, in a northeasterly direction to the center of lot 9, concession 4; Denison township, a distance of approximately five miles.

Two sections from the dyke were examined. The rock from this offset is of the quartz-diorite type previously described. Both Knight, (1923), and Coleman, (1905, P. 114), have remarked on the large proportion of fragments of greenstone and sediments included in the dyke rock. The minerals observed in these sections are:

	Amphibole	30 per cent
	Biotite	7 per cent
	Plagioclase	45 per cent
	Quartz	13 per cent
The accessories are:	Ilmenite Magnetite	2.5 per cent
	Apatite	.5 per cent
	Sulfides	.2 per cent

The amphibole in the sections from this dyke have the same characteristics as the amphiboles observed in the sections from the Copper Cliff offset. Two varieties of amphibole are present, green-hornblende and actinolite. There is a gradational change between the two as indicated by an increase in extinction angle measured $Z \wedge c$ maximum 18° to maximum 25°, and a change in pleochroism and absorption Z Y X; blue-green, light green, pale green changes to deeper bluish green, green, pale bluish green.

The biotite is the dark brown variety, and is flaky but when associated with the amphibole it is shreddy. In both sections examined some of the biotite flakes show pleochroic halos and have bleached edges.

Quartz may be either interstitial to the other minerals or may radiate from a well-defined crystal of plagioclase as an intergrowth of quartz and feldspar.

The plagioclase feldspars are long, slender laths with some evidence of zoning and are more clouded than the feldspars in the Copper Cliff offset. In checks made on Carlsbad-albite twinning the extinction angles gave an average of An43 - andesine. Extinction angle measured $\perp Z$ $(X \wedge 010) = -20^{\circ}$, An42 - this is andesine. The refractive indices are greater than Canada balsam. Polysynthetic twinning in the feldspar is either not well developed or has been obliterated by alteration. The feldspar in many places has started to alter to saussurite. The plagioclase, when viewed under white light, exhibits a clouding more or less confined to the central part of the zoned crystals, which may be due to alteration.

The order of crystallization, the texture, and alteration in the rock from this dyke are comparable to the quartz diorite of the Copper Cliff offset. There is evidence of a progressive alteration from amphibole to biotite probably due to hydrothermal alteration (Plate 7, Fig. 1).

Foy Offset

This dyke lies north of the Sudbury basin. Its contents, unlike the other dykes, consist of a breccia of older rocks cemented together by the offset igneous rock. Two sections from this dyke show the rock to be a quartz diorite. The minerals are:

amphibole	25	per cent
biotite	8	per cent
plagioclase	50	per cent
quartz	14	per cent

Accessories are:

apatite	0.5	per cent
ilmenite magnetite	2.5	per cent
sulfides -	trace	

The amphiboles have the same characteristics as the amphiboles observed in sections of quartz diorite from the Copper Cliff and Worthington offsets. The biotite is the dark brown variety and may be flaky or shreddy. When flaky the biotite sometimes shows pleochroic halos and bleached edges, and when shreddy, the biotite is associated with the amphibole. Quartz is interstitial to other minerals and an intergrowth of quartz and feldspar is often found radiating from a crystal of plagioclase. The plagioclase feldspar is finer than in the other dyke rocks. Because of its cloudy and dark appearance, determinations are very difficult. Some zoning can be distinguished and there is evidence of saussuritization. Extinction angles measured $\perp Z$ $(X \wedge 010) = -20^{\circ}$, An42 $\perp X$ $(Z \wedge 001) = -20^{\circ}$, An46. The refractive indices are greater than Canada balsam average An44, this is andesine. The accessories include apatite, opaque oxides, and a trace of sulfides.

As the texture in these sections is obliterated by alteration it is impossible to determine the order of crystallization of the minerals (Plate 7, Fig.2). The feldspar is altered to saussurite, and, when viewed under white light, the dusty cloudiness that was present in the main irruptive, (Copper Cliff and Worthington offsets) seems to be replaced by a dark, felt-like cloudiness which could possibly be due to kaolinization of the feldspars.

Contact Greenstone

South of number one mine on the west side of the dyke, the greenstone is dark grey, almost black in colour, faintly glistening, schistose rock. A thin section cut from a specimen taken near the contact with the Copper Cliff offset shows the rock to be a fine-grained aggregate of pale brown biotite with a smaller amount of plagioclase. The rock contains frequent disseminations of opaque oxides and, in addition to plagioclase, contains a considerable amount of quartz, both granular and as an intergrowth with feldspar.

Creighton Granite

The bulk of the granite is a porphyritic rock characterised by square phenocrysts of potash feldspar of diameter up to an inch or more and in a pink or grey, granitic matrix. Along the contact between the Creighton granite and the Copper Cliff offset, the granite tends to have a gneissic texture (Plate 9, Fig. 3). A section cut from a specimen taken on this contact just north of Lady MacDonald Lake shows the following characteristics:

The minerals are:	Microcline Perthite Albite	70 - 65 per cent
	Quartz	25 - 30 per cent
Accessories are:	Biotite Epidote	5 - 8 per cent

The texture of this rock is fine-grained-granular and is of a gneissic texture which is indicated by a preferred orientation of minerals (Plate 8, Fig. 1). Although no marked contact metamorphism is found in either the dyke rock or the granite, yet the quartz diorite has an alignment of mineral grains. This could be the result of shearing of the dyke rock, or it may be evidence of flow.

Murray Granite (Lady Violet)

The Murray granite is a pink, medium-to-fine-grained rock. Burrows and Rickaby, (1934, P. 32), Coleman, (1905, P. 124), Phemister, (1925, P.29), all agree that this granite is younger than the dyke rock but that metamorphism produced by these rocks is slight.

In two thin sections examined, the granite is seen to consist of:

Essential:	Perthite Microcline Oligoclase-albite Orthoclase	70 per cent
	Quartz	25 per cent
	Biotite	3 per cent
Accessories:	Chlorite Opaques Apatite Epidote	2 per cent

One section was cut from a specimen taken near Murray mine and another was cut from a specimen taken from a dyke found cutting the Sudbury intrusive.

The microcline shows characteristic cross-hatching and the perthite is seen to be microperthite (Plate 8, Fig. 3). The plagioclase was determined by measuring extinction angle $\perp Z$ $(X \wedge 001) = 14^{\circ}$ - An10, the plagioclase is albite-oligoclase. The orthoclase is biaxial negative with $2V = 65^{\circ}$, and Ny, Nz both less than Canada balsam.

A specimen of granite was taken from an outcrop found within the Copper Cliff offset just north of number 2 mine. The writer is unable to determine whether the outcrop is or is not a dyke cutting the quartz diorite.

Megascopically the granite has a greyish, pink colour and is medium-to-fine-grained with a typical granitic texture. Microscopically the rock is seen to have an allotriomorphic, granular, medium-to-fine-grained texture. The minerals present in this section are:

Orthoclase Albite-Oligoclase Microcline	65 per cent
Quartz	28 per cent
Biotite Chlorite (penninite)	5 per cent
Epidote Apatite Myrmekite	2 per cent

The quartz in this section is strained. There is no proof to show that this outcrop is of either Murray or Creighton granite age. The mineralogical composition is not distinctive.

Rosiwal Analysis of Copper Cliff Offset

Minerals	Assumed S.G.	Calculated Mass (per cent) I	II	III	IV	V	VI
Amphibole	3.1-3.3	30.1	19.2	27.7	30.4	27.5	23.1
Biotite	2.9-3.1	10.9	13.5	13.0	10.5	11.3	14.4
Plagioclase	2.67	50.4	55.0	44.4	42.2	49.2	46.1
Quartz	2.65	7.0	6.1	12.0	12.1	11.9	12.7
Granophyre	2.6	Trace	2.8	.5	2.6	-	Trace
Opaque oxides	5.0-5.1	1.4	2.5	1.0	1.6	1.2	2.0
Apatite	3.2	.5	.4	.5	.3	.2	1.0
Sulfides	4.5	.2	.2	.2	.2	Trace	.4
TOTAL		100.5	99.7	99.3	99.9	101.3	99.7
Specific Gravity		2.83	2.87	2.85	2.80	2.79	2.81

Specific Gravity determinations made by means of beam balance.

