THE PETROLOGY OF GABBROIC SILLS IN THE VOLCANIC SERIES
OF
ROY AND McKENZIE TOWNSHIPS,
CHIBOUGAMAU REGION, QUEBEC

by

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ABSTRACT

Metadiabase sills constitute up to 27 percent of a steeply-dipping assemblage of ancient volcanic rocks in Roy and McKenzie townships, Chibougamau region, northwest Quebec.

Three rock types are represented. They are, from lower to upper parts of the sills, metapyroxenite, metadiabase, and diabase-pegmatite. Comparison is made with "metadiorite" and "metagabbro" sills in an adjoining area. Chemical and planimetric analyses show that layering of the sills is the result of magmatic differentiation which is characterized by iron-enrichment. The metadiabase sills are similar to the intrusive phase of plateau-type basaltic magma in chemical composition and in trend of differentiation.

The rocks are metamorphosed to the greenschist facies.

It is concluded that the sills are an integral part of the volcanic assemblage and represent contemporaneous intrusion of basaltic magma.

CHAPTER I

INTRODUCTION

GENERAL STATEMENT

This thesis presents a petrological and chemical study of certain gabbroic and diabasic rocks which occur in an ancient volcanic assemblage in the Chibougamau area of northwestern Quebec. The volcanic rocks are extensively invaded by intrusive bodies that range from granite to dunite.

The rocks studied are medium-grained to fine-grained intrusives genetically related to, and an integral part of the volcanic formations. The intrusives occur as sills which range from a few feet to 2,000 feet in thickness. They constitute between 0 and 27 percent of a volcanic assemblage of 15,000 feet to 22,000 feet total thickness. Differentiation in the sills is characterized by iron-enrichment.

The area studied covers the southwestern quarter of Roy township and part of the southeast half of McKenzie township, Abitibi-East county, Quebec. This study is part of a programme of detailed mapping in the Chibougamau district conducted by the Quebec Department of Mines.

ACKNOWLEDGMENTS

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Gratitude for much pertinent information is extended to Dr. J. R. Smith, formerly with the Quebec Department of Mines, under whose direction the writer spent his first summer in the area. Likewise, the aid of all field assistants is readily acknowledged. They were Terence T. Quirke, Jr. and Gaston Pouliot, Senior Assistants; Jean-Jules Panneton, Richard Grenier, Roger Martin, Jacques Vallerand, Junior Assistants; and Ferdinand Lavoie, Cook.

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Appreciation is expressed for the aid rendered by my colleagues in many small but important ways.

To Brigid Patricia, my sincere thanks, for her encouragement and "devotion to duty".

LOCATION AND ACCESS

Chibougamau lies in the eastern part of Abitibi Territory, Quebec, approximately 320 miles north of Montreal, and 150 miles northwest of Lake St. John.

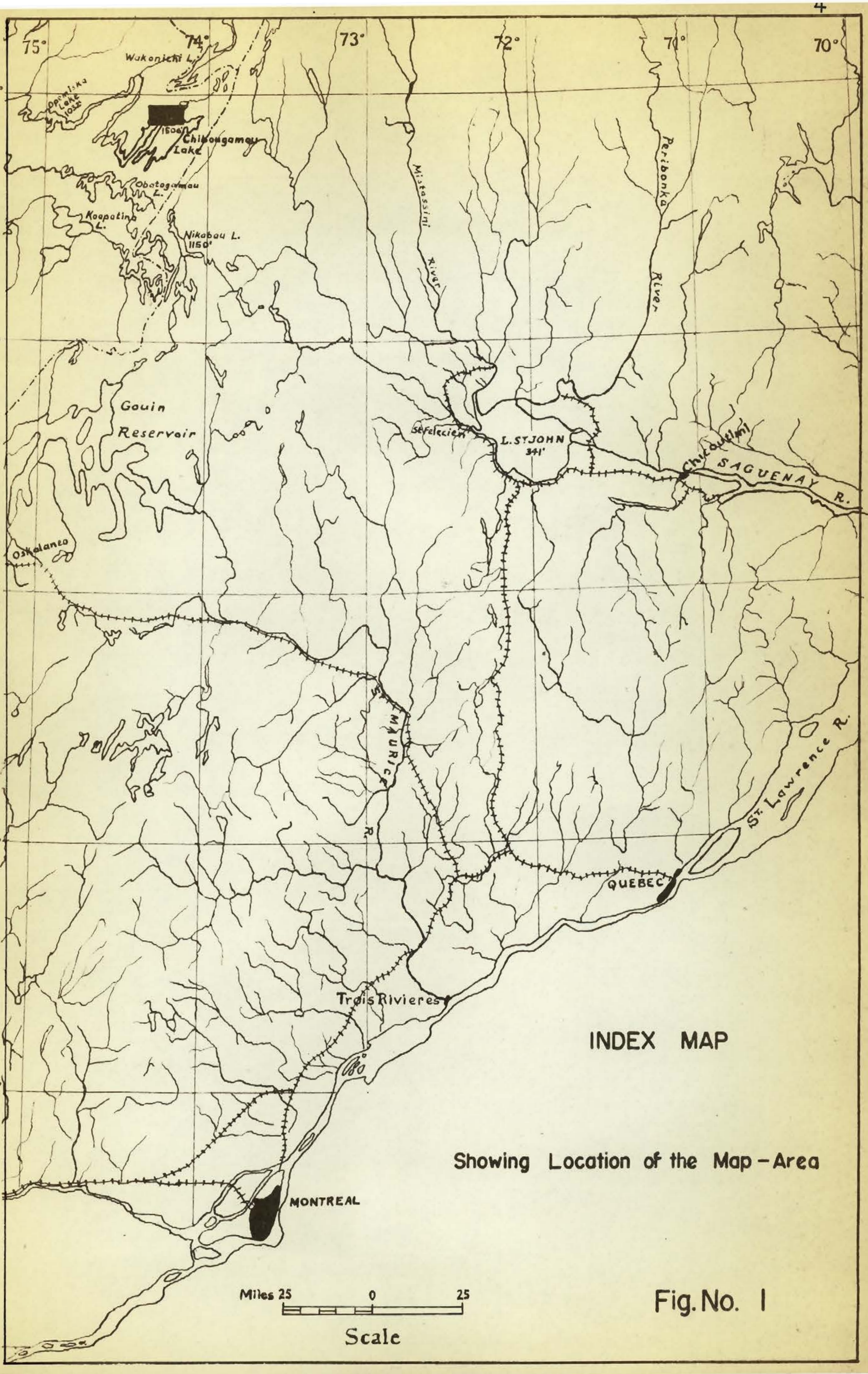
The area is easily reached by a gravel highway from St. Felicien at the west end of Lake St. John. A branch road from Chibougamau extends west to Opemisca and a new road is under construction to Lake Waconichi.

Air services to the region are available from Montreal; St. Felicien and other bases on Lake St. John; and from Senneterre on the Quebec-Cochrane branch of the Canadian National Railway. Two aeroplane companies maintain permanent bases within the area.

Rail lines to Chibougamau are under construction from Senneterre and from St. Felicien.

HISTORY AND TECHNICAL SURVEYS

Missionaries and traders visited this part of northwestern Quebec as far back as the 17th Century, but their published descriptions contain no mention of metalliferous resources. Attention was first drawn to what is now known as the Chibougamau region by the report of James Richardson of the Geological Survey of Canada, who explored the section in 1870. Later, in 1884, Bignell and Low passed



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Showing Location of the Map-Area

Fig. No. 1

through the region in their Mistassini expedition, Low revisiting the area in 1892 and 1905. Professor R. W. Brock in 1896 made a reconnaissance of a region west of Lake Waconichi.

In August, 1903, Peter McKenzie of the McKenzie Trading Company visited Richardson's "Paint Mountain" on what is now Portage Island. During this visit McKenzie discovered a large auriferous quartz vein which today carries his name, showings of copper, and an island on which there occurs asbestos (Asbestos Island). During the following year (1904) McKenzie returned with Obalski, then Inspector of Mines for the Province of Quebec. Obalski's report of November, 1904, notified the public of these mineral occurrences. He was followed in 1908 by Professor E. Dulieux who made an extensive examination of the mineral deposits discovered by that date.

Widespread interest was aroused during the next few years and the Quebec Government was pressed to build a railway to help in opening up this part of the country. A special commission was appointed to report on the economic possibilities of the area. The "Chibougamau Commission", composed of Dr. A. E. Barlow, Special Lecturer of Economic Geology at McGill University, as Chairman, Mr. E. R. Faribault, of the Geological Survey of Canada, and Professor J. C. Gwillim, Professor of Mining at Queen's University, visited the area with a large party in 1910. In their report, published in 1911, it was concluded that the mineral discoveries then known did not justify the construction of a railway into the area. This dampened interest in the region for a number of years, but prospecting continued and other discoveries were made.

Systematic investigation was resumed in 1927 when Mawdsley undertook detailed mapping in the David Lake area. He was followed by Retty who mapped McKenzie township during 1929. Mawdsley returned in 1930 and started a programme of detailed mapping which was completed by Norman in 1934. Their report, published in 1935 as Memoir 185 of the Geological Survey of Canada, presents a comprehensive account of the geology and mineral deposits of the greater part of McKenzie, Roy, Obalski, and Lemoine townships, and sections of Barlow, Scott, McCorkill and Rinfret townships. During 1935 and 1936 Norman extended this study westwards.

A great stimulus was given to prospecting by the completion in 1949 of a highway from St. Felicien to Chibougamau and by the high price of base metals in the succeeding years. To meet the needs of the revived interest, the Quebec Department of Mines initiated a programme of detailed mapping.

In 1950 and 1951 R. B. Graham mapped the northern half of Obalski township. J. R. Smith extended the work

PLATE 1

Fig. 1 Copper Point, Portage Island, as seen from Lake Chibougamau. Location of the first recorded copper mineralization in the anorthosite.

Fig. 2 Looking south at Portage Island through the Valiquette Narrows at the northern end of Lake Chibougamau. Through here passed Richardson, Bignell, and Low in their geological expeditions.

northwards and eastwards into the southern half of McKenzie township from 1951 to 1954, and G. Allard in 1953 and 1954 concentrated on a detailed structural and petrological study of the southeast sector of McKenzie township in the area adjoining Dore Lake. During 1955 and 1956 the writer extended the detailed mapping into the southwest quarter of Roy township while S. V. Ermengen undertook a surface geochemical investigation of mineralized areas in Chibougamau.

TOPOGRAPHY

Chibougamau lies just north of the height of land between the St. Lawrence River and James Bay at an elevation of 1,100 to 1,900 feet above sea level. The area has a diversified relief. The most conspicuous topographic feature is Lake Chibougamau which covers an area of approximately 90 square miles.

Much of the area to the south and southwest of Lake Chibougamau is low, flat country extensively covered by glacial drift. North and west of the lake, belts of hills and ridges separated by lowlands and narrow valleys, extend regionally east-west and locally northeast. To the north of the hilly belt the terrain is monotonously flat and in certain parts is covered by broad sand plains.

The ridges and lowlands follow the main rock structure in a general east-west direction but the individual hills and many of the small features in the relief trend northeast-southwest, parallel to the regional glacial direction. The northern slopes of the hills are steep and rocky, whereas the southern and southwestern slopes are veneered with glacial rubble that extends as low promontories to the southwest.

The area drains northwest into James Bay by way of the Chibougamau River, a tributary of the Waswanapi and Nottaway Rivers. A few miles north of Chibougamau, drainage is towards Lake Waconichi which in turn drains into Lake Mistassini and the Rupert River.

In the low country, the form of the lakes and rivers is controlled largely by glacial erosion and deposition and trend in a north to northeasterly direction. In the more elevated areas the shape of the lakes reflects largely the rock structure and many are elongated in an east-west direction.

FIELD WORK

The writer spent three summers in the Chibougamau area, in 1954 as Senior Assistant to Dr. J. R. Smith in the southeast quarter of McKenzie township, and in 1955 and 1956 as Party Chief in an adjoining area in Roy township. During 1955 and 1956 the southwest quarter of Roy township was mapped at a scale of 1 inch = 500 feet.

PLATE 2

Fig. 1 Looking east from Paint Mountain, Portage Island, towards Bear bay and Sorcerer mountain.

Fig. 2 Looking west from Cumming's mountain at hilly ground near Lake Bourbeau, north of Chibougamau town.

Geological mapping was carried out along north-south traverses spaced regularly at intervals of 300 to 500 feet. Measurements were made by chain and pacing and corrected for slope distances where necessary. In many areas control was afforded by picket lines laid out by private companies for geophysical surveys. Aerial photographs were used extensively. Field mapping was adjusted to fit base maps at a scale of 1 inch = 500 feet prepared by A. E. Simpson for the Quebec Department of Mines.

LABORATORY WORK

Laboratory work was conducted at McGill University during the winters of 1955-56 and 1956-57.

Optic angle measurements were made by universal stage methods. Index of the hemispheres used is 1.649, that of the immersion liquid 1.648. The angle of inclination was not compensated.

TERMINOLOGY

Textural terms used follow the nomenclature explained by Johannsen (1939, pp. 45-47). The terms are defined as follows:-

Ophitic - a growth of plagioclase laths with random orientation within larger allotriomorphic pyroxenes.

Diabasic - a growth of plagioclase laths with random orientation with interstitial pyroxene.

Subophitic - a texture which is not clearly ophitic but not diabasic.

Diabase - hypabyssal rock of basaltic composition and ophitic or subophitic texture, commonly called dolerite by workers outside North America.

CHAPTER II

GENERAL GEOLOGY

The Chibougamau region lies near the east margin of the Superior Province close to its contact with the Grenville Province (Gill, 1948). All the consolidated rocks in the region are of precambrian age.

The oldest rocks are an assemblage of ancient lava flows and pyroclastics which are extensively invaded by granitic to ultrabasic intrusives. The volcanic assemblage is tightly folded into several major east to northeast-trending anticlines and synclines, and is transected by many faults.

In the vicinity of Chibougamau town volcanic rocks trend roughly east-west and are inclined steeply to the north. The volcanic sequence forms part of the south limb of a broad syncline, the northern limb of which crops out farther north. A series of ultrabasic and basic sills are intruded along the axis of this syncline. Intrusive anorthosite and gabbro constitute the south margin of the volcanic formations. Granite intrudes all the rocks as small plugs and as dykes. The rocks have been strongly altered. Overlying these rocks and apparently little metamorphosed, are gently dipping remnants of a sedimentary series composed largely of conglomerate and arkose.

As shown by pillows, flow lines, and bedding, the main formation of lavas trends fairly regularly east-west, is vertical or is inclined steeply to the north, and faces north. The lava flows are overlain conformably to the north by pyroclastic rocks which are composed of massive to crudely-bedded feldspathic rocks, massive to thinly-bedded tuff and chert, and agglomerate.

Concordant sill-like gabbroic and diabasic intrusives are interlayered with the lava flows and pyroclastic rocks. The sills are common in the western part of McKenzie township but are not present in one section of southwest Roy township. Differentiation is suggested by layering in some sills and it is probable that intrusion took place before folding of the volcanics (Smith, 1953, p. 7). The close association of the sills with the volcanic rocks suggests a genetic relation.

The geological formations are listed in chronological order in the table of formations.

THE VOLCANIC SERIES

The volcanic series consists of metamorphosed lavas, pyroclastic rocks, and intrusive diabase or gabbro. Primary structures and textures are generally well preserved

TABLE OF FORMATIONS*

PLEISTOCENE			Stratified and unstratified boulder till Stratified sands	
	Erosion, Unconformity Faulting, Hydrothermal alteration			
PRECAMBRIAN	PROTEROZOIC	CHIBOUGAMAU SERIES	Pebbly arkose, arkose Conglomerate	
	Erosion, Unconformity			
	Hydrothermal alteration ? Folding, Faulting, Shearing			
			Granite and feldspar-quartz porphyry	
			Syenite	
			Basic dykes ?	
			Intrusive contact	
		ULTRABASIC SERIES	Metagabbro, quartz-metagabbro Dunite, peridotite, pyroxenite	INTRUSIVE ROCKS
	Folding and Faulting, Metamorphism, Hydrothermal alteration			
			Intrusive contact	
	ARCHEAN	DORE LAKE COMPLEX	Metagabbro, quartz-metagabbro Magnetite-serpentine rock (altered peridotite and pyroxenite?) Transition Rock: Anorthositic metagabbro Gabbroic meta-anorthosite Meta-anorthosite	
			Intrusive contact	
	(Folding and Faulting ?)			
		VOLCANIC SERIES	Diabasic metagabbro, metadiabase Intrusive contact Tuff, feldspathic pyroclastics, agglomerate, chert, graphitic tuff (and slate), thin lavas Meta-andesite and tuff, agglomerate Metabasalt and tuff, agglomerate	

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[*] As determined in the southwest quarter of Roy township (Horscroft, Unpublished)

although the original mineral constituents have undergone almost complete alteration.

The lava flows range from dark green and green metabasalt to grey green and green meta-andesite. Regionally, the metabasalt constitutes the southern (lower) third of the main belt of lava flows and the meta-andesite the upper two thirds. The meta-andesite is overlain conformably to the north by a persistent formation of fine-grained to medium-grained pyroclastics with few agglomerates. Acidic lavas are restricted to local areas in the andesitic and pyroclastic formations.

Pillows are represented throughout the volcanic sequence. They are abundant in metabasalt in the southeast sector of McKenzie township (Allard, 1956 b), but are uncommon in the southwest quarter of Roy township. This structure occurs throughout the meta-andesitic lavas and belts of pillowed formations can be traced from the west boundary of McKenzie township to the edge of the southeast quarter of Roy township. The pillowed formations are interlayered with massive flows that range from a few feet to over 100 feet thick. Massive and pillowed flows are interleaved and it is generally not possible to separate individual flows. Amygdules, fragmental and scoriaceous tops, and flow layering are well preserved.

PLATE 3

Fig. 1 Location: Cumming's Lake, Roy township

Fig. 2 Location: Proulx Bay, McKenzie township

Photographs of pyroxenite (Fig. 1) and acidic tuffaceous lava (Fig. 2) showing the contrast in typical weathered surfaces

Thin, lenticular beds of tuff and agglomerate are interlayered with the pillowed and massive lava flows. These pyroclastics constitute but a small portion of the volcanic assemblage in the southwest quarter of McKenzie township (Smith, 1953, p. 6), but are more common in Roy township where they constitute approximately 25 percent of the main belt of metabasalt and meta-andesite in one section. In parts of McKenzie and Roy townships the base of the volcanic series is composed of tuff.

The range in thickness of the volcanic series is as follows:-

Locality-township	Total Thickness of Volcanic Series	Volcanic Rocks	Gabbroic Sills	Reference
Southwest McKenzie		12,000'		Smith, 1953, p.5
Southwest McKenzie	19,000'	14,000'	5,000'	Allard, 1956b, p. 18
Southwest McKenzie	22,000'	16,000'	6,000'	Allard, 1956b, p. 18
Southwest Roy	11,000'	10,000'	1,000'	(Horscroft, Unpublished)
Southwest Roy	9,000'	9,000'	0'	

The figures quoted are approximate but may represent the minimum original thickness. The true thickness cannot be established because the base of the volcanic assemblage is not recognizable and because of possible duplication or elimination by strike faulting.

THE DORE LAKE COMPLEX#

The Dore Lake complex forms the south boundary of the volcanic formations in Roy and McKenzie townships. The complex is described by Allard (1956, a) as a stratiform sheet arched up by the intrusion of granite.

The complex consists of metamorphosed anorthosite, gabbroic anorthosite, anorthositic gabbro, and amphibole schist and magnetite-chlorite-serpentine rock. In most sectors gabbroic phases occur along the edges of the anorthosite and are termed by Mawdsley and Norman (1935) "marginal gabbros". Where recognizable, layering is steeply inclined to the north, or is vertical, and in a general way is conformable with the main volcanic formations.

In many areas the contact between the volcanic series and the Dore Lake complex has been strongly sheared and altered to chlorite-sericite-carbonate-chloritoid schists. These schists occupy a broad fault zone which can be traced for 16 miles as the Lake Sauvage Fault Zone (Allard, 1956 b, p. 156). In the southwest quarter of Roy township, however,

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#(named Dore Lake group by Graham (1956, p. 4) and termed Dore Lake complex by Allard (1956, a & b).)

PLATE 4

Fig. 1 Strongly chloritized meta-anorthosite, drill hole P. 100, Portage Island (Chibougamau) Mines Ltd., Roy township

Fig. 2 Sheared tuff outcropping along the north shore of Bear Bay, Roy township

the schist zone cannot be accurately delineated everywhere and on parts of Portage Island no schist zone can be recognized parallel to the contact.

Shear zones in "anorthosite" are the host for copper mineralization in the new mining camps along Dore Lake. The only available absolute geological age determination in this region was obtained from lead isotope ratios on specimens from Campbell Chibougamau Mines. The age of this mineralization is calculated to be $20 \pm 2 \times 10^8$ years (Wilson et al., 1956).

THE ULTRABASIC SERIES

A series of ultrabasic rocks occurs north of the belt of lava flows described previously. They intrude and are interlayered with feldspathic pyroclastics, tuffs, cherts, and thin lavas.

The ultrabasic rocks are of three main types, viz. serpentinized dunite, peridotite, and pyroxenite. Associated with the ultrabasic rocks and occurring marginal to them, are several formations of gabbro. The ultrabasic rocks and gabbro commonly occur as sills and irregular bodies elongated regionally along the strike of the pyroclastic rocks. Structurally, they are intruded along the axis of a broad syncline.

Most of the ultrabasic rocks are serpentinized and the gabbros uralitized and saussuritized.

PLATE 5

Fig. 1 Pillowed meta-andesite facing to the right, located on the portage between Cumming's Lake and Machin Bay, Roy township

Fig. 2 Conglomerate of the Chibougamau series resting directly on syenite, west of Conglomerate Point, Roy township

GRANITE

A large body of granite intrudes the Dore Lake complex in and near the centre of Chibougamau Lake. Farther north, granite and syenite intrude the volcanic series and the ultrabasic series as small plugs.

Most of the granites are sodic and are fine- to medium-grained. Granitic, porphyritic, and syenitic dykes cut all the rock types described previously. Many of the dykes are intruded parallel to foliation in the invaded rocks. The granite and dyke rocks are strongly sheared in a number of places; all are altered to some extent.

Feldspars in granite consist most commonly of albite and albite-oligioclase, and also of andesine. Chlorite, biotite, hornblende, and apatite are common accessory minerals.

THE CHIBOUGAMAU SERIES#

Slightly metamorphosed sedimentary rocks of the Chibougamau series occur as scattered remnants resting uncomformably on rocks of the volcanic series, the ultrabasic series, granite and syenite. The dip of the sedimentary rocks is between 5° and 50° to the south and

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#(named by Mawdsley and Norman (1935, p. 43).)

southeast. The largest outcrops occur along the northern extensions of Lake Chibougamau where the formation strikes northeast. The outcrops are bounded by faults on the south or southeast side.

The Chibougamau series consists mainly of pebble and cobble conglomerate with interstratified arkose and greywacke. Sedimentary structures commonly preserved are cross-bedding, pre-consolidation slump structures, and differential compaction at the base of cobbles and boulders. Retty (1930, p. 58) suggested correlation of the Chibougamau series with the Cobalt series of eastern Ontario and western Quebec.

FAULTS AND SCHISTOSITY

Shearing has affected all the rocks in the area. Faults can be recognized where movement has brought together contrasting rock types. The most prevalent direction of shearing is, however, parallel to the layering of the rocks. Because of this, it is difficult to establish the amount of movement involved. The presence of many schistose sections suggests that adjustments to folding and intrusion may have involved considerable overall movement, effected probably in a number of stages. Shear zones and fault zones constitute a complex system; many are linked.

In the volcanic series lava flows and intrusive metagabbro and metadiabase are relatively massive whereas tuffs and the contacts between formations are commonly schistose. Lineation within these planes of foliation is inclined steeply to the north and northeast; small drag folds and crenulations in tuffs and some schist zones plunge to the northeast. In most areas relative movements between the various rocks appear to have been a combination of dip-slip and strike-slip movement.

Faults strike approximately east-west parallel to the trend of the formations, northeast, northerly, and northwest.

The most conspicuous transverse faults trend northeast along Lake Dore, along the McKenzie Narrows, and a little farther west, along Contact Bay. At the northeast extremity of Lake Dore a broad zone of shearing trends northeast in the volcanic series, and extends around and across a granite plug on Portage Bay, Lake Chibougamau.

Mineralized shears in the Dore Lake complex trend southeast.

CHAPTER III

THE GABBROIC SILLS

INTRODUCTION

Metamorphosed "gabbroic" or "dioritic" rocks are widely represented in the vicinity of Chibougamau. They occur in various geological associations and are probably of diverse origins. Within the southwest quarter of Roy township and in part of the southeast quarter of McKenzie township, the gabbroic rocks may be divided into three groups on the basis of their associated rocks, their structure, and their (presumed) genesis. The gabbroic rocks are associated with:-

1) the volcanic series,
2) the Dore Lake complex,
3) a series of ultrabasic rocks.

That some gabbroic intrusives may be related to the volcanic assemblage was recognized by Mawdsley and Norman (1935, pp. 11, 22, 27 etc.), Smith (1953, p. 7), and Allard (1956 b). The latter briefly described three sills in the southern sector of McKenzie township.

This thesis is restricted to a study of gabbroic rocks which occur in the volcanic assemblage in the southwest quarter of Roy township and in part of the southeast quarter of McKenzie township, Abitibi-East County, Quebec.

FIELD RELATIONS

The gabbroic rocks occur as long, narrow sills that range in width from 50 to 2,000 feet and in length from a few hundred feet to two miles.

In the southwest quarter of McKenzie township, Smith mapped 5,000 to 6,000 feet of "metagabbro" and "metadiorite" in the volcanic assemblage of 15,000 to 22,000 feet total thickness (Smith, 1953, Preliminary Map No. 945). These rocks have been followed eastwards by detailed mapping for another ten miles into the southwest quarter of Roy township. In the latter area the "metagabbros" are not present in the volcanic assemblage north of Portage Bay, but they reappear farther to the east (Horscroft, Unpublished). In the same belt of volcanic formations, therefore, gabbroic rocks constitute up to one quarter of the total assemblage in a belt mapped in detail for 15 miles along strike.

