

THE PETROLOGY OF ARCHAIC AND PROTEROZOIC ROCKS AT CROSS LAKE  
MANITOBA AND THE EFFECTS OF THE HUDSONIAN OROGENY

A Thesis

Presented to

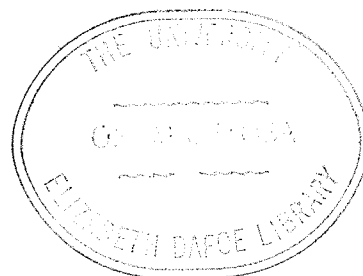
The Faculty of Graduate Studies and Research  
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Doctor of Philosophy

by

Don H. Rousell

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ABSTRACT

The Cross Lake Group, consisting of basalt, conglomerate, and sandstone, lies unconformably on the basement biotite granodiorite gneiss. The area probably underwent two periods of folding and these likely correspond to the Kenoran and Hudsonian orogenies. The only recognizable effects of the Kenoran orogeny are the north north-easterly and north northwesterly - trending cross folds. The Cross Lake Group was folded, metamorphosed, and granitized during the Hudsonian orogeny. The major structural features were produced during the Hudsonian orogeny. These consist of a southwesterly-trending syncline and a northwesterly-trending syncline which merge and continue as one to the southwest and a major anticline situated between the two arms of the synclines. Numerous small-scales folds and lineations are present. Structures, in general, plunge steeply. Gabbro and anorthosite in the form of a sill at Pipestone Lake and a batholith south of the Minago River intrude the Cross Lake Group. These bodies were emplaced before or during the early stages of the Hudsonian folding.

The grade of metamorphism at Cross Lake increases from the lower part of the almandine-amphibolite facies in the southeast to the hornblende granulite subfacies of the granulite facies in the northwest

Garnet, clinopyroxene, and hypersthene progressively develop in basalt with increasing metamorphic grade. Hornblende in basalt decreases in amount, becomes darker in color, and shows an increase in the content of Al in the tetrahedral site and (Na+K) with increasing metamorphic grade. Rocks of the Cross Lake group were locally granitized by post-metamorphic intrusions of quartz-feldspathic material. This produced migmatites and most of the rocks of the gneiss complex.

Northwesterly-trending linear features were formed by tensional forces. These, together with mafic dykes and joints, are all post-Hudsonian in age.

Previous writers suggest that the Churchill and Superior provinces in northern Manitoba are separated by a gneissic zone. This study indicates that the contact between the Cross Lake sedimentary - Volcanic belt ("Superior" province) and the gneissic zone is a gradational one. Rocks south of the contact consist of those of the Cross Lake group and migmatites and rocks north of the contact are migmatites and those of the gneiss complex. Evidence is presented which suggests that the Cross Lake area lies within the Churchill province and that the Churchill-Superior boundary lies south of Cross Lake. The contact is likely a gradational one where effects of the Hudsonian orogeny fade into the Superior province.

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## CHAPTER I

### INTRODUCTION

#### LOCATION, SIZE, AND PHYSIOGRAPHY OF AREA

The geographic centre of the Cross Lake area lies 44 miles north of Norway House and 37 miles southeast of Wabowden. The area is bounded by latitudes  $54^{\circ}30'$  north to  $54^{\circ}45'$  north and longitude  $97^{\circ}30'$  east to  $98^{\circ}15'$  east and comprises a total of 510 square miles (see geological map).

The area is one of low relief with numerous swamps and muskegs. Sedimentary rocks are topographically low and outcrops rise only a few feet above lake level. Granodiorite and gabbro rocks locally form cliffs some 50 feet high. The greatest relief, in the order of 100 feet, is made by glacial ridges east and south-east of Cross Lake settlement. The area is drained entirely by the Nelson River System. Drainage is controlled by bedrock rather than glacial deposits.

#### PREVIOUS WORK

Prior to 1919, geological investigations in the area were in the nature of track or exploratory surveys. These consisted largely of isolated geological observations along major water routes. The first work was done by Bell (1879, 1881) and Tyrrell (1900) in 1890 and 1896. Existing information of the region was compiled by McInnes (1913).

Alcock (1920) did the first systematic mapping of the area at a scale of 2 miles to 1 inch. This comprised the western part of Cross and Pipestone lakes and encompassed the entire area considered in this report. The main areas underlain by sedimentary and volcanic rocks were outlined. Only three rock types, granites, sedimentary rocks, and volcanic rocks are shown on Alcock's geological map and no attitudes are given. He believed that the gneiss complex (9) intruded the sedimentary-volcanic sequence (2, 3, 4). No evidence was found to suggest that conglomerates (3) unconformably overlie volcanic rocks (2) and no volcanic pebbles were found in conglomerates.

Horwood (1934) did reconnaissance mapping at a scale of 4 miles to 1 inch in 1931-32 and this included the eastern two-thirds of the area. He believed that the sedimentary-volcanic sequence (2, 3, 4) lay unconformably on the gneiss complex (9) and that the conglomerates (3) overlie the volcanic rocks (2) unconformably. Evidence presented for the latter is an unconformity and the presence of volcanic pebbles in conglomerate.

In 1960 Bell (1962) remapped the eastern two-thirds of the area at a scale of 4 miles to 1 inch and compiled and revised the previous work. His map differs little from that of the writer. In 1962 Bell commenced reconnaissance mapping of the Wekusko sheet which includes the western one-third of the area. This work is still in progress.

Various mining companies and prospectors have examined showings in the area and some drilling has been done. In 1959 the Noranda Exploration Company did detailed mapping, ground magnetometer work, and drilling in the vicinity of the gabbro sill at Pipestone Lake.

Aeromagnetic maps Wolf 25 and 26 cover most of the area. Copies may be obtained at the Manitoba Mines Branch.

#### PRESENT WORK AND NATURE OF THE PROBLEM

Three 15-minute sheets, comprising 510 square miles, were mapped during the course of three field seasons from 1960 to 1962. Field data were plotted on vertical aerial photographs at a scale of 4 inches to 1 mile and transferred in the field to maps at a scale of 2 inches to 1 mile. The final map is at a scale of 1 inch to 1 mile.

Shorelines consist largely of rock exposures and virtually all were examined. Outcrops inland are small and few can be recognized on aerial photographs in this heavily bush-covered terrain. Pace-and-compass traverses assisted by aerial photographs as a location guide were run at 1200 to 1500-foot intervals over most of the area. Where swamps and muskeg were extensive, rather wider spacing was used. Representative samples were collected for thin sections, chemical analyses, and age determinations.

The primary purpose of the project was to map in detail the broad Cross Lake "greenstone" belt and surrounding gneisses.

Previous mapping had been limited to cursory track and reconnaissance surveys, mainly confined to shorelines. A close examination was made of the gneiss complex (9) in order to attempt separation of it into more than one rock type. Attention was given to the stratigraphy of the sedimentary-volcanic sequence (2, 3, 4) and its relationship to the gneiss complex (9). This was to test the validity of previous rock groups established, their correlation with other areas, and the contention that the gneiss complex (9) represented the basement upon which the sedimentary-volcanic sequence (2, 3, 4) was deposited. Numerous structural elements were recorded and analyzed in order to determine the configuration and origin of this structurally complex area.

More than 300 thin sections were examined. Point counts were made on a number of specimens to provide sound quantitative data as to the mineralogical content of the various rock types. Total rock analyses were made on 24 specimens. Nine mineral analyses were made together with 13 partial analyses of plagioclase. Age determinations were obtained from 3 specimens.

A rather detailed laboratory investigation was made on basalts (2) and comprised point counts, total rock analyses, mineral analyses, and optical determinations. The purpose was to determine the chemical composition of the basalts together with changes in mineral content and mineral composition under progressive regional metamorphism.

In northern Manitoba the Churchill and Superior provinces of the Precambrian Shield are considered to be separated by a gneissic zone. Commercial nickel deposits along the Thompson-Moak Lake belt, near the northern edge of the gneissic zone, has focused a great deal of attention on this region. This has also generated interest as to the nature of the contact between the Churchill province and the gneissic zone and the Superior province and the gneissic zone. The Cross Lake area straddles the contact between the Superior province and the gneissic zone. This study has clarified the nature of the contact and suggests that the Cross Lake area and the gneissic zone were effected by the Hudsonian orogeny.

#### ACKNOWLEDGEMENTS

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concerning mineralogical problems.

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1960 - P. McKenna, Sr. Assist., A. Hodgson,

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L. Grapentine.

1962 - R. Lambo, Sr. Assist., R. Denton, J. Solohub,

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## CHAPTER II

### GENERAL GEOLOGY

#### INTRODUCTION

The Precambrian rocks of the area are outlined schematically in the Table of Formations (page 9). These rocks are grouped according to rock types and described in subsequent chapters. Chapter III describes the basalts (2) and basalt migmatites (6) and Chapter IV sedimentary rocks (3, 4) and sedimentary migmatites (7, 8). Acid and intermediate rocks are discussed in Chapter IV and these include the basement biotite granodiorite gneiss (1) and rocks of the gneiss complex (9). Gabbro-anorthosite (5) and mafic dykes (10) are dealt with in Chapter VI.