I SP No.74 Suite No. 9
Maximum grain size
Mafic 1.5 mm x 1 mm
Feld 1.5 mm x .75 mm
7 runs spaced 2 mm apart
Total length of traverse = 135 mm

II SP No.58 Evans Mine
Maximum grain size
Mafic 1 mm x .5 mm
Feld 1 mm x .5 mm
8 runs spaced 1 mm apart
Total length of traverse = 100 mm

III SP No. 5 Suite No. 1
Maximum grain size
Mafic 1.5mm x .75 mm
Feld 1 mm x .75 mm
7 runs spaced 1 mm apart
Total length of traverse = 100 mm

IV SP No.56 Suite No. 6
Maximum grain size
Mafic 1 mm x .5 mm
Feld
8 runs spaced 1 mm apart
Total length of traverse = 110 mm

V SP No.71 Suite No. 9
Maximum grain size
Mafic 1.5 mm x 1 mm
Feld 1.5 mm x .75 mm
7 runs spaced 2 mm apart
Total length of traverse = 150 mm

VI SP No.40 Suite No. 4
Maximum grain size
Mafic 2.25mm x 1.5mm
Feld 1.75mm x 1 mm
6 runs spaced 2 mm apart
Total length of traverse = 180 mm

Rosiwal Analysis of Main Irruptive

Minerals	Assumed S.G.	% No.1	Minerals	Assumed S.G.	% No.2
Amphibole and Pyroxene core	3.1-3.3	31.2	Diallage	3.2	21.2
Biotite	2.9-3.1	10.3	Orthopyroxene	3.2	7.2
Plagioclase	2.67	48.89	Amphibole	3.1-3.3	10.0
Quartz	2.65	8.0	Plagioclase	2.65	48.7
Granophyre	2.60	.65	Quartz	2.65	9.1
Opaque Oxides	5.0-5.1	1.3	Granophyre	2.6	2.0
Apatite	3.2	.1	Opaque Oxides	5.0-5.1	1.5
Sulfides	4.5	.1	Apatite	3.2	.4
TOTAL		100.54			100.1

SP No. 1 - From area of Little Stobie Mine
Maximum grain size 2 mm x .5 mm
6 runs spaced 2 mm apart
Total length of traverse = 175 mm

SP No. 2 - From Ministic Lake Area
Maximum grain size 1.5 mm x 1 mm
7 runs spaced 1.5 mm apart
Total length of traverse 160 mm

Rosiwal Analysis of Foy and Worthington Offsets

Minerals	Assumed S.G.	I %	II %
Amphibole	3.1-3.3	32.2	27.4
Biotite	2.9-3.1	7.4	9.6
Plagioclase	2.67	42.6	42.7
Quartz	2.65	10.2	12.7
Grenophyre	2.60	3.0	4.0
Opaque Oxides	5.0-5.1	2.7	2.5
Apatite	3.2	.5	.4
Sulfides	4.5	.3	.2
TOTAL		99.9	99.5

SP No. 1 Worthington Offset
Maximum grain size 1 mm x .5 mm
7 runs spaced 1 mm apart
Total length of traverse .98 mm

SP No. 2 Foy Offset
Maximum grain size - Mafic .75 mm x .25 mm
Feld .2 mm x .5 mm
7 runs spaced 1.5 mm apart
Total length of traverse 120 mm

Sample Calculation

Chemical Analysis

Little Stobie Mine - Specimen

	Density		% Vol.		Specimen	% wt.
Amphibole plus Pyroxene core	3.3	x	31.2	=	102.9	37.7
Biotite	3.1	x	10.3	=	30.9	10.5
Plagioclase	2.68	x	48.89	=	132.0	44.8
Quartz	2.65	x	8.0	=	21.2	7.2
Ilmenite	5.0	x)	1.35	=	3.25	1.1
Magnetite	5.1	)		=	3.3	1.1
Apatite	3.2	x	2.1	=	.32	.1
Sulfides	4.5	x	.1	=	-	
TOTAL			100.54		293.87	102.5

	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	P_2O_5	Na_2O	K_2O	H_2O	TiO_2
Amphibole	17.2	3.65	.52	3.8	4.58	3.72		.54	.08	.13	
Albite	15.4	4.35						2.64			
Anorthite	9.7	8.22			4.50						
Biotite	3.76	1.64	.53	1.47	.05	1.23		.36		.37	.27
Quartz	7.2										
Ilmenite				.72							.57
Magnetite			.76	.42							
Apatite							.04				
	55.06	17.86	1.81	6.01	9.19	4.95	.04	3.54	.08	.50	.84

TOTAL = 99.88

Amphibole	Al_2O_3, 9.7; FeO; MgO; CaO; H_2O, 1.33; Na_2O; SiO_2; Fe_2O_3, 5.65; K_2O, .85
Albite	$Na\ Al\ Si_3O_8$
Anorthite	$Ca\ Al_2\ Si_2O_8$
Biotite	(Average) K_2O, 8.83; MgO; FeO; Al_2O_3; TiO_2, 2.6; Na_2O, 3.4; H_2O, 3.5; SiO_2; CaO, .45; Fe_2O_3, 5.04
Quartz	
Ilmenite	$FeO\ TiO_2$
Magnetite	Fe_3O_4
Apatite	$(CaF)Ca_4\ (Po_4)_3$

Chemical Analysis

	I	II	III	IV	V	VI
SiO_2	56.90	55.41	55.06	57.01	55.60	54.61
Al_2O_3	16.57	19.90	17.86	16.86	15.79	15.60
Fe_2O_3	1.25	.75	1.81	2.02	2.10	3.55
FeO	5.46	5.07	6.01	6.86	6.28	6.54
CaO	6.14	6.31	9.19	5.02	8.11	8.82
MgO	3.83	4.27	4.95	5.94	4.80	4.64
Na_2O	4.19	4.08	3.54	6.24	3.63	3.09
K_2O	1.73	1.24	.08	.1	.85	.96
H_2O	1.68	.78	.50	.15	.77	1.74
TiO_2	.80	.93	.84	.58	1.14	1.51
P_2O_5	.42	.48	.04	.42	.17	.21
TOTAL	98.97	98.12	99.88	101.60	98.24	100.27

I SP# Suite #9

II SP# Evans Mine

III Near little Stobie Mine

IV Ministic lake.

V Foy offset

VI Worthington offset

A brief description of a Quartz-diorite from Zeballos Mine for comparison purposes.

Here the average quartz-diorite is a speckled black and white massive rock with conspicuous jointing. It has an even medium-grained texture and consists mainly of quartz, oligoclase, andesine, feldspar, and biotite. The texture is primary and does not show any sign of granulation or recrystallization.

Chemical analysis of quartz-diorite from the central Zeballos and Prident Mines indicate that it is a normal quartz-diorite - (J. S. Stevenson 1950 P. 32).

	I	II	III
SiO_2	65.10	67.56	65.12
Al_2O_3	14.91	15.51	16.18
Fe_2O_3	0.79	0.40	0.33
FeO	4.09	2.70	2.19
MgO	2.42	2.42	0.71
CaO	5.14	3.16	3.99
Na_2O	3.64	3.62	0.15
K_2O	1.01	2.20	4.94
H_2O-	0.06	0.18	0.26
H_2O	1.14	1.20	2.14
TiO_2	0.58	0.52	0.50
P_2O_5	0.19	0.11	0.14
MnO	0.09	0.05	0.07
FeS_2	0.40		
BaO	0.07		
CO_2	0.13		

This quartz diorite from Zeballos mine area B.C. differs decidely in texture and mineralogical constituents from the quartz diorite of the Copper Cliff offset. The texture of this quartz diorite is primary, whereas the texture of the Copper Cliff offset has been effected by alteration. Moreover the quartz diorite from Zeballos area has only biotite as a mafic constituent while the quartz diorite from the Copper Cliff offset has amphibole, biotite, and traces of pyroxene.

