ABSTRACT

GEOCHEMISTRY AND PETROLOGY OF THE NIPISSING DIABASE IN ONTARIO

by John A. Colwell

The Nipissing diabase occurs in the area between the eastern end of Lake Superior and Lake Temiskaming as sill-like bodies (sheets) intrusive into the flat-lying or gently folded Huronian strata and as dikes in the steeply dipping pre-Huronian rocks and in the massive pre-Huronian granites. Sheets range in thickness from 250 feet to at least 1100 feet. Moderate differentiation of the diabase, most noticeable in the sub-horizontal sheets, is shown by the range in rock types from olivine-hypersthene diabase to aplite.

Detailed investigation of the differentiation of the diabase in the Cobalt area has been accomplished by petrographic and chemical study of samples from a vertical mine shaft and a diamond drill core. Analyses of both major and minor elements were made by the interrupted arc method of emission spectrography. This method has given analyses of sufficient precision for the study, and its speed and low cost, relative to chemical methods, has permitted a more complete investigation of the chemistry of the rocks than is usual in studies of this type.

Field and petrographic data indicate that the

intrusions were emplaced essentially in their present form, and that the highly fluid magma had undergone little, if any, crystallization before intrusion.

Samples of the chilled phase of the Nipissing in the Cobalt area indicate that the magma had a uniform composition - differentiation took place after intrusion. The chill composition is similar to that of other tholeiitic intrusions except for the low titanium content, observed in only a few other cases.

The Nipissing diabase in the Cobalt area is a partially-eroded undulating sheet forming a number of basins separated by arches. The trend of differentiation in a typical basin-arch section has been shown to be as follows:

1. A chilled phase of quartz diabase was formed at the margins of the sheet.
2. Fractional crystallization and vertical gravitational settling resulted in the accumulation of minor amounts of olivine in the lower parts of the sill which were not completely resorbed by the quartz diabase crystallizing around them.
3. Lateral, upward movement of acidic constituents toward the arches shifted the magma composition in the lower part of the basins so that olivine and hypersthene became stable phases and together with the plagioclases became more basic for a time, toward the top of the sheet. Later crystallization followed the common trend of iron and sodium enrich-

ment. As a result the olivine hypersthene zone is succeeded by a quartz-hypersthene zone, a quartz diabase zone (hypersthene replaced by pigeonite), and, a varied texture zone, where irregular patches of coarse to pegmatitic diabase indicate enrichment of volatiles. Later phases, postulated to occur mainly in the now-missing upper parts of the arches are granophyric diabase and aplite. This is supported by the occurrence of these phases elsewhere.

The behaviour of minor elements during differentiation shows definite trends in their incorporation into various phases of the diabase, similar to those found in other studies. Nickel and cobalt are enriched in the more basic phases, copper in the quartz diabase, vanadium titanium and manganese in the varied texture and granophyric diabase.

Petrographic and spectrographic study of samples collected throughout the region of Nipissing diabase intrusions shows that intrusions of the area along the north shore of Lake Huron are similar to those in the Cobalt area. Intrusions in the Sudbury area are dike-like and show accumulation textures and more equilibrium conditions than in the other areas, but chemical similarity to the Nipissing as well as field evidence indicates that they too are part of the Nipissing. Regional variations in metalliferous deposits, while not studied in detail, are thought to be due to circumstances arising during differentiation, not to original differences in the composition of the magma.

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by

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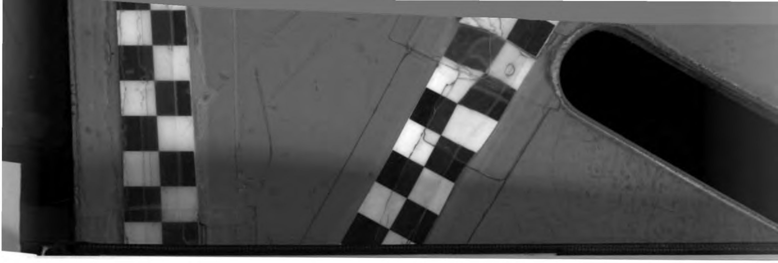

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Dr. R. Thomson of the Ontario Department of Mines kindly provided samples from a diamond drill core and loaned some thin sections.

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INTRODUCTION

Basic intrusives usually referred to as the Nipissing diabase, (locally as Sudbury gabbro) occur as sheets and dikes in the area between the eastern end of Lake Superior and Lake Temiskaming. They are generally closely associated with areas of Huronian metasediments and appear to be related to the period of gentle folding and faulting of these rocks shortly after their deposition. Radioactive age determinations have shown that the intrusions in question are contemporaneous throughout the area.

Previous studies of the intrusives, particularly in the Cobalt area, have shown a variation in lithology, with rock types ranging from olivine-hypersthene diabase through quartz-hypersthene diabase, quartz diabase, to granophyre and aplite. Differentiation due to fractional crystallization has been generally used to explain the existence of these phases, but several authors have considered assimilation of enclosing rocks to be responsible for at least some of the granophyric phase.

There is a regional variation in mineral deposits associated with the Nipissing. The Cobalt area is famous for its silver-cobalt-nickel-arsenic ores, which are considered to be genetically related to the diabase. Minor copper-nickel sulphide deposits occur in or near the diabase in the Sudbury area, while copper deposits were mined for some time in the Bruce Mines area.

This investigation was originally planned to study

the regional petrologic and chemical variation in the Nipissing diabase to determine if trends could be established that might explain the variation in mineral deposits. In order to provide a "standard" for comparison, it was decided to do more detailed work in the Cobalt area, where mine shafts and diamond drill cores provide an opportunity to examine the vertical and lateral variations through the intrusive from top to bottom. Studies, mainly petrographic, by Satterly (1933) and Hriskevich (1952), had shown a regular pattern in the distribution of the phases of the diabase which was ascribed to differentiation of the diabase. As the present study has progressed it became obvious that the additional data on major and trace element variations might generally support their conclusions and further elucidate the mechanism of differentiation and behaviour of elements during crystallization in the Nipissing in particular, and by comparison, in basic intrusives in general. As a result the emphasis of the investigation was shifted somewhat and a large portion of this paper is devoted to the detailed work in the Cobalt area. The study of differentiation is presented separately from the regional study, although the conclusions drawn from the former are considered as they apply to the latter.

Lack of data on sulphur, arsenic and other probable key elements have prevented a proper evaluation of the regional variation in the diabase as it may be related

to the variation in ore deposits but some provisional conclusions are drawn from the present results.

CHAPTER I

GEOLOGY OF THE NIPISSING DIABASE

Regional Setting

The region of Nipissing diabase intrusions lies along the southern margin of the Superior Province of the Canadian Shield between the eastern end of Lake Superior and Lake Temiskaming. Except for a small area of Lower Paleozoic strata north of Cobalt, all of the consolidated rocks of the area are of Precambrian age.

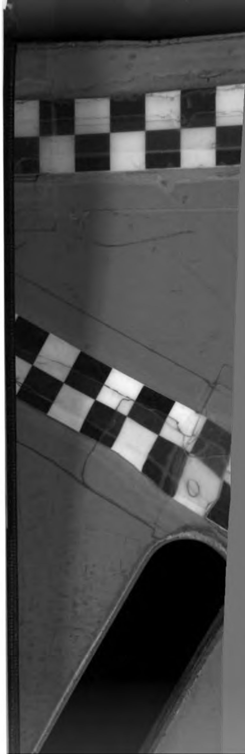
While the geology of parts of the region, particularly in the mining areas of Elliot Lake, Sudbury, Cobalt, and Gowganda, has been studied in considerable detail, much of the region has been mapped only on a reconnaissance basis. Publications of significance to this study may be found in the list of references. The discussion that follows is based largely on the work of Moore (1955), Robertson (1963), J. E. Thomson (1962a, 1962b), and R. Thomson (1962).

For the purposes of describing their relations to the Nipissing diabase the rocks of the region may be simply divided into three groups, corresponding to the stratigraphic divisions pre-Huronian, Huronian, and post-Nipissing. Figure I shows the extent of these groups as well as the distribution of Nipissing diabase intrusions. The ubiquitous olivine diabase dykes of post-Nipissing age are not shown.

The stratigraphic columns in Table I show the

TABLE 1. Table of formations

EON	ERA	OROGENY	ROCK-STRATIGRAPHIC UNITS		
			North shore of Lake Huron	Sudbury	Cobalt
Phanerozoic	Paleozoic				Silurian Ordovician
Proterozoic	Helikian	Hudsonian (Penokean)	Olivine diabase (1.225 b.y.)	Olivine diabase	Olivine diabase
				Sudbury irruptive (1.72 b.y.) Cutler granite (1.75 b.y.)	
	Aphebian		Nipissing diabase (2.155 b.y.)	Sudbury gabbro	Nipissing diabase (2.095 b.y.)
		Kenoran	Huronian	Huronian(?)	Huronian
			Algoman granite (2.5 b.y.)	? and ?	Algoman granite (2.5 b.y.)
Archean				pre-Huronian	Timiskaming
			Keewatin		Keewatin



generally accepted sequences for the three major areas involved in this study. These areas are shown in Figure I, and have been established by the writer for convenience in describing differences in stratigraphy, structure and petrographic and chemical differences in the Nipissing diabase.

Pre-Huronian

The pre-Huronian of the north shore of Lake Huron and the Cobalt area is typical of much of the Superior Province, and includes rocks which were involved in at least one orogeny prior to the deposition of the Huronian. The last of these, the Kenoran orogeny, apparently affected all of these earlier rocks, as radioactive age determinations give fairly uniform ages around 2.5 billion years. The Algoman granites and granite gneisses, present throughout the areas were emplaced during Kenoran times. The other rocks were folded to the extent that dips are almost universally steep to vertical.

The Keewatin includes mainly volcanics-basalt, andesite and minor dacite and rhyolite. While flows, particularly pillow lavas, are the most common volcanic types, tuffs and pyroclastic breccias are locally important. The Keewatin also includes variable amounts of sediments, the most notable of which are banded, siliceous iron formations.

Rocks correlated with the Timiskaming occur in minor amounts in the northern part of the Cobalt area.

From relations outside the region it appears that the Timiskaming generally lies unconformably on the Keewatin, but some conformable sequences are known (Goodwin, 1965). The Timiskaming sequence at Kirkland Lake is unique in the Precambrian of this part of the Shield, because of the presence of trachytic volcanic rocks. Timiskaming sediments, which include conglomerates, graywackes, and quartzites usually are more abundant than volcanics.

The "pre-Huronian" of the Sudbury area has been well studied. J. E. Thomson (1962b) summarized the problems of correlation, and his conclusions have been followed in constructing the stratigraphic column for the area (Table 1). A more detailed subdivision of the stratigraphy is as follows:

Whitewater group
Copper Cliff "rhyolite"
Sudbury group - conglomerate, graywacke, quartzite, limestone
Volcanic complex - Keewatin type

The volcanic complex and the Sudbury group are strongly folded and faulted. While most of the tectonic activity was probably pre-Huronian (Kenoran), post-Nipissing events are reflected in some 1.7 b.y. ages, and in the severe alteration and brecciation (Sudbury breccia) in the basic intrusions.

Huronian

The aspects of stratigraphy and structure of the

Huronian significant to this study have been summarized admirably by R. Thomson (1962) and J. E. Thomson (1962a, 1962b) and the following data is largely theirs.

Huronian rocks occur throughout the region of Nipissing intrusions, except for part of the Sudbury area. Hawley (1962) has suggested that they probably covered this area as well, later being removed by erosion. The correlation of Nipissing and Huronian is lacking, however, north of the area in Figure 1, for Huronian rocks occur at least fifty miles beyond the limit of diabase intrusions.

Early mapping by Collins (1925) along the north shore of Lake Huron (the "original Huronian") resulted in the division of the Huronian into two groups, the Bruce and the Cobalt, separated by a minor erosional unconformity. Thomson's (1960) work has shown that both groups extend as far east as Lake Timagami, while only the Cobalt group appears in the Cobalt-Gowganda area.

The Bruce is the older group, and consists, in ascending order, of the Mississagi quartzite and conglomerate, Bruce conglomerate, Espanola formation - limestone and graywacke, and the Serpent quartzite. The Mississagi conglomerate is unique, being uraniferous in most places and therefore was used by Thomson (1960) as a marker horizon. The maximum thickness of the Bruce is thought to be over 10,000 feet (J. E. Thomson, 1962a). The Cobalt group includes the Gowganda formation - conglomerate (tillite?), graywacke and quartzite, the Lorrain formation

quartzite and conglomerate (notable for the presence of jasper pebbles in places along the north shore of Lake Huron), and an unnamed cherty quartzite formation. J. E. Thomson (1962a) gives the maximum thickness of the Cobalt along the north shore of Lake Huron as about 10,000 feet.

The Huronian strata are generally separated from the pre-Huronian by a profound angular unconformity, where the gently deformed or flat lying Huronian rests on the steeply dipping older rocks.

South of the Murray fault, in the area between Sudbury and Blind River, Huronian strata may occur in the steeply dipping, highly deformed complex of pre-Huronian rocks. Since all the Nipissing intrusions in this area are similar, it does not matter for present purposes whether the rocks are Huronian or pre-Huronian.

Nipissing diabase

The field relations of the Nipissing intrusions in the Cobalt area have been well summarized by R. Thomson (1962) and his data seems to be generally applicable to the whole region of Nipissing intrusions.

The name Nipissing diabase was first applied by Miller (1913) to the gently dipping basic intrusive of the Cobalt area. Because of its general chemical similarity to the Keweenawan basalts of northern Michigan it has commonly been considered to be of Keweenawan age and was thought by Phemister (1928) and Hriskevich (1952) to correlate

with sills in the Lake Nipigon area and perhaps with the Duluth gabbro. Age determinations (discussed more fully later) show however that the Nipissing (about 2.1 b.y.) is much older than any of these (about 1.0 b.y.). As far as the writer has been able to determine, all of the intrusions that may be considered to correlate with the Nipissing are in the area of Figure 1.

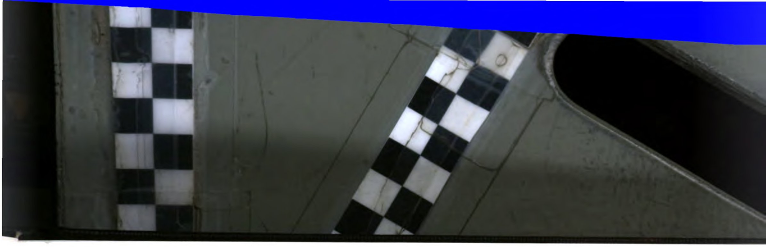
The Nipissing diabase occurs in essentially two forms - as dikes in the pre-Huronian and steeply folded Huronian, and as sill-like bodies (sheets), ranging in thickness from 250 feet to at least 1100 feet, in the gently deformed Huronian. The sill-like nature of the Nipissing may not be observed in some isolated outcrops but it is generally assumed that they are erosional remnants of a sheet.

In only rare cases is the Nipissing a true sill, for any correspondence with bedding surfaces or planes of unconformity is rare. Thomson concluded that the Nipissing in the Cobalt area intruded within a range of 1000 feet of the Huronian - basement contact and that the depth of the sheet was largely controlled by the erosion surface at the time of intrusion. "In other words, the depth from surface at which the diabase intrusive spread laterally was where its hydrostatic pressure was approximately equal to the pressure due to the overlying column of rock."

Pre-Nipissing faults appear to have affected its form in some cases. This is most noticeable in the Huronian at Cobalt, where the usually gently dipping sheet becomes a thin vertical dike along an obvious lineament. In the Beaver and Temiskaming mines the sheet is vertically displaced as much as 300 feet where it crosses a fault zone. Lack of shearing in the diabase suggests that it was the magma moving to a new level along the old fault that caused this "roll", not later movement.

Erosion has apparently not removed as much of the Nipissing in the immediate Cobalt area as it has in other places and hence the probable configuration of the sheet is better determined. It had an undulating form that gave rise to "basins" and "arches" having an amplitude of at least 1000 feet. Erosion in varying degrees would first isolate the basins giving the common ring-like outcrop pattern and later leave only the lower part of the basin as a mass with gently inward dips on all sides. Carrying this further it may be that some of the dikes in the pre-Huronian represent feeders to former sheets in previously overlying Huronian strata. This is not always the case, however, as it appears to be common for such intrusions to occur as sills in flat lying strata and as dikes in steeply dipping or massive units. In explaining the occurrence of sills, Holmes (1965) states that

> The (basaltic) magma evidently ascends with the aid of a hydraulic pressure capable of supporting a column....with a density of about 2.6-2.7. Now, if such magma should enter a thick sequence of sediments, the density of which would probably



> average less than 2.4, it would find it much easier to penetrate laterally along bedding planes and so to lift the light sediments rather than itself.