#### STRATIGRAPHY AND CORRELATION OF THE SEDIMENTARY-VOLCANIC SEQUENCE

##### Previous Interpretation

Horwood (1934) divided the sedimentary-volcanic sequence into the Hayes River Series and an overlying Cross Lake Series. The Hayes River Series consisted largely of basalt with minor conglomerate and the Cross Lakes Series of sandstone, some conglomerate, and minor basalt.

Horwood (1934) correlated the Hayes River Series with Keewatin volcanic rocks of the Lake of the Woods area, Ontario. This was based on structural and lithological similarities. The Hayes River Series of the Cross Lake area was directly correlated

## T A B L E O F F O R M A T I O N S

P R E C A M B R I A N  A R C H A E A N	MIDDLE OR UPPER PROTEROZOIC?	(10) Mafic dykes: hornblende gabbro, diorite, hypersthene gabbro, peridotite.	
	INTRUSIVE CONTACT		
	L O W E R  P R O T E R O Z O I C	MIGMATITES AND GNEISSES DERIVED FROM (2), (3), (4).	(9) Gneiss complex: biotite granodiorite gneiss, hornblende tonalite gneiss, adamellite, feldspar porphyry gneiss, hypersthene gneiss; aplite, pegmatite, quartz veins.
			GRADATIONAL CONTACT
		(8) Sandstone Migmatite: (4) with more than 20% (9) and less than 90% (9) (7) Conglomerate migmatite: (3) with more than 20% (9) and less than 90% (9) (6) Basalt Migmatite: (2) with more than 20% (9) and less than 90% (9)	GRADATIONAL CONTACT WITH (2), (3), (4).
			(5) Biotite gabbro, hornblende gabbro, anorthosite, ovoid gabbro
	INTRUSIVE CONTACT		
	C R O S S L A K E G R O U P	CROSS LAKE GROUP	(4) Sandstones and associates rocks: arkose, subgreywacke, minor feldspathic and lithic greywacke, siltstone, grit, conglomerate; rare protoquartzite, limey shale. Metamorphic equivalents: quartz-plagioclase- biotite--(garnet) paragneiss, sillimanite paragneiss, staurölite schist, meta-argillite.
			(3) Conglomerate
			(2) Basalt: hornblende schist, garnet-diopside schist, hypersthene schist, breccia, gabbro.
UNCONFORMITY			
		(1) Basement biotite granodiorite gneiss.	

with the Hayes River of the area around Oxford Lake. He applied the term Cross Lake Series for geographical reasons alone, and correlated this series with the Oxford Series on the basis of lithology and steep dips.

Horwood's (1934) separation of the sedimentary-volcanic sequence in the Cross Lake area into two series was based on two criteria. The first was the presence of a supposed unconformity between the Hayes River and Cross Lake Series located at the western end of the second largest island between Pipestone and Cross Lakes. The second criterion, considered the most important, was that basalt pebbles at the base of the Cross Lake Series were derived from the Hayes River basalt whereas tonalite fragments predominate higher in the series. The suggestion was that erosion cut through the Hayes River Series and exposed the tonalite basement.

Horwood (1934) considered that the Hayes River Series lay unconformably on tonalite gneiss and that the latter rock covered much of the area. Although no unconformity was observed by Horwood, this was based on the contention that tonalite did not intrude Hayes River rocks and all intrusions cutting the Hayes River were later granite. Because the Hayes River Series was correlated with the Keewatin, Horwood suggested that the tonalite underlying the Hayes River (his Pre-Keewatin tonalite) may represent the oldest rocks in North America.

### Present Interpretation

Present detailed mapping suggests a different interpretation from that of Horwood. The "unconformity" used as a criterion for subdividing the sedimentary-volcanic sequence into two series was examined and later re-examined (located at  $97^{\circ}48'W$ ,  $54^{\circ}34'N$ ). An unconformable relationship was not evident between basalt (2) (Horwood's Hayes River) and conglomerate (3) (Horwood's Cross Lake) to the south. A similar conclusion was reached independently by Bell (1962).

The second criterion, that basalt pebbles of Hayes River origin occur at the base of the Cross Lake Series and tonalite pebbles further up cannot be substantiated either. The conglomerate overlying the "unconformity" consists of pebbles of quartz, quartzite, and silty shale. Six hundred feet further south pebbles are 75 per cent silty shale and 25 per cent quartz, quartzite, and granodiorite. The conglomerate is interbedded with arkosic sandstone and followed by a thick succession of basalt. The section is apparently repeated by folding.

Because of intense folding characterized by numerous reversals and repetition of beds, the writer believes the only location where the stratigraphic succession can be deduced with certainty is that above the unconformity on Cross Island. There, conglomerate (3) immediately above basalt (2) consists of pebbles of quartz, quartzite, and granodiorite. The writer has specifically recorded in his field notes the absence of basalt pebbles. South of

the channel to Ebb-and-Flow rapids conglomerate (3) is exposed immediately to the south of basalt (2). Pebbles are mainly granodiorite. Numerous contacts observed between sedimentary and volcanic rocks on islands in Cross Lake northeast of the settlement, the west end of Pipestone Lake, and the west end of Cross Lake, are all conformable. Nevertheless there appears to be some local erosion of basalt. Greywacke (4) overlies basalt (2) unconformably in an exposure along the Minago River. On the south shore of Pipestone lake, minor beds containing basalt fragments and some quartz pebbles (2e) are enclosed in basalt.

In summary, erosion of basalt (2) appears local rather than general. Erosion did not cut through basalt in order to expose basement granodiorite gneiss (1) (Horwood's tonalite). Exposed areas of the basement were present and supplied sediments throughout the deposition of sedimentary and volcanic rocks.

The writer agrees with Horwood's contention that the sedimentary-volcanic sequence lay unconformably upon basement rocks (1). An unconformity discovered at the north end of Cross Island shows conglomerate (3) overlying basement biotite granodiorite gneiss (1) (Plate 1, page 13). Horwood believed the basement was tonalite and assumed an unconformable relationship because tonalite was never observed cutting the sedimentary volcanic sequence. Present mapping and chemical analyses indicate hornblende tonalite gneiss (9b) was produced by the granitization of basalt (2) by injected quartzo-feldspathic material. Horwood's correlation of the basalts

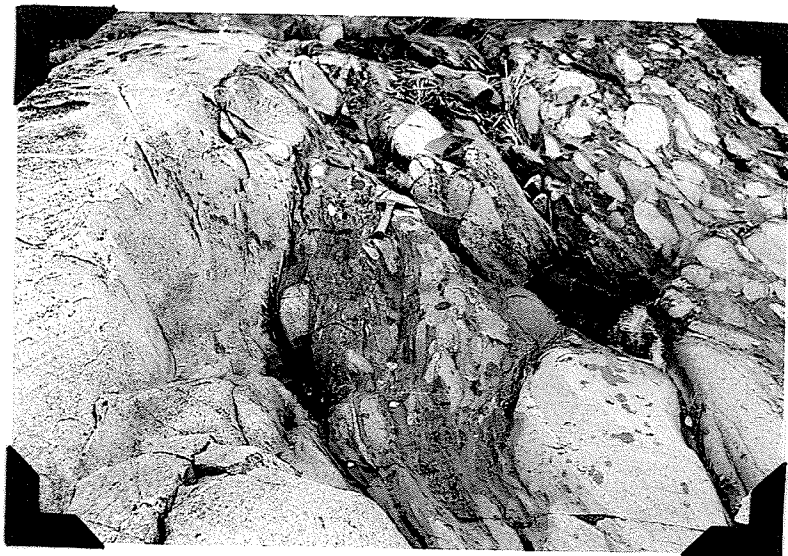


PLATE 1. Unconformity between basement biotite granodiorite  
gneiss and conglomerate - north shore of Cross  
Island.

(2) of the area with Keewatin volcanic rocks has no real basis. Thus his contention that the basement granodiorite gneiss (1) (tonalite of Horwood) is pre-Keewatin is a matter of conjecture.

The Hayes River Series of the Cross Lake area may be roughly the time equivalent of the Hayes River of the Oxford Lake - Knee Lake region. There the Hayes River Group is unconformably overlain by the Oxford Group (Barry 1959, 1960). The lack of a positive unconformity in the Cross Lake area casts some doubt as to the correlation of Horwood's Cross Lake Series and the Oxford Group. The Cross Lake Series however is lithologically more similar to the Oxford Group than to the upper unit of the Hayes River Group. The Cross Lake Series may be the equivalent of the upper unit of the Hayes River Group, the Oxford Group, or both.

Because of the confusion that has arisen in the past due to the practice of equating Precambrian units, separated by great distances, on a lithologic basis and for reasons cited above, the writer prefers to abandon Horwood's two-fold subdivision. The name Cross Lake Group is assigned to the entire sedimentary--volcanic sequence. Above the unconformity on Cross Island the stratigraphic succession and approximate thicknesses are: basal conglomerate (2000 to 3000 feet); basalt (2000 to 3000 feet); conglomerate (1000 to 3000 feet); and sandstone (greater than 5000 feet?). Precise thicknesses cannot be accurately given because of folding. Elsewhere, the stratigraphic succession could not be precisely determined because of folding and rapid facies changes and because the basal

contact was never found. Rocks of the Cross Lake Group were mapped according to rock types rather than stratigraphic units. Rock types are basalt (2), conglomerate (3), and sandstone (4).