Comparison of chemical analysis of these two rocks shows a decided difference in composition: the quartz diorite from Zeballos is much higher in SiO_2 and decidely lower in Fe_2O_3, FeO, MgO, and CaO. Na_2O and K_2O are about the same.

From these results one can conclude that the quartz diorite of the Copper Cliff offset is much more basic than that from Zeballos mine area, and that it was much more basic even before alteration affected the offset rock. The Zeballos quartz diorite had a parent granitic magma consequently the writer is of the opinion that the quartz diorite of the Copper Cliff offset resulted from a much more basic magma.

PETROGENESIS

This petrographic study of the Copper Cliff offset and the main norite mass indicates that both are variable in composition. The sections from the main intrusive show considerable variation within the rock type, from norite to a dioritic quartz gabbro. The sections from the Copper Cliff offset show a core of quartz gabbro which is slightly more basic than the rest of the dyke rock and which grades to a quartz diorite, which is comparable to the quartz diorite of the Worthington and Foy offsets.

The Effects of Assimilation

The rock of the Copper Cliff offset contains sedimentary and greenstone inclusions which show evidence of having been attacked by the magma.

If the norite were the initial magma and the quartz gabbro and the quartz diorite contaminated rocks derived from this magma, then a chemical analysis should show the following variations: an increase of silica and aluminum in the contaminated magma and in the majority of cases an increase in potassium; a decrease in lime and magnesia. The chemical analysis indicated that these variations might occur in a selection of two specific examples, whereas the analysis, as a whole, did not conform to this pattern but showed the composition of the rock to be fairly constant.

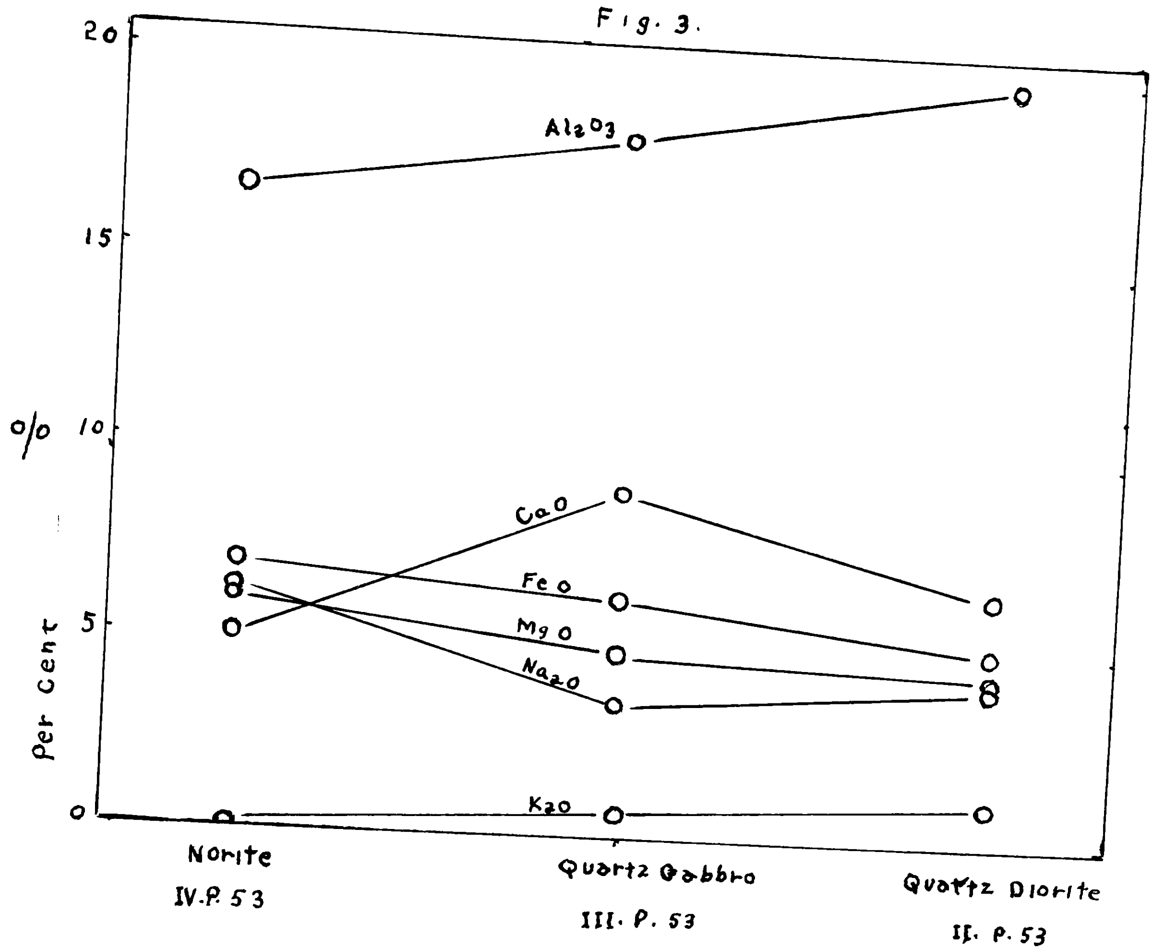
The presence of much amphibole and biotite indicates a considerable water content. The fact that the wall rocks contain water does not justify any assumption that much water was driven from them into the magma. The well known fact, that many magmas give off hydrous emanations, makes it seem unlikely that a wall rock which receives water from a magma, should contribute water to the magma. Although little, if any, water passed into the magma from the contact zone, xenoliths present in the intrusive indicate that other xenoliths were assimilated into the magma and did add water to it.

The average igneous rock contains about 1.15 % H_2O. Acid rock magmas may contain up to 10 % H_2O . By taking the composition for average norite and making successive additions of sedimentary and flow rock with the mean composition of the country rock in the area, we find that the mixture seems normal until the additions amount to about 20 per cent.

If 20 per cent of the present rock is derived from sediments and greenstone that contained 4 % H_2O, the magma from this mixture would contain about 20 % of 4 %, or .8 % of resurgent water. Thus, from the most liberal allowance for assimilation and for connate water driven by gas pressure into the magma from the walls, the total water added to the magma will be scarcely 1 % of the magma. In comparison with the 4 % H_2O which probably was in the primary magma and of which over 1 % remains in the rock, the addition of connate water from the sedimentary rock must have been of little importance.

In considering the possibilities that the norite, quartz gabbro, and quartz diorite may be related as crystal differentiates, we may attempt to show the nature of the material that must have been subtracted from the norite to give quartz gabbro and quartz diorite. The writer has plotted the composition of the rocks as in an ordinary variation diagram and produced the straight lines indicating the change of each oxide in a direction away from the quartz diorite.

Fig. 3.



The foregoing has been a discussion of the petrogenesis of the Sudbury intrusive, showing how the rock of the Copper Cliff offset could well be a result of fractional crystallization or assimilation. The writer thinks this assimilation may be treated as a part of fractional crystallization and as governed by the same general laws. Some of the inclusions described on (P. 35) have the appearance of being pseudomorphous after staurolite but there is no evidence for assimilation comparable to that found in Aberdeenshire,(Read, 1923, pp. 446-486).

From field study it would appear that the Copper Cliff offset filled a trough-like structure, which had formed with a northerly plunge, in the country rock before the intrusion of the magma and which subsequently was eroded to a near horizontal surface as found to-day. When the magma of noritic composition became confined within the trough, crystallization took place more rapidly there than in the main body of the intrusive due to closer contact with the cold country rock.