The metagabbros trend nearly east-west and are concordant with the layering in the volcanic rocks. Their common form is that of sills. However, cross-cutting relations are present in a wide outcrop north and northwest of Proulx Bay. At the west end, the metagabbro forms a number of small salients into pillowed lava and the contact trends northwest, a direction which is contrary to the east-west regional strike. The contact is sheared locally, but exposures are good enough to indicate intrusive relationships. The east end of this metagabbro outcrop occurs along the edge of a cliff face which trends north. The upper part of the cliff is composed of volcanics and the lower of metagabbro; the field relations indicate that the contact dips north. Farther west, a gabbro-lava contact trends east-west across a steep-sided hill approximately one hundred feet high, indicating a vertical attitude. In many areas, the contacts of the sills are either sheared, or obscured by drift, or the relief is too low to establish any indication of the attitude.

Contacts of the gabbroic sills with the volcanic rocks are in general schistose. Where not sheared, many contacts are gradational and gabbroic and volcanic rocks merge within a distance of a few feet. This is especially true in areas of fine-grained gabbroic types where the absence of distinctive textural or mineralogical features makes it impossible to pinpoint contacts. Sharp contacts are most readily apparent in areas where light coloured volcanics are intruded by medium-grained gabbro. In these areas, the contacts may be narrowed down to a few inches. Chloritization and epidotization is common at the contact, No definite chill zones have been recorded.

PLATE 6

Fig. 1 Contact between metadiabase (D) and tuff (T). The pencil lies along the contact. West of the Valiquette Narrows, Roy township.

Fig. 2 Sheared contact between metadiabase (M) and pillowed meta-andesite (A). A fine-grained grey dyke (D) cuts across the contact. McKenzie township.

By contrast, the contacts of basic and acidic dykes are sharp and may be determined to within an inch or less. The edges of the dykes are chilled against, but do not appear to have affected the gabbros to any significant extent. These basic dykes cut across the sheared contacts between the volcanics and the gabbros and are not considered to be genetically related to the latter rocks.

Fragments of volcanic rocks and tuffs that range from a few feet to 400 feet wide and up to 1,000 feet long are preserved within the thick sills. Many occur as large blocks engulfed by the gabbro. Their original character is clearly displayed by volcanic structures in the lavas and by bedding in the tuff.

The fine-grained gabbros grade into recognizable volcanic rocks on the one hand and into medium-grained gabbros on the other. The gradation can be seen in drill cores and in outcrop. Field evidence in many areas fails to distinguish between intrusive rocks and possible coarser parts of flows.

Some sills are layered. In many the northern parts contain quartz and elongated minerals (the so-called "meta-diorite"), and the southern part equant minerals (the "meta-gabbro"). The two types merge gradually so that it is not possible to determine the attitude of the layering. Strike-wise, the layering conforms with the structure of sills.

In thin sills quartz and micropegmatite may be present in small amount only, or may be absent; the texture is ophitic to subophitic. Thick sills are slightly coarser-grained than thin sills; their texture is subophitic to gabbroic.

The quartz-rich phases occur near the centre or northern (i.e., presumably the upper) parts of the sills and nowhere at the base. In the upper parts of sills, the texture is dominated by the prismatic habit of amphibole randomly intergrown with plagioclase. Gradation in the textural and mineralogical characters of the rocks suggests that the layering originated by differentiation rather than by separate intrusion.

Layering is well represented in a sill located in the southeast quarter of McKenzie township 3 miles west-northwest of Proulx Bay, Dore Lake. This sill was mapped by J. R. Smith in 1953-1954 and was revisited by the writer who re-examined the occurrence and collected a representative suite of specimens. Subsequent petrographic study has modified Smith's mapping only in small details (Smith, J. R., Unpublished).

The chemistry of this sill - hereafter referred to as the "Smith sill" - has been studied. The field characters of the sill are as follows.

The Smith sill intrudes a volcanic assemblage of intermediate composition (meta-andesite?). Ultrabasic rocks and associated gabbros are intruded north and east of the sill. The Smith sill is wide in proportion to its length as compared with the average sill in the area, and is a little over a mile long and slightly over one third of a mile wide.

The sill is composed of three main rock types:-

a) metapyroxenite which forms a band to 150 feet wide along its southern contact,

b) metagabbro-metadiabase which forms the southern half of the sill,

c) quartz-diabase and diabase-pegmatite which forms the centre and northern parts of the sill.

At surface, these rocks form 5%, 58%, and 37% of the sill respectively. The attitude of the layering and hence the true thickness of the sill is not known.

The layering trends in general east-west parallel to the strike of the enclosing rocks. Near the east end, the contact between the diabase-pegmatite and the metadiabase swings north, confining the quartz-rich phase to the north-western sector, whereas the metapyroxenite is widest in the southeast. The structure may dip north, but in the present study is regarded as being vertical in conformity with other sills in the area. In the accompanying diagrams thickness is measured as "horizontal distance from base of sill", i.e. plan distance.

MEGASCOPIC DESCRIPTION

Three types of rock are present in the sills. They contain the following essential minerals: amphibole (after pyroxene), chlorite, altered plagioclase, and quartz; and as accessory minerals, leucoxene (sphene), pyrite, and magnetite.

The textures are best seen on weathered surfaces, especially under a cover of moss, where differential etching has resulted from weathering and the chemical action of roots. The textures are not as well displayed by freshly broken surfaces because of a general dark colour of alteration.

The rocks may be classed as fine-grained to medium-grained, and are of three types:

(a) metapyroxenite,
(b) metadiabase and metagabbro,
(c) quartz-diabase and diabase-pegmatite.

(a) Metapyroxenite:

In handspecimen, the metapyroxenite is composed of equant crystals of dark amphibole ranging from $\frac{1}{4}$ to $\frac{3}{4}$ cm. in size. The rock is massive. Patches are strongly chloritized and serpentinized.

(b) Metadiabase (metagabbro):

This rock constitutes the bulk of the sills. It includes uniformly medium-grained and fine-grained spotted or mottled types.

The most conspicuous mineral is black to dark green amphibole from 1 mm. to 1 cm. in size, of irregular, but roughly equant shape. Cleavage planes on the amphibole are well preserved and produce a characteristic lustre mottling. By contrast, the altered feldspars are inconspicuous. The feldspars are white to pale green on freshly broken surfaces and project into and are enclosed by the femic areas. Where recognizable as tiny laths, the feldspars are a few millimetres long.

The proportion of feldspars to femic minerals varies. In light-coloured types feldspars and their alteration products are in excess of the femic minerals in the proportion 6:4, but in darker varieties, the femic minerals may be in excess.

The proportions of the minerals are difficult to estimate on fresh surface because of the dull appearance of the feldspars. Generally, leucocratic types are dark and the femic minerals occur as irregular spots, producing a somewhat ophitic texture. The feldspars, lacking cleavage and good crystal outline, occur as a "paste" between the femic minerals.

PLATE 7

Fig. 1a

Fig. 1b METADIABASE H55/C25

Illustrating fresh and weathered surfaces of the same specimen

PLATE 8

Fig. 1 METADIABASE H55/C3

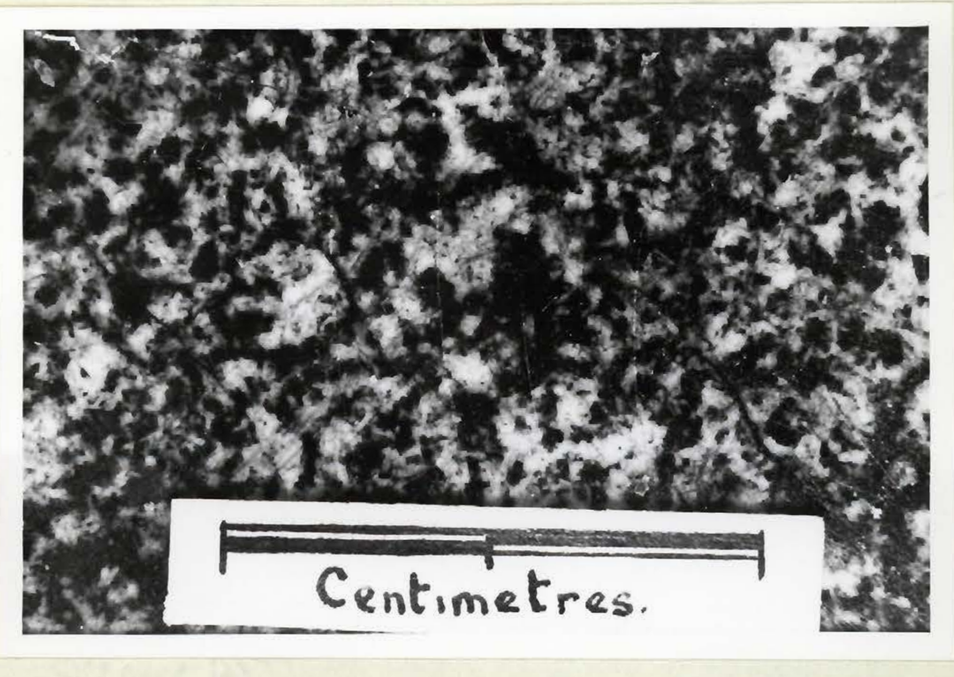


Fig. 2 METADIABASE H55/B6

Illustrating a fresh surface (Fig. 1) and polished surface (Fig. 2) of medium-grained metadiabase. Dark areas are actinolite + chlorite; light areas are saussuritized plagioclase.

PLATE 9

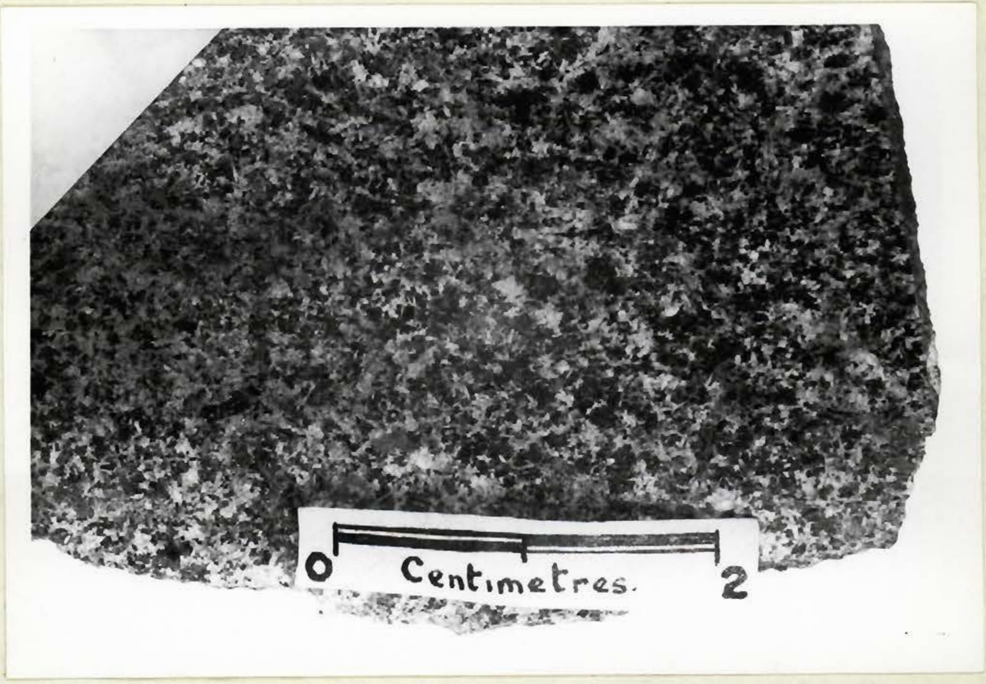


Fig. 1 METADIABASE H56/314

Polished surface of metadiabase from near the base of a thin sill.

(c) Quartz-diabase and diabase-pegmatite:

The most distinctive textural feature is produced by dark green to black prisms of randomly oriented amphibole from 1 mm. to over 1 cm. long. Both prismatic and equant amphibole crystals may occur together and it is not always possible to assign intermediate rock types to either the metadiabase or the diabase-pegmatite. In many areas the prismatic habit of the amphibole is distinctive and it may be used to trace out certain formations, but where the rock is strongly chloritized, the texture is not visible on fresh surface. The haphazard arrangement of the former amphibole may still be recognizable on weathered surfaces.

Feldspars do not generally exhibit crystal outline and their cleavages are inconspicuous. They are green to pale green with small white patches locally and occur as elongated crystals a few millimetres long intergrown with the amphibole. Where the rock is chloritized, the feldspars are enveloped by the chloritic matrix.

Quartz is common as rounded crystals 1 to 2 mm. in size. It is present as small "eyes" which are readily distinguishable against the dull background of altered amphibole and feldspar. In some sills quartz is not visible in the diabase-pegmatite but in others it forms up to 30 percent of the rock. Where abundant, the quartz occurs as blebs 1 to 3 mm. in size. Most of the quartz is closely

PLATE 10

Fig. 1 DIABASE-PEGMATITE H55/C7

Fig. 2 DIABASE-PEGMATITE H55/C14

Fine-grained diabase-pegmatite; fresh surface (Fig. 1) and polished surface (Fig. 2). The white vein in figure 2 is composed of albite.

PLATE 11

Fig. 1 DIABASE-PEGMATITE H55/B21 (Smith Sill)

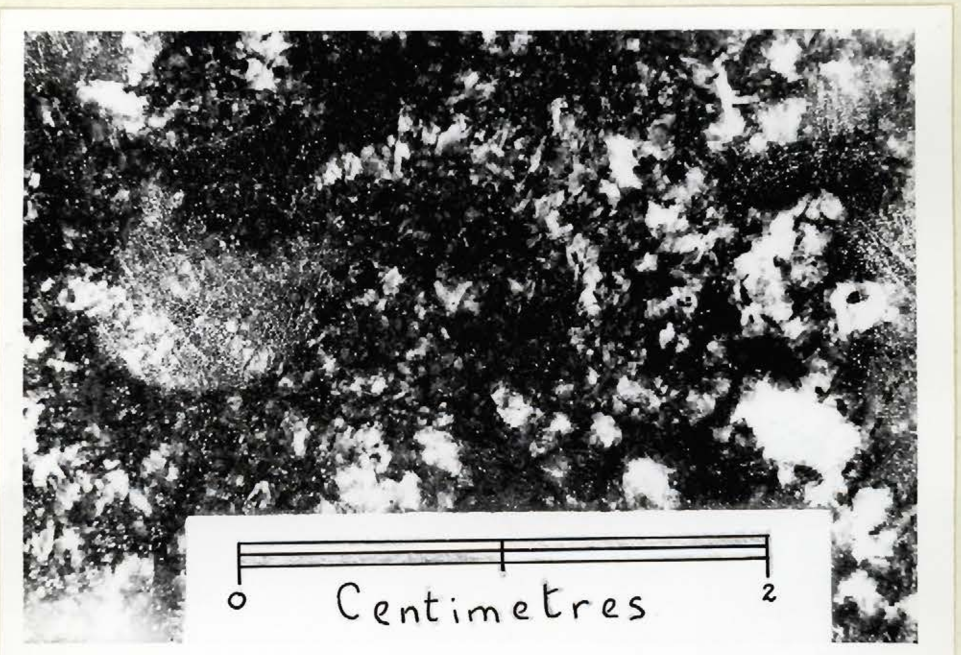


Fig. 2 DIABASE-PEGMATITE H55/B22 (Smith Sill)

Polished surfaces of diabase-pegmatite. The texture is preserved in Fig. 1, but has been obliterated by chloritization in Fig. 2. Black areas are amphibole chlorite; white areas are albite quartz.

associated with the feldspar.

Small, white to yellow crystals of leucoxene (sphene) and pyrite are common accessories.

In general these rocks are uniformly massive and well jointed. Where sheared, they are readily converted to chlorite schist and chlorite-carbonate-quartz schist. Quartz veins are widespread and occur in thick as well as in thin sills. The veins are lenticular and most of them extend for a few feet only, but a number are continuous for 200 to 300 feet as irregular vein systems. They are sparsely mineralized with pyrite and lesser chalcopyrite.

CHAPTER IV

PETROGRAPHY

Detailed petrographic examination was undertaken on specimens taken across five sills in addition to a number from widely scattered points. Sixty-five sections of gabbroic rocks were examined.

Three rock types are represented, viz. metapyroxenite, found in one sill only, metadiabase (metagabbro) which constitutes the bulk of the sills, and micropegmatite, diabase-pegmatite or quartz-diabase. Each rock type is described below.

THE METAPYROXENITE

The metapyroxenite was found only in the Smith sill. The rock is composed mainly of plates of amphibole and talc-magnetite aggregates, with subordinate chlorite, serpentine, and carbonate.

At the south contact of the sill, the southern margin is composed mainly of talc-magnetite aggregates, but amphiboles are the chief constituent farther north. At the north contact of the sill, only amphibole is present.

(i) Talc-magnetite Aggregates:

The former presence of olivine is shown conclusively by the crystal shape of talc-magnetite-carbonate pseudomorphs. Most of these are rounded, many show at least some crystal outline, and a few are euhedral. They range from 0.3 mm. to 2 mm. in diameter. No olivine is present. Some pseudomorphs are composed only of talc and magnetite; others contain much fine-grained carbonate as well.

The talc occurs as a felt of small laths randomly oriented within the area of former olivine. A few talc crystals occur as plates 0.5 mm. long. The talc laths in one pseudomorph may be aligned, but not with laths in adjacent pseudomorphs. Hence there is no directive structure. The talc is everywhere associated with small crystals of magnetite. Together they constitute aggregates which clearly outline the pseudomorph.

The magnetite grains are generally larger than .025 mm. They occur as scattered individual grains, irregular aggregates and blebs to 0.2 mm. in diameter, and as irregular rods and streaks. In most pseudomorphs these streaks are aligned along the crystal edges or within the crystal itself. Irregular, curved streaks probably fill cracks in the former crystal, but regularly oriented streaks are very likely controlled by definite crystallographic directions. In the majority of pseudomorphs the magnetite granules and rods are strictly confined to the area of the pseudomorph, but exceptions do occur where the magnetite extends across the border of the olivine pseudomorph into adjacent minerals. Many of the magnetite grains have crystal outlines and a few are euhedral. Some occur as slivers lying between the talc laths and others form thin veins which cut across the talc crystals. There is no alteration to leucoxene or sphene.

Most pseudomorphs have sharply defined margins which consist of concentrations of iron ores and aggregates of fine-grained carbonate and talc. Where enclosed by amphibole, the talc-magnetite pseudomorph is sharply separated from the enclosing mineral and crystals do generally not project from one pseudomorph into the other. Where there is a concentration of magnetite along the contact, the irregular nature of the magnetite and continuity into the talc-magnetite pseudomorph suggests that the magnetite is genetically related to the olivine crystal. Only in a few areas does this magnetite extend into the amphibole.

(ii) Amphiboles:

Amphiboles occur as interlocking equidimensional plates 1 to 2 mm. in size. They constitute up to 85 percent of the rock and occur in three distinct ways, which are briefly, as follows:

(a) a red brown amphibole which forms distinct relics,
(b) a pale green amphibole which forms from (a),
(c) (1) an aggregate of small colourless prisms of amphibole which envelop and can be seen to form from pale green amphibole,
    (2) a mesh of tiny colourless amphibole and chlorite and/or serpentine, with minute disseminated grains of magnetite.

The brown amphibole forms equidimensional crystals some of which contain magnetite. The brown variety is ringed by a pale green amphibole which in turn alters to a colourless to very pale green variety, all being in optical continuity. The change in colour is generally gradational although some sharp transition is also present. In the brown variety iron ore occurs as streaks with a distinct orientation, in most crystals parallel to the cleavage, but also oblique to it. This alignment of the iron ores is not present in the pale green amphibole where the magnetite forms discrete particles and occurs in lesser amount. In general, the amphiboles contain little or no magnetite.

The brown and pale green amphiboles have the following pleochroic formulae:-

Brown Variety	Pale Green Variety
X = brownish-yellow	X = pale greenish-yellow
Y = red brown	Y = pale green
Z = deep red brown	Z = pale green

Measurement of the optic angle on the red amphibole had the following results:-

$2Vx = 76^\circ, (74^\circ), 80^\circ, 80^\circ.$ Average = 79°

$Z/c = 16^\circ$

The same measurements conducted on an optically continuous crystal with brown and green parts yielded the following:-

Brown section: $2\ Vx = 80^\circ$ $Z/c = 16^\circ$

Green section: $2\ Vx = 80^\circ$

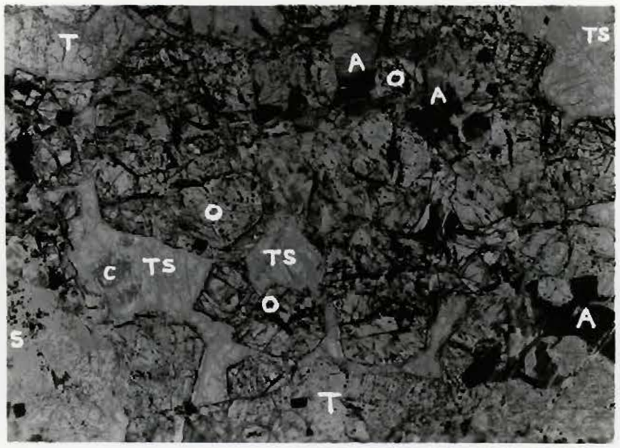
Pale green amphiboles not associated with brown amphibole have the following optical character:

$2\ Vx = 80^\circ, (92^\circ), 85^\circ, 81^\circ.$ Average = 82°

$Z/c = 13^\circ, 21^\circ, 17^\circ, 12^\circ.$ Average = 16°

PLATE 12

Photomicrographs

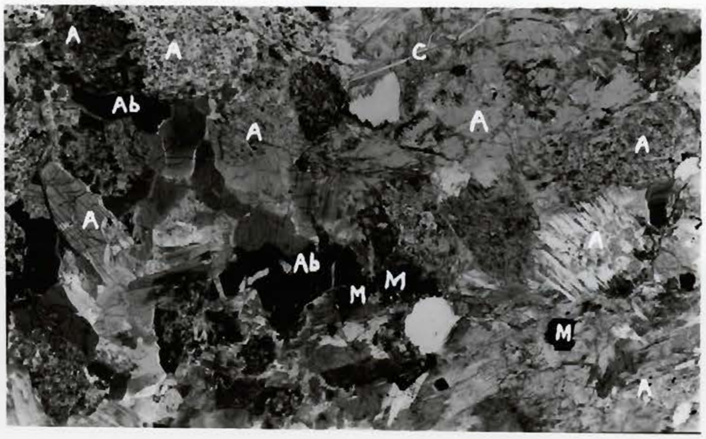


Plane-
polarized
light

X 13

Fig. 1 Olivine-rich section
at base of the Smith
sill. H55/B3

Magnetite-talc aggregates after olivine (O); talc (T); serpentine (S); carbonate (C); brown to green amphibole (A).



Nicols
Rotated
20°

X 13

Fig. 2 METAPYROXENITE H55/B4
(near base of Smith sill)

Slide is composed mainly of plates of actinolitic amphibole (A); brown amphibole (Ab); magnetite (M); carbonate (C).

The brown and green amphiboles are negative.

The colourless amphibole extends irregularly through the light green. In advanced stages of alteration only small remnants of brown amphibole remain as "islands" in a sea of pale green and colourless amphibole with scattered tiny crystals of carbonate. The colourless amphibole occurs as plates with fibrous or ragged edges where replaced by carbonate in veins.

The pale green amphibole breaks down to tiny colourless laths of amphibole and talc which are not in crystallographic continuity with the pale green amphibole. Their formation thus disrupts the homogeneity of the crystal. In some crystals the secondary minerals have a preferred orientation which may be perpendicular to the trend of the pale green amphibole. As far as can be determined, this alteration occurs uniformly throughout the crystal and shows no change with respect to adjacent minerals or to position within a crystal. Former mineral boundaries can in many places be discerned quite distinctly even between identical aggregates where the mutual boundary is sharp. This transformation of the pale green amphibole is effected with little change in the distribution or amount of the magnetite.

In another type of alteration the pale green and colourless flakes are intimately altered to chlorite (variety pennine) and tiny laths of amphibole and/or talc. A scattering of tiny grains of magnetite is characteristic. This magnetite occurs as dust-like particles when compared with the magnetite in the pseudomorphs after olivine. It occurs as clusters of particles or as discrete particles of .005 mm. size, with a few blebs to .15 mm. Most of the magnetite is randomly scattered but some occurs as trains of crystals oriented perpendicularly to aligned flakes of talc, constituting a rough rectangular grid. The contact between this type of pseudomorph and areas of serpentine may be sharp and linear or the serpentine may replace the aggregates along an irregular contact. The pseudomorph has been found contiguous to a relatively unaltered brown amphibole containing magnetite streaks. The contact can be traced across the transition from brown to pale green amphibole without any noticeable change in the pseudomorphous aggregate. It is interpreted as indicating that the brown to pale green amphibole is a different mineral species to the pseudomorphous aggregate being considered.

The brown amphibole envelops talc-magnetite pseudomorphs after olivine poikilitically; a narrow rim of colourless amphibole is always present except where magnetite is concentrated along the contact. The pseudomorphs after olivine also occur in the fine-grained aggregates with magnetite "dust". These different aggregates stand out clearly not so much because of differences in mineral composition but because of contrasts in crystal sizes and textures. Contacts are relatively sharp.

(iii) Serpentine and Chlorite:

Serpentine and chlorite are present in small amount and constitute approximately 10 to 15 percent of the rock. The serpentine is commonest in sections rich in talc-magnetite pseudomorphs after olivine, and chlorite in sections containing mainly amphibole.

The serpentine occurs in three ways:

(a) as patches between pseudomorphs,
(b) as veins,
(c) as an alteration in some of the pseudomorphous aggregates described above.

The serpentine is pale green in colour and non-pleochroic. Birefringence is low with grey to blue interference colours. Much of the serpentine appears to be massive, even under high power, but in some areas a felt of tiny crystals approximately .025 mm. long can just be resolved.