### Tectonics and Sedimentation

The sedimentary-volcanic sequence at Cross Lake has the following characteristics: mainly arkosic sandstones; conglomerates; cross-bedding and scour; local diastems in conglomerates and basalts; and interbedding of sediments and basalts. This association suggests a continental orogenic environment with rapid erosion and deposition under shallow-water deltaic conditions. Pettijohn (1943) suggested that graded-bedded greywackes form the bulk of Archaean sedimentary rocks and that the lavas are often spilitic. Cross-bedded arkoses (4) are the main sedimentary rock type at Cross Lake, and the basalts (2) are not spilitic.

Pettijohn (1943) believed... "That the major belts of sediments traceable across the Shield are in part fringed with conglomerates and that the present boundaries of these belts are, therefore, nearly the original limits". The Cross Lake sedimentary-volcanic belt is not fringed by conglomerates. It is fringed and surrounded by migmatites (6, 7, 8) and gneisses (9) produced by the granitization of the Cross Lake group (2, 3, 4). This suggests that the depositional basin was more extensive than the remnant structural basin.

### CHAPTER III

#### THE BASALTS

##### GENERAL CHARACTERISTICS

The basalts (2) comprise approximately 15% of the exposed rocks of the area. They have all undergone recrystallization and deformation so that although the term meta-basalt may be more appropriate, they are hereafter referred to as basalts as a matter of convenience. Mesoscopic features vary but they are not sufficiently distinctive or consistent to justify dividing basalt (2) into more than one unit on the geologic map.

The distribution of basalt (2) is shown in Figure 3-1 (page 17). Basalt occurs mainly along the southeast-trending arm of the Cross Lake sedimentary-volcanic belt, in the vicinity of Pipestone Lake. It also occurs as bands along the northeast-trending arm of the belt and as narrow bands within the gneiss complex (9).

Single basalt units a few tens of feet thick and enclosed by sedimentary rocks (3, 4) occur in islands in the northeastern part of Cross Lake. The thickest sections of basalt which appear to be relatively undeformed occur 5 miles south of the Hudson's Bay Post and at the east end of Pipestone Lake. At the former locality, the thickness is approximately 4000 feet and at the latter it is 9000 feet or more. The thickness of the total basalt section is unknown.

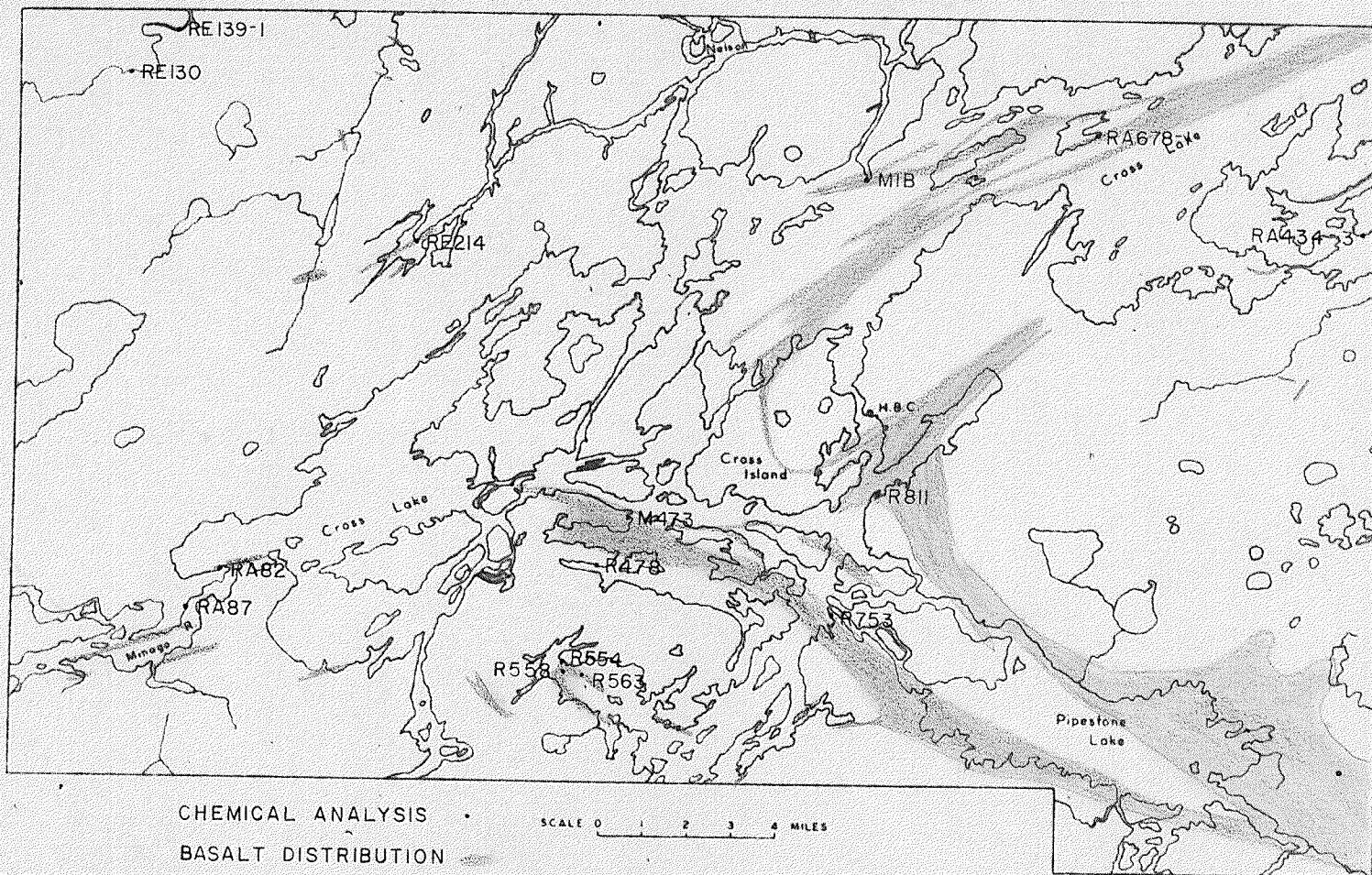


FIGURE 3-1. DISTRIBUTION OF BASALT AND LOCATION OF CHEMICALLY ANALYZED SPECIMANS

Pillows are common (Plate 2, page 19) and excellent examples occur on the shoreline of Pipestone Lake and the west side of Cross Island. Top determinations based on pillows must be used with caution because of distortion; for some exposures, the "top" could be interpreted in either direction.

Basalts are almost invariably foliated. The foliation is considered to be a combination of a secondary foliation imprinted upon and in the same direction as primary banding or layering. The degree of foliation may range from a moderately foliated rock to a platy-weathering schist. Foliated basalts sometimes enclose medium-to-coarse-grained gabbroic bodies. Contacts are gradational. These bodies represent either conduits or recrystallized basalts.

Banding, due to variations in proportions of light and dark minerals, was mainly produced by the introduction of quartzo-feldspathic material along foliation planes. The width of the quartzo-feldspathic layers range from microscopic size to sills several feet across. Some of the banding may be the result of primary flow or metamorphic segregation. The grade of metamorphism is sufficiently high to cause segregation.

Pyroclastic rocks are not present in the area. Minor bands consisting of angular blocks of basalt set in a coarser matrix of similar composition are considered to represent flow breccia (2d). Narrow bands enclosed in basalt and consisting of elongated basalt fragments (average length 3 inches) are considered to be sedimentary breccia (2e) because they contain a few rounded quartz pebbles.

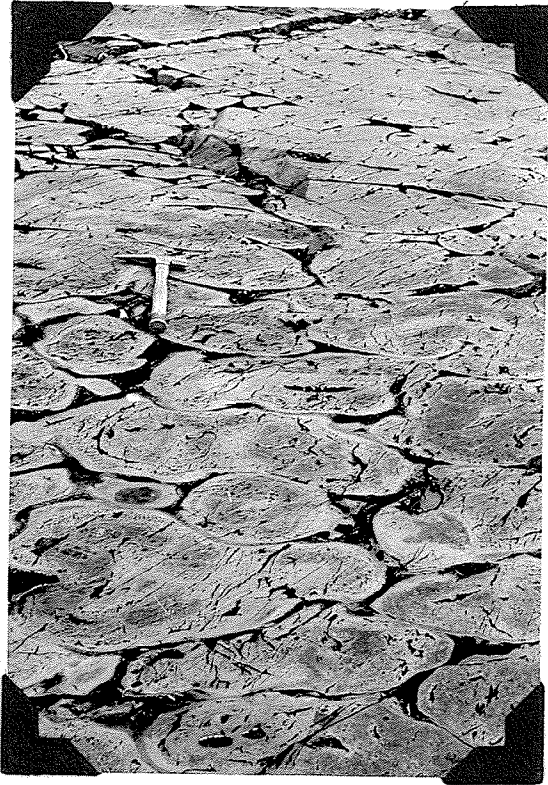


Plate 2. Pillowed Basalt on north shore of Pipestone Lake.

CHEMISTRY AND PETROLOGY OF THE BASALTS

Total rock analyses of 15 specimens of basalt (2) from the area were made and are given in Table 3-1 (page 21). The modal analyses for these specimens are set out in Table 3-2 (page 22). For comparative purposes, a number of analyses representative of various basic extrusive rocks were selected from the literature and these are given in Table 3-3 (page 23).