The feldspars in the southern end of the Copper Cliff offset do not show such marked zoning as elsewhere in the funnel of the offset and in the main irruptive. The feldspar in the norite is albite rich labradorite and zoned crystals have rims of oligoclase composition. The feldspar in the quartz gabbro core of the Copper Cliff offset is the same, in the remainder of the dyke the feldspar is andesine which also has rims of oligoclase composition in zoned crystals. Within the main irruptive, especially in the southern range there is rock that can be termed dioritic quartz gabbro rather than norite. The difference in feldspar composition is not great enough to rule out the hypothesis that the offset is an apophysis of the main norite intrusive.

Further evidence in favour of the hypothesis that the dyke is the same age as the intrusive is found in comparing the chemical compositions of the offset rock with rock from the main irruptive. In the case of each constituent the range for the offset rock overlaps the range for the norite, sometimes on one side, sometimes on the other.

The mafic content of the main eruptive and the quartz gabbro core in the offset differs somewhat from the mafic content of the quartz diorite of the offset. There is no evidence of pyroxene cores in the rock south of Lady MacDonald Lake such as there is in specimens taken from the dyke north of Lady MacDonald Lake and the main irruptive. Apart from this the mafic content of altered norite, quartz gabbro, and quartz diorite is the same.

Evidence of movement within the Copper Cliff offset is indicated by: slight brecciation in places; bent feldspar laths; fractured feldspar laths. The offset rock shows evidence of hydrothermal action, during which the previously formed minerals were attacked and replaced by more hydrous silicates which are often fibrous in habit. It is quite likely that the movement indicated released stress within the rock and allowed hydrothermal solutions to circulate throughout the rock.

	Pyroxene	Hornblende	Actinolite	Biotite	Chlorite
NORITE	diallage hypersthene	rim (alteration) around pyroxene	-	minor	-
QUARTZ GABBRO	core of pyroxene in amphibole	green hornblende after pyroxene	lighter-blue green amphibole after hornblende or diallage	some possibly primary, some after amphibole - brown variety	penninite antigonite after amphibole and biotite
QUARTZ DIORITE Copper Cliff Offset (1)	minor amount of pyroxene core in amphibole	"	"	"	"
QUARTZ DIORITE Worthington Offset (2)	-	"	"	"	penninite minor
QUARTZ DIORITE Foy Offset (3)	-	"	"	"	-

	Feldspar	Quartz	Granophyre	Accessories
NORITE	Zoned Labradorite center Andesine oligoclase rim Altered to Saussurite	Interstitial	Intergrowth of Quartz and Feldspar	Opaque oxides Apatite Pyrite Pyrrhotite Chalcopyrite
QUARTZ GABBRO	Labradorite altered to Saussurite	"	"	"
QUARTZ DIORITE (1)	Andesine zoned and altered to Sausserite	"	"	"
QUARTZ DIORITE (2)	Andesine zoned	"	"	"
QUARTZ DIORITE (3)	Andesine zoned	"	"	"

<u>TEXTURE</u>

NORITE	Feldspar losing subhedral form, mafics and quartz subhedral to allatriomorphic. General - hypidiomorphic granular.
QUARTZ GABBRO	Feldspar subhedral, stubby laths. Allatriomorphic, mafics and quartz. General - hypidiomorphic granular.
QUARTZ DIORITE (1)	Feldspar subhedral, stubby to slender laths. Allatriomorphic mafics and quartz. General - hypidiomorphic granular to intersertal
QUARTZ DIORITE (2)	Feldspar subhedral, slender laths. Allatriomorphic mafics and quartz. General - intersertal.
QUARTZ DIORITE (3)	Feldspar subhedral to allatriomorphic laths. Allatriomorphic mafics and quartz. General - intersertal

SUMMARY AND CONCLUSIONS

This thesis presents the results of a field and laboratory study of the Copper Cliff offset. This is a dyke that extends south from the main norite intrusive in the vicinity of Pump Lake for a distance of approximately four miles. The dyke intrudes sediments and flows of Keewatin age, Temiskaming type sediments, and sediments of lower Huronian age. The relationship between the granite intrusives, south of the norite irruptive, and the dyke is not easily solved. Coleman, (1905, P. 124), declared Creighton granite was older than the norite whereas Phemister, (1925, P. 29), claimed Creighton granite was younger than the norite. Inclusions that could be granitic were found in the offset north of Lady MacDonald Lake near the contact between Creighton granite (gneiss) and the dyke rock. Burrows and Rickaby, (1934, P.32), Coleman, (1905, P. 124), Phemister, (1925, P.29), agree that the Murray (Lady Violet) granite is later than the main intrusive.

The tables included in the thesis (pp. 61 - 62), give a summary of the petrographic results obtained in the study and comparison of mineral composition, alteration, and texture in the Copper Cliff offset, the main norite mass, and the Foy and Worthington offsets.

Sections from the main intrusive show two phases of alteration; one in which the pyroxenes remain fresh and the feldspars begin to break down; the second, more common alteration, in which the feldspars maintain their subhedral forms and the pyroxenes alter to hornblende, actinolite, biotite, and in some sections to chlorite. This second type of alteration was found in the Copper Cliff offset but the intensity of alteration of amphibole decreases from the main intrusive to Kelley Lake. The Foy and Worthington offsets compare favourably to the southern end of the Copper Cliff offset (that part south of Lady MacDonald Lake) in mineralogical composition.

The texture of these rock types is variable. The texture of the quartz gabbro core of the Copper Cliff offset compares favourably with the texture of the dioritic quartz gabbro from the south range. The texture ranges from hypidiomorphic granular to sub-ophitic, the feldspars showing subhedral form and the mafics and quartz showing allotriomorphic form for the most part. The texture of the quartz diorite becomes fine-grained granular in the southern part of the dyke and could be termed "intersertal", after Johannsen, (1939, P.47). The texture of the Worthington and Foy offsets is comparable to this sector of the Copper Cliff offset.

Chemical analyses calculated from Rosiwal analyses show that there is no abrupt change in these rock types. The chemical analyses of the quartz diorite overlap that of the main intrusive and the difference between the quartz diorite and the main mass is no greater than the difference obtained within the main irruptive itself.

The specific gravity determined from specimens taken from the Copper Cliff offset,(P.50), indicates little if any change from north to south in the dyke. These determinations compare favourably to those made by Collins, (1934, P. 168).

All of the rock types discussed show evidence of hydrothermal alteration of the feldspar and pyroxene of the original norite to uralitic green hornblende. Further alteration to actinolite, biotite, and at times to chlorite is evident in most sections. The quartz also appears to be of a secondary origin.

The petrogenesis of the Copper Cliff offset has long been a topic of controversy. From the petrographic study and field observations the writer believes that the Copper Cliff offset is an apophysis of the main norite intrusive.

BIBLIOGRAPHY

Barlow, A. E. — Nickel and Copper Deposits of the Sudbury Mining District. Geology of Canada 1904.

Bowen, N. L. — The Evolution of Igneous Rocks, Chapter X., PP. 175-220.

Burrows, A. G. and Rickaby, H. C. — Sudbury Nickel Field Restudied, 43rd Annual Report of the Ontario Department of Mines Vol. XLIII, Part II, 1934.

Cathrein, A. — Gsteine der Halbinsel Chalcidice T.M.P.M. Vol. I, PP. 248 - 249, 1878 (Trans).

Cooke, H.C. — Problems of Sudbury Geology, Ontario G.S.C. Bull. No.3, Printed 1946.

Coleman, A.P. — The Sudbury Nickel Field. Report of the Ontario Bureau of Mines, Vol. XIV, Part III, 1905.

Coleman, A. P. — The Sudbury Nickel Deposits. 12th Report of the Ontario Bureau of Mines, Vol. XII, 1903.

Coleman, A. P. Moore, E. S. and Walker, T. L. — The Sudbury Nickel Intrusive - Toronto University Studies. Geol. Ser. 23-28, 1929.