It is generally considered that, with the possible exception of the intrusions in some of the strongly deformed rocks near Sudbury, the present form of the Nipissing is essentially the same as when it was intruded. Minor modifications due to faulting and possible regional tilting are admitted, however. As evidence against later folding in the Cobalt area, it may be noted that the undulating sheet sometimes intrudes undeformed Cobalt strata. If the basin - arch form were due to later folding one would expect deformation of the Cobalt as well. The same conclusion seems to have been reached by several workers in areas along the north shore of Lake Huron. Robertson (1963) related the intrusion of the diabase in the Iron Bridge area to the period of folding of the Huronian rocks, suggesting that dilatancy in the crests and troughs of the folds during a lull in the compressive forces allowed the diabase magma to intrude and become concentrated in these areas. Ginn (1965), in discussing the geology of Nairn and Lorne townships, related the intrusions to fault zones, and found that while some are conformable with the Huronian rocks, others cut across the folds in the Huronian. Grant et al, (1962) in their study of the geology of Broder, Dill, Neelon, and Dryden townships, an area which borders the Grenville, note that the basic intrusives correlating in age with the Nipissing, transect structures in the Subury group of sediments. They make no mention of post intrusive deformation of these rocks other than by fracturing. They conclude that the intrusives and the rocks they cut behaved competently during the Killarnean orogeny, yielding by shearing. Some of the diabases were metamorphosed during this event. Hawley (1962) does include a Penokean (Hudsonian) period of "moderate folding, faulting of Huronian formations" in his table of events, but does not cite any evidence for it in the text.

It seems unreasonable to suggest that the Nipissing was intruded from one orifice and spread as a single sheet through the whole region. R. Thomson (1962) took the opposite extreme and suggested a local source for each basin which he felt was necessary to explain the observed variation in composition. The results of the present study suggest however, that pre-emplacement differentiation was minimal. For example, chilled phase samples from widely separated localites are remarkable similar, suggesting a similar magma.

The writer suspects that pre-Nipissing faults were the probable passage-ways for the magma that was formed during a period of relaxation after gentle folding of the Huronian, and tapped by normal faults.

Post-Nipissing

The only post-Nipissing rocks in the region other than the Paleozoics and rocks south of the Grenville front

are the Sudbury nickel irruptive, a few granite intrusions between Blind River and Espanola south of the Murray fault and the olivine diabase dikes that occur throughout the area. The granites are probably related to the Hudsonian orogeny (about 1.6 b.y.) which is also likely responsible for the folding of the other rocks in this area (south of the Murray fault). The olivine diabase dikes are distinctly younger, as shown by the fact that they transect the older rocks and structures. They are generally unaltered and are distinguished from the Nipissing by a typically brownish weathered surface and the ubiquitious olivine grains (Simony, 1964 reports an average of 20.2 per cent olivine in four specimens from the Timagami area). Moore (1955) reported the presence of quartz diabase dikes cutting the Nipissing in the Gowganda area, and considered them to be similar in age to the olivine diabase dikes, one of which was also noted in the area.

Age determinations

A number of radioactive age determinations have been reported for the rocks of the region (Fairbairn et al 1960, 1965; Faure et al, 1964; Stockwell, 1964; van Schumus 1965). Both the potassium-argon and rubidium-strontium methods were used. The ages given in Table I are those which are thought to be most accurate and which are of significance to this study. Not included are ages from the Sudbury "pre-Huronian" that are geologically puzzling (Fairbairn et al, 1965) nor those thought to t

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have been affected by later orogenies (eg. dates as young as 1.685 b.y. on the Nipissing, van Schumus, 1965).

The 2.5 b.y. date for the Algoman granites is common throughout the Superior province, occurring in the Keewatin as well, and is taken as the mean age of the Kenoran orogeny. The Nipissing ages for the two separate areas agree very well and help to confirm the contemporaneity of the intrusions. These ages, in conjunction with those on the Algoman are significant in placing limits on the age of the Huronian (i.e. the Huronian was deposited later than 2.5 b.y. and before 2.1 b.y.).

As mentioned before, the Nipissing ages also clearly indicate that it is incorrect to call these intrusions Keweenawan, as has commonly been the practice. Stockwell (1964) defines the Keweenawan as younger than 1.6 to 1.7 b.y. (post Hudsonian or, to use the term more commonly applied in the Lake Superior area to denote the same orogeny, post-Penokean). It is interesting to note that both the Cutler granite at 1.75 b.y. (van Schumus, 1965) and the Sudbury irruptive at 1.72 b.y. (Fairbairn et al., 1965) appear to be related to this disturbance.

The olivine diabase dikes, may still be considered as Keweenawan.

It will be noted that the rock units in Table I have been grouped according to Stockwell's (1964) time-stratigraphic classification as well as under the more traditional names. This classification has the advantage

of being based, from its inception, on universally applicable time units, in contrast to the older nomenclature, which is based on local lithologic and structural units.

CHAPTER II

METHODS OF INVESTIGATION

Regional Sampling

In its early stages this investigation was planned only as a regional study of the Nipissing diabase without any particular reference to the study of differentiation. The samples were taken because they seemed to represent "normal" diabase, and granophric and pegmatitic phases were avoided, although they constitute only a small proportion of the exposures. As a result there are only a few granophyres in the regional samples, and none of the coarsest pegmatites.

The sampling was confined to easily accessible outcrops, mainly roadcuts and lakeshores, as time and funds were limited. The distribution of sample locations in Figure I indicates, however, that a reasonable coverage has resulted, except in the area between Sudbury and Gowganda.

In selecting samples care was taken to avoid sheer zones and veined areas, and in all cases samples were taken from below the zone of obvious weathering, which extends less than an inch into the outcrop surface.

Regional sampling in the area north and west of Cobalt as well as the more detailed sampling described below was accomplished during two weeks the writer spent with the Geological Survey of Canada as assistant to p

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Dr. W. Fahrig.

Detailed Sampling

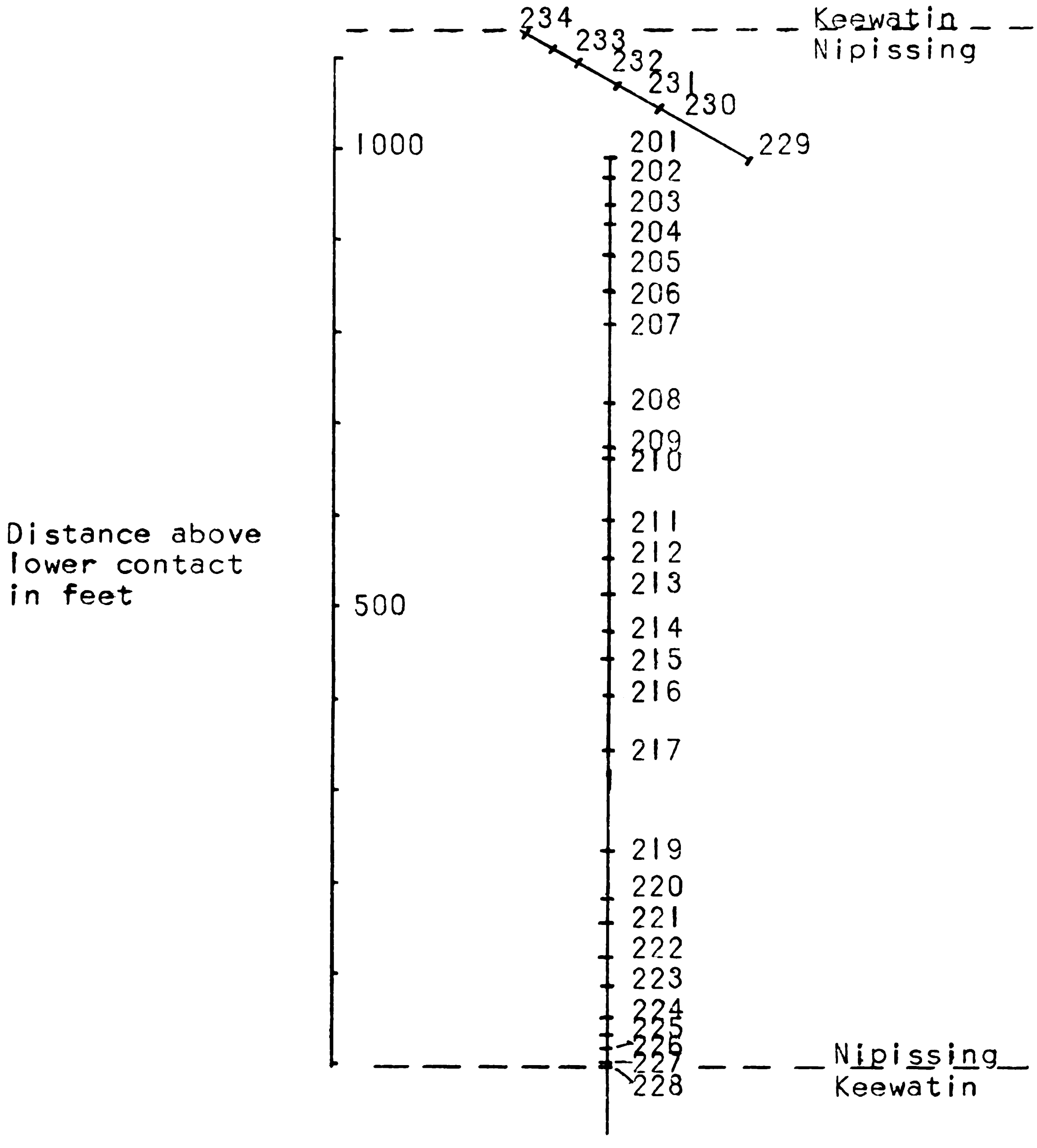
Samples for the study of differentiation and for the establishment of a "standard" section were obtained from the Rix-Athabasca property and from the Nasco Cobalt property, both in the Cobalt area. The general locations are shown in Figure 1, cross sections showing the location of samples are given in Figures 2 and 3.

Samples 201 to 228 were obtained from a vertical winze on the Rix-Athabasca property. Samples between levels were located with reference to the number of 12½ foot ladders passed from the top of the winze. Distances estimated in this fashion checked well with known points (lower levels). Some of the samples show effects of shearing, but no veins were noted. Samples 229 to 234 were taken on the hill above the winze, beginning at the adit entrance. The samples from this property, which give a complete section through the sheet, are hereafter referred to as the "Rix section".

The samples from the Nasco Cobalt property were provided by Dr. Robert Thomson, resident geologist for the Ontario Department of Mines at Cobalt. They came from a diamond drill hole which penetrated the upper 963 feet (vertical projection) of the sheet, and are referred to as the "Nasco section".

Petrographic methods

Thin sections were prepared by the Geological Survey



Plane of section - N90°E

FIGURE 2. Location of samples - Rix section

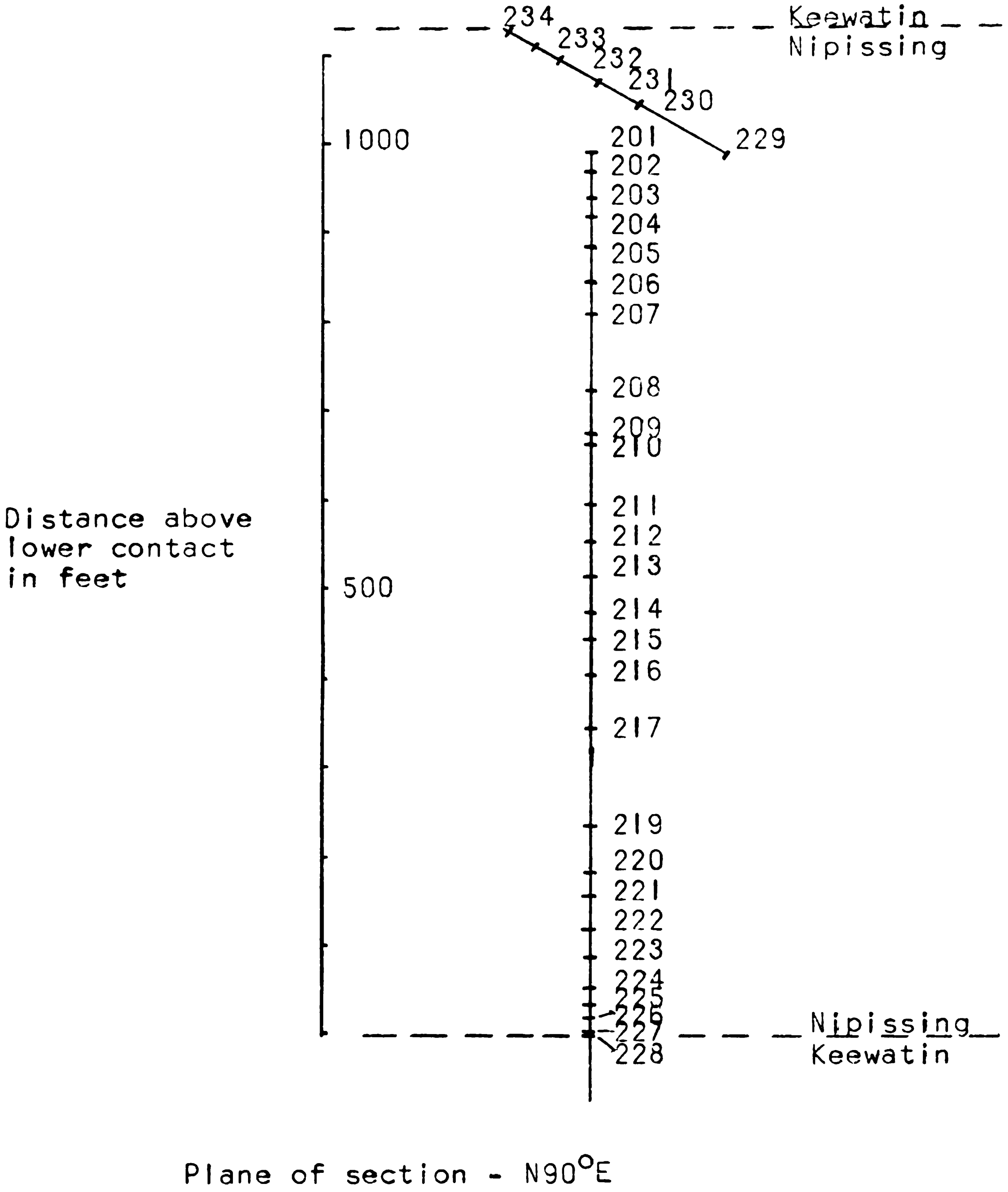


FIGURE 2. Location of samples - Rix section

of Canada for the samples in the Rix section and most of the regional samples. Thin sections for some of the samples in the Nasco section were loaned by Dr. Thomson; several others were prepared by the writer.

The petrographic investigation has been generally confined to the identification of the major minerals and textures present in each sample so that it could be assigned to one of the phases of the diabase. Further study has not been felt warranted for several reasons:

1. The petrography of the diabase in the Cobalt area has been fully described (Hriskevich, 1952). The vertical section described by him is located only 1000 feet from the Rix section, and rough determinations of plagioclase, olivine, and pyroxene compositions at several levels correspond well with his data.
2. The petrographic work done, when combined with the spectrographic analyses, permits the interpretation of the trend of differentiation in the diabase.
3. The spectrographic analyses give concentrations of elements that are considered much more accurate than any that could be obtained from modal analyses of even the least altered sections in view of the zoning of the playioclases and pyroxenes, additionally complicated in the case of the pyroxenes by the common presence of exsolution phenomena.
4. Most sections show considerable alteration.

This is not to suggest that the writer feels any petrographic study to be unnecessary when chemical or spectrographic data are available. In the present case it would have been impossible to trace the trend of differentiation with any confidence without the thin sections. As will be seen later, samples from the Sudbury area have a chemical composition similar to the olivine diabase of the Cobalt area, but their different mineralogy and texture suggest significant differences in their origin. It is clear that the two methods complement one another, and the combination improves the interpretation in studies of this sort.

Chemical Analyses

A number of chemical analyses of the Nipissing were encountered in the literature and have been incorporated in this study. A partial analysis, in duplicate, of one of the samples from the present study was performed by H. Rudnick at Technical Services Laboratories, Toronto. This analysis is presented in Table 2; the others are incorporated in later section.

Spectrographic Analyses

All other analyses, for both major and minor elements, were obtained by emission spectrographic methods, and were performed by the writer at the Geology Department, Michigan State University. The essentials of the methods used and the problems encountered are given in the following paragraphs.