The composition of the Cross Lake basalts and those from the literature are plotted on triangular diagrams in Figure 3-2 (page 24). The lower cluster of points represents plots where weight percent of  $MgO$ ,  $CaO$ , and  $(FeO + Fe_2O_3)$  are end members; the upper cluster of points represent plots with  $SiO_2$ ,  $Al_2O_3$ , and  $(Na_2O + K_2O)$  as end members.

The average  $Na_2O$  and  $K_2O$  contents of Cross Lake basalts is 2.63 weight percent and 0.58 weight percent respectively. The alkali content of Cross Lake basalts is decidedly less than that of spilites and potash-rich volcanic rocks and less than most of the tholeiitic and olivine basalts plotted. Several of the Cross Lake specimens have a  $(FeO + Fe_2O_3)$  content that is distinctly higher than that of any of the tholeiitic or olivine basalts selected from the literature; other specimens are similarly high in  $CaO$ . The  $MgO$  content of Cross Lake basalts is generally low and in several Cross Lake specimens, the  $MgO$  content is lower than any of the volcanic types plotted.

TABLE 3-1

## CHEMICAL ANALYSES OF CROSS LAKE BASALT SPECIMENS IN WEIGHT PERCENT OF OXIDES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	RE214*	R558**	RE139-1**	MIB**	R753**	RA434-3*	M473**	R563*	R811*	RE130*	R554**	RA82**	R478*	RA87*	RA678-1**
SiO <sub>2</sub>	44.22	47.6	48.8	49.1	49.3	49.08	49.6	51.07	51.6	51.63	52.1	53.5	54.89	56.43	57.6
Al <sub>2</sub> O <sub>3</sub>	16.27	14.6	14.5	16.0	16.5	13.31	13.1	17.56	17.1	15.28	17.0	17.5	16.59	16.22	16.0
Fe <sub>2</sub> O <sub>3</sub>	6.83	2.6		3.7	3.0	3.99	3.6	2.76	1.9	4.68	2.12	3.08	3.87	3.28	2.6
FeO	12.73	12.3	13.2	12.55	10.36	11.00	14.20	5.41	7.9	6.42	7.84	6.64	4.36	6.52	4.1
MgO	4.11	7.9	6.75	3.3	5.4	4.97	4.25	4.47	6.15	5.74	5.50	4.80	3.58	4.47	5.3
CaO	11.97	12.3	10.9	9.01	9.2	10.25	10.39	13.36	10.60	11.11	9.11	8.90	9.54	9.62	10.78
Na <sub>2</sub> O	1.40	2.58	3.90	2.4	3.2	2.58	1.00	3.30	3.28	3.09	3.34	3.10	3.08	1.31	1.95
K <sub>2</sub> O	0.38	0.36	0.84	0.45	0.64	0.75	1.10	0.30	0.23	0.60	1.30	0.40	0.80	0.31	0.20
H <sub>2</sub> O <sup>+</sup>	0.80	0.40	-	0.52	1.40	1.19	0.80	0.75	0.19	0.44	0.30	0.08	1.03	0.85	Nil
CO <sub>2</sub>	-	Nil	-	0.74	0.05	Nil	0.79	-	Nil	-	0.04	0.06	-	-	0.60
TiO <sub>2</sub>	0.88	1.57	-	1.92	1.11	1.36	0.67	0.99	0.82	0.56	0.70	0.99	0.72	0.75	0.72
P <sub>2</sub> O <sub>5</sub>	0.11	0.21	-	0.45	0.17	0.11	0.16	0.06	0.09	Trace	0.15	0.16	0.32	0.19	0.09
MnO	0.66	0.26	-	0.25	0.16	0.22	0.71	0.40	0.21	0.23	0.23	0.27	0.08	0.20	0.15
TOTAL	100.36	102.68	98.99	100.39	100.49	98.81	100.37	100.43	100.07	99.78	99.73	99.68	99.22	100.15	100.09

## Classi-

fication Ol. Ol. Th. Ca-Al. Ca.-Al. And. Th. Ca.-Al. Ca.-Al. And. And. Ca.-Al. Qtz. Qtz. Qtz.

Ol. = Olivine basalt Th. = Tholeiitic basalt Ca.-Al. = Calc-Alkalic basalt And. = Andesite Qtz. = Quartz basalt

\*D. Brown, Manitoba Mines Branch

\*\*K. Ramlal, Geology Dept., Univ. of Manitoba -

X-Ray Fluorescence Spectrometer Except for Fe<sub>2</sub>O<sub>3</sub>, FeO, Na<sub>2</sub>O, H<sub>2</sub>O, CO<sub>2</sub>.

TABLE 3-2

## MODAL ANALYSES OF CROSS LAKE BASALTS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	RE214*	R558	REL39-1	MIB	R753	RA434-3	M473	R563*	R811*	REL30*	R554	RA82	R478*	RA87*	RA678-1
Quartz	1.5	2.4		9.6	2.2	4.3	8.3	0.7	0.2	0.2	6.6	6.5	15.5	22.8	2.7
Plagioclase	23.5	22.5	49.7	16.4	23.9	23.9	0.8	46.3	42.2	55.2	41.3	36.9	39.9	31.6	48.9
Hornblende	27.7	74.0	16.8	68.3	52.2	69.5	73.3	24.5	55.3	14.1	46.1	56.3	38.0	36.3	44.6
Epidote					18.8	0.2		0.6					4.5		
Garnet	32.0						7.0							8.4	
Clinopyroxene	15.0		18.3				5.0	25.2		17.4					
Orthopyroxene			3.8												
Biotite			3.6	0.1	0.6	0.7	0.4		0.1		4.5	0.1	0.3	0.1	
Chlorite				0.1											
Calcite				0.4			2.0	0.4			0.1		0.4		2.5
Magnetite	0.2	1.1	7.8	5.1	2.3	0.3	3.2	0.1	2.0	1.5	0.1	0.1		0.7	0.8
Apatite												0.1		0.1	
Sphene						1.1		2.2	0.2		1.3		1.5		0.5
Tremolite	0.1														
TOTAL	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

All 1000 counts per section.

\*Average of 2 thin sections.

All others one thin section.

TABLE 3-3

## CHEMICAL ANALYSES OF BASALTS SELECTED FROM THE LITERATURE IN WEIGHT PERCENT OF OXIDES

	OLIVINE BASALTS					THOLEIITIC BASALTS					POTASH-RICH VOLCANICS		SPIILITE	AV. ANDESITE	AV. QTZ. BAS.
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO <sub>2</sub>	48.18	50.6	47.1	48.44	45	50.45	50.42	50.61	49.98	50	51.07	44.74	51.22	59.59	55.46
Al <sub>2</sub> O <sub>3</sub>	16.10	15.4	15.8	13.27	15	14.98	11.62	13.58	13.74	13	9.93	11.82	13.66	17.31	16.85
Fe <sub>2</sub> O <sub>3</sub>	6.02	4.4	4.0	4.06	13	3.38	2.71	3.19	2.37	13	2.72	3.89	2.84	3.33	2.13
FeO	8.71	6.9	8.3	8.27		7.55	9.07	9.92	11.60		1.19	7.06	9.20	3.13	4.86
MgO	3.90	7.5	7.4	8.21	8	7.67	10.11	5.46	4.73	5	10.31	14.28	4.55	2.75	6.31
CaO	9.89	8.7	9.4	7.72	9	9.17	9.74	9.45	8.21	10	4.87	9.61	6.89	5.80	7.86
Na <sub>2</sub> O	3.48	3.0	3.1	3.47	2.5	2.84	2.09	2.60	2.92	2.8	0.82	2.16	4.93	3.58	3.30
K <sub>2</sub> O	1.56	1.4	1.3	1.55	0.5	0.35	0.39	0.72	1.29	1.2	9.92	2.51	0.75	2.04	1.40
H <sub>2</sub> O±	-	-	-			0.96		2.13	1.22		4.23	0.50	1.88	1.26	0.58
CO <sub>2</sub>	-	-	-									0.21	0.94		
TiO <sub>2</sub>	2.31	1.5	2.9	4.29		2.33	2.97	1.91	2.87		2.13	2.10	3.32	0.77	0.88
P <sub>2</sub> O <sub>5</sub>	0.36	0.4	0.5	0.57		0.27	0.27	0.39	0.78		1.53	0.66	0.29	0.26	0.15
MnO	-	0.2	0.2	0.15		0.08	0.01	0.16	0.24		0.04	0.19	0.25	0.18	0.22
TOTAL	100.52	100.0	100	100	93	99.09	99.49	100.12	99.95	95	98.76	99.73	100.72	100	100

1-13 from Turner & Verhoogen (1960); 14,15 from Barth (1952).

1. Table 14-1: East Otago, N.Z., average of 19.
2. Table 14-3: Victoria, Aust., average of 27.
3. Table 14-4: Carboniferous of Scotland, average of 27.
4. Table 14-7: Tutuila, Samoa, average of 5.
5. Table 15-9: Olivine basalt magma type.
6. Table 18-1: Koolau series, Oahu, average of 10.
7. Table 18-3: Mauna Loa, Hawaii, average of 24.
8. Table 16-10: Average Deccan basalt.