Collins, W. H. — Life History of the Sudbury Nickel Irruptive Trans. Royal Society, Can. Sect. IV, 3rd series, Vol. XXVIII, 1934.

Daly, R. A. — Igneous Rocks and the Depths of the Earth. Chapter XIII, PP. 287-317, 1933.

Fenner, C. N. — Life History of the Sudbury Nickel Irruptive. Geol. Mag. No. 854 (Vol. 72, No. 8) PP. 381-82, 1935.

Grout, F. F. — Petrography and Petrology. P. 225, 1932.

Harker, A. — The Sudbury Laccolite. Geol. Mag. Vol. 63, P. 162, 1926.

Henderson, E. P. — Pyroxmangite from Idaho. Bull. Geol. Soc. America. Vol. 46. PP. 65-67, 1935.

Howe, E. — Petrographical notes on the Sudbury Nickel Deposits. Ec. Geol. Vol. 9. PP. 505-522, 1914.

Johannsen, A. — A Descriptive Petrography of the Igneous Rocks. Vol. 1, P. 47, 1939.

Knight, C. W. — The Chemical Composition of the Norite - Micropegmatite Sudbury, Ontario. Ec. Geol. Vol. 18, No. 6. P. 592-594, 1923.

Lehmann, J. — Untersuchungen Uber die Entstehung der Altkrystallensohen Schiefergesteine Bonn. PP. 197-198, 1884. (Trans.)

MacGregor, A. G. — Clouded Feldspars and Thermal Metamorphism - Mineral Mag. Vol. 22, PP. 524-538, 1931.

Phemister, T. C. — Igneous Rocks of Sudbury and their relation to ore deposits, 34th annual report of the Ontario Department of Mines, Vol. XXXIV, Part VIII, 1925.

Phemister, T. C. — Evidence of Assimilation and Assimilation Processes. Jour. Geol., Vol. 34, No. 7. PP. 653-656, 1926.

Read, H. H. — The Petrology of the Arnage District in Aberdeenshire. Quart. Jour. Geol. Soc., 79 Pt. 4. PP. 446-486, 1923.

Reynolds, D. L. — The Two Monzonitic Series of the Newry Complex. Geol. Mag. 73. PP. 341-342, 1936.

Shand, S. J. — Eruptive Rocks, Chapter VII, PP. 105-116, 1949.

Stevenson, J. S. — Geology and Mineral Deposits Zeballos Mining Camp B.C. Bull., No. 27, 1950.

Vogt, J. H. L. — The Physical Chemistry of the crystallization and magmatic differentiation of Igneous rocks, Jour. Geol., Vol. 24, P. 329, 1921.

Williams, — The Greenstone schists of the Marquette Region of Michigan. U.S.G.S. Bull. 62, PP. 58-60.

Yates, A. B. — The Sudbury Intrusive. Trans-Royal Society of Canada, 3rd series, Sect. IV, Vol. XXXM, 1938.

Yates, A. B. — Properties of International Nickel Co. of Canada. Structural Geology. C.I.M.M. Symposium, 1948.

PLATE NO. 1

Fig. 1 Quartz gabbro from suite # 9. Shows an antigorite crystal enclosed in a biotite flake, and in the upper left hand corner of the picture is a crystal of plagioclase showing evidence of alteration to clinozoisite, epidote, sericite.
Crossed nicols (X50)

Fig. 2 The same under plane light. Note the swollen appearance of the antigorite and the pleochroic halos in the biotite (X50)

Plate 1

Fig. 1.

Fig. 2.

PLATE NO. 2

Fig. 1 Quartz-gabbro from suite # 9. Shows pyroxene (hypersthene) with schiller-like structure altered to green hornblende around the edges. Note the small prismatic crystals of apatite in this Figure. Plane light (X50)

Fig. 2 Quartz gabbro suite # 4. Shows hypidiomorphic texture, subhedral feldspar laths, allotriomorphic mafics, and interstitial quartz. In the lower right hand corner of the picture is a feldspar crystal that shows evidence of alteration along a fracture. Crossed nicols (X50)

Plate 2

Fig. 1.

Fig. 2.

PLATE NO. 3

Fig. 1 Quartz diorite from suite # 9, shows a core of pyroxene with schiller-like structure, in an amphibole crystal. Plane light (X50)

Fig. 2 Quartz diorite from suite # 4, shows an amphibole crystal that is partly altered to chlorite. Note the broad well twinned crystals of plagioclase feldspar. Here the subhedral feldspars and allotriomorphic mafics, with interstitial quartz give the rock a hypidiomorphic texture. Crossed nicols (X50)

Plate 3

Fig. 1.

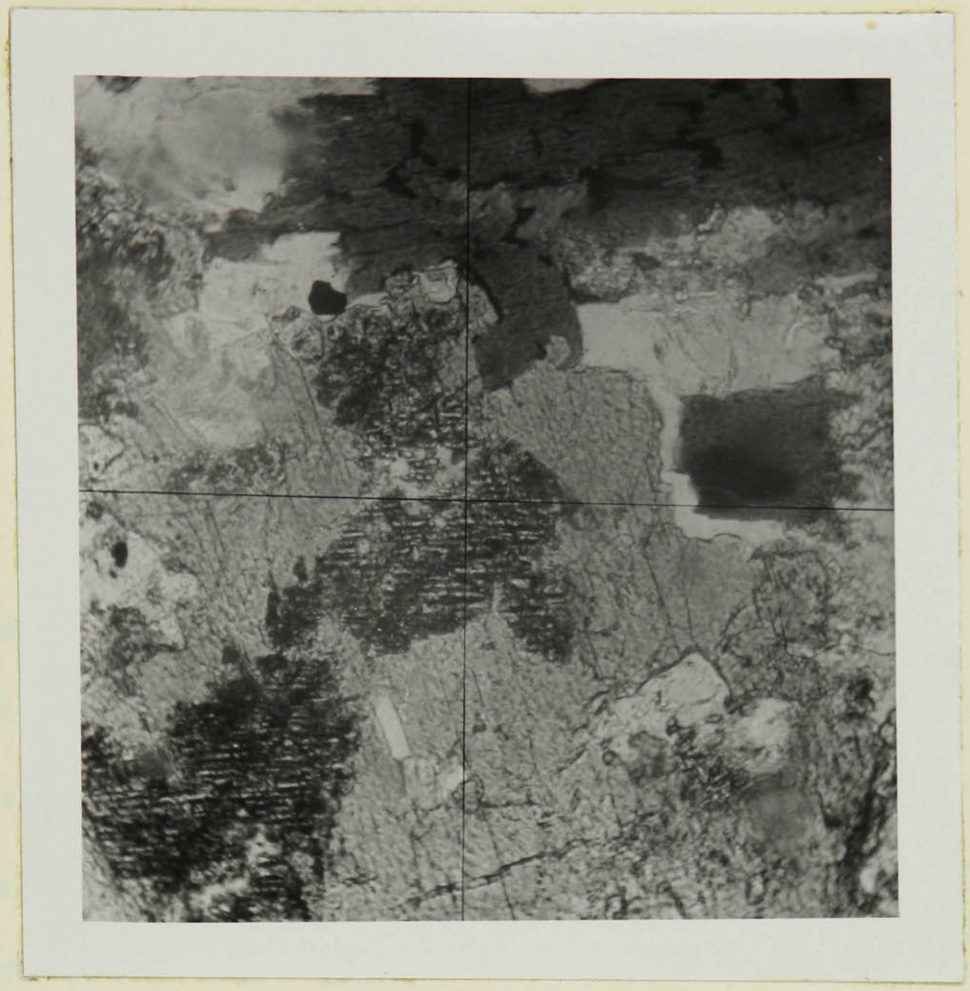


Fig. 2.