TABLE 2. Duplicate chemical analysis of sample 212

	A	B
SiO_2%	50.10	50.08
Al_2O_3%	14.93	14.81
CaO%	14.51	14.65
MgO%	10.95	10.85
Na_2O%	1.21	1.18
K_2O%	.29	.31
Total iron (Fe)%	5.25	5.24

Analysis by Technical Service Laboratories, Toronto
Certificate signed by N. Rudnick

Sample preparation

One or more representative chips, totaling about 20 grams, were taken from the hand specimens. The chips were heated in a furnace at 850°C. for about fifteen minutes and then quenched in water. This practice was suggested by Ahrens (1950) and used by Stonehouse (1954), and rendered the normally very tough diabase more amenable to crushing and grinding.

About half of the samples were ground completely by hand in a porcelain mortar. The rest were crushed to coarse sand size and then ground for twenty minutes in a Spex Mixer Mill fitted with a high-alumina ceramic vial and ball. In both cases grinding was continued until most of the sample was considered to be minus 200 mesh.

A 300 milligram sample was taken from the ground material and mixed with graphite powder (National Carbon Co. Grade SP-2), spectrographically pure strontium carbonate, and tin oxide in the proportions 30 parts sample: 40 parts graphite: 4 parts strontium carbonate: 1 part tin oxide. The graphite serves as a buffer, giving a smoother and more complete burn on the spectrograph than sample alone; the strontium carbonate served as internal standard for determination of magnesium, iron, calcium, nickel, cobalt, vanadium, and titanium; and the tin oxide as internal standard for sodium, manganese, and copper. The selection and use of internal standards followed the suggestions of Ahrens (1950).

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The final mixture was placed in an agate mortar and mixed under acetone for five minutes. As the size of particles of the rock sample was found to affect the analysis (see below), the material was carefully ground as it was mixed in an effort to ensure that each sample would be as fine grained as possible and that all samples would be alike in this respect.

External Standards

Spectrographic analysis requires the use of standard samples of known composition in order to relate the intensity ratios (element/internal standard) obtained to element concentrations. Several kinds of external standards were used in the present study:

1. Standard rock samples - granite G-1 and diabase W-1, prepared and distributed by the U.S.G.S. were used alone and in mixtures of the two. Sample 212, which was chemically analysed, from this study, was also used.
2. W-1 with small additions of a mixture of spectrographically pure SiO_2, MgO, NiO, and CoO.
3. Synthetic standards. Spectrographically pure oxides and carbonates were mixed to give a composition similar to that of the average Nipissing. The mixture was sintered at 1000°C for 24 hours as reccommended by Ahrens(1950). The minor elements were added as oxides and carbonates and dilutions were made with the synthetic rock mixture to give

concentrations ranging from 1ppm to 1 per cent.

Analytical Procedure

The spectrograph used for the analyses was a Bausch and Lomb 2 meter Dual Grating instrument. The source unit was an Applied Research Laboratories M.S.U. - 4 Multisource. Analytical conditions used are given in Table 3.

It will be noted from Table 3 that the interrupted arc method of sample excitation was exployed in this study rather than the continuous arc commonly used in the analysis of rock materials. The interrupted arc is used in the analysis of metals and alloys and Harvey (1957) suggested that it would improve the reproducibility of results if used for rocks. The present study has shown that, with the equipment used, the interrupted arc has some distinct advantages over the continuous arc, but that there are some problems as well.

The advantages of the interrupted arc are:

1. The spectra obtained using the interrupted arc show a much lower level of CN band and background emission than did some experimental runs using the continuous arc. The CN emission is low enough that individual band members are distinquished and spectral lines of other elements in these regions can be seen.
2. A much shorter burning time is required. In the present case fifteen seconds produced spectra of

TABLE 3. Analytical conditions

Excitation:	Interrupted arc, 30 ohms, 40 mfd, 360 mh, 15 sec burn, sample positive
Slit:	20 microns wide, 3 mm long
Transmittance:	60%, additional filtering to 20 % on some lines by split filter
Electrodes:	.242 inch graphite electrodes
Plates:	Eastman Kodak Spectrum Analysis No. 3
Processing:	Developer D-19 3½ min., stop 3% acetic acid 30 sec., fixer Kodak Fixer 10 min.
Photometry:	Jarrel-Ash Microphotometer
Calculations:	Seidel calculating board, calibration curve from iron spectrum by two step filter method (Harvey, 1957)
Analysis lines:	Mg 2783 A Sr 2931 A Mn 2933 A Ca 3007 A Ni 3050 A Sn 3141 A V 3183 A Fe 3198 A Ti 3199 A Cu 3273 A Na 3302 A (upper line) Co 3453 A

equal or better sensitivity as those normally requiring about two minutes with the continuous arc. This is an important factor in reducing the CN and background levels.

The disadvantages of the interrupted arc are:

1. Matrix effects appear to be magnified. The standard spectra prepared from W-1, G-1, mixtures of G-1 and W-1, and small additions of oxides to W-1 give a reasonable working curve for most elements, but these were displaced from those obtained from the purely synthetic mixtures. This is thought to be due to the difference in energy required to dissociate, and excite nickel, for example, as contained in a silicate from that required for nickel in nickel oxide.

The only solution to this problem seems to be to use analysed rocks as standards. In the present case the slope of the working curve was taken from the synthetic mixtures, which cover a wider range of composition than do the rocks, while the location of the curve was determined from the natural standards. The concentration values used for the various elements in W-1 and G-1 were the recommended values of Fleischer and Stevens (1962). This procedure, however, was followed only in the case of the minor and trace elements due to another problem which affected the major elements.

2. Differential grinding effects appear to be more

important in the interrupted arc method than in the continuous arc. Spectrographic results for the one sample which was also chemically analysed for some major elements did not fit the working curve established from analyses of the other rock standards for Mg, Ca, Na and Fe. When it was suspected that the particle size of the sample might be responsible, the following test was made. A sample of one of the rocks was crushed to minus ¼ inch and then ground for 1½ hours in the Spex mill. Small samples were taken at 5 minute intervals and run on the spectrograph. The results showed that line intensity increased rapidly with length of grinding up to about 20 minutes and then more slowly to about one hour, levelling off at this point.

In an attempt to minimize this effect the following steps were taken:

1. Samples were crushed to a smaller size before grinding.

2. The amount placed in the Spex mill was reduced to about 10 grams and an effort was made to keep this amount constant.

3. The careful final grinding of the small portion of the sample after mixing with graphite was instituted. Some analyses had been made before this step was introduced: new results showed higher line intensity in the previously coarser samples and

little or no change in those already ground fine.

During this regrinding it was found that G-1 was quite coarse, and it too was given the same treatment.

New analyses showed that the discrepancy, while much reduced, was still present in the case of Mg, Ca, and Na; whereas the analysis of Fe fit the curve for W-1, G-1 etc. In order to resolve this problem the following was done;

1. No new change was made in the minor and trace element working curves from that noted above. The first reason for this is that the grinding effect appeared to be less for these elements than for the major elements. A second reason is that no independent analyses of these elements were made, as they were on the one sample in the case of the major elements.
2. The slope of the working curves was taken to be that of the W-1, etc samples, while the curve was drawn through the point representing the analysed rock - sample 212.

Whether or not this procedure has resulted in accurate determinations of the various elements in unknown. However, comparison of the final percentages of the major elements with published chemical analyses of the Nipissing and other similar rocks shows that the present values are reasonable.

Precision

The term precision as it is used here refers to the reproducibility of the data. While most of the values are based on a single analysis, a number of duplicate and triplicate analyses were made, and sample 212 was analysed 17 times. From this work it is considered that values for all elements are precise to within plus or minus 10 per cent.

CHAPTER III

DIFFERENTIATION STUDY

Petrography

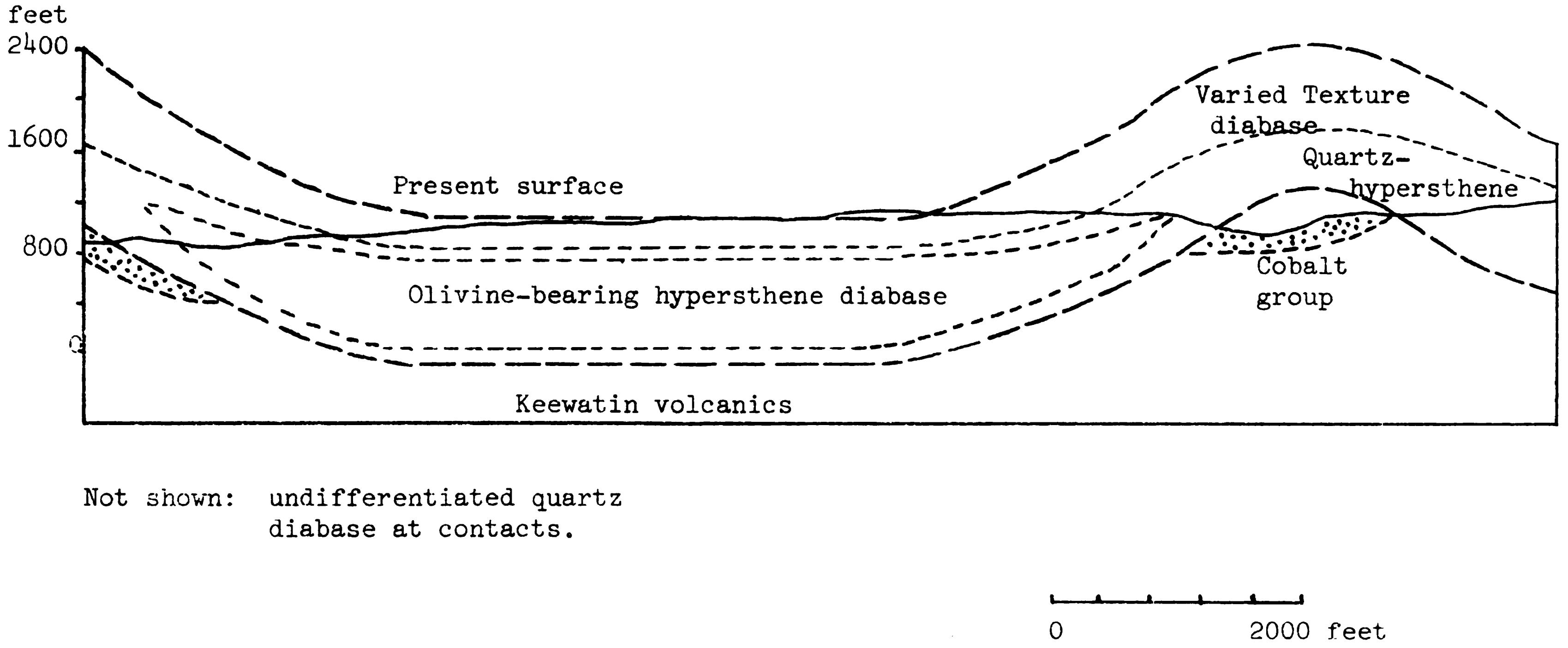
Phases of the Nipissing diabase

From his surface and underground mapping and petrographic study, Hriskevich (1952) found that there are six distinct, mappable phases of the Nipissing diabase at Cobalt, and that these phases appear to be distributed in a fairly regular pattern with respect to the form of the sheet (Figure 4). He described their distribution as follows;

> A chilled marginal layer of quartz diabase occurs at the base of the sheet. Above the quartz diabase and grading into it, is a zone of hypersthene diabase. Overlying the hypersthene zone is the varied texture diabase. Irregular schlieren, patches, and dikes of diabase pegmatite are intrusive into the varied texture diabase. Some diabase pegmatite does, however, occur in the hypersthene diabase zone. Granophyric diabase and granophyre also occur within the varied texture diabase. Narrow dike-like masses of aplite are found in small quantity throughout the whole of the sheet but are much more common in the upper portion. The varied texture diabase grades upward into the quartz diabase zone of the roof contact.

On the basis of the petrographic and chemical data of the present study, the writer has devised a slightly different division of the phases of the Nipissing. While one of these - the olivine phase - is not readily mappable in the field, it is clearly distinguished from the petrographic and spectrographic data. The terms used by the writer are as follows;

Fine-grained diabase -- (called chilled diabase at



Not shown: undifferentiated quartz diabase at contacts.

FIGURE 4. Form and composition of the Nipissing diabase at Cobalt. (after Hriskevich, 1952)

known contacts) -- medium to dark gray. Intergranular to subophitic texture. The "chilled marginal layer of quartz diabase" of Hriskevich.

Olivine-hypersthene diabase -- medium grained, dark gray. Generally subophitic. Characterized by presence of olivine. The lower part of the "hypersthene zone" of Hriskevich.

Quartz-hypersthene diabase -- medium grained, dark gray. Generally subophitic. Large poikilitic plates of orthopyroxene; olivine absent; quartz usually present. The upper part of the "hypersthene zone" of Hriskevich.

Quartz diabase -- medium grained, gray to greenish-gray, but with more obvious color difference between mafics and felsics than in the above types. Subophitic. Hypersthene and olivine absent. Quartz as individual grains and in micropegmatitic intergrowths. May be part of Hriskevich's "varied texture" phase.

Varied texture diabase -- medium to coarse grained, mafics greenish-black, felsics white to pink (granophyric diabase). Hypidiomorphic granular. Minerals similar to quartz diabase. Opaques more abundant than in other phases - mainly magnetite-ilmenite intergrowths.

While no aplites were analysed in the present study, a thin section was obtained from aplitic meterial north of Gowganda. The aplite bordered a carbonate vein containing cobalt mineralization and appeared to grade quickly into normal diabase. The description of aplite that follows includes data from this sample as well as that of Hriskevich (1952).

Aplite -- medium to fine grained. Pink to dull red. Hypidiomorphic to allotriomorphic-granular. Mafics minor or absent. Mainly plagioclase, quartz and micropegmatite. A small amount of microcline is present. Carbonate present in some aplites, partly in miarolitic structures.

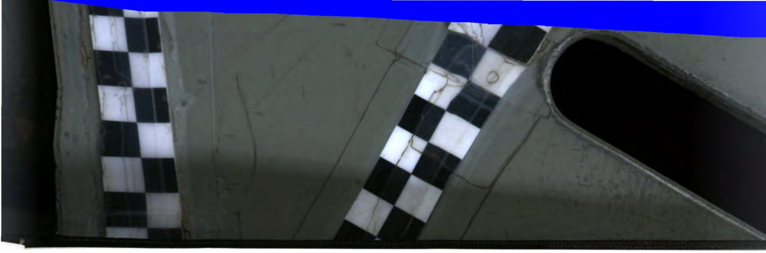
Distribution of phases

The distribution of phases according to the writer's classification is shown in Figure 8. This is an hypothetical cross section based on the petrographic and spectrographic data from the Rix and Nasco sections and projection of this data to a so called "acid" section, the derivation of which is discussed later. The following description of petrographic variation is based on the Colonial Mine section of Hriskevich and the Rix and Nasco sections of the present study.

The chilled diabase at the base of the sheet is composed of plagioclase and pyroxene crystals arranged in sheaf-like or radiating form, along with up to 10 per cent of phenocrysts of plagioclase, pyroxene and olivine. The plagioclase of the groundmass occurs in needle-like crystals about 0.1 mm long while the altered lath-shaped phenocrysts are about 0.5 mm long. The plagioclase composition, according to norms calculated by Hriskevich, is about An_{66}. The pyroxene of the chilled phase appears to be all augite - the grains in the groundmass are too small to be definitely identified. The presence of olivine is inferred from fine grained aggregates of antigorite and chlorite with anhedral to euhedral outline. Iron oxides occur as tiny rounded grains throughout the groundmass.

Grain size coarsens to about 1 mm a few feet from the contact, and the texture becomes subophitic or diabasic as one passes from the chill phase into the fine grained quartz diabase, which in both the Colonial and Rix sections extends for about 100 feet from the lower contact. Plagioclase occurs as lath-shaped crystals about 1 mm long and generally appears to have crystallized earlier than the augite, although the reverse is true in some cases. Pyroxenes include augite, pigeonite, and pigeonite inverted to orthopyroxene. the latter being identified by the lamellae of clinopyroxene exsolved along the 001 direction of the original pigeonite and the common severe gray alteration called "turbid alteration" by Hriskevich. Quartz and micropegmatite occur interstitially. Iron ore, in some cases showing magnetite - ilmenite exsolution occurs as small skeletal crystals. Clusters of rounded aggregates of antigorite and chlorite occur throughout this phase in the Rix section. They are usually rimmed by inverted pigeonite and are interpreted by the writer to be altered olivine.