Narrow, continuous veins of serpentine extend between the individual pseudomorphs and generally does not cut through these crystal areas. Tiny flakes and laths of talc are ubiquitous in the serpentine and very fine-grained, disseminated magnetite is present as clusters of tiny crystals. The serpentine everywhere contains small crystals of carbonate which form a border to the veins. Where serpentinization is pronounced, the carbonate forms a ring around talc-magnetite pseudomorphs and extends into the pseudomorphs along irregular "cracks" containing magnetite. The carbonate is fine-grained and forms few crystals as large as .1 mm. in diameter.

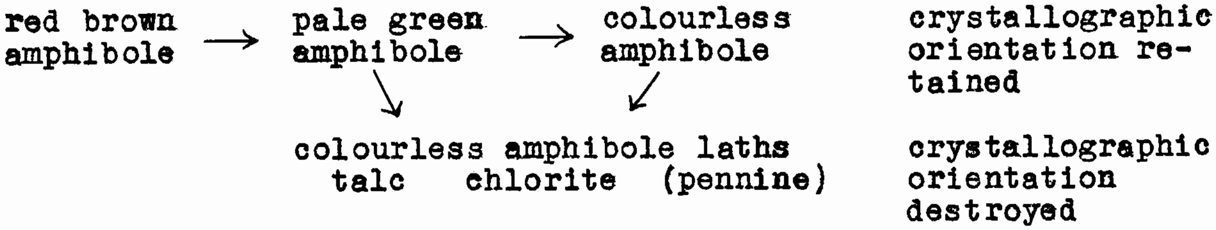
Two types of chlorite may be distinguished. Both are weakly pleochroic from straw yellow to pale green.

Fibrous pennine occurs as irregular aggregates within amphibole plates. It is readily distinguished by an anomalous blue interference colour.

A second type of chlorite forms plates to .8 mm. long and has a grey brown birefringence. It is everywhere associated with fine-grained carbonate and these two minerals together occur as patches between the pseudomorphs. Many amphiboles are fibrous around their edges and interlock with the chlorite and carbonate which generally do not penetrate the amphibole along its cleavage. Some chlorite and carbonate cuts sharply across brown amphibole.

No mineral assemblage suggests the former presence of feldspar.

The changes in the amphiboles may be illustrated as follows:-



Formation of serpentine, chlorite, and carbonate appears to be a late alteration.

THE METADIABASE

The metadiabase is composed mainly of uralitized pyroxene and saussuritized plagioclase, subordinate chlorite and quartz, and accessory sphene (leucoxene), magnetite, pyrite, and apatite. The most common size of amphibole pseudomorphs after pyroxene is 2.5 mm. and altered plagioclase feldspars 1 mm.

Primary textures are on the whole well preserved. Most sections display subophitic relationship of amphibole pseudomorphs to altered plagioclase. The thin sills are commonly ophitic whereas the thicker sills are subophitic. The equant development of the crystals in the thick sills has led to their nomenclature as metagabbros. However, the amphibole pseudomorphs are everywhere approximately twice the length of the plagioclase laths and overlapping of the two minerals is generally present. The rocks are better termed diabasic gabbros, and are in this description included under metadiabase.

(i) Pyroxene:

A primary clinopyroxene occurs only as small relics. It is colourless, clear and unaltered, is free from inclusions, and has high birefringence and good cleavage. The mineral is optically positive and has the following additional optic characteristics which fall into two groups:

(a) 2Vz = 63°, 60°,57°, (74°) Average 2Vz = 60°
Z/c = 43°, 59°,59°, (59°) Average Z/c = 50°

(b) 2Vz = 49°, 50°,53° Average 2Vz = 51°
Z/C = 35°, 34°,39° Average Z/c = 36°

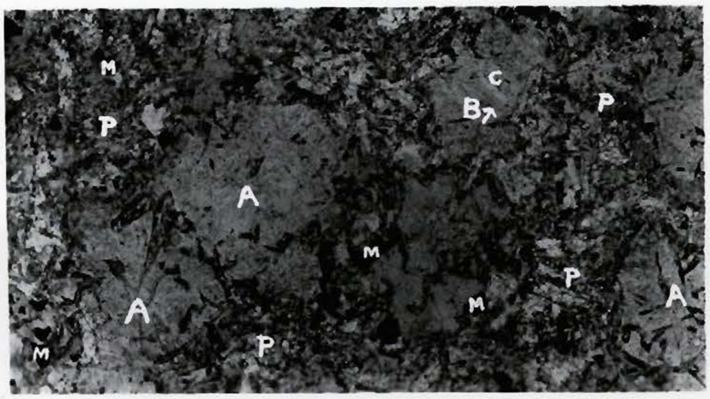
PLATE 13

Photomicrographs

Crossed Nicols

X 11

Fig. 1a



Plane-polarized light

X 11

Fig. 1b

METADIABASE H55/D6

Equant crystals of actinolite (A) with interstitial strongly saussuritized plagioclase (P).

Note the relics of augite (B) replaced by chlorite (C); magnetite (M).

The minerals have positive elongation. They are identified as varieties of augite.

The pyroxene relics are up to .6 mm. size. Several fragments may be grouped together in one area and their former continuity is shown by a common optic orientation. The mineral occurs only as relics within larger crystal aggregates composed mainly of amphibole. Pale green amphibole (actinolite) or chlorite may be in contact with the pyroxene in different parts of a crystal and each of these minerals forms caries which project into and cut across the pyroxene. Amphibole pseudomorphs retain the shape and twinning but are not in optic continuity with the pyroxene relics.

(ii) Amphibole:

Amphibole occurs in crystals that range from under .5 mm. to 5 mm. in size. Their outline is irregular but the general shape is equant. They are mostly in ophitic to subophitic relationship with saussuritized plagioclase. Near the base of some sills there is little overlap of the feldspar on the amphibole. The amphibole is extensively altered to chlorite and these two minerals constitute an aggregate which is pseudomorphous after pyroxene. That the amphibole is uralite, is shown conclusively by the presence of augite relics and by the shape of the pseudomorphs.

A few amphiboles occur as homogeneous or compact plates but in most sections, and especially in those from the thinner sills, the amphibole has been converted to a fibrous aggregate. Alteration of amphibole to chlorite extends irregularly through the crystal, proceeding in part along the cleavage directions, but also cutting across the cleavage. Much of the chlorite is irregularly streaky and patchy. The unreplaced parts of the amphibole are in optic continuity so that where chloritization is intense, only a skeleton of amphibole remains. In a few sections the cores of amphibole crystals have been totally replaced by chlorite.

Homogeneous crystals have frayed edges and irregular mutual contacts. Fibrous amphibole consists of an aggregate of tiny amphibole laths and chlorite, the fibres of one pseudomorph lying roughly parallel but not aligned with fibres in adjacent crystals. In schistose sections chloritization completely replaces and destroys the former shape of amphibole; considerable carbonate is generally present.

Amphibole and associated chlorite have a similar pale green colour but their pleochroism varies slightly. They may readily be distinguished under crossed nicols by their differing birefringence. Some amphiboles have an anomalous grey green interference colour caused probably by incipient chloritization. Small grains of epidote and sphene are scattered through many of the amphiboles and the chlorite. In one section chlorite has completely replaced amphibole, the product consisting only of a mass of tiny chlorite flakes and scattered crystals of epidote.

The amphiboles are pale in colour, are weakly pleochroic, and have moderate birefringence. The most common type has a pleochroic formula as follows:

X = pale greenish-yellow to olive green Y = pale green Z = pale green

Many crystals have small differences in the shades of green and the following pleochroism is also present:

X = very pale green (almost colourless) Y = green Z = bluish-green
X = pale olive green Y = grass green Z = grass green
X = green Y = very pale green Z = pale bluish-green

In general, the later generations of amphibole tend to be of paler colour. The bluish-green type is an exception to this generalization for it has been found cutting across pale green amphibole.

PLATE 14

Photomicrographs

Plane-
polarized
light

X 11

Fig. 1 METADIABASE H55/B8

From the lower part of the Smith sill. Note the strongly saussuritized plagioclase (P) interstitial to large plates of actinolitic amphibole (A).

Plane-
polarized
light

X 11

Fig. 2 METADIABASE H55/B10

From the Smith sill. Saussuritized plagioclase (P) and actinolite (A) in subophitic texture; magnetite (M).

Note the larger proportion of plagioclase as compared with Fig. 1 above.

Additional optic properties of the olive green to pale green amphibole are:-

elongation positive
optically negative

2Vx = 78°, 77°, 72° Average 2Vx = 76°
Z/c = 15°, 17° Average Z/c = 16°

2Vx = 64°, 64° Average 2Vx = 64°
Z/c = 19°, 15° Average Z/c = 17°

nX = 1.632 (± .003)
nZ = 1.658 (± .003) nZ - nX = 0.026

The amphibole is identified as actinolite.

(iii) Chlorite:

Chlorite occurs in two ways:-

(a) As an alteration of amphibole with which it is intimately intergrown as described above. The chlorite closely resembles the amphibole in colour, in both the pale green and bluish-green types. It does not form large blades, but occurs as a mass of tiny crystals.

(b) As irregular "patches", some of which clearly lie between interlocking feldspar laths, but show no effects of reaction with the feldspar. The patches have a watery appearance and are composed of a felt of tiny interlocking laths. The patches may be elongated and form veins, others are roughly equant and range in size to over 1 mm. The chlorite is weakly pleochroic in shades of olive green. Some contain carbonate and epidote and laths of pale bluish-green amphibole. This chlorite has low birefringence with anomalous interference colours of blue and pale brown. It is possibly an alteration of chlorophaeite.

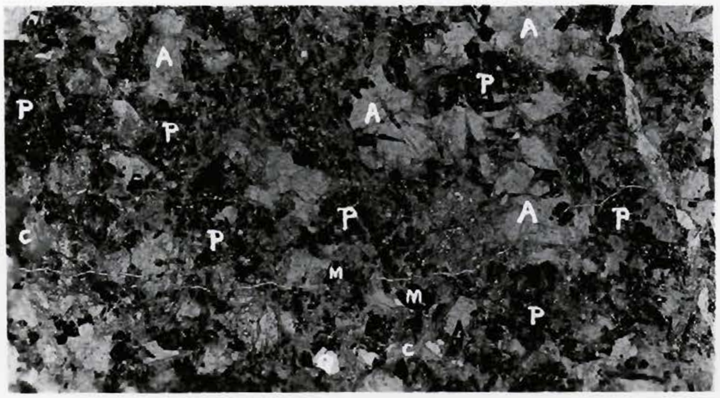
(iv) Plagioclase Feldspar:

Saussuritized plagioclase is in general the most abundant constituent. It shows a rather good idiomorphic development but in a number of areas the crystal outline is obscured by heavy saussuritic alteration. Crystals are stubby rather than slender and range in length from .3 to 2.0 mm., the average being 1 to 1.5 mm.

The feldspars are everywhere strongly saussuritized although the degree of alteration varies. In sections near the base of the sills the plagioclase is commonly an impenetrable dark mass of fine crystals composed mainly of clinozoisite. In these masses albite forms irregular small pellucid patches and in a few sections outlines the crystal boundaries. Towards the centre and upper (northern) parts of sills the crystals are clearer, but are everywhere speckled with aggregates of clinozoisite.

PLATE 15

Photomicrograph



Plane-
polarized
light

X 11

Fig. 1 METADIABASE H56/314

From the lower part of a thin sill. Plates of actinolitic amphibole (A) with interstitial strongly saussuritized plagioclase (P); few crystals of quartz (Q); chlorite (C); magnetite (M).

The laths may be clearly outlined, but their contacts are irregular. This irregular boundary occurs along both feldspar - feldspar and feldspar - amphibole contacts. Where the feldspars are in contact with amphibole, tiny needles of amphibole project into the feldspar, but no chloritization is apparent.

Twinning is sharply defined in some sections. In others it is barely recognizable. Most crystals are twinned according to the Carlsbad law but a number have polysynthetic twinning. The twin planes of the latter type may be broad and only two or three lamellae may be represented in one crystal; some are as narrow as .001 mm.

Symmetrical extinction angles and low refractive indices compared with balsa indicate that the composition of the present feldspars is Ab_{96} An_{04} to Ab_{92} An_{08}.

Most feldspars are randomly oriented; a few laths are bent. Where sheared, the albite forms a mozaic of clear grains.

(v) Clinozoisite:

Clinozoisite is abundant as small crystals in the altered plagioclase. It occurs in aggregates to .6 mm. in size and is euhedral toward the clear patches of albite.

(vi) Epidote:

This mineral is present only in small amounts in altered plagioclase. It also occurs as small crystals in the amphibole and forms veinlets .2 mm. wide which cut across feldspars and amphibole alike.

(vii) Sphene, Leucoxene, Ilmenite, Magnetite:

Lamellae of sphene are intergrown with magnetite in a triangular network, characteristic of the ex-solution features of ilmenite in magnetite. Some crystals are composed of approximately 85 percent magnetite and 15 percent sphene. In many sections the sphene is turbid and may be composed largely of leucoxene in which magnetite or ilmenite forms scattered dust-like inclusions.

Sphene occurs less commonly as discrete small crystals. All occurrences of sphene and magnetite-sphene intergrowths have a marked preference for areas of amphibole.

(viii) Quartz:

Quartz is present in small amounts as clear, unstrained crystals interstitial to the feldspars. It occurs also as a mozaic of small crystals with associated epidote and chlorite, and as few narrow veinlets.

(ix) Pyrite:

Pyrite in small amount is commonly associated with quartz and magnetite-sphene intergrowths.

(x) Apatite:

Only a few crystals of apatite are present.

THE QUARTZ-DIABASE AND DIABASE-PEGMATITE

Quartz-diabase and diabase-pegmatite constitute the central and northern sections of many sills. In some sills quartz is absent, or is present only in small amount. In other sills quartz forms up to 29 percent of the rock as a micropegmatitic intergrowth with plagioclase feldspar. Where the quartz is abundant, the rock is granophyric.

The diabase-pegmatite is slightly coarser-grained than the metadiabase and is characterized by the idiomorphic development of altered amphibole laths and plagioclase, the amphibole forming elongated single crystals intergrown with the feldspars. Many of the amphiboles are divided longitudinally by twin planes, and a number are curved. In a number of thin sills diabase-pegmatite is not present although quartz forms up to 3 percent of the rock.

The main petrographic differences between metadiabase and diabase-pegmatite are illustrated in tabular form below.

	Metadiabase	Diabase-pegmatite
Texture	Subophitic to ophitic	idiomorphic with interstitial micropegmatite
Amphiboles:shape	equant	elongated, strongly chloritized
Amphiboles:length	to 4 mm.	(probably greater than 4 mm.)
Amphiboles:volume %	38 to 52 (av.)	22 (av.)
Amphiboles:colour	pale green	green
Plagioclase:length	.3 to 2 mm.	1 to 4½ mm.
Plagioclase:volume %	47 to 58 (av.)	49 (av.)
Quartz:volume %	0 to 3½	0 to 29

The volume percentages of the main constituents of diabase-pegmatite are:

	Volume %
Saussuritized plagioclase	41 to 58
Amphibole (+ chlorite)	12 to 34
Quartz	0 to 29
Accessories	3 to 10

(i) Plagioclase Feldspar:

Saussuritized plagioclase is the major constituent. It occurs as well-formed, interlocking and rather stubby crystals to 4½ mm. in length. All the plagioclase is saussuritized and consists of scattered small clinozoisite and epidote crystals in a base of clear albitic feldspar. The plagioclase in the diabase-pegmatite is clearer than the plagioclase in the metadiabase and does not contain nearly as much clinozoisite. A few crystals are roughly zoned with clinozoisite concentrated at the centres of the crystals.

Carlsbad and polysynthetic twins are abundant, but only a few pericline twins are present. The amount of clinozoisite in twinned plagioclase is approximately the same as that in the plagioclase intergrown with quartz in micropegmatitic structure.

Symmetrical extinction angles and low relief indicate that the composition of the twinned plagioclase is Ab_{97} An_{03} to Ab_{92} An_{08}.

(ii) Quartz:

Quartz occurs in two ways:-

(a) As irregular areas to 1.5 mm. size interstitial to the plagioclase laths. Quartz has good crystal outline where

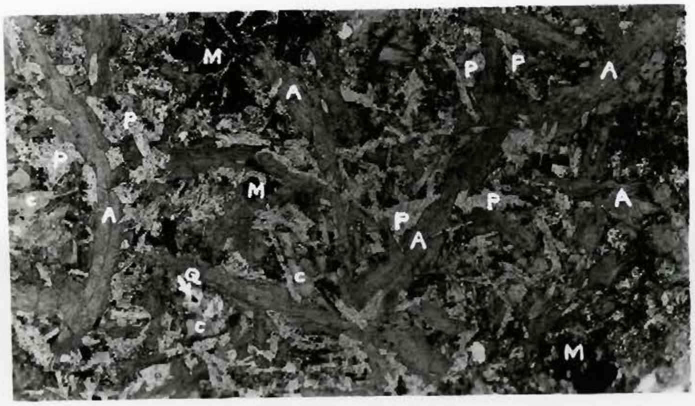
PLATE 16

Photomicrographs

Crossed Nicols

X 11

Fig. 1a



Plane-polarized light

X 11

Fig. 1b

DIABASE-PEGMATITE H55/C16

Elongated, randomly oriented actinolitic amphibole (A) and smaller saussuritized but relatively clear plagioclase (P); magnetite (M); quartz (Q); chlorite (C).

Note the twinning and the curvature of the amphiboles.

present against euhedral plagioclase. Contacts between quartz and the plagioclase are sharp.

(b) The bulk of the quartz is in micropegmatitic intergrowth with albitic plagioclase as irregular areas up to 2.5 mm. in size. A few euhedral plagioclase laths are completely enveloped by the micropegmatite. These laths are clearly defined and a few are in optic continuity with plagioclase in the micropegmatite. No definite replacement of the euhedral laths is apparent. The micropegmatite is interstitial to, and later in crystallization than the plagioclase laths.

The quartz is not absolutely clear but contains many tiny colourless needles, and crystals of apatite.

(iii) Amphibole:

Amphibole occurs in strongly chloritized, irregularly elongated crystals. They form no large homogeneous plates and are aptly described as "shredded". Much of the amphibole occurs with chlorite in streaky patches and veins which cut across plagioclase and quartz. The amphibole and chlorite crystal aggregates constitute approximately one quarter of the rock. In a few sections the amphibole is

PLATE 17

Photomicrographs

Crossed Nicols
X 11

Fig. 1a

Plane-polarized light

X 11

Fig. 1b

DIABASE-PEGMATITE H56/312

From the upper part of a thin sill. Elongated, randomly oriented actinolitic amphibole (A) and saussuritized but clear plagioclase (P); magnetite (M).

completely replaced by chlorite and tiny grains of magnetite.

The amphibole in the diabase-pegmatite is slightly darker green and more strongly pleochroic than that in the metadiabase. The birefringence is masked by its colour. Two types, differing slightly in colour, have the following pleochroic formulae:-

X = greenish-yellow Y = green Z = blue green
X = yellowish-green Y = green Z = green

Magnetite, magnetite and sphene, epidote, and apatite, are common inclusions. Epidote is more abundant in the altered amphibole than in the saussuritized plagioclase.

(iv) Chlorite:

Chlorite is present as tiny flakes which occur in two ways:

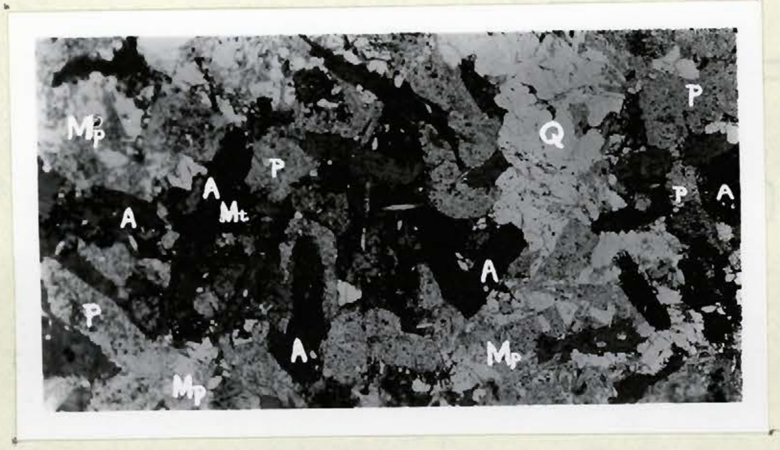
(a) Intimately associated with, and as an alteration product of amphibole. This chlorite is pleochroic with X = grass green and Z = pale yellow.

(b) With carbonate and epidote in narrow veins. This chlorite is bluish-green and has a pleochroism of:-

X = bluish-green Z = pale yellow

PLATE 18

Photomicrograph



Plane-
polarized
light

x 11

Fig. 1

DIABASE-PEGMATITE H55/B21

From the Smith sill. Elongated strongly chloritized green amphibole (A); saussuritized but clear plagioclase (P); micropegmatite (Mp); quartz (Q); magnetite (Mt).

Note the euhedral laths of plagioclase and amphibole.

(v) Magnetite:

Magnetite has two modes of occurrence:

(a) As crystals to .5 mm. intergrown with sphene. In these crystals the proportion of sphene ranges from approximately 10 percent to 60 percent.

(b) As small crystals in, and surrounding chlorite pseudomorphs after amphibole. Some of this magnetite projects into quartz as thin veins, and occurs also with chlorite as stringers.

(vi) Apatite:

Apatite is common as tiny euhedral crystals and slender prisms. It is present in quartz, plagioclase, and altered amphibole.

(vii) Pyrite:

Pyrite is a common, but scattered accessory.

Epidote, and epidote with tiny laths of grass green amphibole, occur as narrow veins which cut across quartz, plagioclase feldspar, and amphibole. These veins are in turn transected by thin veins of chlorite.

PLATE 19

Photomicrograph

Crossed Nicols X 11

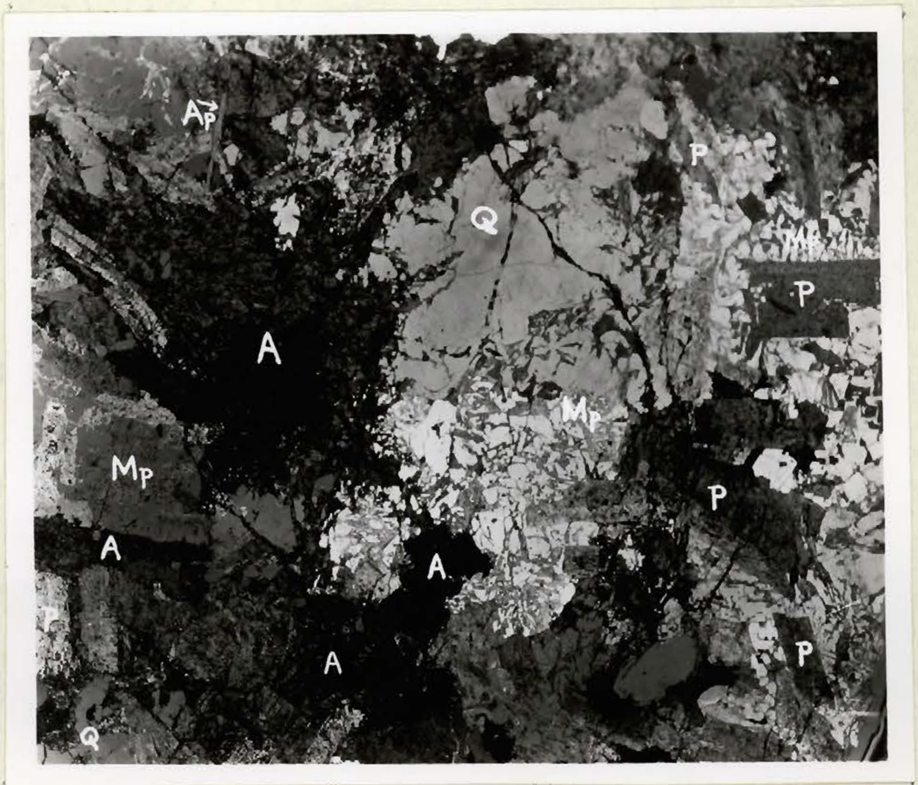


Fig. 1 DIABASE-PEGMATITE H55/B22

From the Smith sill. Plagioclase laths (P); quartz (Q); micropegmatite (Mp); apatite (Ap); irregular areas of strongly chloritized green amphibole (A).

Note the chlorite streaks cutting across the other minerals and the euhedral shape of the plagioclase laths some of which are completely enclosed by micropegmatite.

Staining of diabase-pegmatite with sodium cobaltinitrite according to the method outlined by Chayes (1952), failed to identify potash feldspar.

CHAPTER V

METAMORPHISM

ZONAL CONCEPT

The work of Barrow in the Dalradian schists of the southeast highlands of Scotland late in the 19th century demonstrated the feasibility of mapping zones of progressive regional metamorphism based upon mineralogical criteria. Each zone is defined by an index mineral the first appearance of which (in passing from lower to higher grades) marks the outer limit of the zone in question. The early work was carried out on argillaceous rocks for three reasons:

(a) because of their sensitivity to variation in temperature and pressure,

(b) because of their wide distribution, and

(c) because of their approximately uniform chemical composition.

The sequence of index minerals, in order of increasing metamorphic grade, is chlorite, brown biotite, almandine, staurolite, kyanite, sillimanite.

Studies of the metamorphism of argillaceous rocks in other countries have substantiated the early work in Scotland. However, small variations from the above are the rule, and are to be related probably to differences in chemical composition or in conditions of metamorphism.

The zonal concept has been applied less successfully to the metamorphosed derivatives of basic igneous rocks, "green beds", pyroclastics, greywackes, and impure limestone and dolomites. Important in this field are the work of Eskola (1922), Vogt (1927), Turner (1933), Wiseman (1934) and Sugi (1935).

In the derivatives of basic igneous rocks (including pyroclastics and "green beds") the association of chlorite with albite at low grades, and of hornblende with more calcic plagioclase at moderate to high grades, is characteristic. Wiseman (1934) showed that neither chlorite nor amphibole is a satisfactory zonal index mineral, since chlorite survives throughout the biotite zone as defined for associated argillaceous rocks, while the high-grade hornblendes merge into actinolitic amphiboles that are stable under some conditions even at the lowest grades within the zone of chlorite.