PLATE NO. 4

Fig. 1 Quartz diorite from Evans Mine section, shows an intergrowth of quartz and feldspar radiating from a well formed plagioclase crystal.
Crossed nicols (X50)

Fig. 2 Quartz diorite from suite # 4, shows good hypidiomorphic texture. Note the alteration of the feldspar lath to clinozoisite, epidote, and sericite.
Crossed nicols (X50)

Plate 4

Fig. 1.

Fig. 2.

PLATE NO. 5

Fig. 1 Sedimentary inclusion from the Copper Cliff offset in the vicinity of specimen # 19, just north of suite # 2. Shows evidence of recrystallization. Note the feldsparth crystals showing good twinning.

Crossed nicols (X50)

Fig. 2 Feldspathic inclusion from the offset found near west contact suite # 2, shows evidence of recrystallization. In the upper left hand corner is the contact between this inclusion and quartz diorite.

Crossed nicols. (X25)

Plate 5

Fig. 1.

Fig. 2.

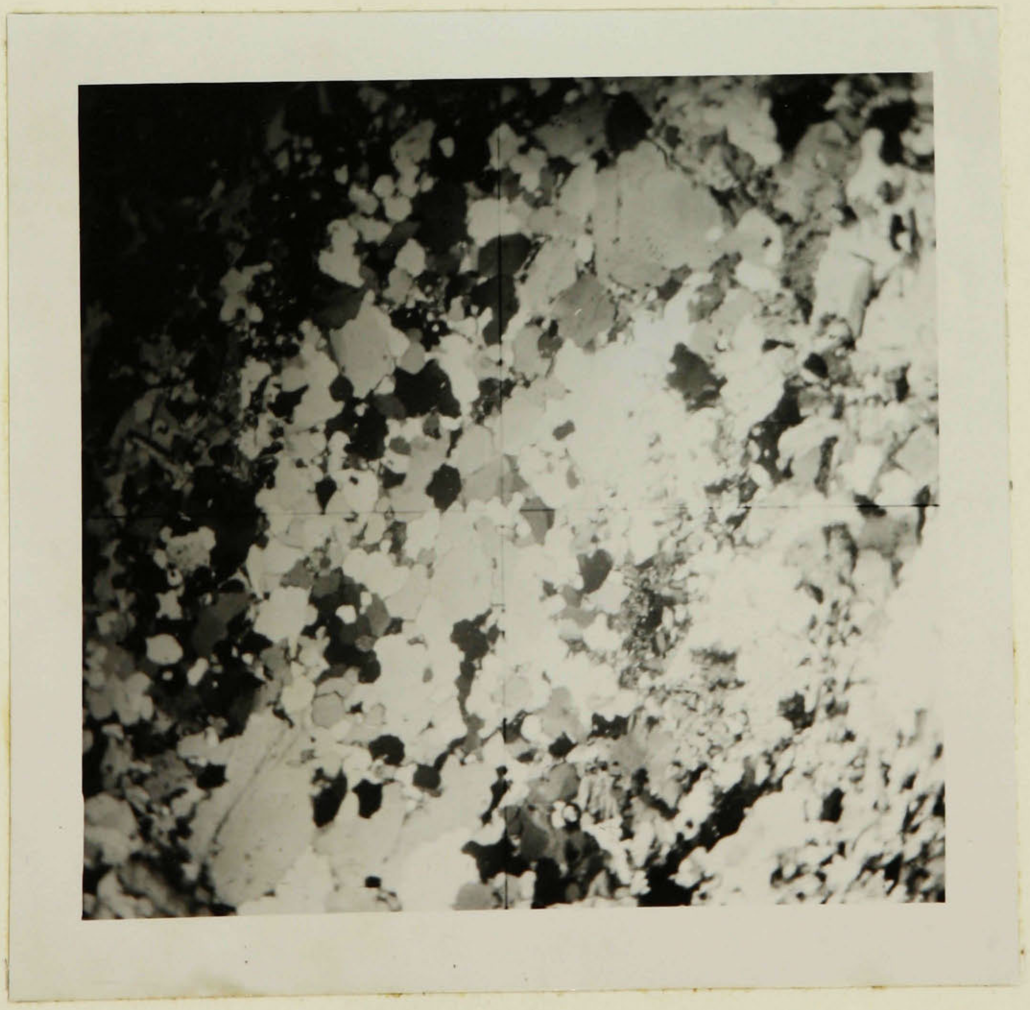


PLATE NO. 6

Fig. 1 Norite from Ministic Lake area, shows zoned feldspars that have in part lost their sub-hedral form. The texture is hypidiomorphic to subophitic.
Crossed nicols (X30)

Fig. 2 Dioritic quartz gabbro from near Little Stobie Mine, shows hypidiomorphic to subophitic texture and in the center is a crystal showing alteration of pyroxene to green hornblende. In the bottom left hand corner is a crystal with vein matter of a secondary nature filling a fracture in it.
Crossed nicols (X50)

Plate 6

Fig. 1.

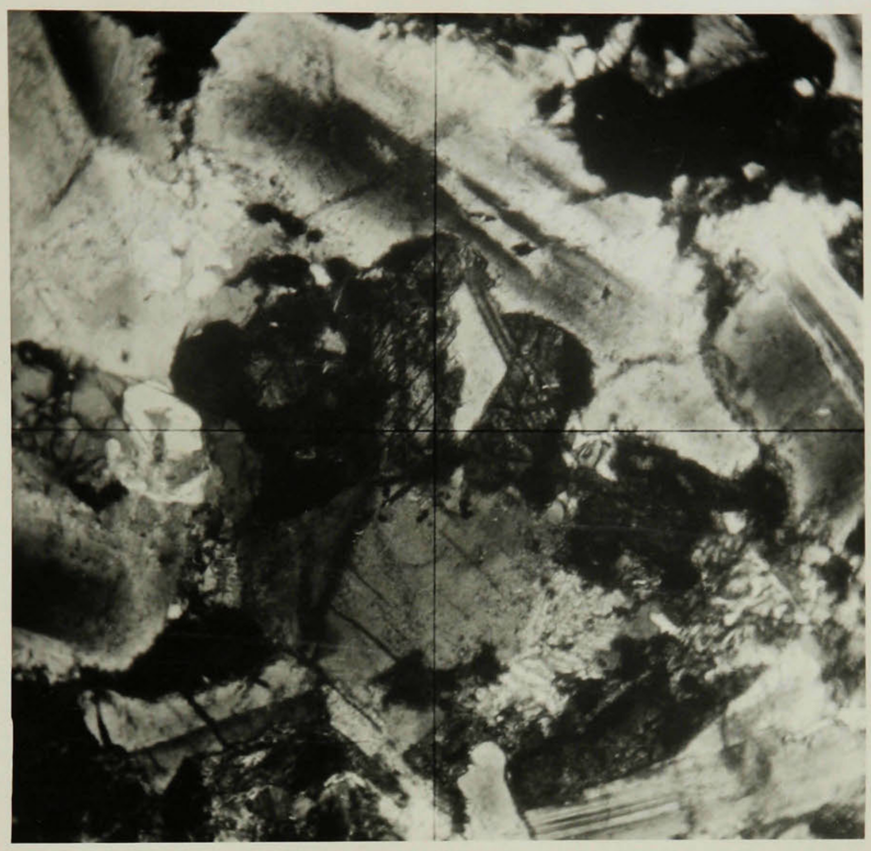


Fig. 2.