The olivine-hypersthene phase begins with the rather abrupt appearance of large untwinned plates of orthopyroxene



in sample 222 of the Rix section, and extends for over 600 feet. With the exception of these plates which average about 5 mm in length (ranging, according to Hriskevich, to 15 mm) the grain size is only a little coarser than in the fine grained diabase, plagioclase crystals having an average length of about 1.5 mm. Pigeonite and inverted pigeonite disappear rapidly, their place taken by the hpyersthene. The hypersthene shows little or no pleochroism. The grain rims usually have a slightly higher birefringence than the core. The plates typically contain numerous well-formed plagioclase crystals and occasional grains of augite. Olivine occurs as clear anhedral to euhedral grains and clusters of grains. The lack of significant magnetite in altered olivines attests to its high magnesium content. Iron oxides occur in the lower part of this phase but are almost totally absent in the upper 450 feet.

Olivine disappears at about 750 feet above the base of the Rix section and quartz reappears in increasing quantities approaching the quartz-hypersthene phase. Other minerals generally remain the same, although their character is a little different in some cases. The orthopyroxene shows stronger zoning and exsolution of clinopyroxene appears around the margins of the plates, eventually extending throughout some grains. Pigeonite and inverted pigeonite reappear in the upper part of this phase, as iron oxides. The amount of quartz and micropegmatite increases. The disappearance of hypersthene at about

950 feet above the base in the Rix section marks the beginning of the quartz diabase. Its mineralogy is quite similar to that of the fine-grained diabase above the lower chill zone except that olivine is absent. Quartz, micropegmatite and iron oxides are generally more abundant than in the fine-grained phase. In both the Colonial and Rix section patches of coarse-grained material appear almost immediately in this phase (varied texture diabase). In the Nasco section, on the other hand, it appears from the hand specimens and a few slides that about 290 feet of medium grained (about 1.5 mm) quartz diabase occurs between the hypersthene zone and the varied texture phase. Grain size in the varied texture phase of the Rix section reaches a maximum of about 5 mm while Hriskevich describes pegmatitic patches with pyroxenes up to 5 cm long. Micropegmatite and iron oxides seem to be most abundant in the coarser phases.

Variation in mineral composition

Olivine: The range in olivine composition noted by Hriskevich in the Colonial Mine was from $Fo_{72.5}$ to Fo_{85}, but in contrast to other sills of similar composition the most magnesian olivine was not nearest the base. Instead the composition varied from $Fo_{72.5}$ at 100 feet above the base to Fo_{85} at 400 feet and back to $Fo_{72.5}$ at the point where olivine disappeared, 700 feet above the base. The maximum amount of olivine - 26.9 per cent - was noted at 600 feet. Rough determinations indicate the same trend to be present in the Rix section.

Plagioclase: A similar situation to that of olivine occurs in the case of plagioclase norms calculated by Hriskevich from his chemical analyses show An_{66} in the chill zone, $An_{74.5}$ at 180 feet, $An_{80.5}$ at 600 feet and An_{68} in varied texture diabase 920 feet above the base at the Colonial Mine. Determinations on minerals show this same trend. The An content drops sharply in the granophyric diabase and aplite - one aplite norm gives An_0. Plagioclase varies in amount in the sections from about 30 per cent to a little over 50 per cent, being least abundant in some olivine - hypersthene diabases, and most abundant in the quartz and varied texture phases.

Pyroxenes: Hriskevich found remarkably little variation in the composition of hypersthene or augite in the Colonial Mine, although the former was a little more iron rich near the base and again toward the top (especially the rims of the grains) than in the middle of the hypersthene zone. Compositions given were - hypersthene about $Mg_{73}:Fe_{27}$, augite about $Ca_{39}Mg_{51}Fe_{10}$.

The data for the major constituents are summarized in Table 4.

Minor constituents - primary minerals: Biotite occurs as small reddish-brown flakes in all phases of the diabase; amounts are rarely over 1 per cent. Apatite occurs in all phases except the olivine - hypersthene phases and is most abundant in the coarser phases of the

TABLE 4. Major mineral constituents of the phases of the Nipissing diabase.

	Minerals					
Phase	Quartz	Plagioclase	Augite	Pigeonite	Hypersthene	Olivine
Upper chilled diabase	x	x	x			
Varied texture diabase	x	x	x	x		
Quartz diabase	x	x	x	x		
Quartz-hypersthene diabase	x	x	x		x	
Olivine-hypersthene diabase		x	x		x	x
Fine grained diabase	x	x	x	x		x
Lower chilled diabase	x	x	x			x

varied texture diabase and in granophyre and aplite.

Spectrographic Data

Composition of the chilled phase

The composition of the chilled phase of intrusives is commonly considered to represent the original composition of the magma. Therefore, samples were taken from this phase when it was encountered both in the sections and on the surface, so that an estimate of the magma composition could be made. Analyses of these samples are presented in Table 5, along with others from Hriskevich.

Inspection of the table shows that some of the samples differ markedly from the general pattern with respect to one or more elements. Sample 227, for example has high Na_2O, Ti and Mn compared with the other samples, and as will be seen later, is anomalous in the section in which it occurs, even though there is no apparent difference between it and 228 in thin section. Similarly, Hriskevich did not see any obvious reason for the deviation of 114, but felt that it should not be used in calculating the average composition of the chilled phase. One reason for the anomalous samples may be contamination from carbonate and aplite veins which commonly occur along or near the contact of the Nipissing.

The "average" chilled phase composition which appears in Table 5 was calculated from the ten analyses which are most alike (indicated #). Values for the minor elements are averages for the eight samples from the

TABLE 5. Analyses of the chilled phase of the Nipissing diabase.

Sample number	MgO %	FeO^b %	CaO %	Na$_2$O %	Ni ppm	Co ppm
312^a#	7.5	9.4	10.9	1.74		
166^a#	7.5	9.5	11.5	1.83		
114^a	9.0	10.6	5.7	2.88		
234#	7.6	7.3	8.1	1.88	78	40
227	10.0	11.2	5.8	3.10	90	48
228#	10.0	8.5	11.1	2.05	94	51
151	10.0	7.7	3.5	2.75	94	43
152	8.9	6.5	1.1	4.10	59	31
153#	9.9	7.4	6.4	2.70	59	36
154#	8.4	8.2	10.1	2.28	78	57
81#	9.3	7.0	9.4	1.45	112	40
82#	7.6	6.2	8.6	1.64	62	34
83#	8.0	9.5	10.1	2.25	78	44
84	9.7	7.4	7.8	2.68	78	40
94#	8.9	8.9	8.6	2.60	88	49
Average	8.5	8.2	9.5	2.04	81	44

a - Analyses from Hriskevich (1952)
b - Total iron as FeO
- Analyses used in calculating the average

Mn ppm	Cu ppm	Ti ppm	V ppm	Mafic Index	Felsic Index	Sample number
				56	14	312
				56	14	166
				54	33	114
1400	83	1480	156	49	19	234
4500	4	2370	196	53	35	227
2450	113	2510	174	46	16	228
1120	35	2240	193	44	44	151
560	2	4200	220	42	79	152
1900	72	1360	143	43	30	153
1130	102	2660	213	49	18	154
860	71	1700	180	43	13	81
1120	75	1420	125	45	16	82
1380	133	5400	300	54	18	83
2500	8	1870	149	43	26	84
1440	116	2430	196	50	23	94
1460	96	2370	186	49	18	

present study.

Analyses of the sections

Analyses of the samples from the Rix section and the Nasco section are presented in Tables 6 and 7. The same data are shown in graphical form in Figures 5 and 6. Boundaries of the different phases of the diabase as determined from the petrographic work are indicated.

In order that trends in the data would be more obvious, a smoothing technique was used which gave the "moving average" curves shown in Figures 5 and 6. The technique involves the calculation of what may be called "weighted moving averages" and to the writer's knowledge has not previously been used in studies of this kind.

Calculation of Weighted Moving Averages

Moving averages are commonly used in time series studies in economics (Mills, 1955; Yule and Kendall, 1950) as a means of reducing the effects of minor fluctuations so that trends are clarified. In its simplest form the technique may be expressed as follows

$$\text{average } x_a = \frac{(x_1 + x_2 + \ldots\ldots\ldots\ldots x_n)}{n}$$

$$\text{average } x_b = \frac{(x_2 + x_3 + \ldots\ldots\ldots\ldots x_{n+1})}{n}$$

Thus averages are taken of a desired number of pieces of data in a series as one moves down the series. In economics the data are usually evenly spaced, say one year apart.

In the present case, however, the samples are not

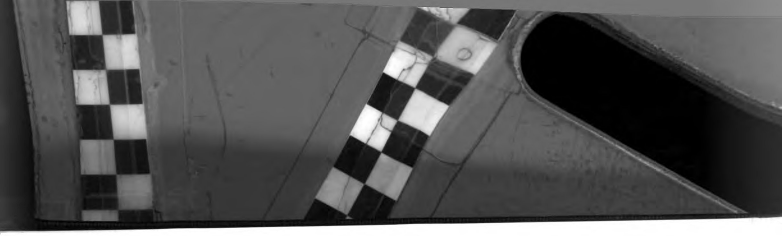
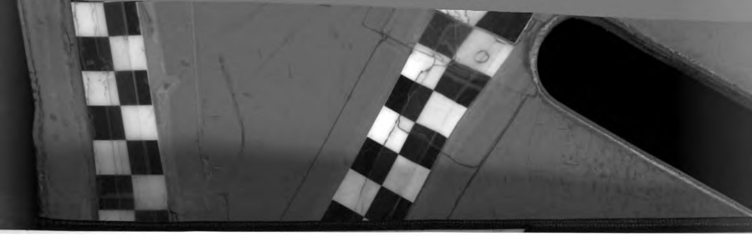


TABLE 6. Spectrographic analyses - Rix section.

Sample number	MgO %	FeO[a] %	CaO %	Na_2O %	Ni ppm	Co ppm
234	7.6	7.3	8.1	1.88	78	40
233	10.3	9.2	11.4	1.90	104	59
232	7.6	11.2	8.2	2.33	58	61
231	8.7	7.9	8.7	1.70	82	43
230	8.7	6.7	9.6	1.56	94	49
229	10.2	6.2	10.5	1.68	94	35
201	6.8	8.8	9.3	2.18	78	55
202	6.9	6.9	9.1	1.89	67	45
203	9.6	8.2	8.0	1.19	170	64
204	7.6	7.0	11.5	1.56	115	49
205	7.1	6.0	10.3	1.49	93	39
206	10.0	7.1	10.7	1.38	163	49
207	8.4	6.5	8.8	1.32	142	53
208	15.4	8.2	13.5	1.13	243	59
209	11.8	6.9	8.3	.96	310	66
210	12.2	6.6	11.9	.91	242	57
211	13.2	7.6	11.5	.95	380	71
212	11.0	6.7	14.5	1.20	272	61
213	15.8	8.4	11.9	1.00	610	99
214	14.3	7.4	13.3	1.22	293	60
215	15.3	9.9	9.3	.41	680	133
216	9.4	5.6	8.0	1.18	243	56
217	10.8	6.4	10.8	1.12	310	65
219	11.7	7.7	7.9	1.15	320	77
220	9.6	6.8	9.1	1.52	206	60
221	9.5	7.8	9.0	1.64	248	65
222	9.8	8.0	10.0	1.50	250	71
223	12.9	8.8	8.1	1.72	460	95
224	10.3	7.2	10.0	1.56	200	59
225	11.5	8.3	9.9	1.25	173	52
226	11.3	7.6	9.9	1.60	150	47
227	10.0	11.2	5.8	3.10	90	48
228	10.0	8.5	11.1	2.05	94	51

a - Total iron as FeO



Mn ppm	Cu ppm	Ti ppm	V ppm	Mafic Index	Felsic Index	Sample number
1400	83	1480	156	49	19	234
2010	92	2980	225	47	14	233
2540	12	3300	245	60	22	232
1500	91	3100	208	48	16	231
1380	83	1400	133	44	14	230
1130	61	960	101	38	14	229
1670	118	1870	175	56	19	201
1600	115	2140	151	50	17	202
1580	71	1390	145	46	13	203
1060	48	1770	149	48	12	204
1020	96	1050	112	46	13	205
1040	71	960	125	42	11	206
1020	57	610	88	44	13	207
1150	71	1080	112	35	8	208
970	36	520	93	37	10	209
830	36	690	108	35	7	210
970	29	610	127	37	8	211
1000	32	1110	148	38	8	212
1000	43	780	112	35	8	213
1080	46	920	113	34	8	214
940	35	680	101	39	4	215
770	27	650	93	37	13	216
700	16	900	119	37	9	217
1020	39	800	111	40	13	219
1180	56	960	124	42	14	220
1360	76	1150	123	45	15	221
1180	70	1270	117	45	13	222
1560	90	1120	128	41	18	223
1220	65	1420	130	41	13	224
1460	87	1460	145	42	11	225
1040	106	1840	156	40	14	226
4500	4	2370	196	53	35	227
2450	113	2510	174	46	16	228

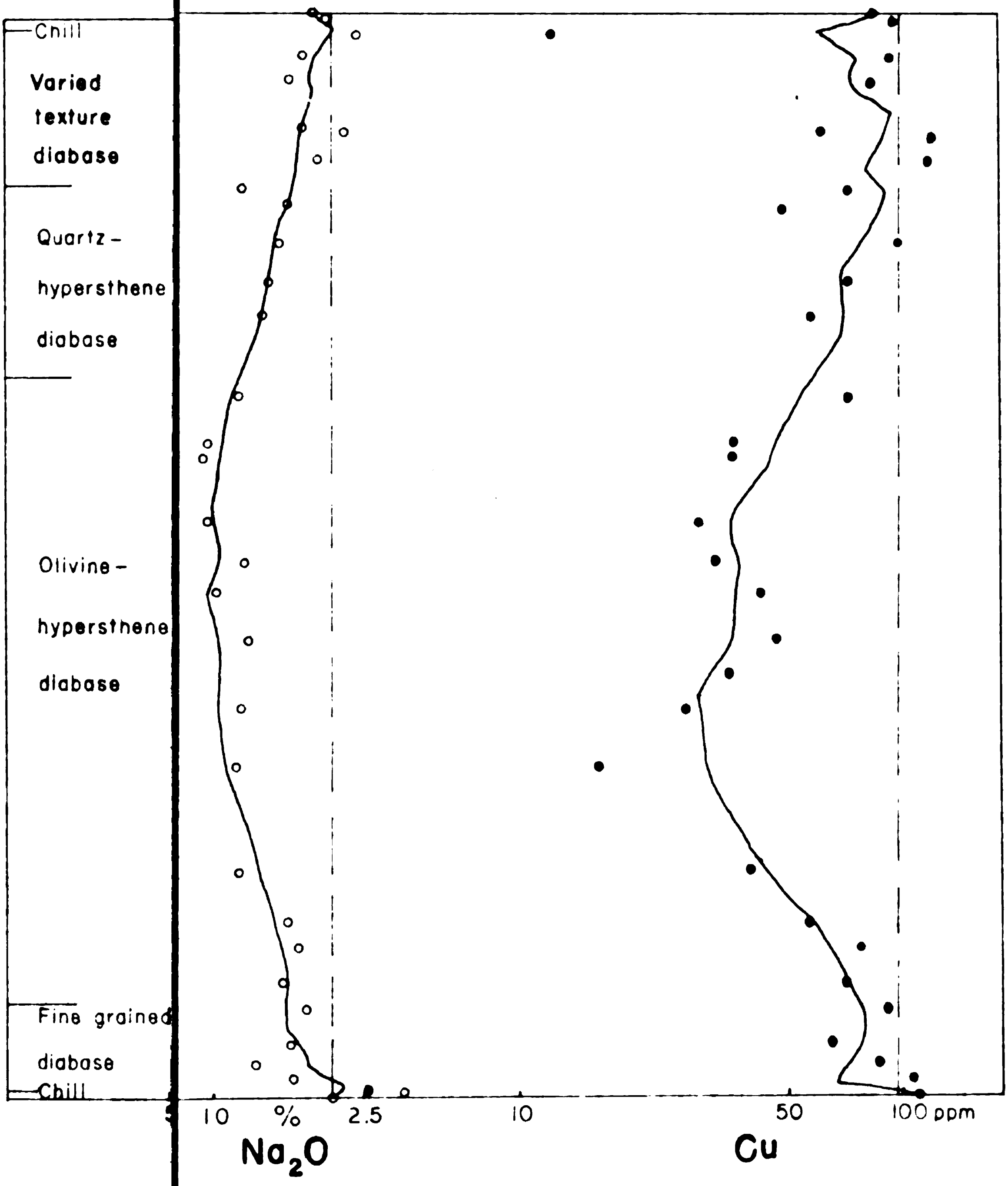
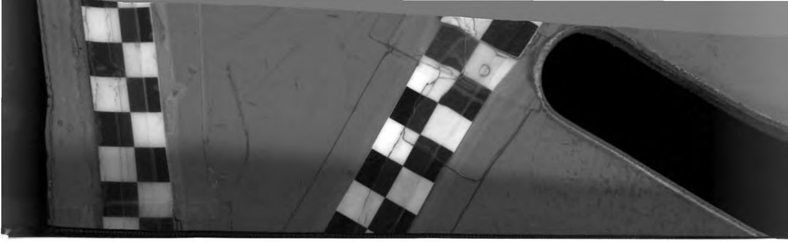

Chill
Varied texture diabase
Quartz-hypersthene diabase
Olivine-hypersthene diabase
Fine grained diabase
Chill
10
%
2.5
10
50
100 ppm
Na_2O
Cu

FIGURE 5.