FACIES CONCEPT

The principle of facies classification of rocks was first applied in a precise manner by V. M. Goldschmidt in an account of contact metamorphism in the Oslo district of Norway and published in 1911. The facies principle was extended by Eskola and he introduced the term "mineral facies" in terms of which were described rocks of any origin which had reached chemical equilibrium under similar physical conditions. He originally defined 5 such minerals facies, viz. sanadinite, hornfels, greenschist, amphibolite, and eclogite.

The facies classification is founded upon petrographic experience that mineral assemblages in metamorphic rocks do in many cases, although not universally, obey the laws of chemical equilibrium. It is deduced that, given a bulk chemical composition and providing that the rock has attained equilibrium, a definite critical mineral assemblage is formed at a particular temperature and pressure within a certain facies. Unfortunately, few exact data exist on the pressure and temperature fields of many mineral combinations commonly encountered in metamorphic petrology so that the pressure and temperature conditions visualized are to some extent merely relative values. The facies does also not indicate whether the rock represents a primary or metamorphic assemblage. Furthermore, it has been found that the bulk composition of the rocks may have been changed particularly at low grade by the activity of water, carbon dioxide, and possibly other substances.

The principle of the facies classification has been severely criticized by Yoder (1955). He presents convincing argument to show that the metamorphic assemblage may be dependent solely on the amount of water present, and that at the same rock pressure and temperature it is possible to have representatives of several facies, as for example, the eclogite, amphibole, and green-schist facies.

Nevertheless, the facies classification may be successfully applied if these shortcomings of the method are correctly assessed. The classification has merit in that it is founded on assemblages which experience has shown are of widespread occurrence.

Facies Concept Applied to Basic Rocks

Many metabasaltic rocks have been slow in responding to plutonic conditions and it came as a surprise to many workers to find original textures in ancient Archaean rocks. An example was described by Sederholm (1923) who found undeformed phenocrysts and amygdules in the Archaean Perno metabasalts.

Poldervaart (1953) in a comprehensive review of the metamorphism of basaltic rocks, notes (p. 266) "that basaltic rocks may follow at least three different trends of metamorphic evolution, often in the same terrain, and apparently even when originally the rocks were of the same composition." Much data relevant to this problem has been obtained from the study of diabases (dolerites) in the central and southwestern highlands of Scotland by Wiseman (1934) and Sutton and Watson (1951). The latter writers conclude that the metamorphism of diabases can follow at least three different courses, in each of which relic minerals and structures can be recognized and each of which is of regional type. They state (op. cit. p. 32) "that although great variations in the course of metamorphisms are to be found in different localities, they are all due to processes which fall within the broad division known as regional metamorphism, and it is to variations within this division and not to such divergent phenomena as pure thermal or dislocation metamorphism, that they must be attributed."

The first major subdivision of metamorphosed basaltic rocks stems largely as a result of the work of Wiseman (1934). In his "normal" trend of metamorphic evolution, he recognized three main stages which may be summarized as follows:-

1) Chlorite, pale green hornblende, albite, and epidote replace the augite and labradorite of the diabase. Traces of the original texture are still recognizable.

(Chlorite and biotite zones of the associated argillaceous rocks)

2) Chlorite disappears; albite and epidote react to produce oligioclase or andesine; garnet appears locally. (Garnet zone of argillaceous rocks)

3) Epidote tends to disappear and augite locally begins to replace hornblende. (Sillimanite zone of argillaceous rocks)

This trend in progressive metamorphism was slightly modified by Eskola (1939) and Turner (1948) and was incorporated in the latter's correlation of critical mineral assemblages in the metabasaltic rocks, as presented in Table I, on the following page.

A second trend in metamorphic evolution of metabasaltic rocks as described by Sutton and Watson (1951), converges with Turner's classification in the amphibolite facies. The process of metamorphism can be divided into six stages as follows: (op. cit. p. 27)

1) Development of dark bluish-green hornblende around pyroxene and iron ore. Clouding of plagioclase. Original texture preserved.

2) Replacement of pyroxene by quartz-hornblende aggregates. Ilmenite rimmed by sphene. Original texture preserved.

3) Recrystallization of clouded labradorite to equidimen-

TABLE I (After Turner, 1948, p. 76)

CRITICAL MINERAL ASSEMBLAGES FORMED DURING PROGRESSIVE REGIONAL METAMORPHISM OF BASIC IGNEOUS ROCKS

Mineral assemblages in basic rocks and metamorphic equivalents	Mineral Facies	Corresponding metamorphic zones of Scottish Highlands
Plagioclase-pyroxene (-olivine) ↓	Gabbro facies	
Plagioclase-hornblende (-diopside) (-garnet) (-epidote or zoisite) ↓	Amphibolite facies	Sillimanite Kyanite Staurolite
Albite-hornblende-epidote (-chlorite) ↓	Albite-epidote-amphibolite facies	Almandine
Albite-actinolite-epidote-chlorite ↓	Greenschist facies	Biotite
Albite-epidote-chlorite (-calcite)		Chlorite

sional clear andesine. Recrystallization of quartz-hornblende aggregates to larger crystals. Partial modification of the original texture.

4) Complete destruction of the original texture with recrystallization of the quartz-hornblende aggregates.
5) Appearance of biotite.
6) Development of green augite.

A third trend of metamorphic evolution of metabasaltic rocks is characterized from the first by the presence of pyroxenes. It is generally regarded as belonging to the granulite facies.

Type of Metamorphism in the Area

The mineral assemblages found in the metadiabase, the diabase-pegmatite and the metapyroxenite all belong to the greenschist facies of Turner (1948). This greenschist facies is defined "to include all rocks formed at grades of metamorphism below that at which almandine appears in pelitic rocks; and the alternative presence of brown biotite, or the assemblage muscovite-chlorite, provides a basis for distinguishing two subfacies of higher and lower grade respectively" (op. cit. p. 93). In terms of critical mineral assemblages in metamorphosed basic igneous rocks, this may be shown as follows:-

albite - actinolite - epidote - chlorite)
)
albite - epidote - chlorite (-calcite))

Turner points out that within the greenschist facies itself there is a rather distinct tendency for actinolite schists to pass over into chlorite schists with little or no amphibole as the grade of metamorphism diminishes, notwithstanding the fact that actinolitic assemblages sometimes remain stable even at the lowest metamorphic temperatures.

Additional factors which may notably influence the nature of the mineral assemblages (besides chemical composition) are:-

1) chemical activity of circulating solutions, particularly water,
2) presence of carbon dioxide,
3) influence of shearing stress.

The effects of water and carbon dioxide on the metamorphism of basaltic rocks in the greenschist facies is given on the following page (Turner, 1935).

The critical mineral assemblage present in the rocks from Chibougamau is actinolite-epidote-albite-chlorite. In few sections, and especially where the rock has been

TABLE II (After Turner, 1935)

GREENSCHIST FACIES CONTROLS

Mineral assemblage	Control
Actinolite-albite-epidote-chlorite	CO_2 absent, H_2O insufficient to form chlorite from actinolite
Albite-epidote-chlorite-calcite	CO_2 present, H_2O sufficient
Albite-epidote-chlorite	CO_2 absent, H_2O sufficient
Albite-chlorite	CO_2 absent, H_2O abundant, removal of Al^{3+} and Ca^{2+}

noticeably sheared, the amphibole has been completely converted to chlorite + magnetite; carbonate may be present. In a number of sections thin veins composed of chlorite, carbonate, epidote, or quartz, cut across the major constituents of the rock. It is clear that their formation postdates the general metamorphism, and they are attributed to the action of concentrations of water and carbon dioxide (hydrothermal action).

In the majority of sections examined, the primary textures are still preserved and the rocks do not display any parallelism of minerals. It is therefore assumed that stress was not important during the metamorphism. The lack of stress is in keeping with the conclusions of Vogt (1927) who considered that diabase may be changed to "green schist" (at high temperature) without stress, while Hess (1933) found that a similar change may be produced by hydrothermal action, likewise without stress.

The metamorphism of the metadiabase, the diabase-pegmatite and the metapyroxenite is considered to have been caused by regional metamorphism.

The transformation of the various mineralogical associations is briefly discussed below.

A. The Metadiabase and Diabase-pegmatite

Plagioclase feldspar:- The altered plagioclases retain their original lath shapes. They have been extensively altered to clinozoisite and albite due to "saussuritization". In this reaction the anorthite molecule of the plagioclase + lime, alters to clinozoisite, while the albite molecule remains unaffected.

The greater abundance of clinozoisite in the plagioclase of the metadiabase as compared to the plagioclase of the diabase-pegmatite, suggests an original more calcic plagioclase in the former - a feature borne out by petrographic calculation.

Recrystallization of the plagioclase is indicated by two features. They are, according to MacGregor (1931), the absence of cloudiness, and, according to Gorai (1951), the preponderance of simple twins (Carlsbad and polysynthetic types).

<u>Actinolite</u>:- That most of the amphiboles in the metadiabase are pseudomorphs after pyroxene, is indicated by their shape and the presence of relics of pyroxene. In the diabase-pegmatite the origin of the amphibole cannot be determined with certainty. It may be after pyroxene, or amphibole, or perhaps both. Published descriptions of similar rocks from other areas suggests that the amphibole is pseudomorphous after pyroxene (see pp. 146-147).

Transformation of pyroxene into amphibole could be brought about by the redistribution of the elements already present in pyroxene. Some of the small variations in the optical properties of the amphiboles (especially the pleochroism) may well be related to original small differences in the compositions of the pyroxenes, or may be related to the incorporation of small amounts of different elements (e.g. alkali) during metamorphism. Differences in the primary composition of the pyroxenes are indicated more directly by the small inclusions of magnetite, carbonate, epidote, and sphene, the presence of which may indicate the inability of the low temperature actinolite to incorporate these substances in its crystal lattice.

Most actinolite is partly altered to chlorite. The intimate intergrowth of these two minerals and their similarity in pleochroism suggests a genetic relation. Some may have formed together, but more generally, however, the chlorite appears as an alteration of the amphibole. The mineral association may be accounted for in two ways.

The first may be represented by a change from augite to an intermediate "hornblende". In the greenschist facies Al^{3+} is more readily accepted into the chlorite lattice than into actinolite with the result that the "hornblende" breaks down to actinolite + aluminous chlorite.

If the actinolite is derived directly from a pyroxene, the necessary alumina to form chlorite could be obtained from breakdown of the anorthite molecule:

$$4AN + H_2O \longrightarrow 2\ \text{Clinozoisite} + Al_2O_3 + 2SiO_2$$

In a number of sections the centres of amphiboles are completely altered to chlorite. This is probably caused by the chloritization of an inner (earlier) magnesium-rich phase of the crystal, the outer relatively iron-rich part being more resistant to chloritization.

Wiseman (1934, p. 364) in a study of the metamorphism of diabases (dolerite) showed graphically that there is a consistent relationship between the refractive indices of "hornblende" and the chlorite associated with it. From this Wiseman concluded: "It can be hardly erroneous to assign a simultaneous origin to the hornblende and the chlorite from the augite and the feldspar."

Pyroxene: Relics of augite preserved in plates of actinolite should be unstable in the greenschist facies. Their presence indicates that equilibrium was not reached throughout the rocks and may perhaps be related to local insufficiency of water. The albite-epidote and actinolite-chlorite assemblages, however, appear to have reached metamorphic equilibrium.

Sphene and Magnetite: Sphene is commonly intergrown with magnetite in a triangular network (similar to the

Widmanstetten texture) characteristic of the exsolution of ilmenite and titaniferous magnetite in magnetite. The titaniferous part of the intergrowth has been incorporated in sphene while the magnetite remains unaffected. Production of sphene from ilmenite requires the addition of lime and silica and the subtraction of iron; the elements required could be obtained from pyroxene during the breakdown to amphibole and chlorite, during which lime and silica are usually liberated. Incomplete reaction in a number of sections is indicated by leucoxene and turbid sphene.

Quartz: Irregular areas of interstitial quartz are clear and are not affected by metamorphism other than by recrystallization.

Micropegmatite: Much of the micropegmatite occurs in irregular areas which, like the quartz, are interstitial. A few euhedral feldspars are completely enclosed by the micropegmatite without noticeable replacement. It is clear that the quartz-feldspar intergrowth crystallized later than the feldspar laths. There is, furthermore, no evidence to suggest that the micropegmatite is of metamorphic origin. It is considered to be late-magmatic or deuteric.

Irregular interstitial patches of pale green chlorite appear to have been derived by alteration in place (chlorophaeite ?). There is no reliable evidence to indicate what the original constituent was.

Veins of chlorite, quartz, epidote, and carbonate, may all have formed by redistribution of the minerals already present in the rocks. Their local development suggests a "secretion-type" origin, but it is possible that this material was introduced together with water and carbon dioxide.

B. The Metapyroxenite

In the metapyroxenite there are no relic pyroxenes. The equant shapes of the present amphiboles suggest that they are pseudomorphs after pyroxenes. Former olivine is shown by the presence of characteristic aggregates of talc-magnetite crystals.

The majority of the constituent amphiboles are pale green actinolite, some of which can be seen forming from a red brown amphibole. The change is accomplished with a slight redistribution of magnetite but the optic angles remain unaffected. The change in colour is attributed mainly to a change in the state of oxidation of the iron.

These amphiboles are in general far less altered to chlorite than are the amphiboles in the metadiabase.

The main mineral assemblage present is actinolite, talc, and chlorite. According to Turner (1948, p. 94) this assemblage is critical for the biotite-chlorite subfacies of the greenschist facies in ultrabasic schists. The assemblage talc-actinolite-chlorite appears to be stable in the metapyroxenite.

Veining by serpentine, carbonate, and chlorite, extends mainly between the major mineral constituents. It is clearly a late alteration of the talc-actinolite-chlorite association brought about probably by the presence of water and carbon dioxide (hydrothermal alteration).

CHANGES IN BULK COMPOSITION DURING METAMORPHISM

As described previously, practically all the mineral assemblages present in these rocks are of secondary (i.e. metamorphic) origin. Before describing any analyses of the rocks, therefore, it should be ascertained as accurately as possible to what extent the bulk composition of the rocks has been affected by the mineralogical re-adjustments.

A study of the minerals present has shown that they are a stable metamorphic assemblage, implying that they are in chemical equilibrium under some specific temperature and pressure conditions. The formation of actinolitic greenschists from basic igneous rocks involves little change in the bulk composition apart from the addition of water, and can be represented by:

$$\text{Augite (or Hornblende)} + \text{Plagioclase} + \text{Ilmenite} + \text{Water} \longrightarrow \text{Actinolite} + \text{Chlorite (aluminous)} + \text{Epidote} + \text{Albite} + \text{Sphene}.$$

An alternative assemblage developed at the same grade of metamorphism is chlorite-epidote-albite-calcite-sphene (with minor quartz), resulting from breaking down of actinolite in the presence of CO_2-bearing solutions according to the equation:

$$\text{Actinolite} + CO_2 + H_2O \longrightarrow \text{Chlorite (non-aluminous)} + \text{Calcite} + \text{Quartz}$$

(Turner, 1949, pp. 52-53)

The slight mobility of alumina, silica, and lime, is shown by the presence of thin veins of epidote, quartz, and carbonate. The veins could have been produced from the mineral assemblages described above by variations in the amount of water and carbon dioxide present. In the rocks being considered, these veins are of local extent and represent, probably, a limited redistribution of the elements already present under the influence of pore solutions.

It is concluded that the composition of the present mineral assemblage reflects satisfactorily the original composition of the rocks. Their chemical analyses may therefore be utilized for petrological comparisons with unaltered rocks of similar origin.

LOCATION OF SAMPLES SUBMITTED FOR CHEMICAL ANALYSIS

The only analyses available are those of specimens taken by the writer and analysed in the laboratories of the Quebec Department of Mines. The samples are from the following areas:-

(a) Nine samples were taken as representative of the Smith sill, respectively Nos. H55/B_3, -B8, -B10, -B16, -B19, -B22, -B25, -B27, and -B29. Nos. H55/B_{10} and -B22 were submitted for complete silicate analyses; the other samples were analysed only for their main oxides.

(b) Four samples were taken as representative of the thinner metadiabase sills, respectively Nos. H55/D6 and H56/312, -314, and -382. These samples were analysed for their main oxides. Sample H55/D6 was taken from a sill located in the southeast quarter of McKenzie township 4,000 feet west of Proulx Bay, Dore Lake. Samples H56/312, -314, and -382 are representative of thin sills between Portage Bay and the Valiquette Narrows in the southwest quarter of Roy township.

Samples submitted for analysis were unweathered and care was exercised to obtain specimens which were neither sheared nor oxidized.

CHAPTER VI

PRESENTATION OF ANALYSES

NORM CALCULATIONS

Two complete silicate analyses of specimens H55/B10 and H55/B22 are presented as cation percentages in the form outlined by Barth (1952, 1955) and Eskola (1954). These two samples are considered to be representative of metadiabase and diabase-pegmatite and were taken at 500 feet and 1600 feet from the base of the Smith sill (very nearly 1/4 way from the base and 1/4 way from the top respectively).

The principles of the norm system were published by Cross, Iddings, Pirsson and Washington fifty-five years ago. In their form of presentation the rock analyses are transformed into standard sets of mineral molecules which form the basis for quantitative and petrological study. These "C.I.P.W. weight norms" with some modifications proposed by Washington and Barth, have until recently been widely applied.

Niggli introduced important changes in the method of presentation of rock analyses. He was the first to apply molecular percentages to petrographic calculations in his "Niggli values" proposed in 1923. The greatest merit of these values lies in the fact that they indicate the proportions of certain groups of molecules more clearly than do weight percentages and can be applied readily in the construction of variation diagrams. A far greater achievement was Niggli's concept of the molecular norm, or what he called "equivalent molecular units" (Niggli, 1936). The unit of the normative minerals was defined as a quantity corresponding to one cation, and weight units were rejected. In this form, the normative minerals could be satisfactorily compared with planimetric (modal) analyses.

Because the terms "molecule" and "molecular norm" are somewhat misleading, Eskola (1954), proposed that these units be called what they are: "one-cation oxides", and "one-cation molecular units". "Division of the weight percentage of the oxides by the equivalent molecular weights of the one-cation oxides gives the one-cation oxide numbers but, because each of these units contain one cation, they also indicate the cation numbers, or the atom numbers". It is this feature "that makes the abstract concept of one-cation formulas so successful in petrologic as well as in mineralogic and chemical calculations", Eskola (1954, p. 5).

In Niggli's computations the atom numbers are combined in certain simple compounds to form the so-called basis which is recalculated to 100, whereafter the basis molecules are recombined to make the norm. Barth simplified these methods of calculation, and showed that the one-cation oxide percentage makes a sufficient basis. Not only the norm, but any mineral association may be calculated, including the mode, the normative minerals being chosen in accord with the mineral facies of the rocks and the one-cation oxide distributed according to the formulae of the normative minerals, the total of the cations all the time remaining at 100. These calculations may be successfully applied to metamorphic rocks where the conventional C.I.P.W. weight norm classification has failed.

The present study follows the system advocated by Barth (1955) who makes the subdivisions catanorm, mesonorm and epinorm:

a) the catanorm corresponds to the C.I.P.W. norm but is given in molecular percentages instead of weight percentages;

b) the mesonorm is constructed for rocks of the amphibolite facies of Eskola;

c) the epinorm is constructed for rocks of the greenschist facies.

The main constituent oxides (SiO_2, CaO, etc.) have approximately the same equivalent weights and consequently the weight norm differs but slightly from the molecular norm which need not be converted back to a weight basis.

It is difficult to normalize minerals of the amphibolite and greenschist facies because they form extensive and complicated series of mixed crystals. The formulae and abbreviations used are listed below.

Mineral	Abbreviation	Formula
Hornblende	Hbl	$Ca_2 Mg_4 Al_2 Si_7 O_{22} (OH)_2$ (with Fe substituting for Mg)
Zoisite	Zo	$Ca_2 Al_3 Si_3 O_{12} (OH)$

Chlorite is regarded as a mixed crystal between antigorite and amesite (daphnite):

Mineral	Abbreviation	Formula	
Chlorite	Chl (1)	$Mg_3 Si_2 O_5 (OH)_4$	with Fe substituting for Mg
	Chl (2)	$Mg_2 Al_2 SiO_5 (OH)_4$	
(Tremolite ((Actinolite	Trac	$Ca_2 Mg_5 Si_8 O_{22} (OH)_2$ (with Fe substituting for Mg)	
Titanite (Sphene)	Ti	$Ca Ti SiO_5$	
Calcite	Cc	$CaCO_3$	

The norms of metadiabase (H55/B10) and diabase-pegmatite (H55/B22) are presented as molecular norms or catanorms in Tables III and IV. The cation percentages in these

TABLE III

CALCULATION OF CATANORM

H55/B10 METADIABASE

Constituent	Weight %	Equivalent Weight	Cation Proportions x 1000	One Cation Oxide %	Ap	Py	Il	Or	Ab	An	Mt	Wo	En	Fs	Q
SiO_2	51.20	60.06	852	49.2				3.0	12.3	10.4		3.7	11.5	6.1	2.2
$AlO\ ^3/_2$	13.67	50.97	268	15.5				1.0	4.1	10.4					
$FeO\ ^3/_2$	1.83	79.84	23	1.3							1.3				
$CrO\ ^3/_2$	0.05	76.01	1	-											
FeO	9.06	71.84	126)	7.4		.05	.6				.65			6.1	
MnO	0.24	70.93	3)												
MgO	8.01	40.32	200	11.5									11.5		
CaO	8.83	56.08	157	9.1	.2					5.2		3.7			
BaO	0.07	153.36	-												
SrO	0.01	103.63	-												
$NaO\ ^1/_2$	2.21	30.997	71	4.1					4.1						
$KO\ ^1/_2$	0.85	47.10	18	1.0				1.0							
ZrO_2	0.01	123.22	-												
$PO\ ^5/_2$	0.12	70.98	2	.1	.1										
TiO_2	0.86	79.90	11	.6			.6								
$VO\ ^3/_2$	0.07	74.95	1	-											
S	0.07	32.066	(2)	(.1)		(.1)									
CO_2	0.11	44.01	(3)	(.2)											
H_2O +	3.01	18.016	(167)	(8.8)											
H_2O -	0.01														
	100.29		1733	99.8	.3	.1	1.2	5.0	20.5	26.0	2.0	7.4	23.0	12.2	2.2

Table III cont'd over/

TABLE III (Cont'd)

One-cation molecular norm or catanorm

Or = 5.0
Ab = 20.5
An = 26.0
Q = 2.2

Wo = 7.4)
)
En = 23.0) Di = 42.6
)
Fs = 12.2)

Ap = .3)
)
Py = .1)
) 3.6
Il = 1.2)
)
Mt = 2.0)

Salic = 53.7 Femic = 46.2

Ab_{43} An_{57} (Or_5)

TABLE IV

CALCULATION OF CATANORM

H55/B22 DIABASE-PEGMATITE

Constituent	Weight %	Equivalent Weight	Cation Proportions x 1000	One Cation Oxide %	Ap	Py	Il	Or	Ab	An	Mt	Wo	En	Fs	Q
SiO_2	57.04	60.06	950	55.9				2.4	21.6	5.7		2.6	3.5	6.4	13.7
$AlO\,{}^{3}/_{2}$	11.90	50.97	233	13.7				.8	7.2	5.7					
$FeO\,{}^{3}/_{2}$	3.02	79.84	38	2.2							2.2				
$CrO\,{}^{3}/_{2}$	0.00														
FeO	10.56	71.84	147)	8.8		.1	1.2				1.1			6.4	
MnO	0.21	70.93	3)												
MgO	2.39	40.32	59	3.5									3.5		
CaO	5.92	56.08	106	6.2	.8					2.8		2.6			
BaO	0.03	153.36													
SrO	0.01	103.63													
$NaO\,{}^{1}/_{2}$	3.80	30.997	123	7.2					7.2						
$KO\,{}^{1}/_{2}$	0.63	47.10	13	.8				.8							
ZrO_2	0.04	123.22													
$PO\,{}^{5}/_{2}$	0.56	70.98	8	.5	.5										
TiO_2	1.62	79.90	20	1.2			1.2								
$VO\,{}^{3}/_{2}$	0.04	74.95													
CuO	0.01	79.54													
$YO\,{}^{3}/_{2}$	0.02	112.92													
S	0.10	32.066	(3)	(.2)		(.2)									
CO_2	0.09	44.01	(2)	(.1)											
H_2O +	1.99	18.016	(110)	(6.1)											
H_2O -	0.01														
	99.99		1700	100.0	1.3	.1	2.4	4.0	36.0	14.2	3.3	5.2	7.0	12.8	13.7

Table IV cont'd over/

TABLE IV (Cont'd)

One-cation molecular norm or catanorm

Or = 4.0
Ab = 36.0
An = 14.2
Q = 13.7

Wo = 5.2)
En = 7.0) Di = 25.0
Fs = 12.8)

Ap = 1.3)
Py = .1)
Il = 2.4) 7.1
Mt = 3.3)

Salic = 67.9 Femic = 32.1

An_{28} Ab_{72} (Or_{4})

calculations afford direct comparison of the chemical compositions. Variations in chemical composition are graphically illustrated in Figure 2 and are listed in Table V.

In both norms salic minerals exceed the femic minerals, the proportion of salic minerals being greatest in the diabase-pegmatite.

Feldspars constitute 51.5 percent of the metadiabase and 54.2 percent of the diabase-pegmatite, the compositions corresponding respectively to $Ab_{43}An_{57}(Or_5)$ and $Ab_{72}An_{28}(Or_4)$; 2.2 percent quartz is present in the metadiabase and 13.7 percent in the diabase-pegmatite. Diopside forms nearly half of the metadiabase (42.6 percent), and only one quarter of the diabase-pegmatite (25.0 percent), but the accessory minerals show the opposite trend, constituting 3.6 percent of the metadiabase and 7.1 percent of the diabase-pegmatite.