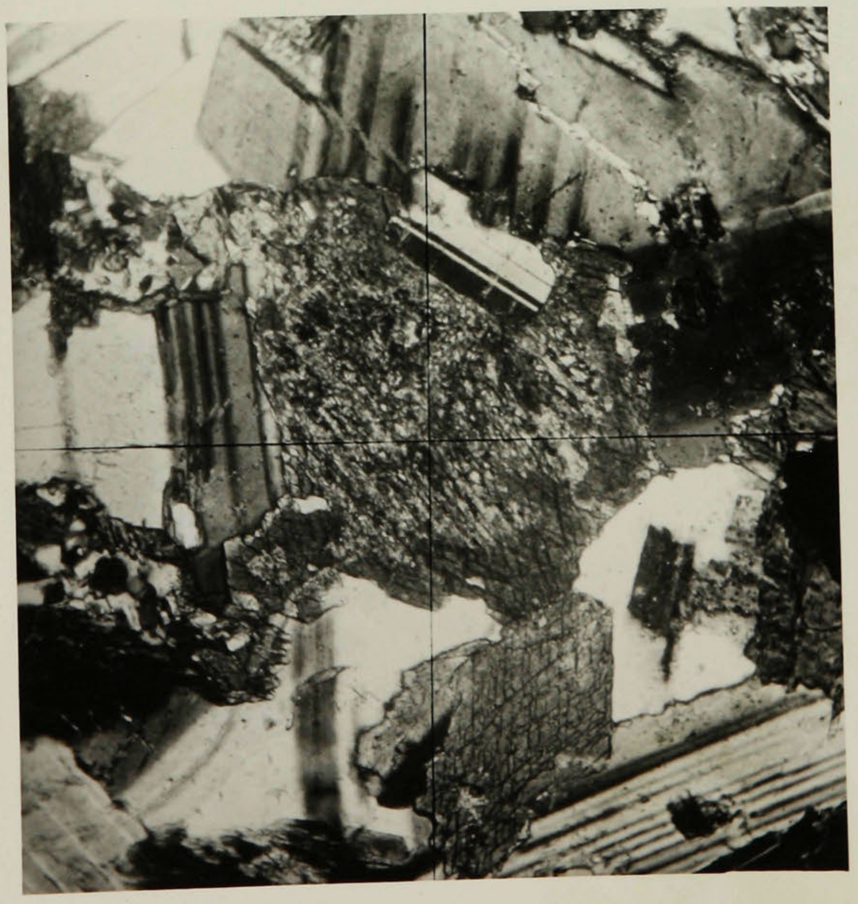


PLATE NO. 7

Fig. 1 Quartz diorite from the Worthington offset, shows a high degree of alteration. Note the granophyre and interstitial quartz.
Crossed nicols (X50)

Fig. 2 Quartz diorite from the Foy offset, shows a high degree of alteration. The slender feldspar laths have a speckled appearance. Note the granophyre and interstitial quartz.
Crossed nicols (X50)

Plate 7

Fig. 1.

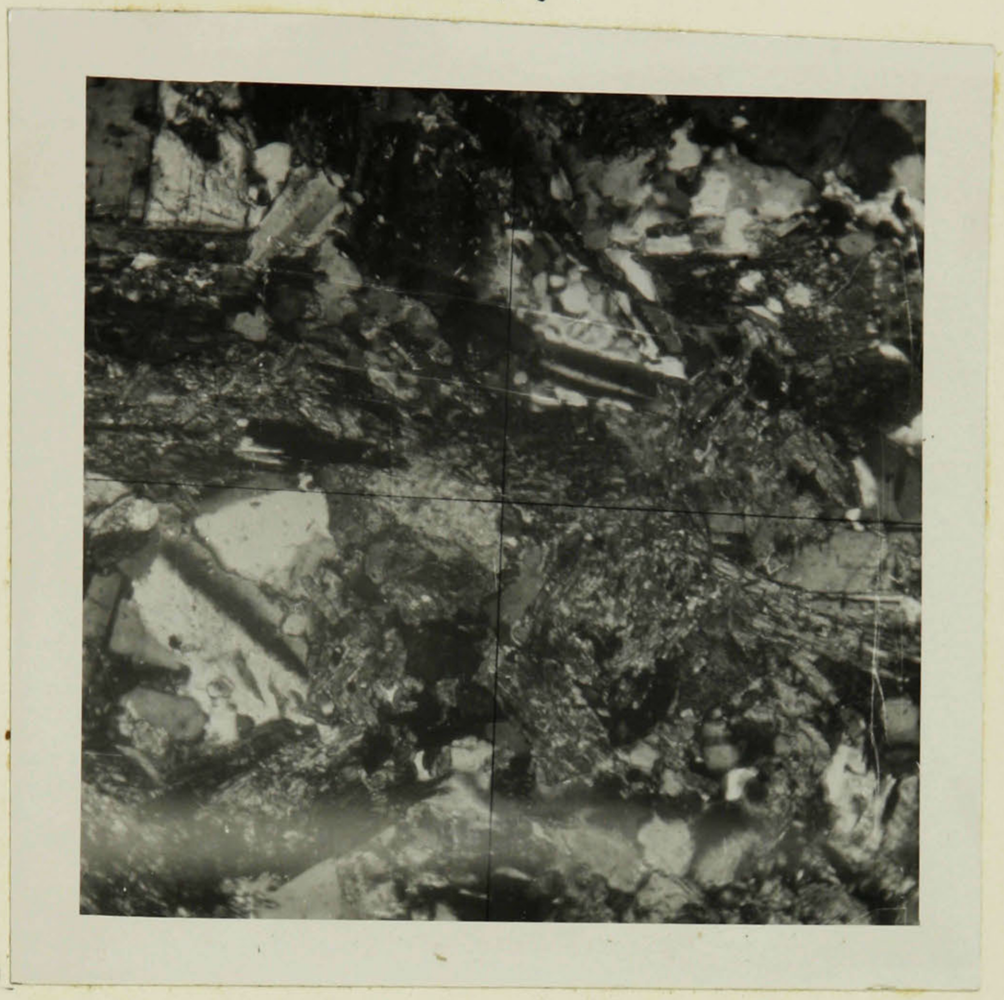


Fig. 2.

PLATE NO. 8

Fig. 1 From suite # 2, shows the contact between Creighton granite (gneiss) and quartz diorite of the Copper Cliff offset. The contact runs through the center of the picture and the dyke rock is at the top.
Crossed nicols (X25)

Fig. 2 Murray granite from near Murray Mine, shows streaked perthite. Note the allotriomorphic, granular texture.
(X50)

Plate 8

Fig. 1.

Fig. 2.