9. Table 15-4: Average of 6 Oregon basalts.
10. Table 15-8: Tholeiitic magma type.
11. Table 21-3: Leucite Hills, Wyoming.
12. Table 21-7: Murambite, Uganda.
13. Table 25-1: Average spilite, 19 analyses.
14. Table 33 : Average andesite.
15. Table 33 : Average quartz basalt.

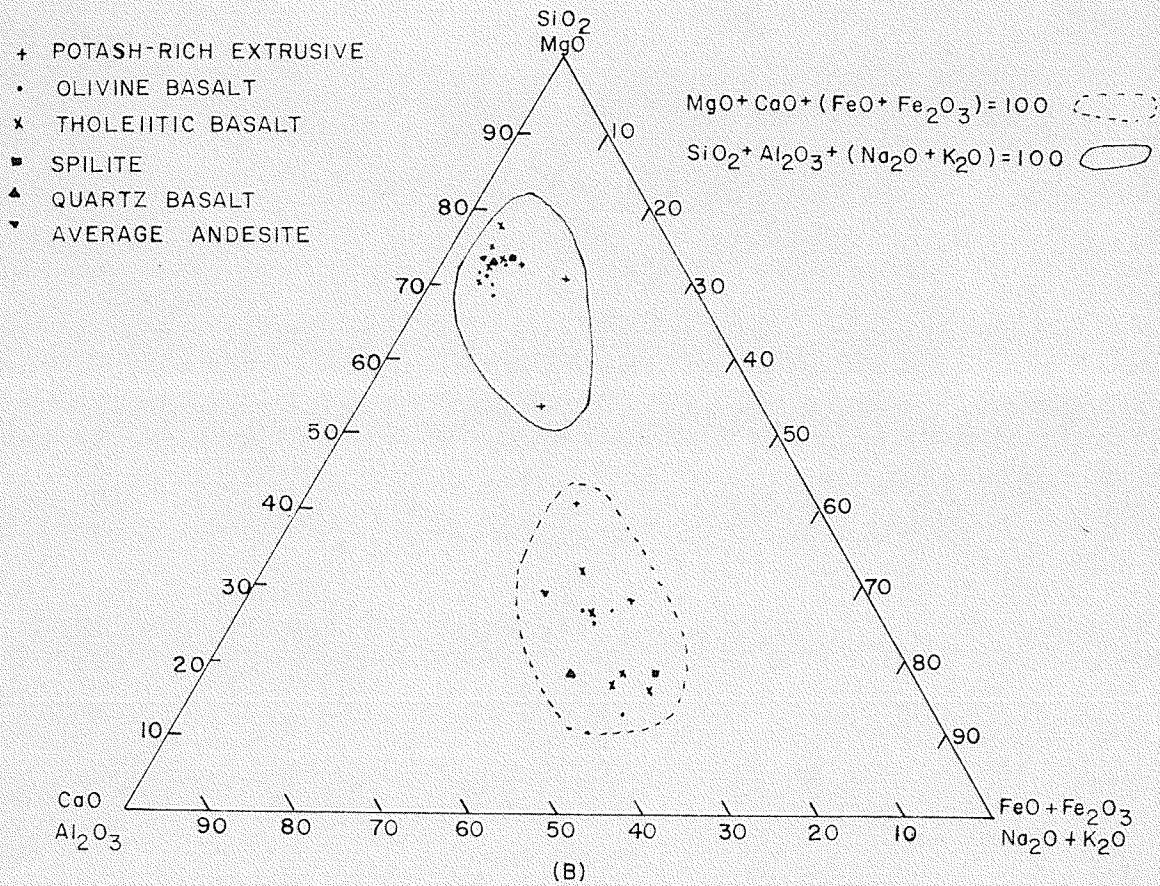
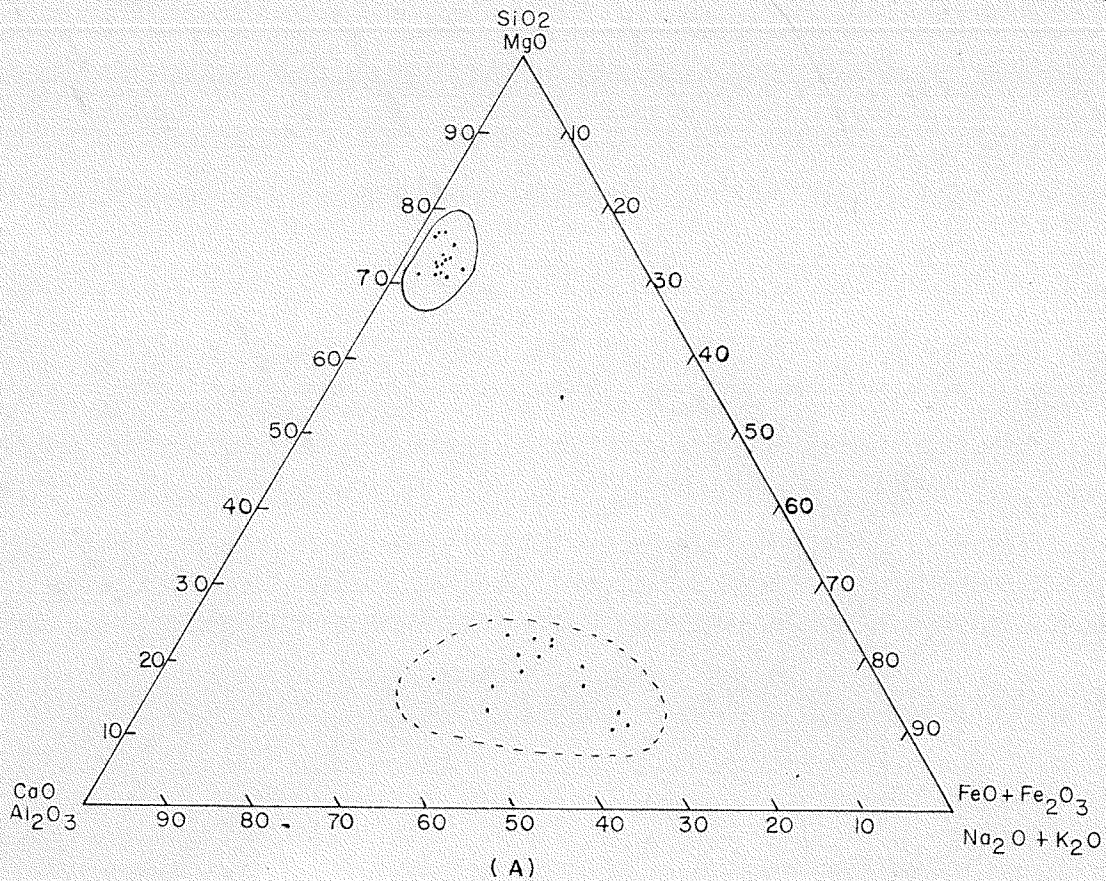


FIGURE 3-2. TRIANGULAR DIAGRAMS OF CROSS LAKE BASALTS (A) AND BASALTS SELECTED FROM THE LITERATURE (B)

The interrelationships between CaO, MgO, and (FeO + Fe<sub>2</sub>O<sub>3</sub>) are more clearly illustrated in Figure 3-3 below. Figure 3-3a indicates that the CaO content of Cross Lake basalts is inversely proportional to the (FeO + Fe<sub>2</sub>O<sub>3</sub>) content. Figure 3-3b and 3-3c show the MgO content is not particularly sensitive to changes in CaO or (FeO + Fe<sub>2</sub>O<sub>3</sub>).