Some of these mineralogical differences are readily explained with reference to the chemistry of the rocks. In comparing the metadiabase with the diabase-pegmatite the change in the composition of the feldspars can be related to a marked increase in the Na^+ and slight decrease in the Ca^{2+} content. K^+, contrary to expectation, shows a slight decrease with increasing Na^+ content. Al^{3+} decreases slightly in the diabase-pegmatite and the Mg^{2+}

VARIATION IN CATION PER CENT IN METADIABASE AND DIABASE-PEGMATITE IN THE SMITH SILL

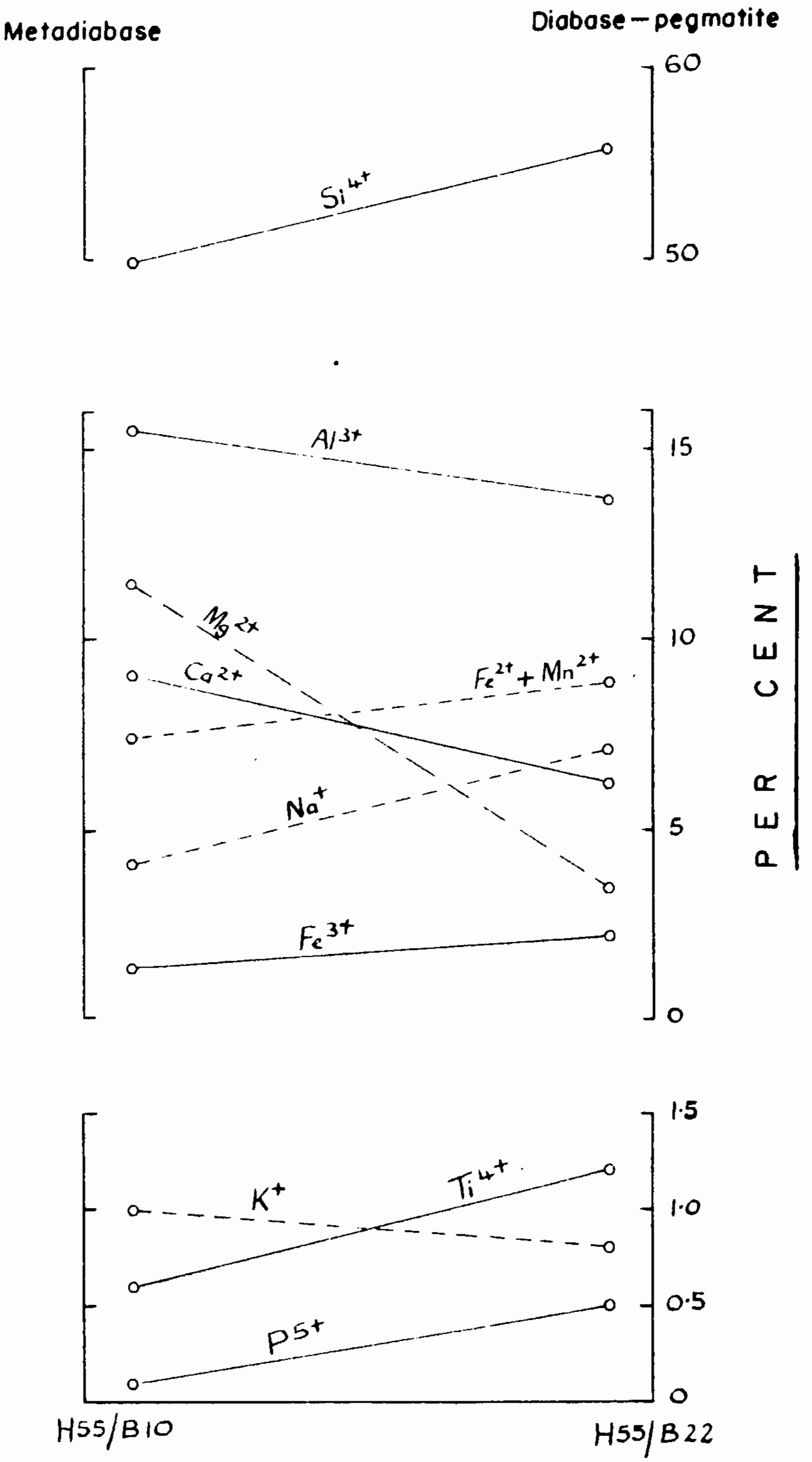


Fig. No. 2

TABLE V

SHOWING DIFFERENCES IN THE CHEMICAL COMPOSITION BETWEEN METADIABASE (H55/B10) AND DIABASE-PEGMATITE (H55/22)

Cation	Meta-diabase (a)	Diabase-pegmatite (b)	Difference between (a) & (b)	Difference expressed as a gain or loss relative to the meta-diabase.
	(H55/B10) %	(H55/B22) %	%	%
Si^{4+}	49.2	55.9	6.7	+ 13.6
Al^{3+}	15.5	13.7	1.8	- 11.9
Fe^{3+}	1.3	2.2	.9	+ 69.2
Fe^{2+}	7.4	8.8	1.4	+ 18.9
Mg^{2+}	11.5	3.5	8.0	- 69.6
Ca^{2+}	9.1	6.2	2.9	- 31.9
Na^{+}	4.1	7.2	3.1	+ 75.6
K^{+}	1.0	.8	.2	- 0.2
P^{5+}	.1	.5	.4	+ 400
Ti^{4+}	.6	1.2	.6	+ 100

shows a marked decrease in the same rock. All the other cations increase in the diabase-pegmatite, the most noteworthy gains occurring in P^{5+} which increases fourfold, and Ti^{4+} which doubles.

Comparison of Epinorms and Observed Modes

The catanorms and epinorms for the metadiabase and diabase-pegmatite are compared with observed modes in Table VI. In general, the epinorms and observed modes correspond reasonably well.

The micrometric measurements of the minerals for the determination of the modes by Rosiwall analyses were executed with difficulty because of the fine grain and common intergrowth of many of the alteration products. Although the greatest care was exercised, the results should perhaps be regarded as approximate only. Newer methods of measurement by Point Counter may give more reliable results.

In compiling the epinorms, the proportions of plagioclase, amphibole, and quartz in the modes were taken as approximate standards of reference. Because of the known mineralogical composition of the rocks, only a limited choice of mineral assemblages are possible. The

TABLE VI

COMPARISON OF NORMS AND MODES

		CATANORM	EPINORM			OBSERVED MODE IN VOL. % (by Rosiwall Analysis)		
H55/B10	METADIABASE							
	Q	2.2		.9	46.4			
	Or	5.0		5.0				
	Ab	20.5		20.5		Acid Plagioclase	23.4	42.6
	An	26.0	Zo	20.0		Clinozoisite	19.2	
	Wo	7.4	Trac	23.3	49.0	Amphibole	37.7	56.5
	En	23.0	Chl 1	7.2		Chlorite	18.8	
	Fs	12.2	Chl 2	18.5				
	Ap	.3		.3	4.2	Accessories	0.9	
	Py	.1		.1				
	Il	1.2	Ti	1.8				
	Mt	2.0		2.0				
H55/B22	DIABASE-PEGMATITE							
	Q	13.7		15.5		Quartz	29.5	
	Or	4.0		4.0	49.6			
	Ab	36.0		36.0		Acid Plagioclase	32.8	41.0
	An	14.2	Zo	9.6		Clinozoisite	8.2	
	Wo	5.2	Trac	13.5	26.6	Amphibole	15.9	26.5
	En	7.0	Chl 1	5.6		Chlorite	10.6	
	Fs	12.8	Chl 2	7.5				
	Ap	1.3		1.3	8.4	Accessories	3.0	
	Py	.3		.3				
	Il	2.4		3.6				
	Mt	3.3		3.2				

results are regarded as being close to the truth, and they may represent the constitution of the rocks more accurately than do the micrometric analyses.

A surprisingly close correspondence was obtained between the epinorm and mode of the metadiabase. The largest difference occurs between the assemblages of amphibole + chlorite. A possible reason lies in the difficulty of assessing the correct proportion of fibrous or flaky minerals which are easily overestimated.

Differences in the proportion of accessories in the epinorm and in the mode may be explained in part by the substitution of titanium and iron in the crystal lattices of the femic minerals, the values of these elements consequently being too high in the epinorm.

In the example of the diabase-pegmatite, correspondence between the epinorm and the mode is not good. There is an appreciable difference in the amounts of quartz. A possible explanation is that some of the clear albite in the micropegmatite might have been mistaken for quartz in the micrometric analysis. It may be significant in this connection that the percentage of feldspar + quartz in the epinorm and in the mode are roughly equal, viz. 65.1 and 70.5 respectively. Other Rosiwall analyses of diabase-pegmatite on different thin sections in the same area showed modal quartz exceeding 20 percent, but none were quite as high as 29.5. A total of 4 other computations from thin sections taken near H55/B22 (but excluding H55/B22) average 23 percent quartz in the mode. It appears therefore that some actual discrepancy does exist. The reason for this is not understood.

COMPARISON OF CHEMICAL ANALYSES

Comparison of Metadiabase in the Smith Sill with Rocks from other Magmatic Provinces

The metadiabase (H55/B10) is similar in chemical composition to some of the great basaltic plateau lavas and their corresponding intrusive phases. Table VII gives the average chemical composition of a number of rocks from various magmatic provinces. Most of this data is taken from Walker and Poldervaart (1949). All compositions are quoted volatile-free so that satisfactory comparisons may be made. This is considered by these writers as essential, for diabases and basalts show great variations in the combined water which they contain. The metadiabase presented here (H55/B10) has a disadvantage in that it is taken from a differentiated sill and so might not represent the true

TABLE VII

AVERAGE CHEMICAL COMPOSITION OF ROCKS FROM VARIOUS BASALTIC PROVINCES (Volatile Free)

	EARLY PRECAMBRIAN				PALEO-ZOIC	TRIAS-LIAS			TERTIARY			CRETACEOUS		RECENT	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	52.9	50.0	51.2	50.2	51.6	51.9	52.5	52.2	51.1	48.2	51.6	50.0	49.5	50.6	50.0
TiO_2	.9	.7	1.1	1.5	2.7	1.1	1.0	1.3	1.0	1.4	1.6	2.9	1.5	3.0	3.1
Al_2O_3	14.1	14.2	14.1	17.7	15.0	15.5	15.4	15.4	15.0	19.1	14.3	14.7	14.1	13.9	13.5
Fe_2O_3	1.9	4.6	3.9	4.2	3.4	1.0	1.2	1.6	3.4	1.2	3.5	3.4	4.8	2.4	2.7
FeO	9.4	8.8	9.3	9.7	9.6	9.7	9.3	8.7	8.4	8.7	9.2	10.3	10.1	11.8	9.1
MnO	.3	.2	.2	.3	.2	.3	.2	.1	.2	.1	.3	.4	.2	.2	.1
MgO	8.3	8.1	7.3	3.8	4.9	8.2	7.1	7.3	6.1	7.9	5.3	5.5	6.1	4.7	7.8
CaO	9.1	11.5	10.5	9.3	8.9	9.7	10.3	10.0	11.1	10.7	10.1	9.6	9.9	8.3	10.5
Na_2O	2.3	1.0	1.9	2.3	2.4	1.8	2.1	2.4	3.0	2.4	2.8	2.0	2.7	3.0	2.4
K_2O	.9	.7	.3	.9	1.1	.7	.8	.8	.6	.2	1.1	1.0	.7	1.3	.5
P_2O_5	.1	.7	.3	.2	.2	.1	.1	.2	.1	.1	.3	.2	.4	.8	.3
Number of Analyses	1	1	1	9	32	6	43	4	3	2	11	4	4	6	23

1. Metadiabase (H55/B10) NEW ANALYSIS. Analysts: F. Claisse, F. East. H. Boileau, J. Gagnon, Provincial Laboratories, Quebec Department of Mines, Quebec.

2. Medium-grained metadiabase which grades into pillow lava. (Pfeffer, 1955, p.92).

3. Coarse-grained metadiabase (Pfeffer, 1955. p.92).

4. Average "Keewatin" basalts according to J. Satterly (Pfeffer, 1955,p.92)

(Continued on next page)

TABLE VII Cont'd

5. Average tholeiite and quartz-dolerite of Northern England and Scotland (Walker and Poldervaart, 1949 p.649).

6. Average Karroo chilled basalt (Walker and Poldervaart, 1949, p.649).

7. Average Karroo dolerite (Walker and Poldervaart, 1949, p.649).

8. Average Palisade chilled basalt (Walker and Poldervaart, 1949, p.649).

9. Average Western Australian tholeiites (Edwards, 1938, p.7, quoted by Walker and Poldervaart, 1949, p.649).

10. Average Skaergaard chilled phase (Wager and Deer, 1939, p.141, quoted by Walker and Poldervaart, 1949, p.649).

11. Average Non-Porphyritic Central Magma (Walker and Poldervaart, 1949, p.649).

12. Average Spitsbergen dolerite (Tyrrell and Sandford, 1933, p.312, quoted by Walker and Poldervaart, 1949, p.649).

13. Average Spitsbergen basalt (Tyrrell and Sandford, 1933, p.312, quoted by Walker and Poldervaart, 1949, p.649).

14. Average Oregon basalt (Walker and Poldervaart, 1949, p.649).

15. Average Hawaii olivine-basalt (Daly, 1944, p.1392).

composition of the average magma.

The chemical composition of the metadiabase (H55/B10) closely resembles that of the average Karroo dolerite and Palisade diabase (Table VII, nos. 7 and 8). As compared with the rock from Chibougamau, each is slightly higher in Al_2O_3 and CaO, and slightly lower in MgO. Their effusive phases (not quoted here) are significantly different only in having relatively lower FeO and higher Fe_2O_3.

Agreement is not as good with tholeiites and quartz-dolerite of Northern England, Scotland, and West Australia (nos. 5 and 9). Compared with the Chibougamau rock, each is richer in Fe_2O_3 and lower in MgO, slightly lower in SiO_2, and slightly higher in Al_2O_3. In addition, the British rocks are higher in TiO_2, and the Australian rocks higher in CaO and Na_2O, and lower in K_2O. Other tholeiitic basic rocks, such as the Spitsbergen dolerite and basalt (nos. 12 and 13), and the Deccan traps, compared to the Chibougamau rock, have lower SiO_2 and MgO, and higher Fe_2O_3 and total iron.

Comparison with the composition of "Keewatin-type" metadiabase from Northern Ontario (nos. 2 and 3) shows that these latter rocks are slightly lower in SiO_2, but higher in Fe_2O_3 and CaO, and lower in Na_2O and K_2O. The average

"Keewatin basalts" (no. 4) are slightly lower in silica and MgO, and higher in Fe_2O_3 and Al_2O_3.

The olivine-basalt provinces of Hawaii (no. 15), Skaergaard (no. 10), and the Hebrides, the oceanic islands St. Helena, Ascension, and Tutuila (not quoted here), have appreciably lower silica than any of the tholeiitic provinces, but the other oxides are fairly variable.

Conclusion:

Distinctive features of the metadiabase are fairly high SiO_2 and MgO, and low Fe_2O_3 and Al_2O_3. The metadiabase compares closely in chemical composition with the average Karroo dolerite and Palisade diabase.

Comparison of Diabase-pegmatite in the Smith Sill with Rocks of Similar Composition

Specimen H55/B22 was chosen as representative of the principal variety of diabase-pegmatite. It represents the upper middle part of the Smith sill.

There is no close agreement in the chemical composition of this rock and any normal plutonic or volcanic rocks as given by Nockolds (1954). The best agreement is with differentiates of basic igneous sheets, a number of which are presented for comparison in Table VIII. (Most

TABLE VIII

CHEMICAL COMPOSITION OF DIABASE-PEGMATITE AND PEGMATITIC DIFFERENTIATES OF BASIC SHEETS (Volatile-free)

	1	2	3	4	5	6	7	8	9
SiO2	58.4	53.5	54.1	62.4	58.4	58.7	58.6	53.4	46.8
TiO_2	1.7	3.0	2.9	1.5	1.0	1.3	1.2	1.4	6.1
Al_2O_3	12.2	13.0	12.5	12.8	14.8	12.0	14.7	18.5	9.5
Fe_2O_3	3.1	4.9	3.5	3.0	2.9	5.8	2.6	2.0	8.2
FeO	10.8	10.4	12.5	8.4	8.2	9.4	8.4	7.7	10.5
MnO	0.2	0.2	0.2	0.2	0.1	0.2	0.1	0.1	0.3
MgO	2.5	2.7	2.7	0.8	3.1	0.7	3.2	2.6	5.5
CaO	6.1	7.3	7.0	4.1	7.4	5.0	7.3	9.4	8.7
Na_2O	3.9	3.7	2.9	5.8	3.7	3.9	2.0	3.8	3.2
K_2O	0.7	1.1	1.4	0.6	0.4	2.4	1.6	1.0	1.0
P_2O_5	0.6	0.3	0.3	0.5	0.1	0.7	0.3	0.1	0.2

1. Diabase-pegmatite (H55/B22) NEW ANALYSIS Analysts: F. Caisse, F.East, H. Boileau, J. Gagnon, Provincial Laboratories, Quebec Dept. of Mines, Quebec.

2. Pegmatitic facies of diabase (#465) at 184 ft. below upper contact, drill hole 3, Dillsburg (Hotz, 1953, pp.690-691).

3. Transitional granophyric diabase beneath granophyre (#645) at 364 ft. below upper contact, drill hole 3, Dillsburg. (Hotz, 1953).(pp.690-691).

4. Granophyre (#601) near lower transition zone 320 ft. below upper contact, drill hole 3, Dillsburg. (Hotz, 1953, pp.690-691).

5. Pegmatitic quartz-diorite (diabase-pegmatite ?), Algoma district, Ontario (Emmons, 1927, p.76).

6. Hedenbergite granophyre (#3047), Skaergaard intrusive. (Wager and Deer, 1939 (a) p.210, quoted by Hotz, 1953, p.693).

(Continued on next page)

TABLE VIII Cont'd

7. Dolerite-pegmatite schliere, 30 m. above base of Hangnest sill. (Walker and Poldervaart, 1949, quoted by Walker, 1953, pp.50-51).

8. Dolerite-pegmatite schliere, 180 m. above base of Palisade sill. (Walker, 1940, quoted by Walker, 1953, p.50)

9. Dolerite-pegmatite vein, Palisade sill, 10 m. above no.8, (Walker, 1953, p.50).

of the analyses have been recalculated by the writer to a volatile-free basis from the analyses quoted).

The differences in the composition of these rocks can be related to three main causes:-

a) Variation in composition of the original magma.
b) Variation in processes of differentiation.
c) The rocks may be representative of different stages in the differentiation.

The analyses have the following features in common: silica averaging between 50 and 60 percent, low MgO, and high total iron with a relatively high proportion of FeO.

Conclusion:

The composition of the diabase-pegmatite (H55/B22) is a good average of analyses of pegmatitic differentiates of basic sheets presented in Table VIII.

Composition of Metadiabase from Thin Sills

Partial analyses of metadiabase from four thin sills are presented in Table IX. These analyses are not quoted volatile-free, so that precise comparisons with previously-quoted analyses are not possible, but significant differences are readily apparent when compared with the metadiabase (H55/B10) from the Smith sill.

TABLE IX

PARTIAL CHEMICAL ANALYSES OF METADIABASE FROM THIN SILLS

	1	2	3	4	Average
SiO_2	47.00	51.47	47.54	50.23	49.06
Al_2O_3	16.35	13.05	16.21	15.64	15.31
Fe_2O_3	3.28	5.77	2.62	4.02	3.92
FeO	7.72	8.75	9.06	6.66	8.05
MgO	8.15	4.49	8.36	6.30	6.83
CaO	11.24	6.82	10.13	10.36	9.64
Na_2O	1.85	4.46	1.88	3.22	2.85
K_2O	0.27	0.22	0.32	0.13	0.24
	95.86	95.03	96.12	96.56	

Analysts: A. D. Klokine, M. Paiement, J. Gagnon, Provincial Laboratories, Quebec Department of Mines, Quebec.

1. Metadiabase, H56/314, near the base of a sill located between Portage bay and the Valiquette Narrows, southwest quarter of Roy township.

2. Pegmatitic stage of metadiabase, H56/312, near the top of same hill as 1 (above).

3. Metadiabase, H56/382, massive sill located between Portage bay and the Valiquette Narrows, southwest quarter of Roy township.

4. Metadiabase, H55/D6, upper central part of massive sill located 4,000 feet west of Proulx bay, southeast quarter of McKenzie township.

Compared with the metadiabase from the Smith sill, the average metadiabase from the thin sills is lower in silica, slightly higher in alumina, has a slightly higher proportion of ferric iron, slightly lower magnesia, and slightly higher sodium and potassium. Similar comparison exists with the average Karroo dolerite and Palisade diabase.

The average analysis of the metadiabase from the thin sills does not correspond to any of the individual analyses quoted in Table VII, but is, with one exception, intermediate to the lowest and highest values presented. The Chibougamau rocks are slightly deficient in FeO.

Oxidation of Extrusives and Intrusives

In a number of areas where extrusive and intrusive phases of the same basic magma are present, the iron is more oxidized in the effusive phase. This fact was observed by Walker and Poldervaart (1949) in the Karroo dolerites and their effusive equivalents, the Stromberg lavas, as well as for the Palisade diabase and the Watchung basalts (op. cit. p. 648). According to them, this agrees with theoretical conclusions reached by Phemister (1934, pp. 40-44). Similar observations have been made by Cornwall (1951 c) in the Keweenawan series where he found that the iron in iron-bearing minerals has been slightly to intensely oxidized by gases that boiled out of the flows during crystallization. Applying this criterion of FeO: Fe_2O_3, the metadiabase in the Smith sill (Table VII, no. 1) would be an intrusive phase, and the metadiabases and "Keewatin-type" basalt of Ontario (Table VII, nos. 2, 3, and 4) would be extrusives. The metadiabases from the thin sills (Table IX) have relatively high ferric iron and would, on a chemical basis, perhaps be classfied as extrusive phases.

DIFFERENTIATION TRENDS IN BASALTIC MAGMA

The problem of composition trends in basaltic magma during crystallization has long been a subject of debate among petrologists. Two main schools of thought prevail: Bowen (1928, pp. 80-83) has favoured alkali- and silica-enrichment of the residual liquid, with the production of dioritic and granitic partial magmas; Fenner (1931, 1938) has argued for iron-enrichment. The problem is summarized by Fenner (1931, p. 549), "in the competition in a crystallizing magma between the two principal solid solution series (e.g. pyroxenes) it is not possible to tell with our present knowledge which side will prevail in the diminishing residual liquid."

Wager and Deer (1939) in a comprehensive study of the strongly fractionated Skaegaard magma, showed that absolute enrichment in iron continued through 95 percent of the crystallization, but that during the crystallization of the remaining 5 percent, the differentiation trend changed abruptly, producing a residue rich in silica and alkalis, but poor in iron (in this occurrence a limited amount of contamination by acid gneiss may have taken place). They argued that the trend of the Skaergaard differentiation (i.e., enrichment in iron) is typical of fractional crystallization of average basalt magma. Edwards (1942) held similar views, stating that the trend toward the enrichment of the residual magma in iron relative to magnesia "is so characteristic of basalts, in general, that it may be regarded as the normal trend in the differentiation of basaltic magmas". (op. cit. p. 605)

The crystallization trends in basaltic magmas are well illustrated by means of triangular diagrams originated by Wager and Deer with FeO, MgO, and $K_2O + Na_2O$ as co-ordinates. They compared the calculated Skaergaard liquids with many analyses of lavas and hypabyssal rocks. The comparisons have been extended by Walker and Poldervaart (1949, pp. 657-661) to other magmatic provinces. In certain of these, where

Fe_2O_3 is proportionally rich, it is advisable that total iron should be used as one co-ordinate instead of only FeO. This method of presentation has been used by Cornwall (1951, b, pp. 165-169) and by Walker in later research (Walker et al., 1952, p. 906).

On these diagrams the crystallization history of basic magmas is shown by two types of trend:

(a) Absolute enrichment in iron followed by enrichment in silica and alkalis is represented by, firstly, a line approximately parallel to the FeO-($K_2O + Na_2O$) side.

(b) The normal calc-alkaline variation in which alkali-enrichment occurs throughout the crystallization period, is shown by a line joining Daly's averages for rhyolite, dacite, andesite and basalt (Daly, 1933, pp. 9-17). This line approximately bisects the ($K_2O + Na_2O$) corner of the diagram.

Comparison of a large number of analyses shows that (a), above, is commonly represented by plateau basalt magma and its intrusive magma, and (b) by differentiation in calc-alkaline provinces and in basic volcanic associations with high Fe_2O_3. A number of triangular diagrams are reproduced in Figures 3 to 6 to illustrate these trends in differentiation.