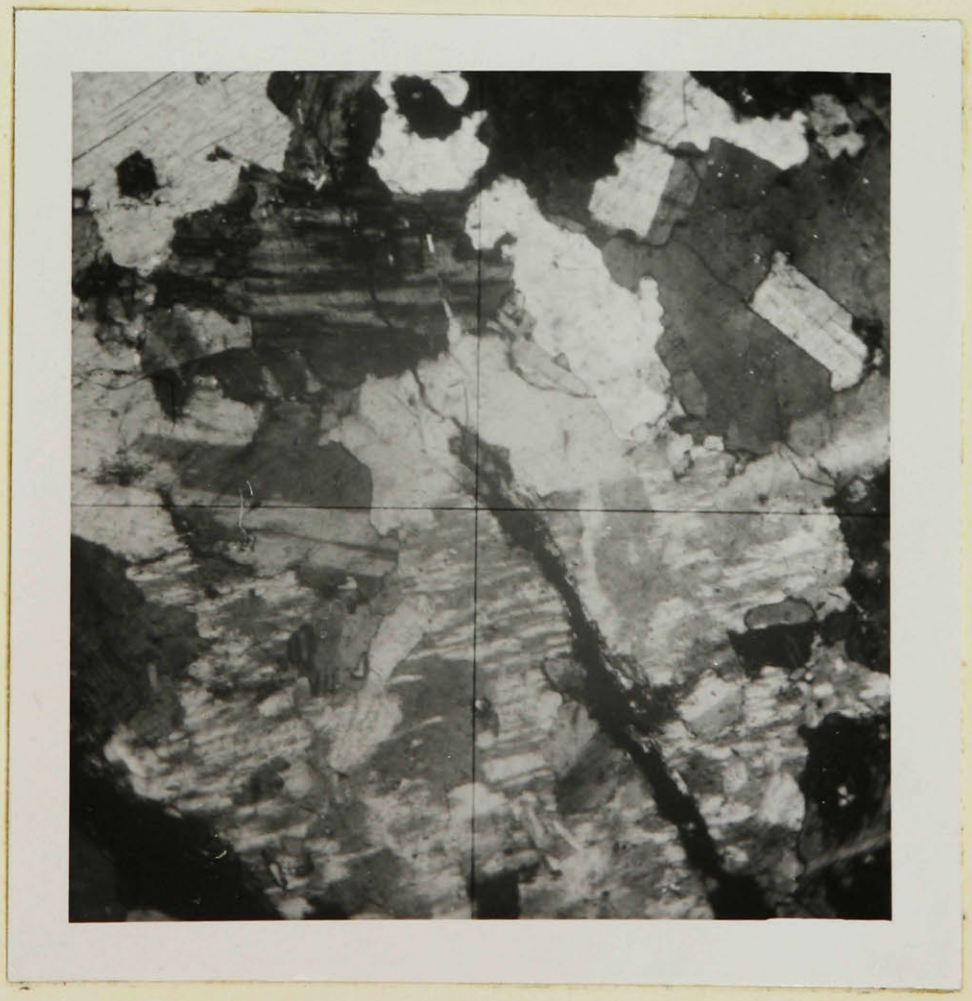


PLATE NO. 9

Fig. 1 Hand specimen from suite # 2, showing feldspathic inclusions in the quartz diorite of the Copper Cliff offset. 1/2 natural size.

Fig. 2 Hand specimen of Creighton granite, showing the gneissic structure. 1/2 natural size.

Plate 9

Fig. 1.

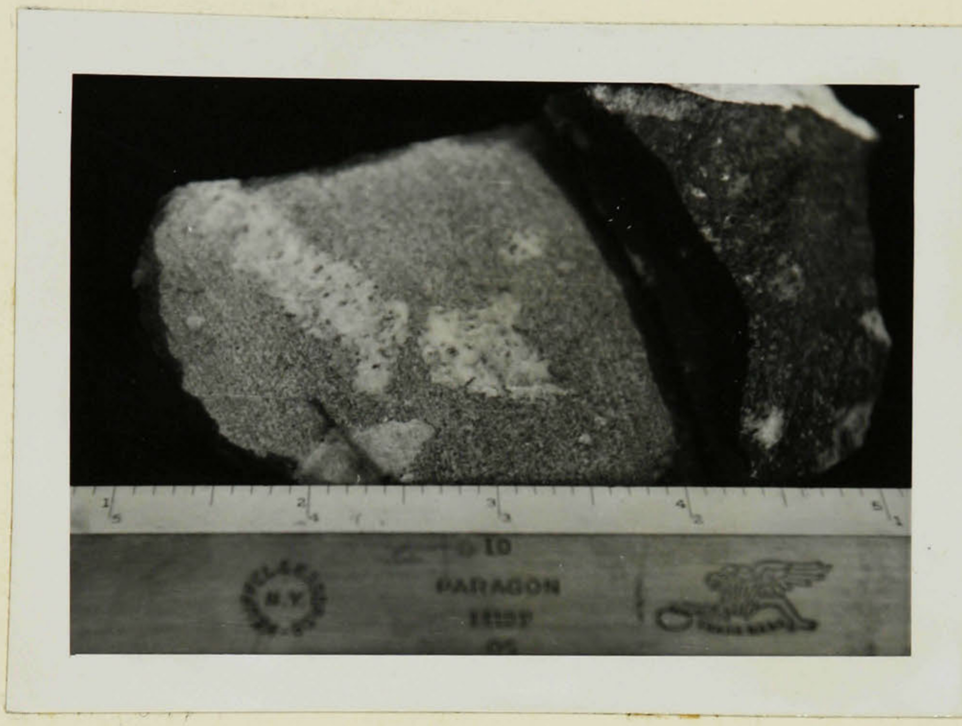
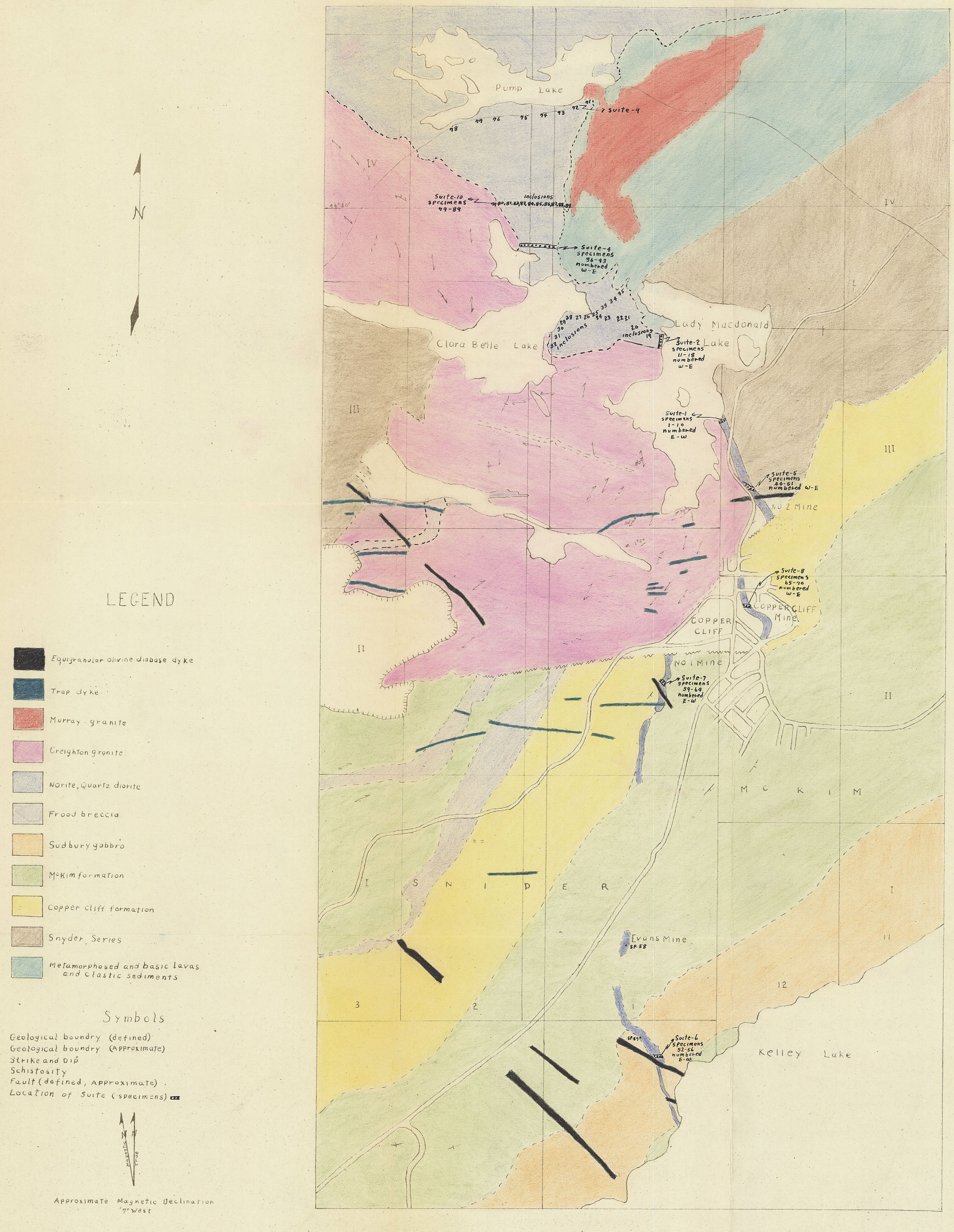


Fig. 2.

Fig. 4.



COPPER CLIFF OFFSET
SUDBURY DISTRICT
ONTARIO

Scale 4 Inches to 1 Mile