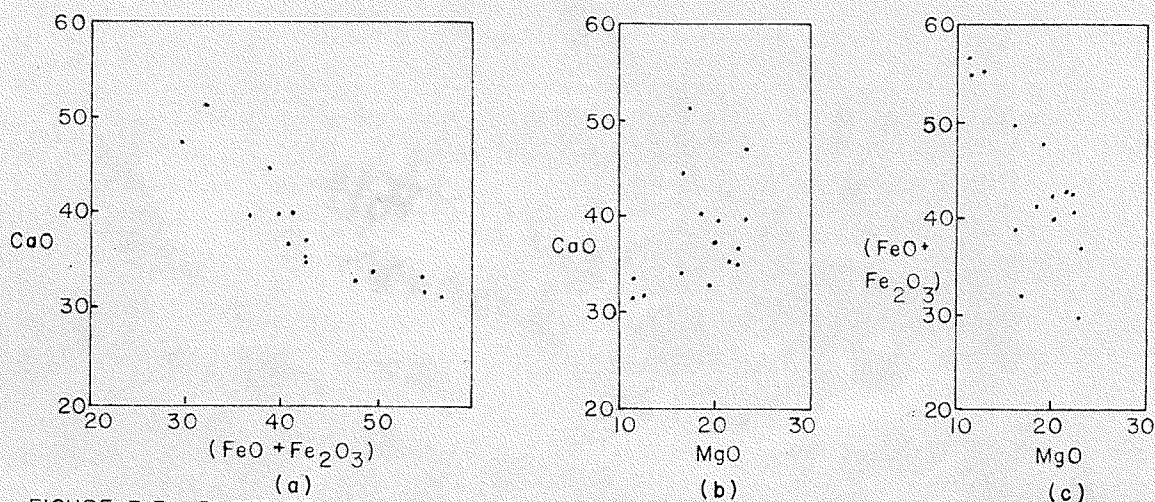
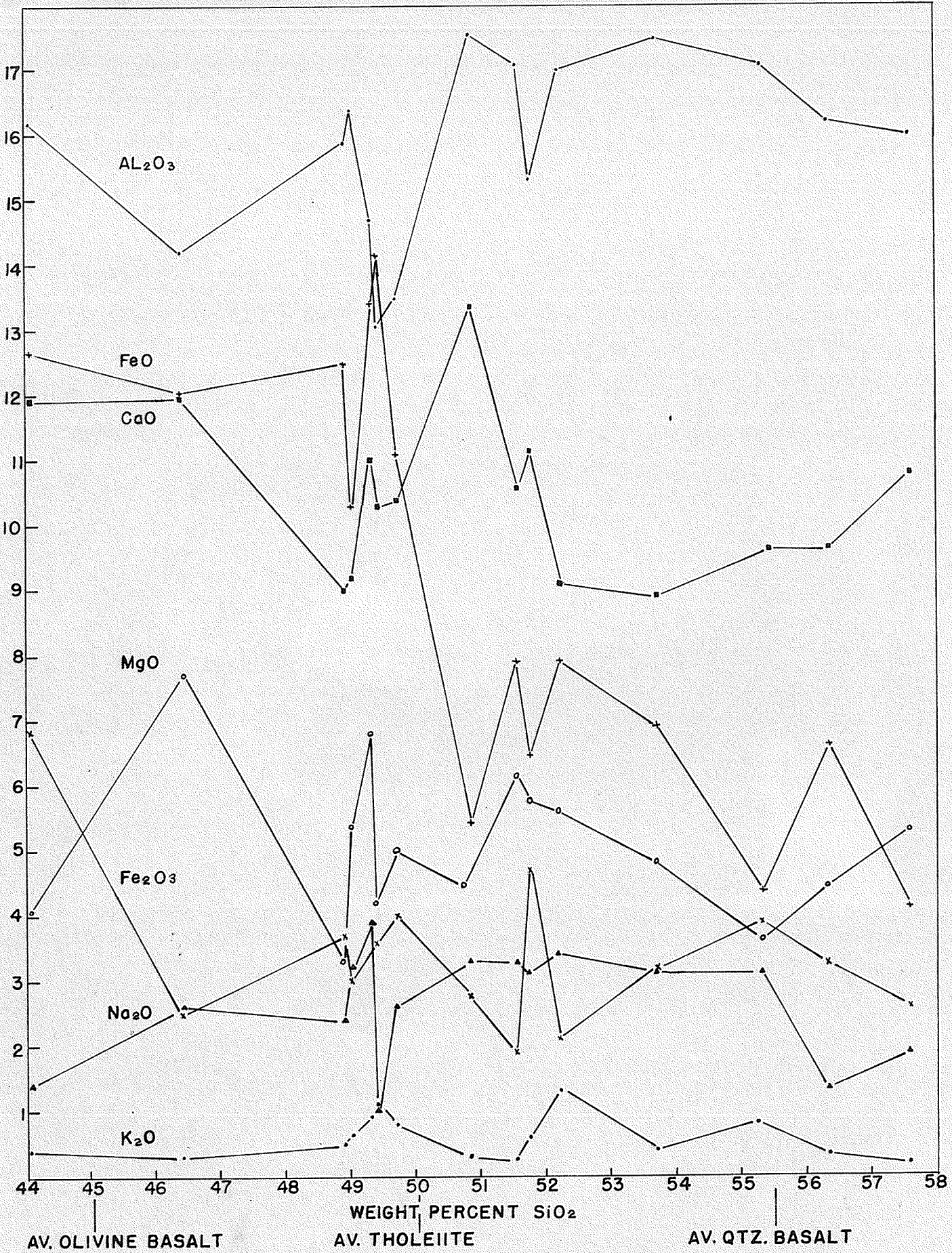


FIGURE 3-3. PLOTS RELATING CaO, MgO, AND (FeO + Fe<sub>2</sub>O<sub>3</sub>) CONTENTS OF CROSS LAKE BASALTS; WEIGHT PERCENT CaO + MgO + (FeO + Fe<sub>2</sub>O<sub>3</sub>) = 100.

The petrologic names of Cross Lake basalts according to Nockold's classification (1954) are given in Table 3-1 (page 21). These are based on Niggli norms calculated by means of a computer program (H. D. B. Wilson - personal communication).

Figure 3-4 (page 26) is a standard variation diagram for Cross Lake basalts. The regular trend of a magma series is not



VARIATION DIAGRAM FOR CROSS LAKE BASALTS

FIGURE 3-4

apparent. There is some increase in  $Al_2O_3$  with an increase in  $SiO_2$  content. The trend of the  $Na_2O$  and  $K_2O$  curves is irregular and they do not increase with an increase in  $SiO_2$ . The sharp break in the  $FeO$  curve might suggest two series. Plots of  $CaO$  and  $(Na_2O + K_2O)$  do not intersect so that the alkali-lime index cannot be determined. The series is decidedly calcic.

Volcanic series are classified according to their tectonic setting and the various series possess certain chemical attributes. Spilitic lavas together with some normal basalts are associated with the geosynclinal phase of a tectonic cycle. The alkaline olivine basalts are typical of oceanic basins. Tholeiitic or flood basalts occur in a non-orogenic continental setting. The basalt-andesite-rhyolite association is characteristic of orogenic belts and is typically developed during and following elevation of folded masses; that is, during the final stages of orogeny.

Volcanic rocks of the Huzi province, Japan (Turner and Verhoogen, 1960, p. 280) are associated with an orogenic belt. They contain a pigeonitic series which chemically resemble Cross Lake basalts. The pigeonitic series has a low  $MgO : FeO + Fe_2O_3$  ratio, and a low alkali content. "Tholeiitic" types in the series resemble normal tholeiites but are higher in  $Al_2O_3$ , as are basalts at Cross Lake.

In summary, Cross Lake basalts have a generally low alkali content, a high  $Al_2O_3$  content, and are high in either  $(FeO + Fe_2O_3)$  or  $CaO$ . The series is strongly calcic. They belong to the basalt-andesite-rhyolite association typical of continental orogenic volcanism.

MINERALOGY

Introduction

Basalts (2) of the area consist of several mineral assemblages. Six specimens, each representative of a particular assemblage, were chosen for detailed study. The mineral content of these specimens is set out in Table 3-4 below in order of increasing metamorphic grade. Minerals analyzed chemically are indicated. Analyses of plagioclase from six additional specimens were made (Table 3-5, page 31).

TABLE 3-4  
MINERAL ASSEMBLAGES OF CROSS LAKE BASALTS

SPECIMEN NO.	ASSEMBLAGE
1 R811	<sup>1</sup> <u>Plagioclase</u> , <u>hornblende</u> .
2 RA87	<u>Plagioclase</u> , <u>hornblende</u> , <u>garnet</u> .
3 RE214	<u>Plagioclase</u> , <u>hornblende</u> , <u>diopside</u> , <u>garnet</u> .
4 R563	<u>Plagioclase</u> , <u>hornblende</u> , <u>diopside</u> .
5 <sup>2</sup> R478	<u>Plagioclase</u> , <u>hornblende</u> , <u>epidote</u> .
6 RE130	<u>Plagioclase</u> , <u>hornblende</u> , <u>diopside</u> , <u>hypersthene</u> .

<sup>1</sup>Minerals underlined-analyzed chemically.

<sup>2</sup>The order of metamorphic grade is mainly based on the chemical composition of hornblende. Although epidote is not a common constituent of Cross Lake basalts, this assemblage (5) was deliberately chosen for study. Epidote is apparently a secondary mineral which developed after metamorphism.

Specimens were chosen which would yield good mineral separations. Samples were crushed and sieved through the 100-mesh size screen and retained on the 200-mesh screen. Separations were made with the Franz Isodynamic separator and with Clerici solution. The remaining impurities were removed by hand-picking.

The specific gravities of the minerals were determined by suspending grains in Clerici solution and calculating the specific gravity of the solution by means of a calibrated pycnometer. Theoretically, the mineral has the same specific gravity as the Clerici solution. Although the accuracy of the Clerici solution specific gravity is the order of  $\pm 0.001$ , that of the mineral is approximately  $\pm 0.003$ . Data are given to the second decimal.

An attempt was made to evaluate changes in kind, quantity, and composition of minerals in terms of rock composition and metamorphism. The metamorphic intensity increases in the area from southeast to northwest.

### Plagioclase

Plagioclase usually occurs as an untwinned mosaic (diameter  $< 0.1$  mm.) in basalts (2a) that have undergone low-grade regional metamorphism whereas grains are larger (diameters 0.5 - 1 mm.) and twinning is more prevalent in the higher-grade basalts (2b). Virtually all grains are twinned and diffuse zoning is common in basalts (2c) of the granulite facies.

Methods of determining plagioclase composition based on measuring extinction angles of the universal stage and refractive indices on grains lying on cleavage faces (Tsuboi's curves) proved unsatisfactory. The CaO, Na<sub>2</sub>O, and K<sub>2</sub>O contents of plagioclase from twelve basalt specimens were determined chemically. The results are given in Table 3-5 (page 31). Nine are andesine, two are labrodorite, and one is bytownite. Grain counts on the least pure sample gave less than 1 percent impurities.