DIAGRAMS ILLUSTRATING DIFFERENTIATION TRENDS IN BASALTIC MAGMA

(after Walker and Poldervaart, 1949, pp. 657-659)

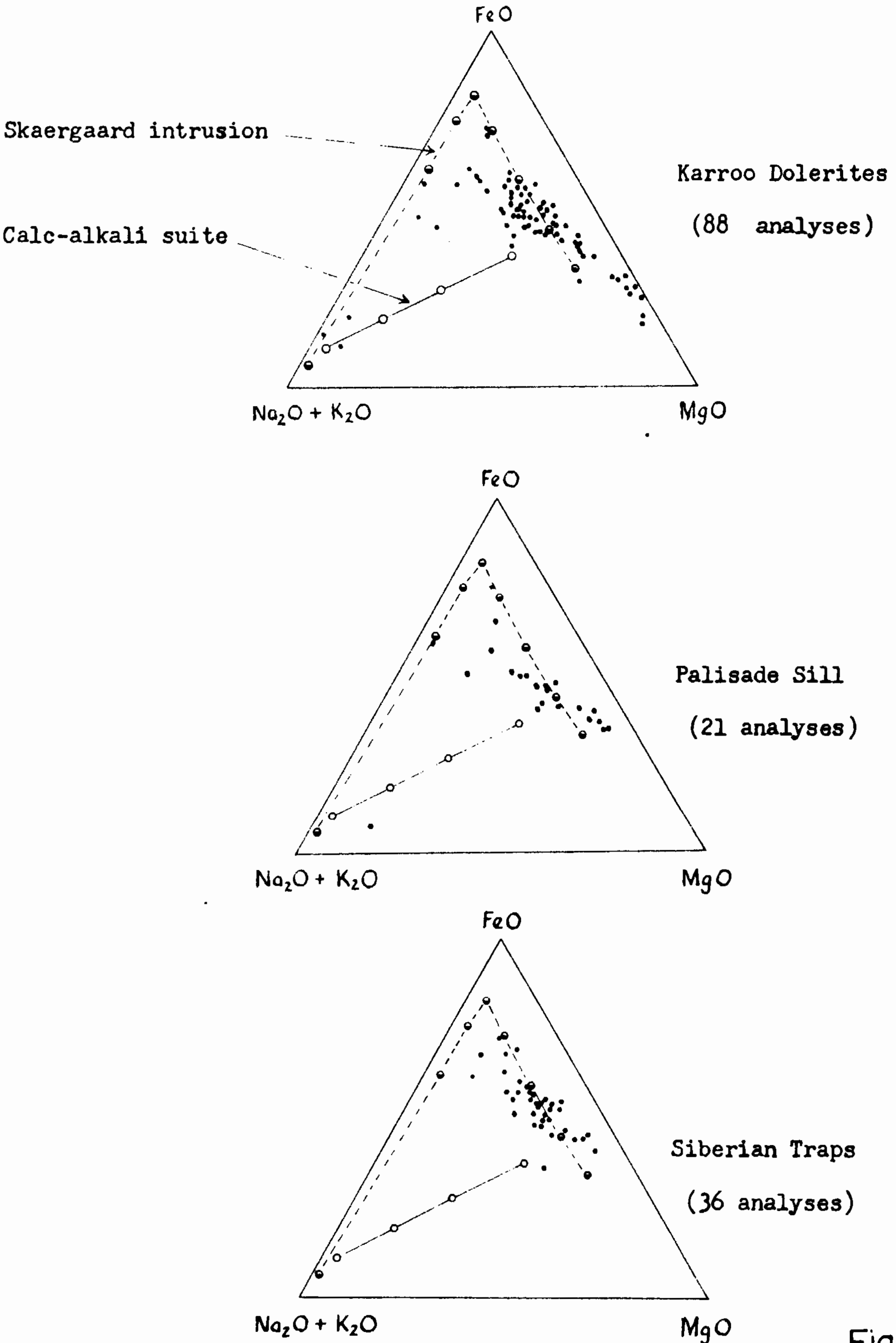
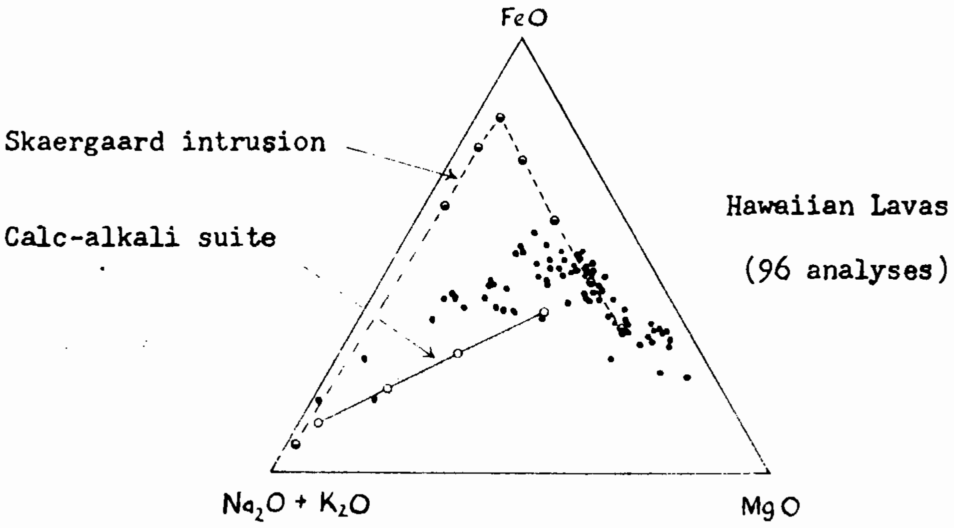


Fig. No. 3

DIAGRAMS ILLUSTRATING DIFFERENTIATION TRENDS IN BASALTIC MAGMA

(after Walker and Poldervaart, 1949, p. 660)



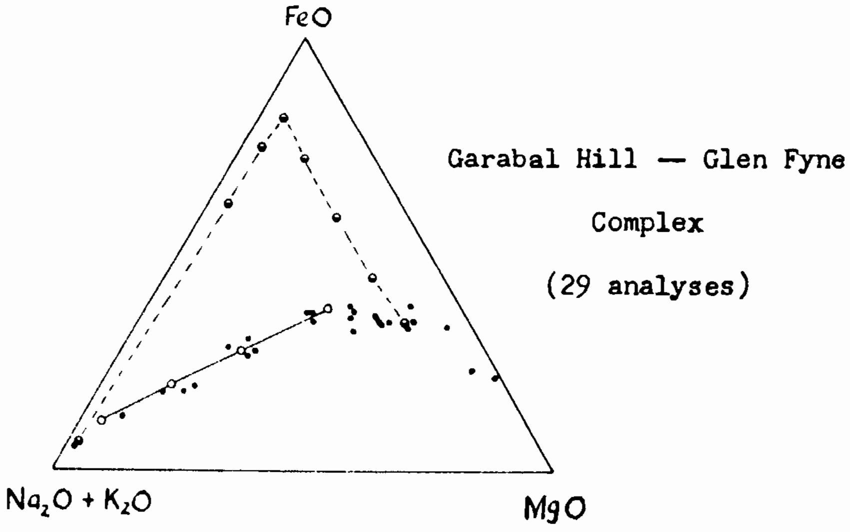
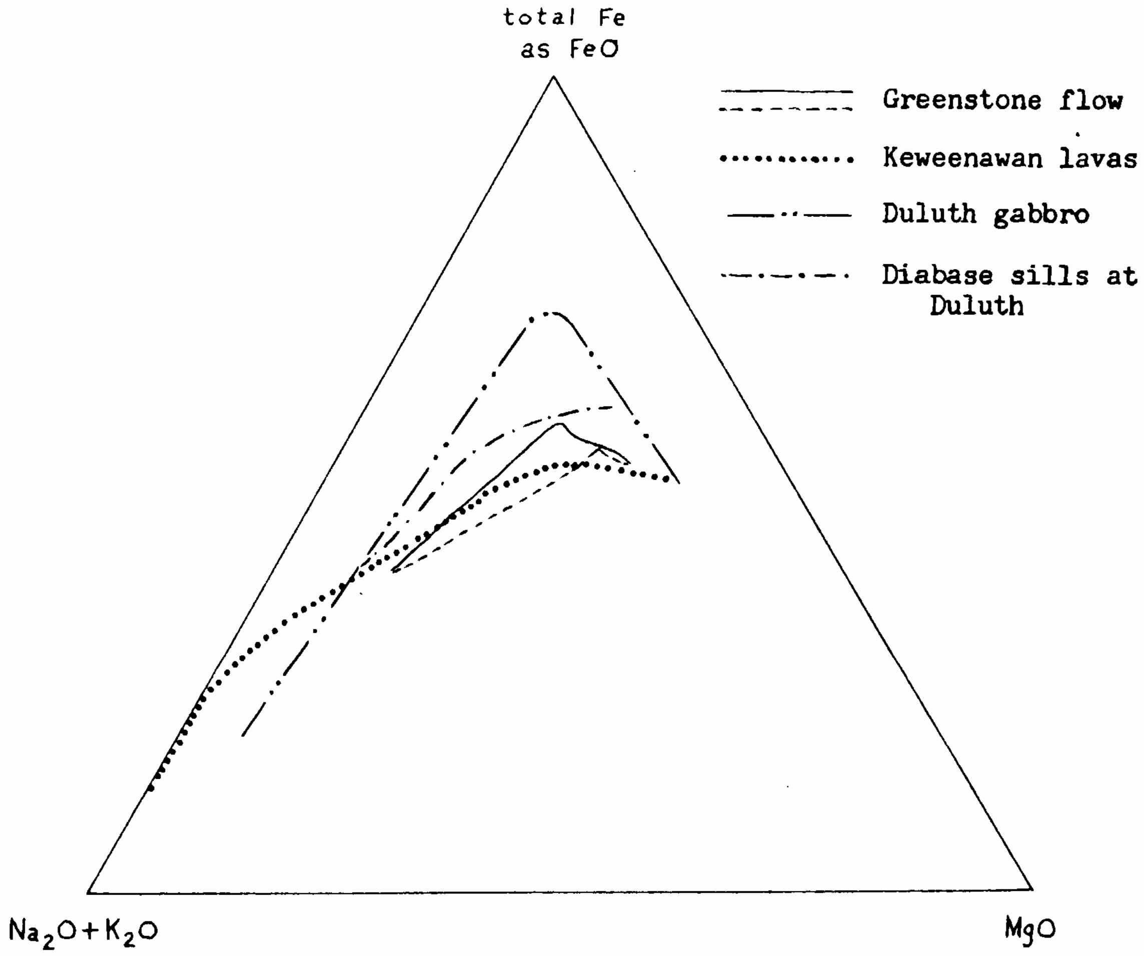


Fig. No. 4

DIAGRAM ILLUSTRATING DIFFERENTIATION TRENDS IN BASALTIC MAGMA

(after Cornwall, 1951b, p. 169)

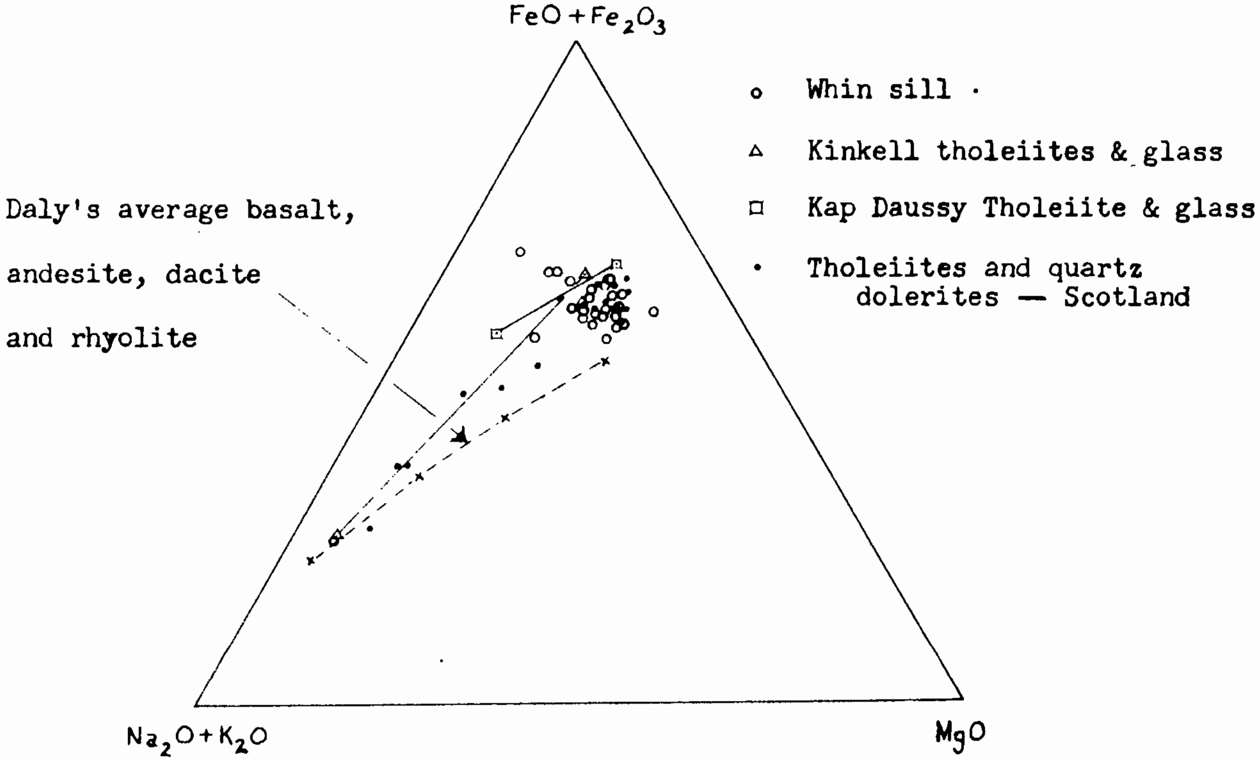


Differentiation Trends of Magmas of the Keweenawan Series

Fig. No. 5

DIAGRAM ILLUSTRATING DIFFERENTIATION TRENDS IN BASALTIC MAGMA

(after Walker et. al., 1952, p. 906)



Differentiation Trends of Tholeiites

Fig. No. 6

The composition of all the available analyses of metadiabase, diabase-pegmatite and metapyroxenite in Chibougamau are plotted on variation diagrams with co-ordinates FeO, MgO, and $(K_2O + Na_2O)$; and $(FeO + Fe_2O_3)$, MgO, and $(K_2O + Na_2O)$, in Figure 7.

Study of these diagrams shows that the trend in differentiation of the Chibougamau rocks has the following characteristics:-

(a) during crystallization, iron increased rapidly while magnesia decreased;

(b) slight but steady enrichment of alkalis occurred throughout the period of crystallization;

(c) late alkali-rich fractions did not form.

This variation bears a close resemblance to fractionation in the Karroo dolerites, the Palisade sill, the Siberian traps, and the Tasmanian dolerites (the latter are not illustrated in the figures). The Karroo dolerites and Palisade sill differ from the Chibougamau, Tasmanian, and Siberian rocks significantly only in that late differentiates rich in alkalis are present in the former and not in the latter groups of localities.

The other examples quoted show only little or moderate enrichment in iron and marked enrichment in alkalis.

DIAGRAMS ILLUSTRATING DIFFERENTIATION TREND IN DIABASE FROM

CHIBOUGAMAU (14 analyses)

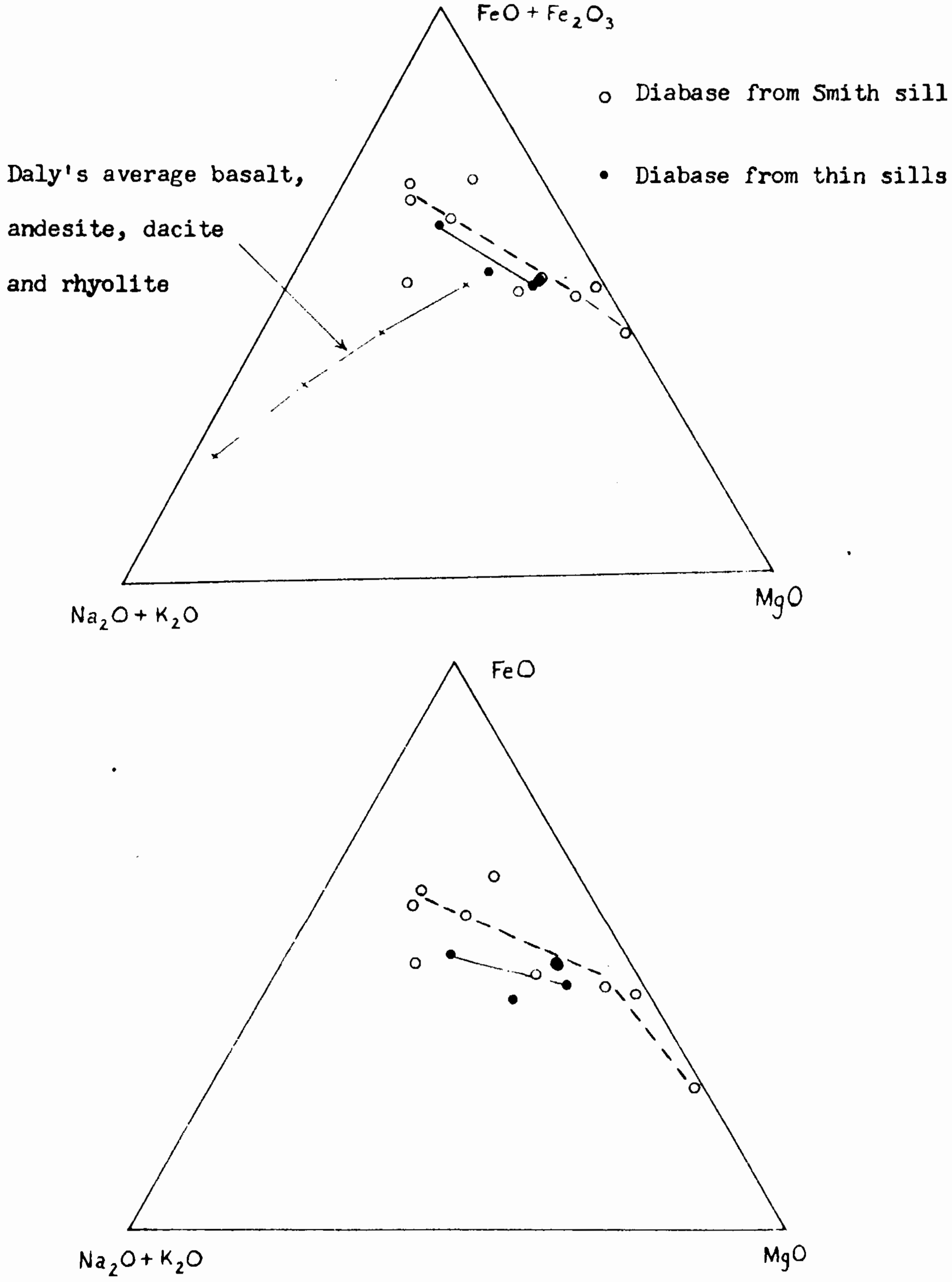


Fig. No. 7

This applies for:

(a) the Hawaiian lavas,

(b) the Garabal Hill - Glen Fyne complex,

(c) the tholeiites and quartz-dolerites of Scotland (except perhaps the Whin sill),

(d) magmas of the Keweenawan series which include the Keweenawan lavas, diabase sills at Duluth, and the Duluth gabbro. (The early differentiate of the Duluth gabbro is marked by iron-enrichment but the late differentiation is alkali-enrichment).

Conclusion:

The crystallization of the Chibougamau diabase is characterized by iron-enrichment. This implies that "during the main period of crystallization, fractionation was more pronounced in the ferromagnesians than in the plagioclase series," (Walker and Poldervaart, 1949, p. 659). The trend of the differentiation is typical of that which operated in many of the plateau basalt magmas (i.e. tholeiitic magmas).

(a) The Smith sill: The trend of differentiation in the Smith sill, when considered in detail, shows that in the early stages of crystallization iron increased rapidly to the near exclusion of alkalis. A slight divergence in the trend from the FeO-MgO side indicates that the alkali increased gradually. The early crystallization is therefore marked by fractionation of ferromagnesian minerals, feldspars being absent in the earliest stages, but increasing slowly. During the crystallization of the bulk of the rock, iron still increased, but not as rapidly as in the previous stage, while alkalis increased steadily. This suggests simultaneous crystallization of ferromagnesians and feldspars.

Hence, the early stage in the crystallization of the diabase in the Smith sill was marked by strong fractionation of ferromagnesian minerals while the proportion of feldspars increased as crystallization proceeded.

(b) The thin metadiabase sills: The trend of differentiation in the thin sills closely follows that which characterizes the crystallization of the main bulk of the Smith sill. This fractionation is marked by moderate enrichment in iron and slight but steady enrichment in alkali. It suggests simultaneous crystallization of ferromagnesians and feldspars.

OXIDE VARIATIONS ACROSS THE METADIABASE SILLS

(a) The Smith sill

Variation of the oxides in weight percent across the Smith sill are shown in Figure 8. Composition trends vary fairly regularly from the base to the upper part of the sill, corresponding to metapyroxenite, metadiabase and diabase-pegmatite.

The silica content ranges from 39.6 percent to 57.0 percent. There is an overlap in the silica percentage in the metadiabase and diabase-pegmatite (diabase-pegmatite in the upper part of the sill, H55/B27, has approximately the same silica content as metadiabase, H55/B10, near the base of the sill).

Total iron ($FeO + Fe_2O_3$) is high at the base of the sill, is less in the metadiabase, and increases again in the diabase-pegmatite. Magnesium decreases steadily from 23.4 percent at the base to 2.3 percent in the diabase-pegmatite. The ratio of total iron to total iron + magnesia increases steadily from the base of the sill to the diabase-pegmatite (Figure 9a).

Only at the base of the sill does magnesia exceed total iron. Furthermore, the increase in the total iron

VARIATION OF OXIDES IN WEIGHT PER CENT ACROSS THE SMITH SILL

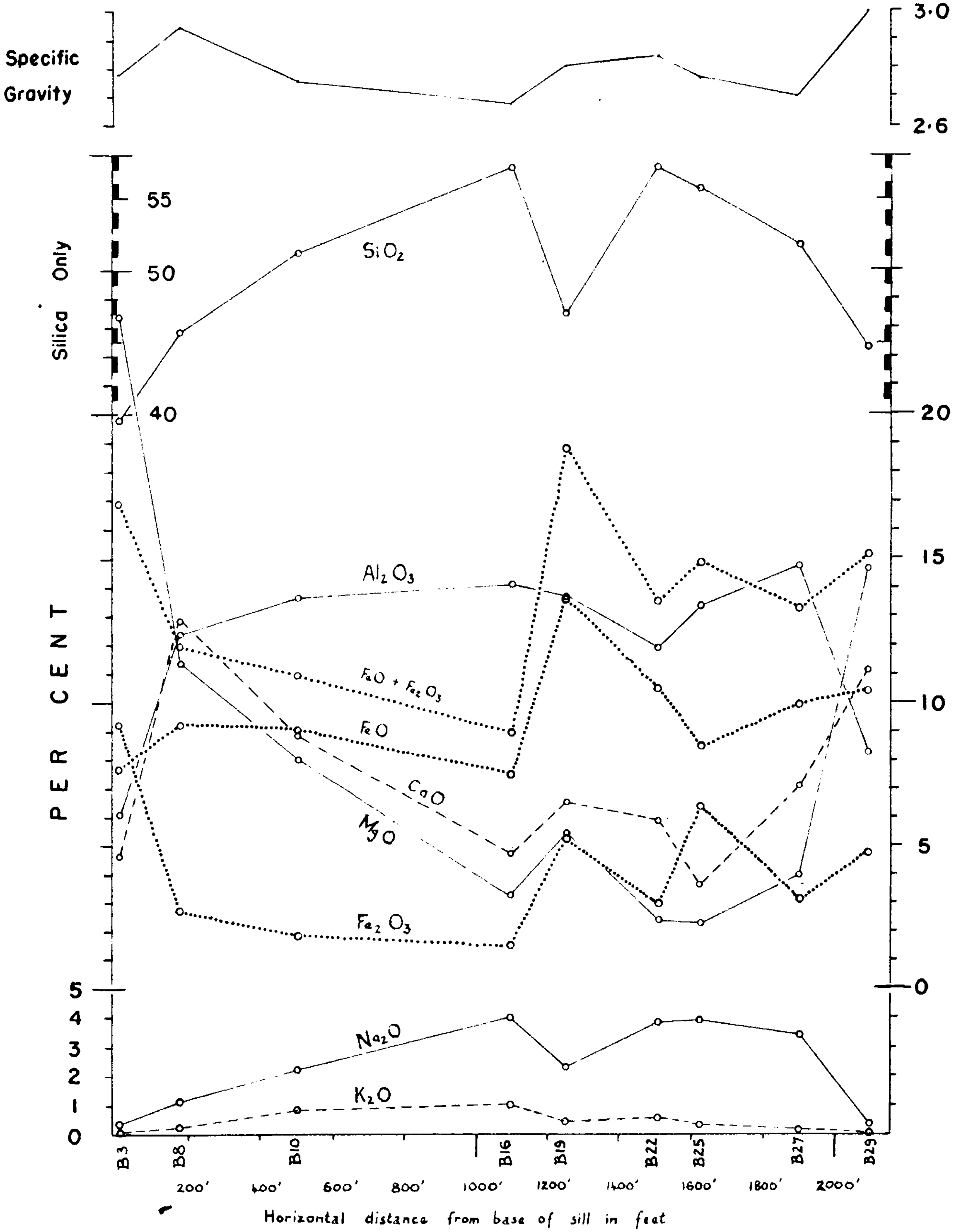


Fig. No. 8

in the diabase-pegmatite is accompanied by an increase in the ferric iron content, indicating a higher degree of oxidation (Figure 9b). The dark colours of the amphibole and chlorite in the diabase-pegmatite may in part be due to this state of oxidation. At the base of the sill, there is, likewise, a high ratio of ferric iron which may be explained as follows: Petrographic study indicates the former presence of olivine, now converted to aggregates of talc + magnetite. During this alteration, iron in the olivine would be oxidized from the ferrous to the ferric state. The process may be represented by the following equation:

$$\underset{\text{(olivine)}}{6MgFeSiO_4} + 2SiO_2 + 2H_2O + 3O = \underset{\text{(talc)}}{2H_2Mg_3(SiO_3)_4} + \underset{\text{(iron ore)}}{3Fe_2O_3}$$

Alumina and lime both increase sharply from the base of the sill to the metadiabase. Thereafter, the alumina remains approximately steady but lime decreases gradually from metadiabase to diabase-pegmatite. Corresponding with the decrease in calcium, there is an increase in soda. The lime to soda ratio is illustrated in Figure 10c. Considering the above three trends together, it is deduced that plagioclase crystallized steadily but that with increasing crystallization the plagioclase became poorer in lime and richer

VARIATION ACROSS THE SMITH SILL IN THE RATIOS OF

(a) Total iron to total iron + magnesia,

(b) Ferric iron to total iron.