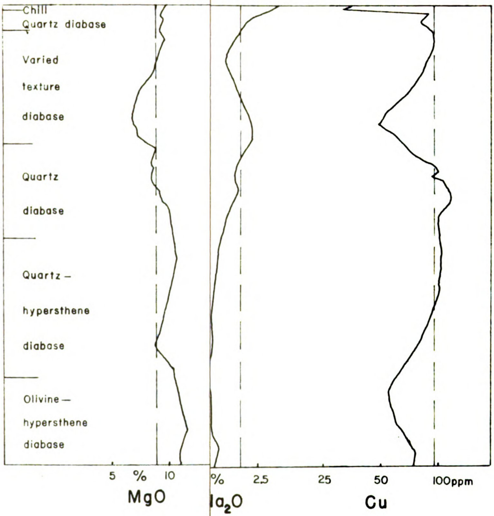
TABLE 7. Spectrographic analyses - Nasco section.

Sample number	MgO %	FeO[a] %	CaO %	Na_2O %	Ni ppm	Co ppm
151	10.0	7.7	3.5	2.75	94	43
152	8.9	6.5	1.1	4.10	59	31
153	9.9	7.4	6.4	2.70	59	36
154	10.8	8.1	9.9	2.90	83	64
155	8.4	8.2	10.1	2.28	78	57
156	9.6	8.0	10.7	1.64	86	51
157	8.6	9.0	10.7	1.90	75	53
158	10.8	8.7	11.5	1.64	106	52
159	7.3	7.6	11.3	1.60	74	52
160	5.4	8.9	9.9	2.02	46	53
161	8.5	10.0	6.0	2.75	43	53
162	3.5	9.7	7.8	2.48	5	51
163	8.8	9.7	9.2	2.46	46	57
164	7.3	9.0	11.6	2.10	56	52
165	9.6	9.6	12.7	1.95	58	61
166	9.2	8.4	8.4	2.23	51	47
167	8.4	9.2	10.7	1.56	61	56
168	7.2	8.1	10.0	1.93	62	51
169	9.3	7.7	4.8	2.20	61	52
170	9.9	7.0	6.4	2.25	66	47
171	8.8	8.4	10.8	1.95	61	57
172	8.4	7.8	12.3	1.89	56	42
173	9.8	8.0	10.0	1.89	67	48
174	9.7	8.7	10.3	1.68	82	62
175	11.5	7.9	11.5	1.75	67	52
176	10.2	8.6	9.9	1.53	93	47
177	10.4	8.3	11.1	1.76	83	45
178	10.3	7.2	10.5	1.45	96	47
179	11.5	9.4	13.6	1.47	131	66
180	8.6	6.5	9.8	1.47	72	42
181	8.0	6.3	10.8	1.56	72	43
182	7.9	6.2	11.0	1.41	83	42
183	9.1	6.5	12.3	1.49	82	44
184	9.2	6.8	13.6	1.42	101	49
185	15.6	9.0	10.1	1.05	563	87
186	11.0	8.8	11.9	1.62	122	57
187	10.6	6.6	9.6	1.68	147	42
188	12.2	7.8	10.4	1.60	213	60
189	11.4	7.5	10.8	1.49	158	58

a - Total iron as FeO



Mn ppm	Cu ppm	Ti ppm	V ppm	Mafic Index	Felsic Index	Sample number
1120	35	2240	193	44	44	151
560	2	4200	220	42	79	152
1900	72	1360	143	43	30	153
1440	118	2940	207	43	23	154
1130	102	2660	213	49	18	155
1310	68	2210	165	46	13	156
1410	104	2990	208	51	15	157
1180	102	2260	180	45	13	158
1410	90	5000	272	51	12	159
1560	44	2800	229	62	17	160
1260	5	3950	193	54	31	161
1560	54	6500	161	74	24	162
1520	40	2950	220	52	21	163
1850	96	3400	207	55	15	164
1670	140	3700	237	50	13	165
1560	66	2140	151	48	21	166
1380	93	2540	196	52	13	167
1240	96	2140	181	53	16	168
1080	115	3200	233	45	31	169
1100	87	2480	180	41	26	170
1540	155	2380	183	49	15	171
1040	104	2540	157	48	13	172
1560	113	1860	143	45	16	173
1400	106	1390	191	47	14	174
1000	85	1280	132	41	13	175
1320	106	1800	135	46	13	176
1060	108	1990	180	44	14	177
1260	107	1550	172	41	12	178
1460	106	2140	204	47	10	179
990	86	1200	113	43	13	180
1280	123	1460	101	44	13	181
770	65	1340	127	44	11	182
770	65	1420	107	42	11	183
890	57	1710	149	43	10	184
1120	38	1560	184	37	9	185
1260	61	1740	184	44	12	186
1180	70	1120	111	38	15	187
1500	83	1710	135	39	13	188
1120	75	1710	133	40	12	189



— — — Avera

FIGURE 6. Chemical variation

equally spaced. Samples were therefore weighted according to their "distance of influence" which was taken to be half the distance to the preceding sample plus half the distance to the next sample. This latter technique is commonly used in determining average values of sections for ore calculations. The purpose here is analogous.

The number of samples to be averaged was arbitrarily set at five and examination of the results shows that this seems to have removed the minor fluctuations without also obscuring any major trends, as a longer average would have. The first and last "averages" in each curve are the values for the first and last samples, while the second and second last averages are weighted averages of the first three and last three samples respectively.

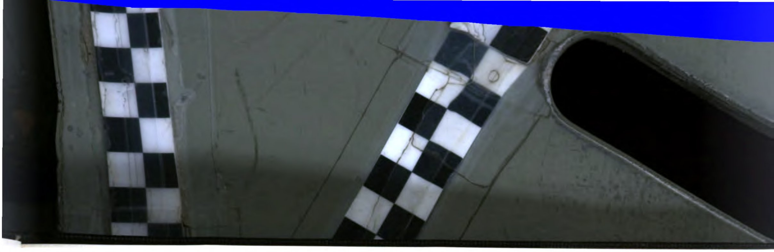
The equation used in calculating the weighted moving averages was

$$\text{average} = \frac{\sum_{n}^{n+4} x \quad \text{D.I.}}{\sum_{n}^{n+4} \quad \text{D.I.}}$$

where x is the concentration of the element
D.I. is the distance of influence.

The averages were plotted at the center of the distance of influence and therefore do not necessarily fall at any sample location.

If the moving average curves are compared with the individual analyses it will be seen that the technique appears to give a satisfactory representation of the overall variation in each section.



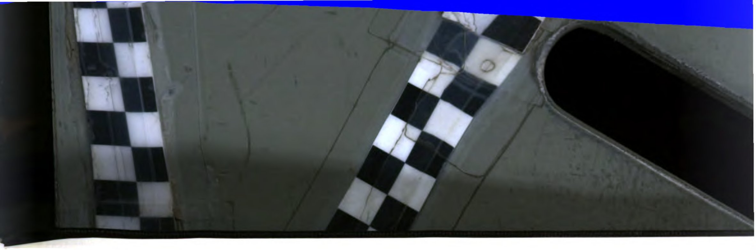
It will be noted in Figures 5 and 6 that element concentrations have been plotted on a logarithmic scale. This method allows comparison of the relative variation of elements no matter what their concentration range may be.

Trends of elements in the sections

The amount of MgO is, as was to be expected, greatest in the olivine-hypersthene zone and lowest in the quartz bearing zone. It is noteworthy that the percentage of MgO over the whole of the Rix section is generally higher than the assumed magma composition - a weighted average for the whole section gives 11.0 per cent MgO as compared with 8.5 per cent for the chilled diabase. The Nasco section also has more MgO than the chilled diabase - 9.6 per cent overall. The trend of nickel is quite similar to that of magnesium, but the concentration difference between the olivine-hypersthene and quartz phases is more marked.

As with MgO, the average concentration of nickel in the two sections is greater than that of the chilled diabase - 250 ppm in the Rix section and 109 ppm in the Nasco section as compared to 81 ppm in the chilled diabase.

Cobalt also appears to follow the MgO trend in both sections, but with less variation between the different phases. Again the overall concentration in both sections is above the average chilled diabase - Rix 63 ppm, Nasco 53 ppm, chill 44 ppm.



Iron shows almost no variation in the Rix section - the average FeO concentration in the olivine-hypersthene diabase is practically identical to that in the quartz diabase, while the overall average in this section is less than the chilled diabase - 7.4 per cent vs 8.2 per cent. The olivine-hypersthene and quartz-hypersthene diabase of the Nasco section have FeO concentrations similar to the same phases in the Rix section while some relative enrichment is evident in the quartz diabase. The average FeO content of the Nasco section, 8.1 per cent, is nearly the same as that of the chilled diabase.

Calcium is enriched in the upper part of the olivine-hypersthene diabase in the Rix section; otherwise it is close to the average chilled diabase - the overall concentration at 10.2 per cent is above that of the chilled diabase (9.5 per cent). Calcium is enriched in nearly all of the Nasco section with the exception of the varied texture portion of the quartz diabase. The overall average is 10.7 per cent.

The trend of sodium is almost directly opposite to that of calcium. Its concentration in both sections is below that of the chilled diabase (Rix 1.32 per cent; Nasco 1.74 per cent; chilled diabase 2.04 per cent).

Vanadium, titanium, and manganese follow generally similar trends. They are impoverished in the quartz-hypersthene and olivine-hypersthene diabase, especially in the Rix section, and are distinctly enriched in the

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varied texture phase of the quartz diabase, especially in the Nasco section. Overall averages are Rix- V-169 ppm; Ti-1130 ppm; Mn-1165 ppm; Nasco- V-169 ppm; Ti-230 ppm; Mn-126 ppm, while the chilled diabase averages are V-186 ppm, Ti-1940 ppm; Mn-1460 ppm. The anomalous Mn content of sample 227, mentioned previously, is clearly seen in the section.

Copper is similar to vanadium, titanium and manganese in that it is below the average chilled diabase in the olivine-hypersthene and quartz-hypersthene diabase, but it is enriched in the quartz diabase rather than in the varied texture diabase where its concentration is again below the average. Overall averages are Rix 56 ppm, Nasco 83 ppm, chilled diabase 96 ppm.

Mafic and felsic indices

Mafic and felsic indices have been used by Wager and Deer (1939) and others as a means of showing the relative "acidity" of differentiates of intrusions. The mafic index given in the tables is the ratio of total iron as FeO to the sum of MgO and total iron as FeO, or

$$\text{Mafic index} = \frac{FeO}{MgO + FeO}$$

The felsic index is the ratio of Na_2O to the sum of CaO and Na_2O, or

$$\text{Felsic index} = \frac{Na_2O}{CaO + Na_2O}$$

The felsic index differs from those calculated elsewhere

in that potassium is not included, since it could not be determined.

The variation in mafic index in the sections is somewhat more regular than the variation in felsic index and therefore is used more often later. The indices clearly show the enrichment of iron and sodium relative to magnesium and calcium in the more acidic phases.

Differentiation of the Diabase

Introduction

In this section the petrographic data and the spectrographic analyses of the major elements will be examined for the evidence they provide regarding the differentiation of the Nipissing in the Cobalt area. The minor element data will be used only where necessary, as the intent is to establish the trend of differentiation from the other evidence and then relate this trend to the behavior of the minor elements.

Composition and nature of the magma

On the basis of his study of field and petrographic relations, Hriskevich concluded that the Nipissing was intruded as a highly fluid magma, citing as evidence the following;

1. The individual sheets are of considerable extent and maintain a relatively constant thickness.
2. Phenocrysts are rare even in the chilled diabase, and those that are present show no sign of any flow structure, nor is there any flow structure in the

rest of the intrusion.

3. The accumulation of olivine in the basins could not have occurred in a very viscous magma.

He further concluded from comparison of orthopyroxene-pigeonite compositions with the experimentally determined orthopyroxene-pigeonite inversion curve that the original temperature of the magma was about 1120°C and that the major part of the crystallization occurred during a temperature drop of about 35°C.

There is nothing in the present data that contradicts any of these conclusions. The absence of flow structures has been noted although there is a suggestion of some alignment of some of the large orthopyroxene plates in a few of the sections. The relatively fine grained nature of most of the rock and the presence of olivine in the quartz-bearing diabase near the base of the Rix section would seem to indicate that once crystallization began, it proceeded fairly rapidly. The dike-like form of some granophyres and aplites indicates, however that the late liquids were mobile for some time after most of the diabase had solidified.

In view of the apparent fluidity of the original magma, it seems likely that the average composition of the chilled diabase calculated earlier reasonably represents the composition of that magma. The only case in which the chilled phase composition has been thought to differ from the magma was in Olmsted's (1966) study of the Mineral

Lake intrusion. In that instance, however, there was strong evidence from fluxion structures and broken crystals that the magma was partically solid when it reached the level from which the chilled sample was taken. Consequently, the liquid that formed the chilled phase was already the product of strong differentiation.

The magma composition as determined from the chilled diabase average agrees well with the petrographic classification of the Nipissing as a tholeiitic quartz diabase (Turner and Verhoogen, 1960) in that it is similar to that of other intrusions of tholeiitic affinity. Table 8 shows the comparison in composition of the Nipissing with other intrusions. A distinctive feature of the Nipissing is the low Ti content; in this respect it is more like the thick Stillwater and Bushveld intrusions than the sill-like Palisades, Karroo dolerites, and Tasmanian dolerites.

Trend of Differentiation

The vertical distribution of phases in the sections through the Nipissing sheet is generally similar to that found in other basic intrusions thought to have been differentiated by fractional crystallization and gravitational differentiation in that the early-formed mafic minerals are concentrated in the lower part of the sections and the late, felsic minerals are most abundant near the top. The extreme fractionation that gives rise to essentially monomineralic phases in thick intrusions such as the Skaergaard, Bushveld, Stillwater, and Mineral Lake did not

TABLE 8. Composition of chilled phase of some intrusions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
SiO_2		50.7	51.5	47.9	52.5	52.2	53.2
Al_2O_3		17.6	18.7	18.9	15.4	15.4	15.4
Fe_2O_3		.3	.3	1.2	1.2	1.6	.8
FeO	8.2[a]	9.9	9.0	8.7	9.3	8.7	8.3
MgO	8.5	7.7	6.8	7.8	7.1	7.3	6.7
CaO	9.5	10.5	11.0	10.5	10.3	10.0	11.0
Na_2O	2.0	1.9	1.6	2.4	2.1	2.4	1.7
K_2O		.2	.1	.2	.8	.8	1.0
TiO_2	.4	.5	.3	1.4	1.0	1.3	.7
MnO	.2	.2	.5	.1	.2	.1	.2

a Total iron as FeO

(1) Average Nipissing chilled diabase (this study)
(2) Stillwater border facies (Hess, 1960)
(3) Bushveld (Hess, 1960 after Daly, 1928)
(4) Skaergaard (Wager and Deer, 1939)
(5) Average Karoo dolerite (Walker and Poldervaart, 1949)
(6) Average Palisade chilled basalt (Walker and Poldervaart, 1949)
(7) Average Tasmanian chilled dolerite (McDougall, 1962)

have time to develop fully in the more-rapidly crystallized Nipissing. In this respect the Nipissing is much like the Palisades, and both were classified by Hess (1960) in his "thick sill" group.

While the general trend of differentiation in the Nipissing conforms to that of other intrusions, there are important differences to be seen on detailed comparison. If the Rix section is compared with the section of the Palisades sill given by Walker (1940) it will be noted that the most basic portion, defined on the basis of mafic index and presence of olivine occurs about 450 feet above the base in the Nipissing, whereas it is close to the chilled zone in the Palisades sill. Since the later is the normal case, and is to be expected as a result of the gravitational settling of the earliest, more magnesian olivines, it is clear that some other factor must have been operating in the Nipissing in addition to vertical gravitational differentiation.