The plots of Figure 3-5 (page 32) relate the plagioclase composition in terms of percent anorthite, albite, and orthoclase molecules to the rock composition in terms of atom percent calcium, sodium, and potassium respectively. The numbers adjacent to the plots are in order of increasing metamorphic grade of the specimen and correspond to the assemblages of Table 3-4 (page 28).

A direct relationship between the calcium content of the rock and the calcium content of plagioclase is not evident on the plot. There is some suggestion that the sodium content of plagioclase increases with an increase in sodium in the rock but this is not positive. Eight of the points are clustered within a small range of plagioclase and rock composition.

Sen (1959) believed that the amount of potassium in plagioclase is independent of the potassium content of the rock. There is some indication in Figure 3-5A that the potassium content of plagioclase increases with an increase in potassium in the rock. The three specimens with the highest total rock potassium content all

TABLE 3-5  
 CHEMICAL ANALYSES OF PLAGIOCLASE

SPECIMEN NO.	WEIGHT %			PLAGIOCLASE COMPOSITION		
	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	% An	%Ab	% Or
*RE130	7.90	6.64	0.43	38.7	58.8	2.5
*R478	6.18	4.37	0.41	42.4	54.3	3.3
*RE214	10.86	4.29	0.10	57.7	41.7	0.6
*R563	8.54	6.82	0.14	40.3	58.9	0.8
*R811	6.46	7.16	0.15	32.7	66.4	0.9
*RA87	7.64	1.43	0.10	73.6	25.2	1.2
**RE139-1	7.35	6.2	0.36	38.7	59.1	2.2
**R753	7.20	5.99	0.75	38.0	57.3	4.7
**RA678-1	10.95	3.95	0.30	58.5	39.5	2.0
**R558	8.35	6.54	0.36	40.5	57.4	2.1
**R554	6.3	5.4	0.54	37.7	58.5	3.8
**RA82	6.6	5.3	0.2	40.2	58.4	1.4

\* D.F. Brown, Manitoba Mines Branch: Ca,K,Na - Standard chemical

\*\*K.Ramlal, Dept. of Geology, Univ. Of Manitoba:  
 Ca,K - X-Ray Fluorescence Spectrometer  
 Na - Standard chemical

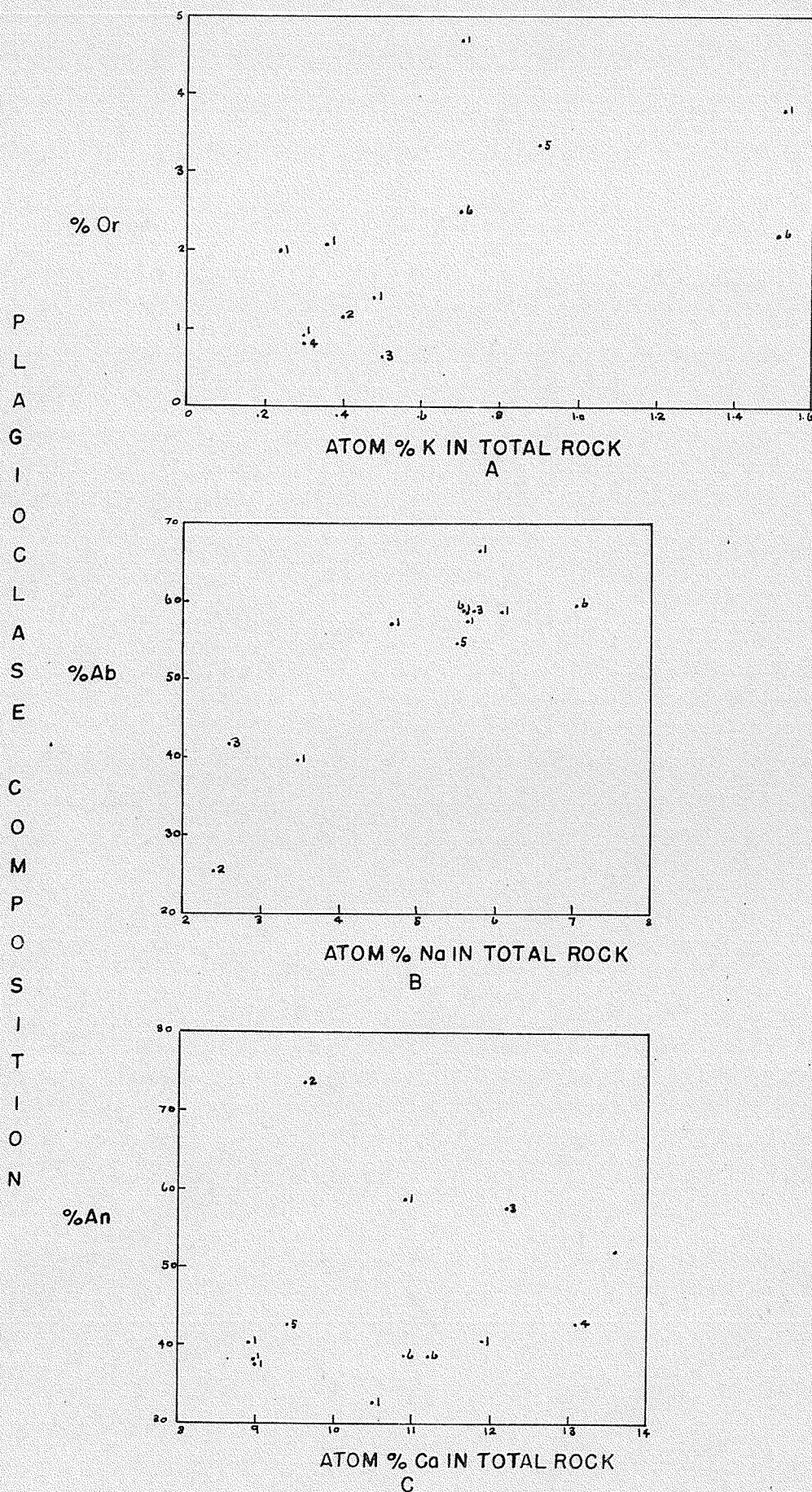


FIGURE 3-5. GRAPHS RELATING PLAGIOCLASE COMPOSITION TO ROCK COMPOSITION OF BASALTS. 1,2, ETC. IN ORDER OF INCREASING METAMORPHIC GRADE

contain 1 to 4.5 percent biotite by volume. The others contain little or no biotite. Biotite forms by the alteration of hornblende brought about by the introduction of potassium. Some of this potassium may have entered the plagioclase molecule. The potassium content of plagioclase in terms of percent orthoclase molecule varies between 0.6 and 4.7 percent. The average is 2.1 percent. This is in good agreement with Emmons (1953) who found for a variety of rock types a maximum of 4.2 percent and an average of 1.9 percent. Emmons (1953) found sericite in the specimens with a high potassium content and believed 1 percent for the orthoclase content of plagioclase would be more normal. The writer did not observe any sericite in plagioclase.

The analyses do not take into account the possibility that some of the potassium may be present as second-phase antiperthite or K-feldspar detectable only by X-ray powder photographs (R. B. Ferguson - personal communication).

Metamorphism in the area ranges from the lower part of the almandine-amphibolite facies to the hornblende-granulite subfacies of the granulite facies. A progressive relationship between the metamorphic grade and plagioclase composition is not evident on the plots of Figure 3-5. The composition of nine of the 12 specimens are between An 37 and An 43. Sen (1959) reported an increase in potassium content of plagioclase with increased metamorphic grade but this cannot be demonstrated here.

Hornblende is the only mineral that coexists with plagioclase in all assemblages. Virtually all the sodium is distributed between these two minerals. Figure 3-6 (page 35) relates the calcium and sodium content of plagioclase in terms of the percent anorthite and albite molecules to the calcium and sodium content of coexisting hornblende in terms of atom percent calcium and sodium. The plots do not show a positive relationship. The relationship of plagioclase composition to that of coexisting minerals is further discussed in the section on cation distribution.

Figure 3-7 (page 35) relates the sodium and potassium content of plagioclase in terms of percent albite and orthoclase molecules. There is some indication that the potassium content increases with an increase in sodium content. Emmons (1953) concluded that the potassium content does not increase with an increase in sodium although his Figure 5 suggests this trend.

In conclusion, 9 out of 12 plagioclase specimens have a composition near An 40. The composition does not appear to be controlled by rock composition nor does progressive metamorphism appear to cause systematic changes in plagioclase composition.

### Hornblende

Composition      Refractive indices were measured on hornblende fragments lying on the (110) cleavage face. The composition of hornblendes in terms of the ratio given below was obtained by applying the refractive indices to Parker's curves (1961).