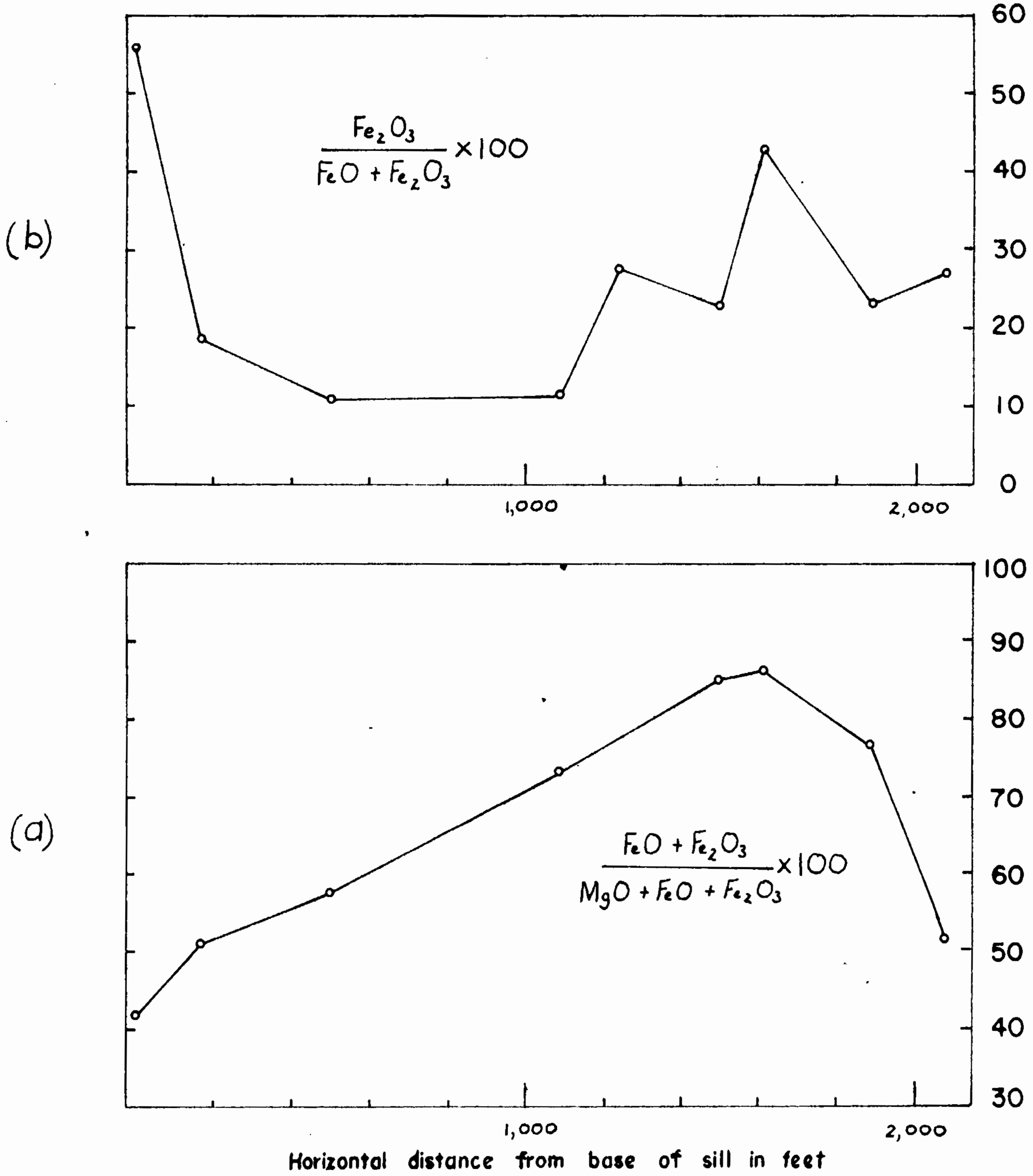


Fig. No. 9

VARIATION ACROSS THE SMITH SILL IN THE RATIOS OF

(a) **Potassium oxide to sodium oxide,**

(b) **Ferrous oxide to ferric oxide,**

(c) **Calcium oxide to sodium oxide.**

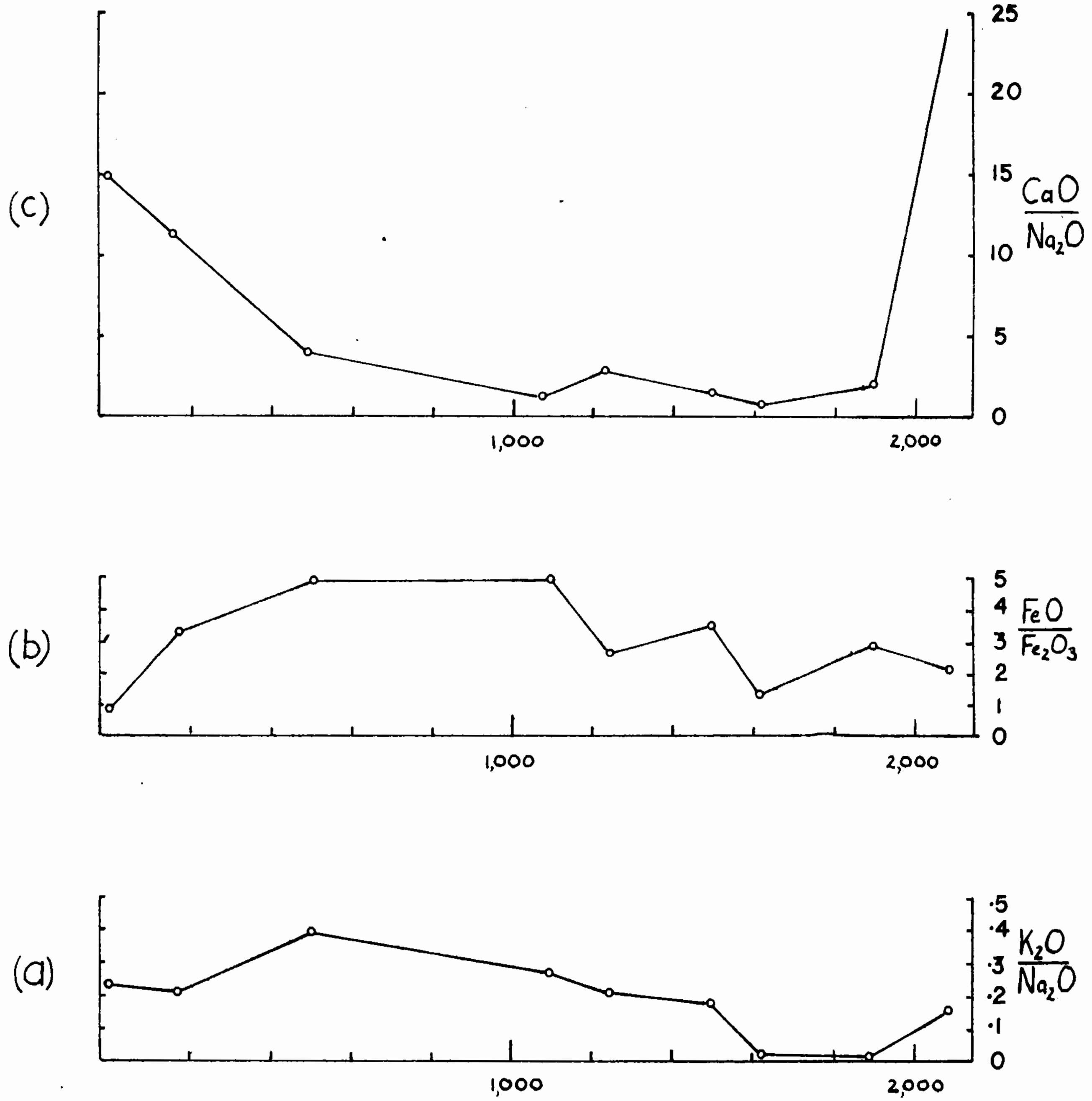


Fig. No. 10

in soda. This is supported by petrographic study and by petrographic calculation.

The content of K_2O is lower in the diabase-pegmatite than in the metadiabase. It may be explained by an original low content of K_2O which was gradually decreased because of incorporation in solid solution by the crystallizing plagioclase, the residual liquid becoming impoverished in this constituent.

The composition of metadiabase and diabase-pegmatite is easily compared in terms of cation percentages, derived in the norm calculations and illustrated in Figure 2. Table V contrasts the two analyses and shows the difference in cations expressed as percent (+) or (-) relative to the metadiabase (i.e. the percentage cations to be added to or subtracted from the metadiabase to form diabase-pegmatite). These differences in composition clearly reflect a trend in differentiation, the late liquid being:

(a) impoverished strongly in magnesia,
(b) impoverished moderately in calcium and aluminum,
(c) enriched very strongly in phosphorus,
(d) enriched strongly in titanium, sodium, and ferric iron,
(e) potassium remains approximately constant.

In terms of mineralogical change, this is explained by:

(a) decrease in the femic minerals,
(b) less calcic and more sodic plagioclase,
(c) large increase in apatite and quartz,
(d) increase in magnetite-ilmenite.

The change in composition between the metadiabase and diabase-pegmatite reflects clearly a trend in magmatic differentiation.

In Figure 8 there are some irregularities which should be accounted for:

(i) The upper part of the sill is similar in composition to the lowermost (ultrabasic) part. If the former is regarded as a chilled phase, the earliest intrusion would be ultrabasic. The uppermost specimen analyzed consists of actinolitic amphibole, similar to, but finer-grained than the rock at the base. Megascopically, it is fine-grained, dark and massive, and has no diagnostic features. It is not impossible that it represents the lower part of an overlying lava sequence, but the close similarity with its basal "counterpart" strongly suggests that it is genetically related to the sill.

(ii) Within the lower part of the diabase-pegmatite, one analysis (H55/B19) contrasts strongly with those adjoining it and disrupts the regularity of the profiles. Megascopically, the rock is a black, fine-grained metagabbro. Petrographic description shows it to be composed of saussuritized plagioclase (52 percent), amphibole + chlorite (32 percent), quartz (10 percent), and apatite (1 percent). The contact with diabase-pegmatite is not exposed. At 200 feet south of this sample location the quartz-diabase is cut by a diabase-pegmatite vein 1 foot wide with crystals to 1 cm., and by a thin, dark, fine-grained dyke. This diabase-pegmatite vein may be similar to some of the "dolerite-pegmatite" described by Walker (1953) as a late stage differentiate which was forced into rifts in the crystal mesh when crystallization was far advanced.

The anomalous sample H55/B19 is interpreted as a basic injection.

The mineralogical and chemical variations across the main part of the Smith sill are satisfactorily explained by crystallization differentiation in a basic magma, the continuous chemical and mineralogical trends indicating differentiation rather than separate intrusion. Analysis of the upper part of the sill suggests the presence of an upper ultrabasic intrusive.

Early accumulations of olivine-rich phases are known from many differentiated basic sheets of which the Karroo dolerite and Palisade diabase are examples. In each of these occurrences olivine is concentrated near the base, but plagioclase is almost everywhere present, to form olivine basalt and picrite basalt. In these rocks pyroxene appears to have formed later than some of the feldspars. There is, however, in the Smith sill, no evidence for the former presence of feldspar at the base of the sill which consisted entirely of olivine + pyroxene, and pyroxene. This is not without example, and Edwards (1942) has described pyroxene-rich sections in the Mt. Wellington sill. His oxide variations at the base of the sill are analogous with those in Figure 8. Edwards (op. cit., p. 468) described this as follows: "The chilled bottom of the sill has served as a floor on which early-formed magnesia-rich pyroxenes have accumulated by sinking down from the more slowly cooled parts of the sill. The shape of the alumina profile shows that this involved a reciprocal displacement upward of the remaining liquid portion of the sill as a whole".

The late appearance of large amounts of quartz may be related to the fact that olivine crystallized early and failed to react with the magma to produce pyroxene, leaving the residue relatively enriched in silica.

(b) The thin metadiabase sill

Figure 11 illustrates the variation of the oxides in weight percent across a thin sill. Samples H56/314 and H56/312 were taken at approximately 20 feet from the base, and 50 feet from the top of a sill 150 to 200 feet thick. These two specimens of metadiabase are compared in tabular form below.

	Base of sill (H56/314)	Top of sill (H56/312)
Texture	subophitic	idiomorphic
Plagioclase	strongly saussuritized, shapes not preserved	moderately saussuritized randomly oriented laths .5 to 1 mm.
Amphibole	strongly chloritized, pale green, equant	fibrous, green, elongated
Magnetite-sphene	few crystals	abundant
Quartz	few interstitial crystals	not observed

MODAL ANALYSES (volume percent)

	(H56/314)	(H56/312)
Plagioclase	51.5	56
Amphibole - chlorite	47.0	34
Magnetite - sphene	1.0	10
Quartz	1.5	0

VARIATION OF OXIDES IN WEIGHT PER CENT ACROSS A THIN METADIABASE SILL

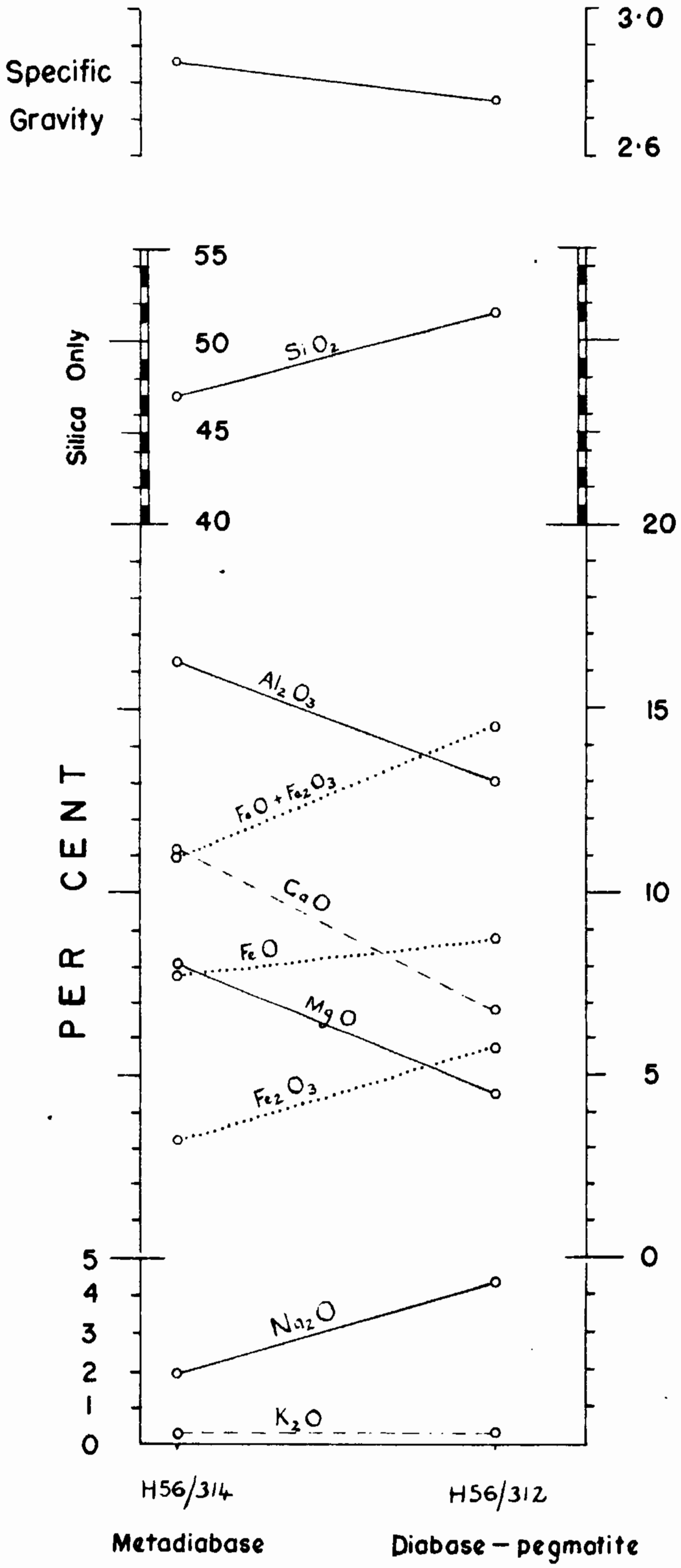


Fig. No. 11

Noteworthy is the presence of small amounts of quartz in the metadiabase at the base of the sill and none in the upper part of the sill.

The variation in chemical composition between the lower and upper parts of the thin sill closely follows that between metadiabase and diabase-pegmatite in the Smith sill (see Figures 8 and 11). The thin sill has higher ferric iron and sodium oxide. In both sills the pegmatitic facies is not enriched in potassium.

In each sill the upper (pegmatite) stage is more highly oxidized, as is shown by the

$$\frac{Fe_2O_3}{FeO + Fe_2O_3} X\ 100 \quad \text{values,}$$

illustrated in Figures 9 and 12. In the state of oxidation, the thin sill corresponds to the middle and middle-upper parts of the Smith sill.

VARIATION ACROSS A THIN METADIABASE SILL IN THE RATIOS OF

(a) Total iron to iron + magnesia,

(b) Ferric iron to total iron.

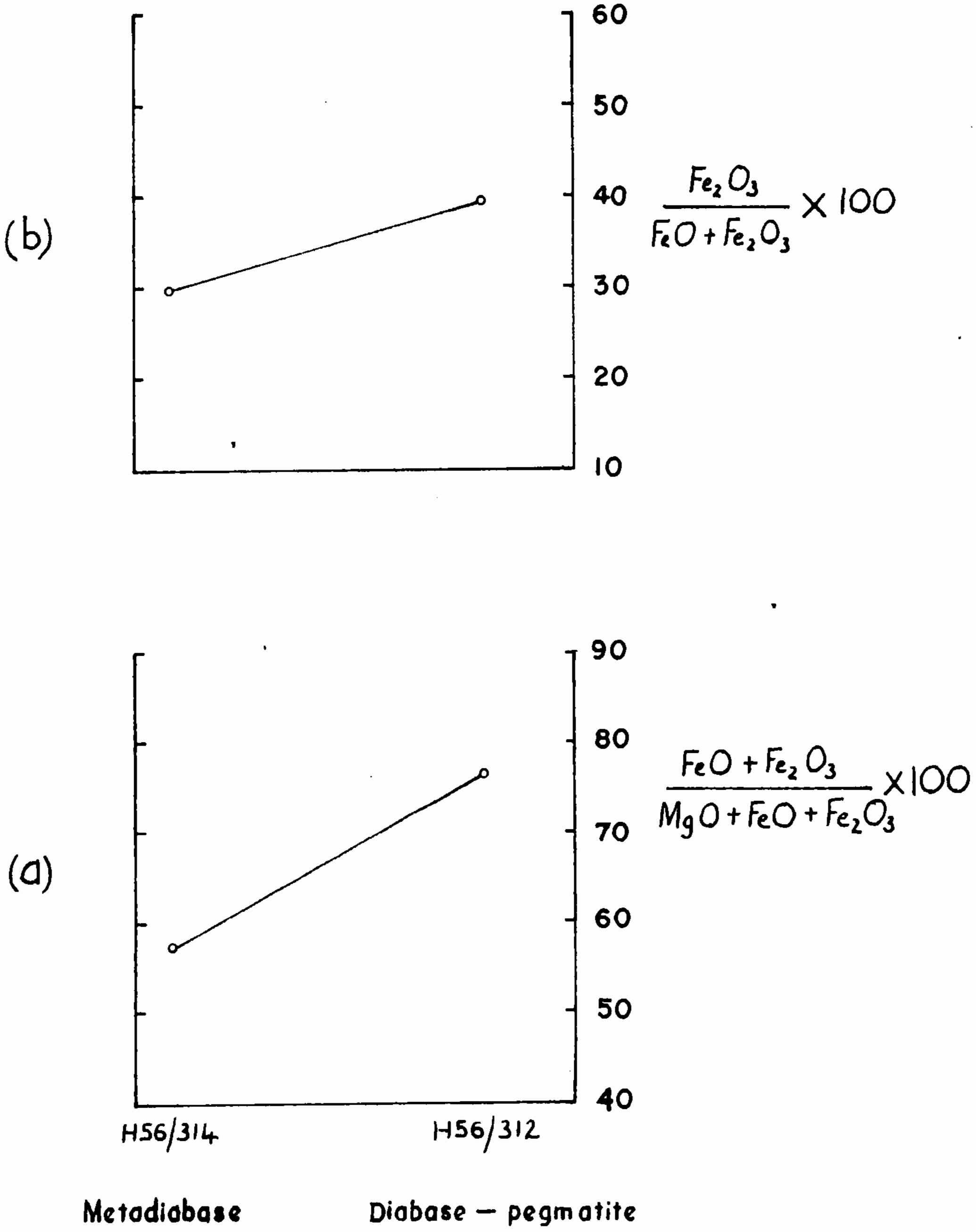


Fig. No. 12

CHAPTER VII

CONCLUSION

ORDER OF CRYSTALLIZATION

The metadiabases, in common with similar rocks throughout the world, are characterized by ophitic to subophitic texture. This texture has figured prominently in the interpretation of the order of crystallization of the rock-forming minerals.

An important contribution in this field was made by Krokström (1932, 1936) who reached two main conclusions:

(i) in the ophitic texture plagioclase crystallizes early, followed by pyroxene at a rather late stage,

(ii) in the diabasic texture pyroxene crystallizes during or even before the plagioclase.

Further, he maintained (1936, p. 140-141, 241-242) that enrichment in iron and silica would produce a diabasic rather than ophitic texture, and that the ophitic texture is met with only in rocks of rather limited chemical composition (undersaturated).

The first two deductions have been widely applied by some petrologists, but with misgivings by others who stress the importance of chemical composition and magmatic conditions on the order of crystallization. Shand (1947,

p. 114), for example, maintains "that there is no such thing as a constant order of crystallization, applicable to all magmas or even to one magma under different physical conditions."

Walker (1957) has recently conducted a statistical investigation of the textures in several hundred thin sections of intrusive dolerites, tholeiites, and olivine-basalt. His conclusions (op. cit. p. 1) are summed up as follows: "Evidence gained from chilled contacts and from fresh tholeiites shows that in tholeiitic suites both pyroxene and plagioclase started to form at a very early stage and continued to crystallize in ophitic relationship and in fairly constant proportions throughout the cooling history. In olivine-basalt providences, however, olivine or plagioclase is the first mineral to form, being followed much later by pyroxene."

These diverse interpretations show that the crystallization of the minerals cannot be determined merely on a basis of texture.

Referring now to the Chibougamau rocks, layering in the Smith sill is reconstructed as having been originally from top to bottom as follows:-

Mineral Association	Texture
Feldspar - pyroxene - (amphibole) - micropegmatite	idiomorphic
Feldspar - pyroxene - quartz	idiomorphic
Feldspar - pyroxene	ophitic to sub-ophitic
Pyroxene - feldspar	ophitic to sub-ophitic
Pyroxene	granular
Pyroxene - olivine	granular (poikilitic)

In the thin diabase sills the mineral associations are reconstructed as follows:

Mineral Association	Texture
Feldspar - pyroxene - (amphibole) - (quartz)	idiomorphic
Feldspar - pyroxene	ophitic to sub-ophitic

Assuming that the formation of the layers in the Smith sill were produced by crystallization differentiation, the minerals would have crystallized in the order olivine, pyroxene, feldspar + pyroxene, micropegmatite, quartz.

In the thin sills laths of plagioclase within the pseudomorphs of amphibole suggests crystallization of some early feldspar, but the main crystallization of feldspar and pyroxene probably occurred simultaneously, with quartz crystallizing last.

Changes in the textures of the sills from ophitic and subophitic in the lower to idiomorphic in the upper parts, can be related to the changes in chemical composition, viz. increase upwards of iron and silica, in the proportion of sodium to calcium, and to a greater concentration of volatiles.

Pyrite is closely associated with quartz in many sections. Both are late in the sequence of crystallization.

Apatite occurs in, or overlaps on to all the essential minerals. It crystallized after quartz.

Magnetite-sphene intergrowths, representing primary magnetite-ilmenite or magnetite-titaniferous magnetite, are closely associated with the femic minerals. The iron minerals probably crystallized late. Much of the finely dispersed magnetite is of secondary origin but some clusters may be primary.

There is no direct evidence to indicate whether the prismatic amphibole crystals in the diabase-pegmatite are primary or whether they are pseudomorphs after pyroxene. Primary amphibole is suggested by the shape and the position in the upper parts of supposedly differentiated bodies where volatiles would be concentrated. However, workers on basic sheets have noted the elongated shape of primary pyroxenes in acid differentiates. Hotz (1953, p. 683), for example, in a description of the pegmatitic facies of Triassic diabase in southeast Pennsylvania states, "purplish-brown augite in elongate crystals averaging 3 mm. in length and as much as 7.5 mm. long is the principal pyroxene; less than 5% of pigeonite is present. The pyroxene crystals are mostly single individuals rather than intergrown groups. Many are twinned on (100)." Also Walker (1953, p. 46) in a general survey of dolerite-pegmatite, describes the pyroxene as "chiefly purple or brown augite or ferroaugite with characteristic bladed habit, often curved. Some crystals show a conspicuous median line which forms the spine of typical herringbone twins."

Amphiboles in the diabase-pegmatite have, in common with the pyroxenes described by Walker and Hotz, an elongate shape, twinning, and curvature. It is a fair inference therefore that the amphiboles in the diabase-pegmatite are pseudomorphous after pyroxene.

The uralitic amphiboles at the base of the Smith sill do not show much alteration to chlorite. This may indicate that early magnesium-rich pyroxene was able to break down almost directly to actinolitic amphibole. Higher in the sill and in the thinner metadiabase sills the actinolite + chlorite assemblage probably reflects an original more augitic pyroxene. During the alteration of this pyroxene, alumina, calcium, lime, iron, and titanium, in excess of that able to be incorporated in the actinolitic amphibole, formed chlorite, and in some crystals, epidote, calcite, magnetite, and sphene. Zoning of the original pyroxenes is suggested by the chlorite-rich central section of a number of amphibole pseudomorphs.

SUMMARY OF THE GENERAL FEATURES OF THE SILLS

The sills described are concordant bodies within a steeply-dipping assemblage of basic volcanic rocks. A few are irregular and cut across the volcanic formations locally. Chilled edges have not been recorded.

Three rock types may be distinguished in the sills; metapyroxenite, identified in one sill only; metadiabase, which constitutes the bulk of the sills; and diabase-pegmatite which occurs near the centre or upper parts of the sills. The metapyroxenite, metadiabase, and diabase-pegmatite grade into each other. In some sectors metadiabase grades into volcanic rocks.

The metadiabase of the sills is characterized by ophitic to subophitic texture. The main constituents are strongly saussuritized plagioclase and uralitic amphibole, with plagioclase in excess. A little quartz may be present. Accessories occur in small amount.