The answer to this would seem to lie in the fact that the Nipissing shows lateral as well as vertical variation. This was clearly demonstrated by Hriskevich (Figure 4), and is further confirmed by the present data. The Rix section, which would appear to be typical of a section in the deepest part of a basin has an overall composition considerably more basic than the original magma (average chilled diabase). This is evidenced by the higher MgO and lower FeO content, as well as by the distinctly lower

Na_2O content of the Rix as compared to the magma. The Nasco section appears to be representative of a section part way between a basin and an arch. While this section is not complete, it is definitely more acid than the Rix section, as is shown by the greater thickness of quartz and varied texture phases. The MgO and FeO content is closer to that of the chilled diabase. The Na_2O, while also closer to the magma is still definitely lower. A section at the top of an arch was not available in the Cobalt area. Obviously, it would, as suggested by Hriskevich, have to be more acid than the Rix or Nasco sections if the whole intrusion is to have the same composition as the chilled diabase. The possible composition of the "acid section" will be estimated later. Since this involves a number of assumptions, it seems best to examine the nature of differentiation on the basis of the observed data at hand.

The explanation for the lateral as well as vertical differentiation would appear to lie in the assumption, supported by field evidence, that the sheet had its undulating character when the magma was cooling. It would be expected that the lighter constituents would not only rise vertically, but would also move laterally to where the roof of the sheet had a higher elevation, in other words toward the arches. The mafic constituents, on the other hand, would tend to move downward and laterally toward the deeper part of the basins.

Taking into account the apparent vertical and lateral movements the writer suggests that the course of differentiation of the Nipissing proceeded as follows;

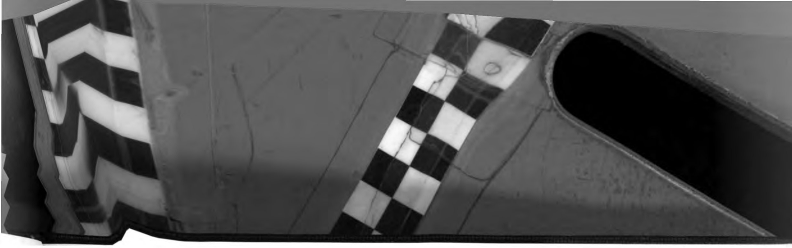
1. The chilled diabase formed by the rapid crystallization of undifferentiated magma.
2. Vertical differentiation shifted the composition in the lower part of the sheet so that olivine became a stable constituent. It also is possible that the appearance of hypersthene is due to this shift to a more magnesian composition and not solely to temperature drop as Hriskevich suggested.
3. The lateral, upward movement developed more slowly than vertical differentiation. It further shifted the magma composition in the lower part of the sheet so that more magnesian olivines and slightly more calcic plagioclases were crystallized. This trend reached a limit in the Rix section at about 450 to 500 feet above the base, judging from the mafic and felsic indices, and at about 300 feet above the base of the Nasco section (assuming the sheet to be 1100 feet thick here as it is in the Rix section).
4. Further crystallization followed the normal trend of iron and sodium enrichment relative to magnesium and calcium. The iron enrichment is clearly seen in the trend of the mafic index in the Rix section, say from sample 208 to sample 201

(Table 6), and in the Nasco section from sample 185 to sample 162. The sodium enrichment may be seen in the felsic indices for the same samples, but is seen more dramatically in granophyric diabase and aplite analyses (Table 11). That enrichment in water, and possibly other volatiles, occurred is suggested by the varied texture diabase and diabase pegmatites. Granophyric diabase would be expected in more acid sections near the arches - a little occurs in the Nasco sections (samples 161 and 162). The usual occurrence of aplite as dykes and veinlets suggests that it was still a liquid when the sheet had crystallized to the extent that cooling fractures began to develop and that the aplite followed these fractures toward the edge of the sheet and into the host rocks. If the silver-bearing carbonate fluids also are differentiated from the diabase, as Hriskevich and others have considered them to be, they appear to have been emplaced in the same way.

Composition of the "Acid" Section

It has already been noted that an example of a section at the top of an arch, which would be expected to contain the highest proportion of acidic phases, was not available in the Cobalt area. Its possible composition can, however, be estimated from the present data if a number of assumptions are made.

1. The overall composition of the sheet is the same



as the chilled diabase.

2. The Rix section is typical of the most basic sections and the Nasco section is typical of the upper part of an intermediate section.

3. Since the sheet is of fairly uniform thickness, its thickness in the Nasco section area is assumed to be 1100 feet. The sampling covered the upper 975 feet. Examination of the lower part of the Rix section suggests that it would not be unreasonable to assume that the remaining 125 feet has an average composition close to the average of sample 189 and the chilled diabase. The calculation of the overall composition of the extended Nasco section on this basis is shown in Table 9.

4. The location of the Nasco section relative to its distance up the side of a basin is unknown. For reasons that will be apparent later, it was assumed to be one-quarter of the way up the side of a typical basin.

If these assumptions are made the concentration of each element in an "acid" section can be calculated as shown in Table 10. The results are shown diagrammatically in Figure 7.

It will be noted that the calculation for nickel gives a negative value for the "acid" section. A positive value can be obtained by moving the Nasco section deeper into the basin or by assuming that the nickel trend is as

TABLE 9 - Calculation of extended Nasco section

	Analysed portion 975'	Average of 189 & chilled diabase 125'	Composition of extended section
MgO %	9.6	10.0	9.6
FeO %	8.1	7.9	8.1
CaO %	10.7	10.2	10.6
Na_2O %	1.74	1.77	1.74
Ni ppm	109	120	110
Co ppm	53	51	53
Mn ppm	1260	1290	1270
Cu ppm	83	86	83
Ti ppm	2300	2080	2280
V ppm	169	160	168

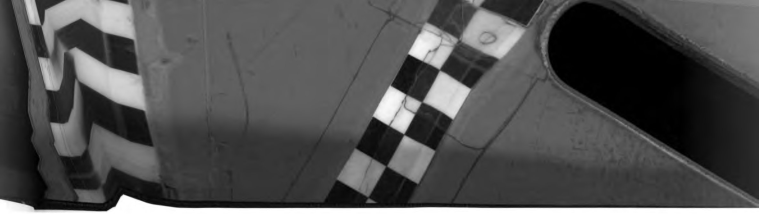


TABLE 10. Composition of acid section - from other sections

	Rix section	Nasco section (extended)	Acid section
MgO %	11.0	9.6	6.1
FeO %	7.4	8.1	8.6
CaO %	10.2	10.6	7.9
Na_2O %	1.32	1.74	2.64
Ni ppm	250	110	-14
Co ppm	63	53	24
Mn ppm	1170	1270	1820
Cu ppm	56	83	126
Ti ppm	1130	2280	2900
V ppm	125	168	230

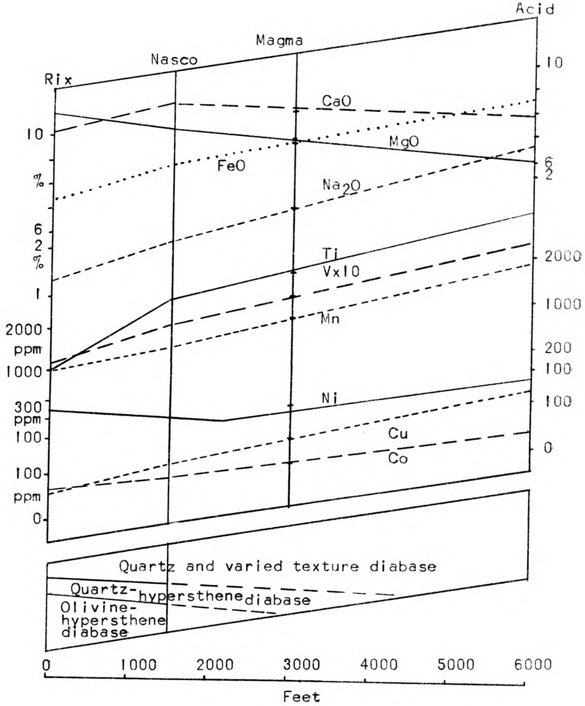


FIGURE 7. Chemical variation between Rix, Nasco, and "acid" sections.

shown in Figure 7, paralleling the rapid decrease in olivine-hypersthene diabase and then nearly constant in the more acid part of the sheet. This seems to be reasonable in view of its fairly constant concentration in the quartz and varied texture phases of the Nasco section. No change was made therefore in the position of the Nasco section.

The question now arises as to whether the composition of the "acid" section is reasonable. In an attempt to test this, the writer prepared a diagram (Figure 8) showing the possible distribution of known phases of the diabase. In arriving at this distribution it was assumed that the olivine-hypersthene and quartz-hypersthene phases would continue the rate of decrease they show between the Rix and Nasco sections. Estimation of the amount of granophyre and aplite presented a problem because the proportion of these phases has not been accurately determined anywhere in the Nipissing, although Collins (1917) considered the amount of aplite to be less than one per cent. In other intrusions, Hess estimated that the Stillwater magma could have produced about 2 per cent granite; Olmsted, by measuring the area exposed in the Mineral Lake intrusion, considered 7.7 per cent "granite and transition" to be present; Grout (1947) suggested that differentiation of basaltic magma could yield a maximum of 10 per cent granite by volume.

In the case of the Nipissing, however, much material of granitic composition would not be expected as differentiation is not as strong as in thicker intrusions. This is

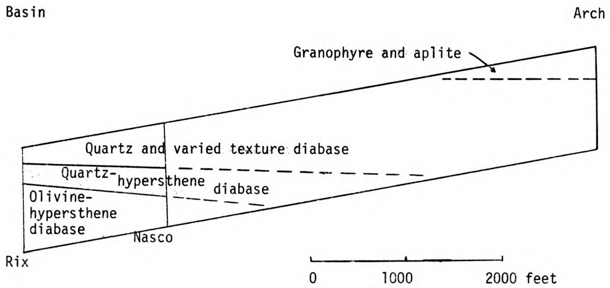
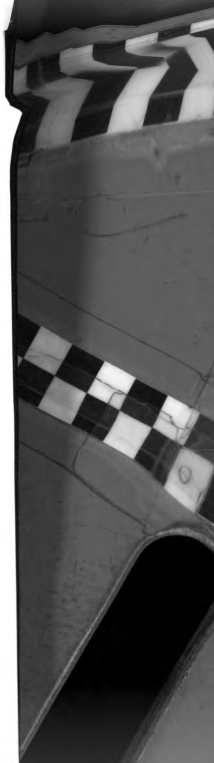


FIGURE 8. Hypothetical section showing distribution of phases in the Nipissing diabase at Cobalt



substantiated by the presence of micrographic quartz-feldspar intergrowths throughout the quartz-diabase phase.

With these poor guide lines, the writer has arbitrarily assumed that the Nipissing contains about 5 per cent total aplite and granophyre; I per cent aplite and 4 per cent granophyre, distributed as shown in Figure 8. This means that the acid section would have about 30 per cent aplite and granophyre. As no complete analyses of either phase were made in the present study, analyses quoted by Hriskevich were used to determine the average composition of these phases, as shown in Table II. The remaining 70 per cent of the acid section was first assumed to have the same composition as the quartz diabase of the Nasco section. Combination of this with the aplite, and granophyre yields a slightly more basic rock than that previously calculated for the "acid" section. Since it is likely that the quartz diabase would be more acid near the upper part of the section another calculation was made assuming the 70 per cent to have the composition of the varied texture diabase of the Nasco section. It will be seen from Table 12 that the result is remarkably close to the "acid" section calculated from the chemical data alone, in other words, the latter corresponds to a possible combination of observed phases.

In view of the lack of an actual "acid" section it is not possible to assess whether the assumed section corresponds with nature. Several suggestions however may be considered.

TABLE II. Analyses of granophyre and aplite

	Granophyre[1]	Aplite[2]
MgO %	3.9	.9
FeO[3] %	10.5	2.2
CaO %	3.7	.9
Na_2O %	5.97	6.90
Ti ppm	5400	3000

1. Average of analyses 7,8,10,11,21 (Hriskevich, 1952)
2. Average of analyses 12,13,14 (Hriskevich, 1952)
3. Total iron as FeO

TABLE 12. Comparison of acid sections

	Acid section calculated from other sections	Acid section 30% granophyre and aplite 70% Nasco varied texture
MgO %	6.1	6.4
FeO %	8.6	8.9
CaO %	7.9	7.9
Na_2O %	2.64	3.29
Ti ppm	2900	4.00

1. The "acid" section before any differentiation would most likely have had the average magma composition.

2. Some vertical differentiation seems to have occurred in the Nasco and Rix sections before the lateral differentiation became effective.

These two points suggest that the acid section might contain some material more basic than the varied texture diabase of the Nasco section, and it would seem that is an error has been made in the nature of the phases in the "acid" section it has been in assuming the lower 70 per cent to be more acid than it probably would be. This in turn indicates that the assumed amount of granophyre and aplite is probably not excessive.

Behaviour of minor elements during differentiation

If it is assumed that the trend of differentiation shown by the petrography and major elements has been correctly interpreted, some inferences may be drawn about the behaviour from their distribution of minor elements during differentiation.

Nickel shows a greater range of concentration in the sections than any of the other elements studied. Its concentration in the original magma as judged from the chilled diabase, was 81 ppm. The trend of nickel is much like that of magnesium but more pronounced as is obvious from Figure 5, indicating that nickel is preferentially incorporated in the more basic rocks, particularly the olivine-hypersthene diabase. Studies on individual minerals in other intrusions by Nockolds and Mitchell (1949), DeVore (1955), and Wager and Mitchell (1951) indicate that most of the nickel occurs in the olivines, lesser amounts in the orthopyroxenes and clinopyroxenes and very little in the feldspars. Values given by DeVore suggest the relative distribution to be about olivine 100; orthopyroxene 30; clinopyroxene 20; with higher concentrations in all cases in the more magnesian members. The enrichment of nickel relative to magnesium in early olivines has been noted by Wager and Mitchell (1951), and suggests that Ni-olivine is more stable than Mg-olivine. This is supported by data on the unit cell size of Ni-olivine given in Table 13, but both of these observations are surprising in view of the lower melting point of Ni_2SiO_4- 1620°C compared to 1890°C for Mg_2SiO_4. Ringwood (1956) has suggested that in natural olivines the presence of iron may lower the thermal stability enough that the nickel enters the structure in preference to magnesium and replaces some of the iron. Clearly, the problem is not conclusively resolved, but the observed pattern cannot be denied, for it has appeared in every study of basic intrusions.

The entry of nickel into the basic rocks in excess of its concentration in the liquid results in its rapid decrease in later phases, as is clearly shown in the trend. Hriskevich (1952) found very little nickel in the aplites, but some is present in the carbonate veins, which he interpreted

TABLE 13. Unit cell size and melting point of some olivines

	Cell parameters			m.p.
	aÅ	bÅ	cÅ	°C
Ni_2SiO_4	4.71	10.11	5.91	1620
Mg_2SiO_4	4.76	10.20	5.98	1890
Co_2SiO_4				1345
Fe_2SiO_4	4.82	10.48	6.11	1205
Mn_2SiO_4	4.86	10.60	6.22	

Sources: Deer, Howie and Zussman (1963)
Ringwood (1956)
Handbood of Chemistry and Physics, 47th ed. (1966)

as the final differentiate. It would appear from this that nickel may be excluded from late minerals, to the extent that its concentration in the liquid rised again in the final stage. Wager and Mitchell (1951) noted this same late rise in the Skaergaard.

Cobalt exhibits somewhat the same trend as nickel and magnesium but its enrichment in the basic rocks is much less than either of these. Studies by others on minerals show the same tendency. DeVore's data suggest that the relative distribution of Co in olivine, orthopyroxene and clinopyroxene is in the proportions 100:50:40. Wager and Mitchell found no cobalt in plagioclases while noting its presence in coexisting pyroxene, ilmenite, magnetite and olivine, the latter having the higher concentration, especially in the earlier phases. They noted a similarity in the trends of cobalt and iron during the course of differentiation. The present data suggest that Co-olivines and pyroxenes should be a little more stable than the iron forms but less stable than those containing Mg. This is supported by melting point data on olivines given in Table 13.