The diabase-pegmatite is characterized by elongated and randomly oriented amphibole and plagioclase. The plagioclase in the diabase-pegmatite is not as strongly saussuritized as in the metadiabase, and exceeds the amphibole in amount. Quartz ranges from 0 (in the case of some of the thin sills) to 29 percent. Where quartz is abundant it is intergrown with sodic plagioclase as micropegmatite; euhedral crystals of feldspar occur as inclusions in the micropegmatite. Accessories, chiefly magnetite-sphene, are common. The diabase-pegmatite is slightly coarser-grained than the metadiabase.

Chemically, the change from the lower to the upper parts of the sills is characterized by: increasing SiO_2, TiO_2, P_2O_5, Na_2O, FeO and Fe_2O_3 with proportionally higher Fe_2O_3; decreasing Al_2O_3, MgO, and CaO. Potassium oxide in the upper parts of the sills is approximately equal in amount to that at the base of the sills (i.e. there is no enrichment of potassium oxide in the pegmatitic rocks).

Former pyroxene was in greatest amount near the base of the sills and feldspar near the upper parts of sills.

In one sill the southernmost margin was composed almost entirely of pyroxene.

ORIGIN OF THE SILLS

The close association of the sills with a basic volcanic assemblage suggests a genetic relationship. This is supported by the lithologic similarity between fine-grained metadiabase and massive flows, gradational contacts, and an apparent lack of chilled edges on the metadiabase sills.

Formation of the various rock types within the sills could possibly be ascribed to the following modes of origin:

(1) as separate intrusions,

(2) formation by syntexis - that is, by assimilation of the intruded rocks,

(3) formation of the different rock types by differentiation within the sill between the time of intrusion and complete solidification.

Formation of the Diabase-pegmatite as Separate Intrusions

The close, if not exclusive, association of diabase-pegmatite with metadiabase seems to rule out the possibility of separate intrusions. This is especially the case in many long, narrow sills. The chemical and mineralogical data which have been presented show a gradation between the metadiabase and diabase-pegmatite, and this suggests a genetic relationship. Detailed mapping in the area under consideration has revealed diabase-pegmatite only within metadiabase sills.

Formation of the Diabase-pegmatite by Syntexis

There is no direct evidence to indicate that the diabase-pegmatite was produced by the assimilation of the intruded rocks. A number of volcanic fragments are preserved within the metadiabase sills, notably northwest of Proulx Bay, Dore Lake. That some assimilation did take place may be admitted, and may perhaps explain the lack of chilled borders. Chemical study of the composition of the included rocks could be of assistance in determining the composition of the mineralogical changes to be expected. However, megascopic examination has failed to distinguish any marked difference between the intruded volcanic rocks and the associated basic intrusives. There is in particular, an absence of strongly silicic rocks and the invaded rocks in general are presumed to be similar in composition to the metadiabase sills.

Formation of the Diabase-pegmatite by Differentiation

The formation of different rock facies within basic intrusives by processes of differentiation has been widely accepted. A large number of alternative theories have been suggested so that each intrusive should be examined in its own environment. Differentiated bodies that may be relevant in the present discussion, to quote a few, are: the Karroo dolerites, the Tasmanian dolerites, the Palisade diabase, the Triassic diabase in Pennsylvania, and the Keweenawan series.

The trend of differentiation in the Chibougamau rocks has been described previously with reference to triangular variation diagrams as fractional crystallization. The trend in chemical composition, which is satisfactorily reflected in mineralogical changes, is towards late enrichment in silica, iron, titanium, phosphorus, and sodium, and corresponding impoverishment in calcium, magnesium and aluminum; potassium remains relatively steady.

The pegmatitic stage of the metadiabase is marked by the idiomorphic development of amphibole (presumably after pyroxene) and plagioclase, and slight coarsening in grain. Two types of diabase-pegmatite may be distinguished.

The first, as evidenced by some thick sills, contains appreciable quartz in micropegmatitic intergrowth with sodic plagioclase, as for example in the Smith sill. Strong enrichment in micropegmatite constitutes local granophyric patches which are similar in many respects to granophyres of other basic differentiates. The diabase-pegmatite of the Smith sill may be compared with "dolerite-pegmatite" which constitutes up to 25 percent of certain cross-sections of dolerite sills in the Midland Valley of Scotland and which have been described by Robertson (1937), as quoted by Walker (1953, p. 44). The diabase-pegmatite may be equivalent to the "transitional granophyric diabase" described by Hotz (1953) from differentiated diabase near Dillsburg, Pennsylvania.

The diabase-pegmatite in the Smith sill is finer-grained than, and does not have the intrusive character of "pegmatitic schlieren" or "dolerite pegmatites" described by Walker (1953). These pegmatitic rocks are present, for example, in the Karroo dolerites and in the Palisade diabase.

The second type of diabase-pegmatite, common in thin sills, contains little or no quartz. It appears to be similar to "dolerite" described by Lane (1909) and Butler and Burbank et al. (1929) in some of the thick Keweenawan lavas. This "dolerite" is termed "pegmatitic facies" of ophitic basalt by Cornwall (1951 a).

Original layering in the Smith sill, as reconstructed from the metamorphic assemblage now present, and supported by variation trends, indicates that fractional crystallization was a dominant process in the differentiation of the rocks. Differentiation into the pegmatitic facies is probably related also to the concentration of mineralizers in the upper parts of the sills, leading specifically to the formation of, and enrichment in micropegmatite, magnetite-ilmenite, and apatite. Presumably the action of mineralizers would have been most effective in the thick sills because of their long period of cooling. The increase in the ratio of ferric iron to ferrous iron in the pegmatitic stage is evidence for the crystallization of this fraction at a lower temperature, and later stage (Cornwall, 1951 b, pp. 159-160).

Fenner (1926) has advocated the importance of mineralizers in the formation of igneous rocks and has suggested that they may be responsible for the formation of some types of hydrothermal metamorphism, or by "deuteric action" (Shand, 1944). The role of deuteric action cannot be established in the diabase-pegmatites for virtually all the original mineral assemblages have been destroyed by metamorphism. It has been stated previously why the amphibole in the diabase-pegmatite is considered to be pseudomorphous after primary pyroxene.

The differentiation in these sills was perhaps not a simple process and some variations can probably be related to differences in composition and physical conditions during and after intrusion.

It is concluded that chemical, mineralogical, and theoretical considerations substantiate a proposed origin for the main variations in the sills by magmatic differentiation.

In most of the thin sills within the area being considered, the intrusive is composed of metadiabase only, or the southern edge is composed of metadiabase and the northern or central sections of diabase-pegmatite. The thin sills appear to be fairly regular in trend and uniform in composition.

A number of thick sills display irregularities which should be considered.

The Smith sill is composed of three rock types. The variation and distribution of the rocks is satisfactorily explained by differentiation. The uppermost part of the sill is too basic to be a chilled phase of the first intrusion, and cannot be explained as a product of magmatic differentiation of the sill. It is suggested therefore, that it may be related to a separate ultrabasic intrusive, or may be the basal part of an overlying sill. Neither of these explanations, however, is satisfactory.

A thick sill-like intrusive situated northwest of Proulx Bay, Dore Lake, cuts across the strike of the volcanic formations. The sill contains from one to three pegmatitic zones, each of which trends parallel to the regional strike. These zones may be explained by repeated intrusions, each of which differentiated separately. A mechanism whereby multiple thin pegmatitic differentiates may form, is outlined by Cornwall (1951, a) for some of the thick lava flows in the Keweenawan series. He considers the following factors as important in the differentiation of the flows which he studied (op. cit. p. 190): (1) cooling at a moderate rate, predominantly from the top; (2) differential settling of plagioclase, olivine, and ophitic pyroxene crystals; (3) local concentration of volatiles and transport of materials by migration of the volatiles; (4) periodic convective overturn of the magma during the later stages of crystallization. Two hypotheses are considered. The first is based on the assumption that convective overturn was important, and the second is based on the assumption that it was not. Cornwall believes that either or both of these hypotheses may be correct, and considers it possible that there was convective overturn in the thicker flows and not in the thinner flows. A similar mechanism involving cooling from above, and convective overturn, could probably account for the structure of the sill northwest of Proulx Bay, although it is possible that more than one intrusion may have taken place. Field observation failed to distinguish any evidence for such intrusions, but in many areas outcrops are not complete enough to permit the recognition of these relationships.

Differentiation of Parental Magma

Information on the nature of the basic magma that gave rise to the metadiabase sills may be gained by consideration of the variation diagrams in Figure 7. It has been explained previously that conditions of crystallization of the metadiabases produced differentiation characterized by marked enrichment in iron oxides with respect to magnesium. The overall trend may be interpreted to indicate that there was little to moderate differentiation of the parental magma before intrusion. The absence of late enrichment in alkali is noteworthy.

Conclusions drawn by Cornwall (1951, b, pp. 169-170) on the differentiation of magmas of the Keweenawan series indicate that the Keweenawan lavas and the Duluth gabbro were derived from the same parental magma, but that the courses of differentiation were different. The diabase sills at Duluth, as indicated in Figure 5, are interpreted as having formed from magma that corresponds to partially differentiated magma of the Duluth gabbro, and that the sills are therefore possibly offshoots of that body. The final differentiates in all Keweenawan rocks are marked by alkali-enrichment.

THE MAGMA-TYPE REPRESENTED BY THE METADIABASE SILLS AND RELATION TO THE VOLCANIC SERIES

Kennedy (1933) advanced evidence for the twofold primary subdivision of basaltic magmas into the undersaturated, oceanic, or olivine-basaltic type, and the saturated, or tholeiitic type. It has been common practice to refer basaltic magmas to either of these types, or to an intermediate type.

Kennedy's views have not gone unchallenged, and some petrologists think that there may be chemical differences in basalts of various ages from different provinces. Green and Poldervaart (1955) have compared the averages of a large number of superior analyses from various basaltic provinces of various geological ages. They find that basaltic composition does not alter with time nor do they find distinct types of magma that might correspond to "primitive" magmas. Instead, there seems to be a continuous series from silica-saturated to silica-undersaturated basalts, some high in alumina, others of normal or low alumina content.

Furthermore, they do not agree with Kennedy's two primitive basaltic types but maintain instead that the variations in composition of basaltic magma in one province, and from one province to another, may be more adequately explained by contamination, mixing of magmas, crystallization differentiation, and a type of pneumatolytic action related to "degassing" of the earth's interior.

That tholeiites are more common in the continental shields than in the oceanic islands is accepted by most authors, but details of processes operating in the formation of the basaltic crust are controversial. In previously described chapters analogies were drawn between the Chibougamau metadiabase and some of the great plateau basalt magma-types of the world in chemical composition and in trend of differentiation. From these considerations it may be concluded that the Chibougamau metadiabase represents the tholeiitic or silica-saturated magma-type. Because the tholeiitic metadiabases are the intrusive phase in the volcanic series in Chibougamau, it is probable that the volcanic rocks have plateau-type characteristics.

This conclusion is not necessarily valid for, as emphasized by Green and Poldervaart (op. cit., p. 178), silica-saturated basalts do occur in the oceanic areas, and olivine-basalts do occur on the continents. The Karroo province of southern Africa may be quoted "as an example of a tholeiite province in which one may observe all gradations between typical tholeiites and typical olivine basalts" (op. cit., p. 178).

Relevant to this discussion are the conclusions of Pfeffer (1955) who deduced on the basis of a structural, petrographic, and chemical study that the "Keewatin-type" volcanic assemblage in the O'Sullivan lake area of Ontario belongs to a plateau basalt complex. He believes, further, that this conclusion may be applied to many, if not most, of the "Keewatin-type" lava assemblages throughout northern Ontario. Insufficient work has been done to date to compare the Chibougamau volcanic assemblage with plateau basalts, but they do have in common the large quantities of lava emitted, the presence of many sills, and basic character. In the southern and southwestern parts of McKenzie and Roy townships the basal third of main lava sequence is basaltic in composition, and the upper two thirds is "andesitic". This subdivision is partly based on colour. Mineralogically, the main difference appears to be in greater amount of plagioclase and lesser iron ores in the meta-andesite.

Field relations demonstrate convincingly that many of the sills are genetically related to the volcanics and probably represent contemporaneous intrusion. For this to be true, the intrusives and their extrusive counterparts should have a similar chemical composition. However, the main metadiabase intrusives in the upper two thirds of the lava sequence are basaltic in composition, but the intruded rocks are mainly "meta-andesites".

In the southwest quarter of McKenzie township (Smith, 1953, p. 5), and in the southwest quarter of Roy township (Horscroft, Unpublished), pillows are more common in the meta-andesite than in the metabasalt. Furthermore, in McKenzie township where there are few tuffaceous beds in the lava sequence, the metadiabases reach their maximum development, but where the tuffaceous beds assume greater proportions as in the southwest quarter of Roy township, the metadiabase is less abundant. Allard (1956, b, pp. 65-66) suggests that the appearance of the metadiabase "only above a certain height in the volcanic series . . . may be explained by the excessive load over the lower part of the volcanic pile. Higher up in the series, the force of intrusion of the magma might have been sufficient to pry apart the volcanics and make room for the magma between the flows." Allard's interpretation implies that a considerable thickness of extrusives had already accumulated before intrusion began. The present writer's opinion is that intrusion and extrusion probably occurred almost simultaneously. Smith (1953, Preliminary Map 945) shows "metadiorite" and "metagabbro" low down in the metabasalts, and Graham (1956) in describing the lower part of the volcanic series in the northern half of Obalski township, states (p. 4): "also present are dykes and sills of related rock believed to be contemporaneous with the igneous activity which accompanied the formation of the volcanic complex." Within the southwest quarter of Roy township it has not been possible to distinguish between medium- to fine-grained basaltic flows and possible intrusives.

Many of the variations exhibited by the lava flows and by the intrusive metadiabase can probably be explained in terms of variations in the formation of the extrusives and intrusives with regard to their geographic and tectonic environment, and to differences in chemical composition. Insufficient data are available at present to allow further interpretation or correlation.

In the area under consideration, metadiabase and diabase-pegmatite are invariably restricted to the same sills, and the pegmatitic facies is towards the northern (upper) parts of the intrusive. Nowhere does the diabase-pegmatite form individual sills. This constant association is not maintained between "metagabbro" and "metadiorite" as mapped by Smith (1953) in the southwest quarter of McKenzie township (Preliminary Map 945), although Smith does suggest differentiation in some of the sills before folding (op. cit., p. 7). It is probable that in some areas Smith's "metagabbro" and "metadiorite" correspond to the present "metadiabase" and the "diabase-pegmatite". Some of the inconsistencies in correlation may be due to inconsistencies in terminology used by the various workers in the field work.

The present study has been directed toward obtaining a clearer understanding of some of the problems relating to the variation and distribution of these "gabbro" sills.

AUTHOR'S CLAIM OF CONTRIBUTION TO KNOWLEDGE

The author claims that this study has presented new information on the petrogenesis of the metadiabase sills in the volcanic series of Roy and McKenzie townships, Chibougamau region, Quebec, and is a contribution to knowledge.

Detailed petrographic examination shows that the minerals present are an assemblage which is stable in the greenschist facies of metamorphism. The mineralogical transformations of the primary rocks have taken place without appreciable change in bulk chemical composition. Original textures may still be recognized.

Two new silicate analyses and eleven partial chemical analyses are presented. Chemical and planimetric analyses show that layering of the sills is the result of magmatic differentiation characterized by iron-enrichment. In trend of differentiation and in chemical composition, the metadiabase is similar to some plateau-type basic sheets.

Three rock facies are represented, viz. metapyroxenite, metadiabase, and diabase-pegmatite. The metadiabase and diabase-pegmatite are probably similar to "metagabbro" and "metadiorite" in previously-mapped areas. The metadiabase is closely related to the volcanic series in distribution, and a genetic association is inferred. Variations in the proportions of metadiabase present may probably be ascribed to variations in the tectonic and geographic environments during extrusion and intrusion.

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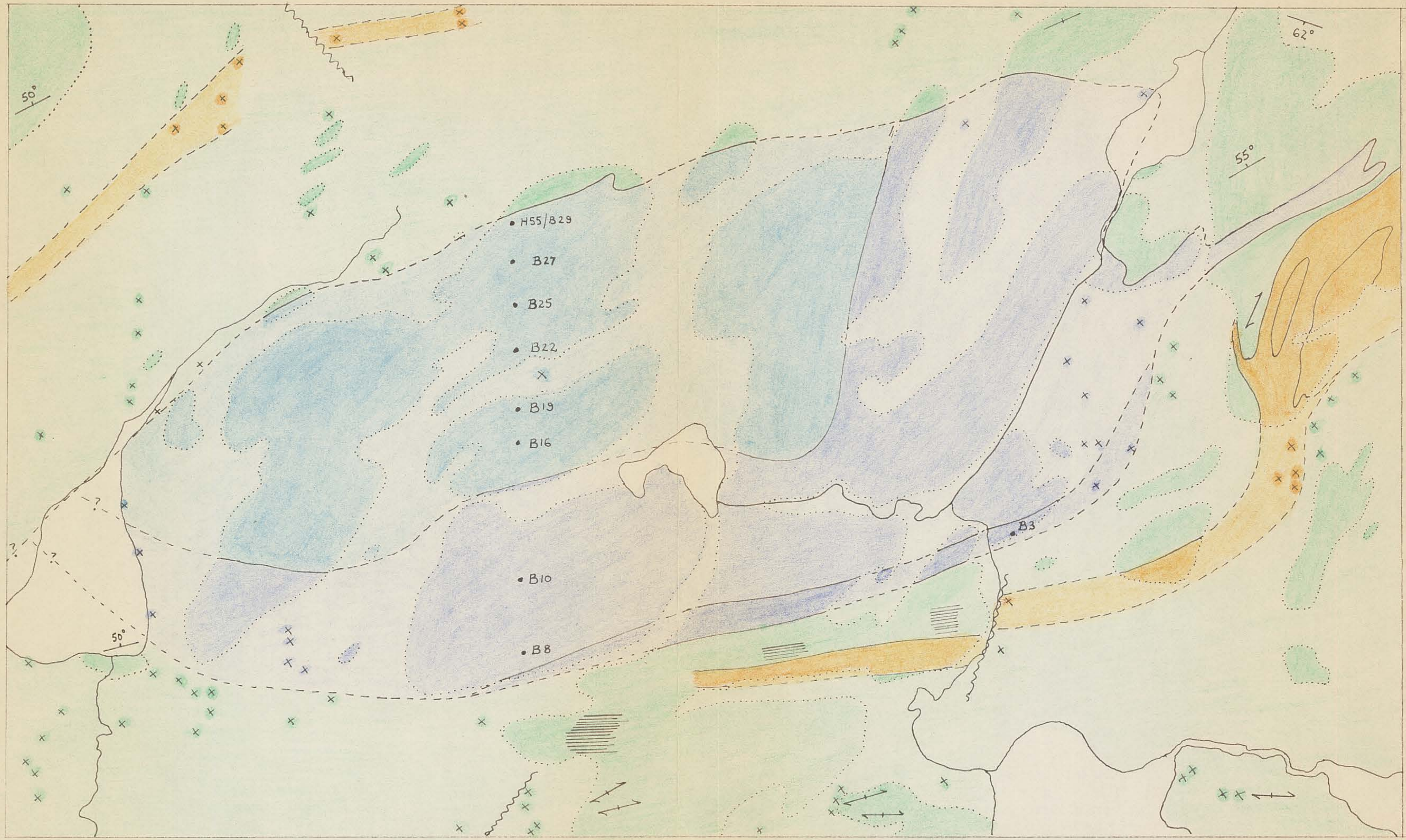


LEGEND

🟧 Ultrabasic Series

🟦 Diabase – pegmatite

▨ Metadiabase

▨ Metapyroxenite

🟩 Meta-andesite, tuff, chert

• H55/B10 Location of samples analysed series H55/B—

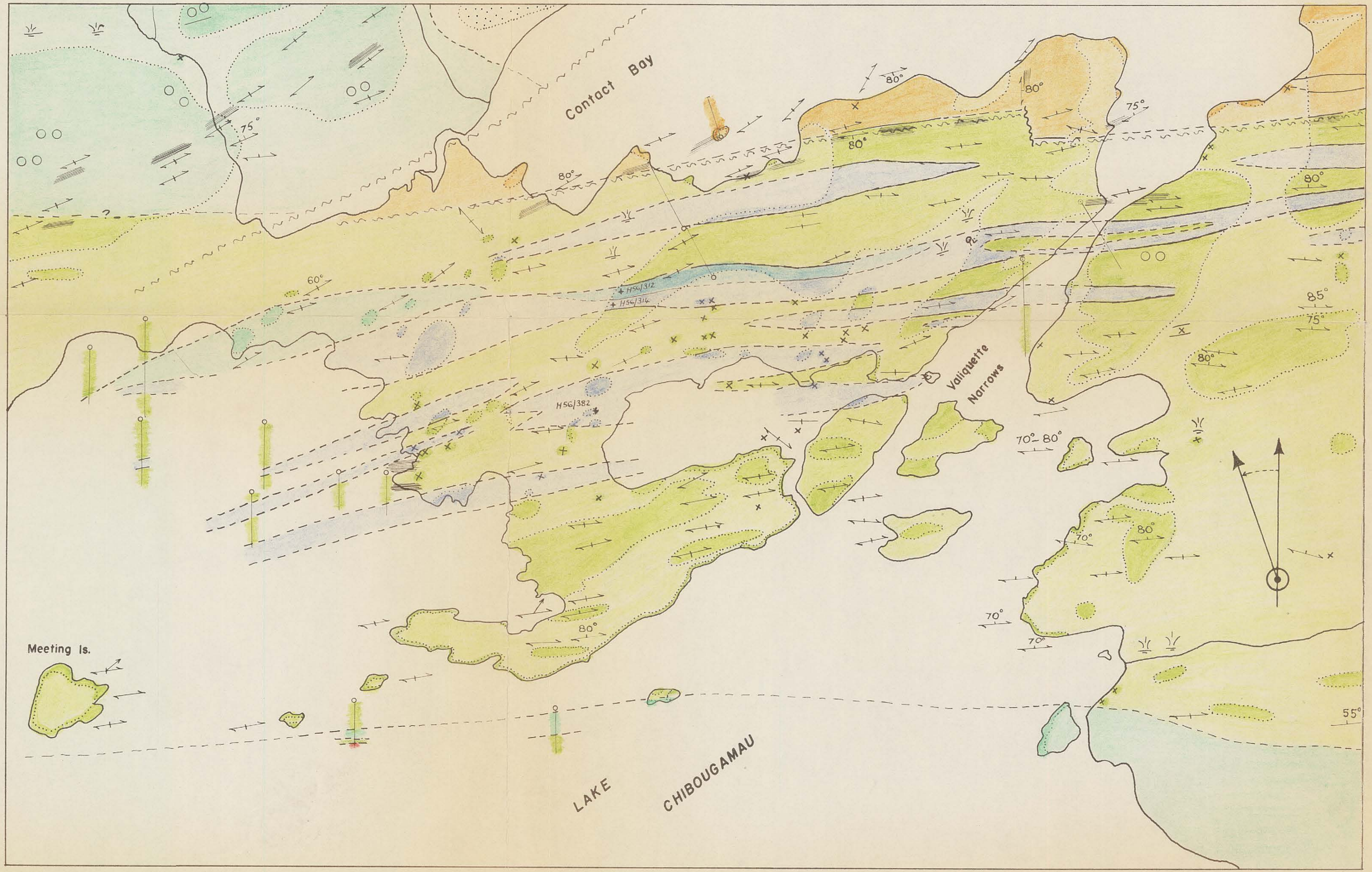
MAP SHOWING

GEOLOGY OF THE SMITH SILL

0 500 1000

FEET

(After J.R. Smith, Unpublished)



LEGEND

⁙	Chibougamau Series
🟥	Feldspar - quartz porphyry
🟧	Pyroxenite
🟦	Diabase - pegmatite
⬜	Metadiabase
🟨	Tuff, agglomerate, thin lavas
🟩	Meta - andesite
+ H56/314 + H56/312 + H56/382	Location of samples submitted for analysis

MAP SHOWING

DISTRIBUTION OF METADIABASE SILLS

IN THE VOLCANIC SERIES

0 500 1000
FEET

(After F.D.M. Horscroft, Unpublished)

LEGEND

PRECAMBRIAN

PROTEROZOIC

CHIBOUGAMAU SERIES

- ▨ Conglomerate, thin beds of arkose

ARCHEAN

INTRUSIVE ROCKS

- 🟥 Feldspar-quartz porphyry, feldspar porphyry, granite dykes
- 🟥 Granite, Syenite
- ▬ Basic dykes

DORE LAKE COMPLEX

ULTRABASIC SERIES

- 🟦 Metagabbro, quartz – metagabbro
- 🟪 Metagabbro (feldspathic)
- 🟧 Pyroxenite, altered and unaltered
- 🟫 Peridotite and dunite, mainly serpentinized
- ⬛ Magnetile – serpentine rock (metapyroxenite, peridotite)
- ▨ Metagabbro, quartz – metagabbro
- 3B Transition rock — Anorthositic rocks
- 3A Meta – anorthosite — Anorthositic rocks

VOLCANIC SERIES

INTRUSIVES

- 🟦 Diabase – pegmatite
- ▨ Metadiabase
- ▨ Metapyroxenite

EXTRUSIVES

- 🟨 Tuff, feldspathic pyroclastic rocks, agglomerate, chert, graphitic tuff (slate), felsitic and acidic lavas
- 🟩 Meta – andesite, minor tuff
- 🟩 Metabasalt, minor tuff

SYMBOLS

- ○ Pillowed
- × Observed outcrop and outcrop area
- — Trend or strike lines
- Strike and dip of layering
- Strike and dip of layering and direction of top
- Primary foliation in igneous rocks
- Strike and dip of schistosity or cleavage
- 20° Direction and plunge of lineation
- Geological boundary: defined, assumed
- Fault
- Shear zone or schist zone
- Diamond drill hole
- Swampy ground

GEOLOGY OF THE SOUTHWEST QUARTER OF ROY TOWNSHIP AND PORTION OF McKENZIE TOWNSHIP

0 500 1000 1500 2000 Feet
Scale

Geology of McKenzie township by J.R.Smith and G.Allard 1953 – 1954
Geology of Roy township by F.D.M.Horscroft 1955 – 1956

Compiled by: F.D.M. Horscroft, April 1957