On the basis of the unit cell sizes one would expect manganese to enter olivine and pyroxenes less readily than iron. This is supported by the data of Wager and Mitchell - they note enrichment of manganese in the late olivines and pyroxenes, with both containing about the same amount. The presence of minor amounts in plagioclase and

apatite led them to the conclusion that manganese may substitute for calcium as well as for iron. The results of the present study confirm that manganese enters the early phases in lesser amounts than its concentration in the magma, with the result that it builds up in the magma and appears in greater concentrations in late phases. The trends of copper in the Rix and Nasco sections agree well with the findings of Wager and Mitchell (1951) and show that copper in early minerals is less than the magma concentration but soon rises to a level about the same as the magma. The few values for acidic rocks indicate a sharp drop in copper in late phases. Wager and Mitchell concluded, from their mineral analyses, that copper enters pyroxene, plagioclase, olivine, magnetite, ilmenite and apatite, probably proxying for ferrous iron and sodium, as well as forming sulphides, in late stages of crystallization. While no chalcopyrite was noted in any of the rocks in the sections, it does occur in places in the Nipissing.

The trends of V and Ti are remarkably similar - both seem to have been excluded from the early rocks and, especially in the case of Ti, enriched in the varied texture diabase. Wager and Mitchell found that in the Skaergaard some Ti entered early clinopyroxenes but the amount was less than that in the magma, with the result that Ti accumulated in the magma until ilmenite was precipitated. The same situation seems to apply here. The early rocks - olivine and hypersthene phases contain less Ti than the chilled diabase. It may occur in the augites, but some probably also occurs in the rare iron oxides. The latter increase considerably in the varied texture diabase, where exsolution phenomena in the iron oxides indicate the presence of ilmenite. The chemical analyses of granophyric diabase, quoted by Hriskevich, indicate that the above average Ti continues into this stage, while the lower values in the aplite suggest that, as Wager and Mitchell indicate, the magma became depleted in Ti in its final stages of crystallization. The same explanation probably applies to vanadium as this is indicated by Wager and Mitchell's data. They found, however, that most of the V in the oxides occurred in the magnetite, presumably replacing ferric iron - in one instance 2000 ppm, was found in magnetite compared to 6000 ppm - 200 ppm and <5 ppm in coexisting ilmenite, clinopyroxene and olivine. In view of the much greater abundance of augite than oxides in the rocks of the present study, it is likely that much of the V and Ti in the rock is in the pyroxene even though the oxides are richer.

CHAPTER IV

REGIONAL VARIATION

Introduction

In this section the petrographic and spectrographic data for the regional samples are examined and compared with the results of the differentiation study in order to determine whether there are any regional differences in the Nipissing. The data has been divided into the three areas mentioned earlier - north shore of Lake Huron, Sudbury area and Cobalt area (Figure 1).

North Shore of Lake Huron

The diabase intrusions in this area would seem to be well correlated with the Nipissing on the basis of the age determinations. Folding is more definite here than in the Cobalt area, although still quite gently, and the rough alignment of the larger intrusions with fold axes is obvious, especially in the case of the mass north of Thessalon which appears to lie on the south limb of an anticline.

Examination of the thin sections shows that quartz in present in all samples. Samples 29 and 30 contain hypersthene, 25 may have been hypersthene bearing but is so altered that it is difficult to be sure, 17 is a sample of granophyric diabase, 27 and 15 are fairly fine grained (near chill zone ?), while all of the others belong to the quartz-diabase and varied texture diabase phases.

The spectrographic data is presented in Table 14. The results in general, and the mafic indices in particular,

TABLE 14. Spectrographic analyses - Nipissing diabase - north shore of Lake Huron

Sample number	MgO %	FeO^a %	CaO %	Na_2O %	Ni ppm	Co ppm
25	11.5	7.4	12.0	3.00	130	51
24	9.6	6.8	11.5	1.70	125	44
23	7.1	9.4	9.2	2.40	72	59
26	8.8	7.4	20.0	2.20	83	44
31	9.8	8.0	10.4	1.70	149	56
27	8.7	8.0	9.7	1.82	93	51
28	7.4	7.8	7.0	2.70	315	43
30	10.2	7.0	10.7	1.60	146	42
29	9.1	7.8	8.6	1.60	118	53
22	8.0	11.0	9.9	1.82	56	56
21	4.5	9.3	6.3	2.70	42	49
19	6.8	9.2	9.0	2.65	66	47
20	7.6	9.3	9.5	2.15	90	59
17	5.8	7.3	8.3	3.90	38	17
18	11.5	10.7	10.5	2.00	93	61
16	6.3	11.1	9.0	2.40	27	66
15	8.8	7.1	4.3	2.10	82	51
14	10.0	11.4	6.4	2.20	88	44
12	9.3	10.7	10.8	1.95	72	62
13	7.4	7.9	9.5	2.15	96	51
11	8.3	8.9	10.1	1.97	122	64

a - Total iron as FeO

Mn ppm	Cu ppm	Ti ppm	V ppm	Mafic Index	Felsic Index	Sample number
1180	120	2430	196	39	20	25
950	59	1640	151	41	13	24
1700	250	4600	256	57	21	23
810	89	4400	247	46	10	26
1400	57	1710	180	45	14	31
1440	147	2380	175	48	16	27
1810	135	2630	194	51	28	28
1240	76	1220	139	41	13	30
1220	80	1560	155	46	16	29
1750	60	6900	252	58	16	22
1950	300	9900	630	67	30	21
1780	130	4900	176	58	23	19
1610	138	4000	194	55	18	20
1100	22	15000	400	56	32	17
2200	84	5900	280	48	16	18
1950	216	6200	267	64	21	16
1300	75	2140	137	45	33	15
1120	88	6400	235	53	26	14
1720	69	6400	291	54	15	12
1280	108	2880	195	51	18	13
1060	79	3600	203	54	16	11

agree with the conclusion from the petrographic evidence that the diabase at the surface is a little more acidic than that in the sections at Cobalt. Comparison of the average of the analyses for this area with the weighted average of the quartz diabase and varied texture phases of the Nasco section (Table 15) shows good agreement. In view of the unusually low average titanium content of the Nipissing at Cobalt as compared to other basic intrusions (Table 8) the similarity in these samples is noteworthy.

The high titanium and vanadium content of sample 17 (granophyric diabase) was expected from the amount of iron oxide in the thin section, and conforms well with the trend seen in the differentiation study, which showed concentration of these elements in later differentiates. The low copper content of this sample is in agreement with the view that copper is concentrated in the intermediate quartz-bearing phases and depleted in later fractions.

Sudbury area

The diabase in this area is usually referred to as Sudbury gabbro and has generally been thought to correlate with the Nipissing. This would seem to be confirmed in the eastern part of the area, where intrusions in the Sudbury group extend into the overlying Huronian rocks in the area mapped by J. E. Thomson (1960).

Examination of the thin sections shows that while four of the samples (32, 9, 10, and 79) have textures

TABLE 15. Average analysis of north shore of Lake Huron and analysis of quartz and varied texture diabase of Nasco section

	North shore of Lake Huron	Quartz and varied texture diabase-Nasco
MgO %	8.4	8.4
FeO %	8.7	8.9
CaO %	9.7	10.2
Na_2O %	2.2	1.95
Ni ppm	100	62
Co ppm	51	53
Mn ppm	1460	1390
Cu ppm	113	84
Ti ppm	4600	3070
V ppm	236	194

typical of the Nipissing elsewhere, the others seem to be unusual. Most of these are highly altered but sample 5 is quite fresh and shows texture that can be interpreted in the other samples. Sample 5 has stubby euhedral grains of augite and pigeonite (some hypersthene ?) enclosed in large plates of plagioclase. A modal analysis of the rock shows it to contain only 18 per cent plagioclase as compared to the usual 30 to 55 per cent in the rest of the Nipissing. Some of the other samples in this area appear to have even less. The amount of pigeonite is 15 per cent; the remaining 67 per cent is all augite. Zoning is absent in the plagioclase as well as in the pyroxene.

The nature of this sample would seem to leave little doubt that it is an accumulation of pyroxene crystals. The lack of zoning in the pyroxenes or the large unzoned plagioclases enclosing the pyroxenes and the simple mineralogy suggest that near-perfect equilibrium attended the crystallization, something not seen in the sub-horizontal sheets or sills. The most likely place for such conditions to occur would seem to be in more deeply buried intrusions, having a shape giving a long vertical extent to the differentiating magma. The dike-like nature of the intrusions in this area is thought, therefore, to be responsible for the unusual nature of the rocks.

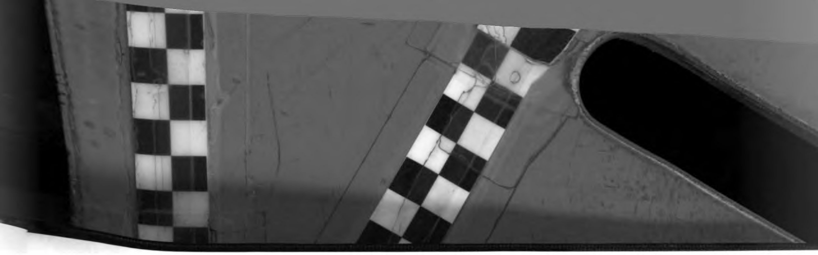
The spectrographic data, presented in Table 16, show that these rocks are among the most basic of any of the Nipissing samples - as basic as any of the olivine-

TABLE 16. Spectrographic analyses of Nipissing diabase - Sudbury area

Sample number	MgO %	FeO[a] %	CaO %	Na_2O %	Ni ppm	Co ppm
32	7.5	7.3	8.5	1.54	74	59
9	9.5	10.2	13.0	2.09	78	79
10	7.6	8.5	10.4	2.45	82	53
8	21.4	10.0	9.3	.40	830	104
7	18.3	9.4	9.3	.80	620	103
6	14.3	7.6	13.2	1.60	242	53
77	16.6	9.2	16.0	.83	470	79
5	14.3	7.6	8.0	1.20	400	70
79	9.7	9.9	11.9	1.52	93	61
3	13.1	7.3	11.4	1.27	240	65
4	13.7	7.7	10.8	1.37	340	71
78	11.8	6.5	12.4	1.95	176	47
1	14.0	8.1	13.9	1.09	264	79
2	11.5	7.7	13.6	1.56	165	57
72	9.5	9.3	10.8	1.30	104	42
73	12.6	7.7	11.6	1.18	189	55
71	13.1	9.4	12.8	1.43	129	59
74	11.5	9.5	13.4	1.37	104	59

a - Total iron as FeO

Mn ppm	Cu ppm	Ti ppm	V ppm	Mafic Index	Felsic Index	Sample number
1150	150	3400	137	49	15	32
1380	67	5900	280	52	14	9
1240	13	2880	184	53	19	10
1340	6	650	203	32	4	8
1150	54	1550	234	34	8	7
1150	75	1420	221	35	11	6
1240	19	1270	227	36	5	77
1520	51	2520	210	35	13	5
1500	138	5500	220	51	11	79
1150	82	650	149	36	10	3
1120	14	1030	184	36	11	4
1260	43	750	117	36	14	78
1040	123	930	184	37	7	1
930	47	1490	171	40	10	2
1260	77	1150	112	49	11	72
1220	108	750	133	38	9	73
1460	123	1680	195	42	10	71
1650	133	2010	214	45	9	74



hypersthene phase in the Rix section. If these rocks originated from the Nipissing magma a considerable portion of the upper part of the intrusions is missing. This would support Hawley's (1962) suggestion of post Nipissing domal uplift of the Sudbury area and the removal, by later erosion, of Huronian rocks that may have covered the area. The arcuate arrangement of Huronian outcrops around the northern part of the area supports the idea of domal uplift.

Sample 79 is surprising in the midst of these basic rocks, although it is a little further south than any of them. It is similar to the typical quartz diabase both in petrography and element concentrations. The writer is inclined to suggest that it may be part of a down faulted block.

Sample 32 is interesting in that it is the only Nipissing sample to show bent and broken grains, especially feldspars, and thus provides evidence of post Nipissing deformation in this area.

Cobalt area

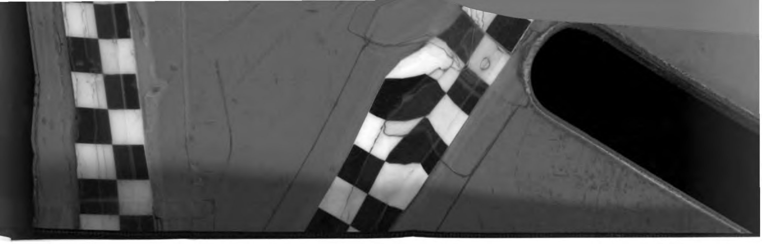
For convenience of presentation the samples in this area have been separated into those between Cobalt and the eastern end of the Sudbury area and those at Cobalt and to the north and west. Analyses for the area are given in Tables 17 and 18.

Samples 75 and 76 (Table 17) are of interest in that they seem to continue the trend of more basic rocks

TABLE 17. Spectrographic analyses of Nipissing diabase - between Cobalt and Sudbury

Sample number	MgO %	FeO^a %	CaO %	Na_2O %	Ni ppm	Co ppm
75	15.7	11.3	15.7	1.10	213	114
76	10.8	7.8	12.2	2.02	126	47
70	10.0	7.2	14.5	2.10	139	44
69	9.2	8.0	9.9	1.85	94	47
68	7.6	8.3	8.9	1.85	80	47
67	9.3	8.3	11.4	1.80	80	43
66	7.3	7.6	9.6	1.80	67	48
65	12.2	8.9	14.2	1.29	165	49
64	12.1	9.7	14.1	1.64	131	60
63	9.2	7.6	13.0	1.66	104	51
53	11.3	11.4	11.2	2.06	58	53
52	10.0	9.1	10.8	1.82	123	54
51	9.7	9.2	12.6	1.72	110	48
50	8.0	10.6	11.2	2.23	61	70
49	7.9	9.9	9.3	2.28	54	59
48	9.7	9.4	11.0	1.93	123	48
47	10.2	9.4	13.0	1.76	130	56
46	10.6	8.0	9.4	1.74	102	52
45	8.7	7.7	11.3	2.05	96	44
44	8.4	10.6	11.0	2.06	83	53
43	9.3	17.3	13.1	2.28	109	42
42	7.9	13.1	10.7	2.04	64	65
41	9.2	7.6	9.0	1.72	98	46
40	6.8	5.7	7.4	1.60	75	38
39	6.8	5.7	7.1	1.16	67	31
62	8.0	8.0	10.1	1.76	75	49
61	10.6	17.2	12.2	1.80	144	150
37	7.5	8.8	6.4	2.18	38	52
38	6.3	6.8	8.2	1.97	40	44
54	11.5	8.3	12.5	1.62	120	51
56	7.9	9.1	8.0	2.48	34	40
55	7.6	6.8	8.6	2.28	78	43
57	17.2	12.8	11.4	1.40	580	101
33	11.8	6.1	7.5	1.12	264	45
34	6.2	8.5	6.3	2.71	19	42
35	4.9	7.0	5.1	2.15	22	39

a - Total iron as FeO



Mn ppm	Cu ppm	Ti ppm	V ppm	Mafic Index	Felsic Index	Sample number
940	19	2210	200	42	7	75
940	123	1810	151	42	14	76
1240	103	2010	153	42	13	70
1360	130	2480	176	48	16	69
1580	119	2950	188	52	17	68
1240	101	2800	160	47	14	67
1280	157	2420	169	51	16	66
1000	400	1930	148	42	8	65
1240	120	2980	208	44	10	64
700	123	2330	176	45	11	63
2030	184	4800	282	50	15	53
2000	93	3400	266	48	14	52
1200	86	3100	224	49	12	51
2070	177	3400	208	57	17	50
1900	140	4400	350	56	20	49
1460	123	3400	241	49	15	48
1660	147	3600	233	48	12	47
1500	91	2240	192	43	16	46
1500	87	2110	175	47	15	45
1960	73	4900	233	56	16	44
2120	295	3700	273	65	15	43
2000	194	8400	650	62	16	42
1200	130	1990	147	45	16	41
1160	50	1360	120	46	18	40
1240	69	1080	85	46	14	39
1340	135	2380	156	50	15	62
1900	490	12000	1400	62	13	61
2100	130	2380	200	54	25	37
1200	118	2110	156	67	19	38
1200	73	1990	180	42	12	54
2650	101	4600	253	54	24	56
1340	108	1990	132	47	21	55
1500	128	3300	213	43	12	57
900	53	940	85	34	13	33
1820	22	2700	213	58	30	34
1680	113	2070	104	59	29	35

TABLE 18. Spectrographic analyses of Nipissing diabase - Cobalt area

Sample number	MgO %	FeO[a] %	CaO %	Na_2O %	Ni ppm	Co ppm
83	8.0	9.5	10.1	2.25	78	44
84	9.7	7.4	7.8	2.68	78	40
81	9.3	7.0	9.4	1.45	112	40
82	7.6	6.2	8.6	1.64	62	34
80	7.3	8.8	9.8	1.89	59	53
92	5.4	10.6	7.2	2.55	26	68
90	9.2	8.4	10.5	1.83	125	57
91	5.4	8.6	8.0	2.28	27	45
85	10.6	7.9	13.0	1.55	178	60
86	17.7	8.4	12.2	1.26	460	73
89	10.0	6.5	13.7	1.53	126	53
88	8.7	5.9	12.0	1.68	146	45
87	11.6	8.6	10.5	1.60	184	65
58	8.0	7.2	8.1	2.55	93	35
59	8.8	6.3	9.6	1.90	112	44
94	8.9	8.9	8.6	2.60	88	49
60	9.9	7.9	11.5	1.80	118	50

[a] - Total iron as FeO

Mn ppm	Cu ppm	Ti ppm	V ppm	Mafic Index	Felsic Index	Sample number
1380	133	5400	300	54	18	83
2500	8	1870	149	43	26	84
860	71	1700	180	43	13	81
1120	75	1420	125	45	16	82
1650	108	3200	151	55	16	80
1800	53	9300	374	66	26	92
1340	86	2140	195	48	15	90
1600	145	3800	168	61	22	91
1260	65	1640	205	43	11	85
1240	43	940	149	32	9	86
960	52	1610	143	39	10	89
800	71	1240	137	40	12	88
1340	75	1930	160	43	13	87
1900	110	3000	167	47	24	58
1100	61	880	113	42	17	59
1440	116	2430	196	50	23	94
1150	140	2270	180	44	14	60

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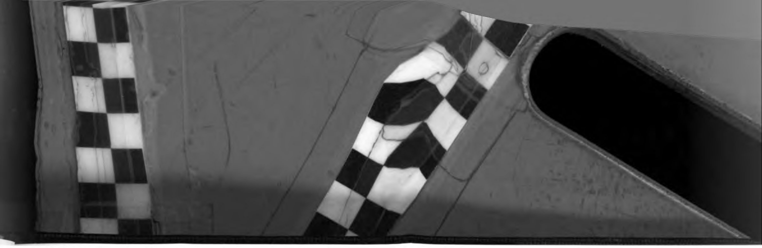
seen in the Sudbury area, although texturally they are like the normal Nipissing. The other samples in the area between Sudbury and Cobalt include representatives of nearly all of the phases of the Nipissing - 57 and 33, while highly altered, appear to be olivine-hypersthene diabase, 55 is a quartz-hypersthene diabase, the others appear to be quartz and varied texture diabases. With the few exceptions noted below the spectrographic data are similar to those for the same phases in the Rix and Nasco sections.

The high titanium content of sample 61 is clearly due to the concentration of iron oxide in the sample. Since vanadium appears to occur in the oxides as well, its high concentration is to be expected. The same explanation may apply to the cobalt enrichment. Examination of this sample and sample 64 under reflected light showed that a sulphide mineral, probably chalcopyrite, was present, accounting for the abnormal copper values in these samples.

The samples from the area around Cobalt and to the north and west also show considerable variation (Table 18). 86 and 88 are olivine-hypersthene diabase. 59, 60, 85, 87, and 89 are quartz-hypersthene diabase. Except for the chill phase samples (81, 82, 83, 84, 94) all of the others are from the quartz and varied texture phases. Again the analyses correspond well with similar phases in the sections.

Comparison of areas

The foregoing indicates a basic similarity in the



Nipissing intrusions over the whole regions, in that the phases present and the concentrations of the various elements in them are similar to those observed in the detailed work in the Cobalt area. The unusual rock in the Sudbury area is compositionally similar to the olivine-hypersthene phase of the sections; their different mineralogy and texture is due to differences in the extent to which equilibrium between the various minerals was attained, not to any basic difference in the process involved.

That there are regional differences in the samples is shown by consideration of the averages of the analyses for the different areas (Table 19). The average for the north shore of Lake Huron is slightly more acidic than the average chilled diabase, the area around Cobalt and to the north and west is a little more basic, than the chilled diabase, the area between Cobalt and Sudbury is more basic yet, and the Sudbury area is composed largely of very basic rocks.

There are two possible explanations for this.

1. There are real differences in the overall composition of the Nipissing.
2. The composition of the Nipissing is uniform, but erosion has exposed different average levels of the differentiated intrusions in the different areas.

That the latter is a possible explanation is indicated in the Cobalt area from the results of the present work,

TABLE 19. Average analyses of various areas

	Chilled Phase	Cobalt	Cobalt-Sudbury	Sudbury	North shore of Lake Huron
No. of samples	10	17	36	18	21
MgO %	8.5	9.1	9.3	12.8	8.4
FeO %	8.2	7.9	9.1	8.5	8.7
CaO %	9.5	10.0	10.5	11.7	9.7
Na_2O %	2.0	2.0	1.9	1.4	2.2
Ni ppm	81	122	110	256	100
Co ppm	44	55	55	66	51
Mn ppm	1460	1380	1500	1260	1460
Cu ppm	96	83	133	73	113
Ti ppm	2370	2630	2860	1970	4600
V ppm	186	182	236	188	236
MAFIC INDEX	49	46	49	40	51

as well as from the studies by Hriskevich (1952) and R. Thomson (1962). Erosion in this area has removed the most acidic phases of the diabase, exposing a considerable proportion of the more basic rocks. Random surface samples, therefore, have a more basic composition than the magma.

Extending the hypothesis to the other areas, it would then appear that between Cobalt and Sudbury erosion has been a little deeper than at Cobalt, especially near Sudbury. The suggested doming of the Sudbury area, has resulted in the almost exclusive appearance of very basic phases on the present erosion surface.

The rather abrupt transition from the Sudbury area to the north shore of Lake Huron is reasonable, occurring as it does across the major fault zone. The latter area has had the least amount of erosion, with the result that the phases seen are mainly acidic. (Granophyre is often mentioned in reports on the area, eg. Robertson, 1963).

Relation of metalliferous deposits to the Nipissing diabase

As noted in the introduction, one of the purposes of this investigation was to determine whether the variation in types of deposits associated with the Nipissing diabase could be related to any regional differences in the Nipissing.

The deposits in the Nipissing can be grouped into three main types. Quartz-carbonate veins carrying chalcopyrite, pyrite, and minor specularite are typical of the north shore of Lake Huron area. Small deposits of massive and disseminated pyrite, chalcopyrite, and nickel-bearing pyrrhotite seem to be typical of the Sudbury area (eg. Ginn, 1965). The Cobalt area is well known for its unusual silver-cobalt-nickel-arsenic mineralization which occurs mainly in carbonate veins, although a few of the "north shore type" copper showings have been noted, expecially in the Timagami area (Simony, 1964).

As detailed studies of the various deposits have not been made, it is not possible to relate them positively to specific phases or structures in the diabase, but some inferences about their variation would seem obvious in view of other results of this investigation. Thus it is not surprising to find copper deposits along the north shore of Lake Huron as the "average" diabase here is quartz diabase, the phase found to be most enriched in copper in the differentiation study. The presence of quartz and carbonate suggests that while the sulphides may have formed as immiscible droplets in the quartz diabase, they were segregated into the late liquids trapped in this phase. Fracturing of the nearly solid diabase would have allowed the escape of this hydrothermal fluid, and the formation of veins extending through the diabase and into the country rock.

The presence of nickel in the sulphide deposits in the Sudbury area would appear to be related to the very basic composition of the diabase, as the differentiation study showed considerable enrichment of nickel in the most basic phase. The massive and disseminated nature of most of these deposits may indicate that they represent varying degrees of accumulation of sulphide droplets formed early in the crystallization process. The slight enrichment of copper at the base of the Rix section suggests that this might have occurred elsewhere as well.

The silver deposits of the Cobalt area have been explained as having formed at the last stage of crystallization of the diabase (Hriskevich, 1952). The occurrence of nickel and cobalt is thought to be due to their exclusion from the late phases of the diabase (granophyre and aplite), and the resulting concentration in the final fluids.

It is apparent that the different types of deposits seen in the north shore of Lake Huron and Sudbury areas may be due to the level of erosion of the diabase (i.e. nickel-copper deposits may occur in buried basic phases along the north shore, and hydrothermal copper deposits may have occurred in the eroded upper parts of the intrusions of the Sudbury area). All phases of the diabase are seen, however, in the Cobalt area, and no deposits of either type are known to occur. In view of the similar copper and nickel contents of similar phases of the diabase in all three areas the writer suggests that the absence of copper or nickel sulphide deposits is due to a deficiency of sulphur. This is also supported by the low sulphur content of the silver deposits themselves, where such elements as arsenic, antimony, and bismuth, which are usually much subordinate to sulphur in amount, become

important constituents.

There are two possible reasons for the dificiency of sulphur in the Cobalt area -

1. The original magma was deficient in sulphur in this area.

2. Sulphur was lost from the magma before the formation of the metalliferous deposits in the Cobalt area.

To accept the first explanation would be to assume that there are regional differences in the Nipissing. This has not been demonstrated for any of the elements determined in the present study, but since the sulphur content of the rocks was not determined, it remains a possibility. Because of the constancy of the other elements, however, the writer prefers the assumption that the original magma in the Cobalt area had the same sulphur content as in the other areas, and would offer the following suggestions in explaining its preferential loss.

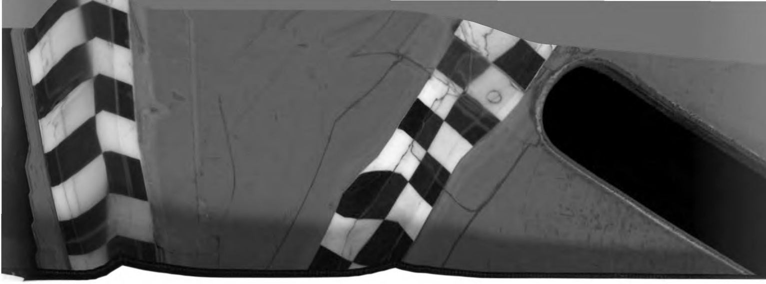
1. The Huronian rocks are thinner in the Cobalt area than in the north shore of Lake Huron area. The Nipissing magma may have risen closer to the surface at Cobalt before it was able to spread out into sheets. The lower confining pressure of overlying rocks could have been low enough to allow much sulphur to escape.

2. Lineaments possibly related to pre and post Nipissing faults seem to be more common in the

Cobalt area than in the north shore area, and may also have allowed greater sulphur loss in the Cobalt area.

3. The intrusions in the Sudbury area may have been more deeply buried than those at Cobalt, or the much smaller horizontal surface area of the dikes may have allowed less sulphur loss than from the sub-horizontal sheets.

The resolution of the questions raised here obviously requires further studies, beginning with sulphur analyses. The significant point is that regional variations in types of deposits associated with a given type of igneous rock may be due to minor changes in physical conditions during differentiation and not to a change in "metallogenetic province".



CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

The purposes of this study, as noted in the introduction have been to investigate the local variations in the Nipissing diabase of the Cobalt area, on a chemical, petrographic and structural bases, to determine whether similar intrusions in adjoining areas are related to the Nipissing and, if so, whether there are any regional differences in the character of the Nipissing that might explain the regional variation in types of metalliferous deposits associated with this rock.

The emphasis in the study has been on chemical variations in both major and minor elements. Analyses were made by a somewhat novel method (interrupted arc) of emission spectrographic analysis which appears to have given satisfactory results for both the major and minor elements involved. The speed and low cost, relative to chemical methods, of obtaining analyses in this was has permitted a much more complete investigation of the chemistry of the rocks than is usual in studies of this type.

The field and petrographic studies show that the Nipissing was intruded as a fluid magma, generally forming sill-like bodies (sheets) in the flat-lying or gently folded Huronian rocks and dikes in the steeply dipping or vertical pre-Huronian and in the massive granites. The level of the sheets was probably determined in part by the

then-existing erosion surface and in part by the Huronian-pre-Huronian unconformity. The result in the Cobalt area was an undulating single sheet having a number of basins separated by arches.

The thickness of the sheets ranges from less than 200 feet to at least 1100 feet, the latter being typical of the Cobalt area. Erosion has apparently removed part or all of the diabase in many places so that it is not possible to determine the original areal extent of the sheets. The largest mass exposed is west of Lake Timagami and covers an area of about 100 square miles.

Samples of the chilled phase of the Nipissing in the Cobalt area indicate that the intruded magma had a fairly uniform tholeiitic composition - differentiation of the magma took place after intrusion. The chill composition is similar to that of most other tholeiitic intrusions except in its low titanium content, which has been observed in only a few other cases.

Petrographic and spectrographic (major and minor elements) studies of samples from a mine shaft and an inclined drill hole in the Cobalt area have been combined with the earlier surface and underground data, and show that the trend of differentiation in a typical basin-arch section is as follows:

1. A chilled phase of quartz diabase was formed at the margins of the sheet.
2. Fractional crystallization and vertical gravit-

ational settling resulted in the accumulation of minor amounts of olivine in the lower parts of the sill which were not completely resorbed by the quartz diabase crystallizing around them.

3. Lateral, upward movement of acidic constituents toward the arches shifted the magma composition in the lower part of the basins so that olivine and hypersthene became stable phases and together with the plagioclases became more basic for a time, toward the top of the sheet. A limit to this was reached and later crystallization followed the common trend of iron and sodium enrichment. As a result the olivine hypersthene zone is succeeded by a quartz-hypersthene zone, a quartz diabase zone (hypersthene replaced by pigionite), and, a varied texture zone, where irregular patches of coarse to pegmatitic diabase indicate enrichment of volatiles. Later phases, postulated to occur mainly in the now-missing upper parts of the arches are granophyric diabase and aplite. This is supported by the occurrence of these phases elsewhere in the region.

The behaviour of minor elements during differentiation shows definite trends in their incorporation into various phases of the diabase, similar to those found in other studies. Nickel and cobalt are enriched in the more basic phases, copper in the quartz diabase, vanadium, titanium and manganese in the varied texture and granophyric diabase. Data from other studies on the unit cell size of nickel, cobalt, and manganese olivines indicate the stability of these minerals relative to magnesium and iron olivines, and the observed trends fit this data very well, even though these elements are probably not exclusively related to the olivines.

The regional study shows that intrusions of the area along the north shore of Lake Huron are similar to those in the Cobalt area, and their contemporaneity is confirmed by age determinations. Intrusions in the Sudbury area are dyke-like and show accumulation textures and more equilibrium conditions than in the other areas, but chemical similarity to the Nipissing as well as field evidence indicates that they too are part of the Nipissing. Regional variations in metalliferous deposits, while not studied in detail, are thought to be due to circumstances arising during differentiation, not to original differences in the composition of the magma.

Conclusions

1. The Nipissing diabase intrusions are contemporaneous and uniform in original composition in the region between the eastern end of Lake Superior and Lake Temiskaming.
2. Differentiation of the magma occurred after intrusion, and produced rock types more basic and, later, more acidic than the magma.

3. Differentiation was lateral as well as vertical, due to the inclined attitude of most of the intrusions.

4. The behaviour of minor elements during differentiation follows the same rules as those that govern the behaviour of major elements.

5. The type and occurrence of associated metalliferous deposits may also be governed by variable conditions during differentiation.

6. Surface sampling of differentiated igneous intrusions may not give an accurate picture of their overall composition, nor of the extent of their variation.

Suggestions for further work

The Nipissing diabase is well suited for studies of various aspects of the problems of petrogenesis of basic intrusions. The varying degrees of erosion of the sheets, and the mine shafts and drill cores, permit unusually thorough examination of most levels of the intrusions from the lowest parts of basins to the top of arches. Further study might well result in the discovery of some of the feeders of the sheets.

The extent of the area intrusions makes significant studies of regional variation. It is hoped that the regional variation of sulphur and other elements related to the problem of variation in metalliferous deposits can be studied in the near future. Relation of these deposits to specific rock types in the diabase would also be of value.

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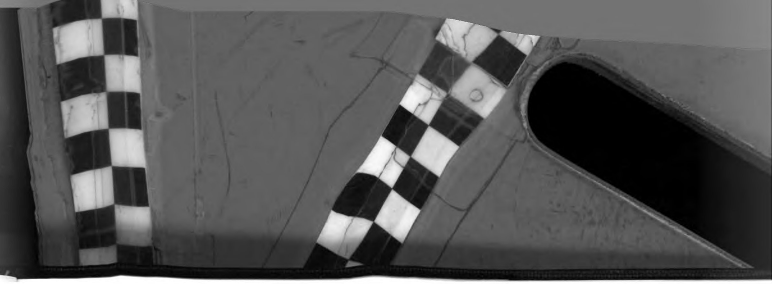

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