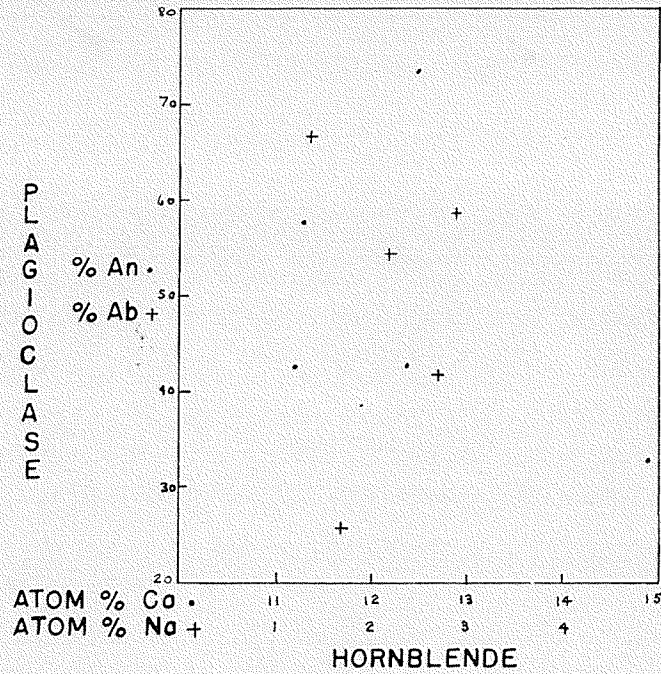


FIGURE 3-6. PLOTS RELATING CALCIUM AND SODIUM IN COEXISTING PLAGIOCLASE AND HORNBLende OF BASALTS

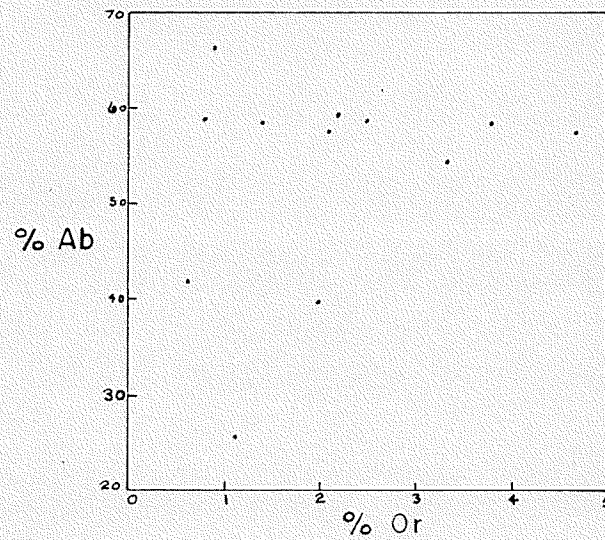


FIGURE 3-7. PLOTS RELATING PERCENT ALBITE AND PERCENT ORTHOCLASE IN PLAGIOCLASE OF BASALTS

This is compared to the ratio calculated from chemical analyses.

		Sample No:	R478	R811	RA87	RE214	R563	RE130
$\frac{\text{Fe}+\text{Mn}+\text{Ti}}{\text{Mg}+\text{Fe}+\text{Mn}+\text{Ti}} \times 100$	) Parker:		55	28?	45	65	44	61
	) Analyses:		46.7	38.5	46.6	58.8	55.3	--

The agreement is generally poor. The strong color of hornblende makes refractive indice determinations difficult.

Optic and extinction angles were measured on thin section grains using a 3-axis Universal stage. Strong absorption caused orientation difficulties for the former measurement; for the latter, cleavage traces on grains cut parallel to the optic plane are barely visible and are often irregular. Buddington and Leonard (1953) discuss similar difficulties and point out that there appears to be no reliable method for determining  $Z \wedge c$  in hornblende.

Five hornblendes were analyzed by standard chemical methods. They are from the assemblages shown in Table 3-4 (page 28). Hornblende from specimen RE130 could not be separated despite repeated attempts to do so. The volume percent of impurities was obtained by performing 1000 grain counts per specimen, using a mechanical stage. The volume percent of inclusions in grains was estimated and recorded. The volume percent impurities for the various samples are:

R 563	-	1	%
RA 87	-	2.2	%
R 478	-	4.18	%
RE214	-	3.77	%
R 811	-	1.45	%

The chemical compositions and specific gravities for most of the impurities were known so that corrections on hornblende

compositions were made with a reasonable degree of confidence. Table 3-6 (page 38) sets out the chemical compositions and physical properties of hornblendes. The corrections for impurities necessitated calculating totals to 100 percent. The writer is aware of the shortcomings of applying standard techniques of rock analysis to minerals.

Classification      The chemical complexity of amphiboles has led to a classification in terms of various end-members that is complex and often confusing. Cross Lake amphiboles cannot be assigned mineral names simply by glancing at standard end-member formulas nor is this practice very enlightening. The writer has adopted the structural formula proposed by Berman (1937) and used by contemporary authors such as Engel and Engel (1962). This is  $W_{2-3}(XY)_5(Z_4O_{11})_2(OH,F,Cl)_2$  where  $W = Ca, Na, K, (Ba)$ ,  $X = Mg, Fe^{+2}, Mn$ ,  $Y = Al, Fe^{+3}, Ti$ , and  $Z = Si, Al$ . (See Table 3-6.)

In order to classify Cross Lake hornblendes, the classification outlined by Deer, Howie, and Zussman (1963, Vol. II) is used. They employ the type formula  $X_{2-3}Y_5Z_8O_{22}(OH)_2$ . Their X is W in Berman's formula and Y is Berman's X+Y. The subdivision of Y into two parts is based solely on valence and as Deer et al (1963) point out has no structural significance. Cross Lake amphiboles are within the calcium amphibole sub-group, where Ca is the dominant ion in the X position.

The calcium amphibole sub-group is further subdivided on the basis of several end-members each with a specific name.

TABLE 3-6

## CHEMICAL AND PHYSICAL DATA FOR HORNBLLENDE

	1		2		3		4		5		6	
	R811		RA87		RE214		R563		R478		RE130	
SiO <sub>2</sub>	46.03	45.77	43.69	43.19	42.26	42.43	42.62	42.43	42.32	42.36		
Al <sub>2</sub> O <sub>3</sub>	11.72	11.67	14.00	14.17	11.61	11.28	11.66	11.61	11.96	12.04		
Fe <sub>2</sub> O <sub>3</sub>	2.32	3.12	3.52	3.88	4.49	4.30	4.52	4.5	6.39	6.36		
FeO	11.59	11.83	13.12	13.38	16.14	15.95	16.07	16.0	14.19	14.06		
MgO	10.90	10.8	8.97	8.8	7.24	7.25	7.85	7.81	9.61	9.52		
CaO	14.69	14.6	12.18	12.0	10.84	11.2	11.69	11.64	11.00	11.03		
Na <sub>2</sub> O	0.74	0.75	0.89	0.88	1.24	1.21	1.62	1.61	1.18	1.21		
K <sub>2</sub> O	0.13	0.14	0.42	0.41	0.96	0.92	0.66	0.66	1.34	1.36		
H <sub>2</sub> O <sup>±</sup>	1.17	1.16	2.24	2.18	2.22	2.13	1.75	1.74	0.88	0.88		
TiO <sub>2</sub>	0.50	0.57	0.92	0.90	2.42	2.32	0.81	0.81	0.71	0.76		
P <sub>2</sub> O <sub>5</sub>	0.06	0.06	0.12	0.12	0.08	0.08	0.17	0.17	0.19	0.19		
MnO	0.15	0.15	0.14	0.13	0.06	0.06	0.58	0.58	0.23	0.23		
BaO	-	-	-	-	0.40	0.39	-	-	-	-		
	100 <sup>1</sup>	100.62 <sup>2</sup>	100 <sup>1</sup>	100.04 <sup>2</sup>	100 <sup>1</sup>	99.52 <sup>2</sup>	100 <sup>1</sup>	99.56 <sup>2</sup>	100 <sup>1</sup>	100 <sup>2</sup>		

STRUCTURAL FORMULAE<sup>3</sup>

W	{	K	0.02		0.08		0.20		0.12		0.24	
	{	Na	0.20	2.45	0.34	2.35	0.36	2.35	0.48	2.47	0.34	2.29
	{	Ca	2.23		1.93		1.77		1.87		1.71	
	{	Ba					0.02					
X	{	Mg <sup>++</sup>	2.31		1.98		1.64		1.75		2.08	
	{	Fe	1.38	3.71	1.62	3.61	2.06	3.71	2.01	3.83	1.72	3.83
	{	Mn	0.02		0.01		0.01		0.07		0.03	
Y	{	Al	0.50		0.88		0.53		0.45		0.19	
	{	Fe <sup>+++</sup>	0.25	0.80	0.39	1.37	0.51	1.32	0.51	1.05	0.70	0.97
	{	Ti	0.05		0.10		0.28		0.09		0.08	
Z	{	Si	6.54	8.00	6.44	8.00	6.44	8.00	6.39	8.00	6.14	8.00
	{	Al	1.46		1.56		1.56		1.61		1.86	
	{	OH	1.10	1.11	2.20	2.21	2.26	2.27	1.74	1.77	0.84	0.87
		P	0.01		0.01		0.01		0.03		0.03	
<sup>4</sup> Fe <sup>+2</sup> /Mg		0.60		0.82		1.26		1.15		0.83		
F <sub>2</sub> O <sub>3</sub> /FeO		0.20		0.27		0.28		0.28		0.28		
Specific gravity		3.21		3.23		3.31		3.25		3.27		3.29
2V, degrees		73		73		73		79		68		74
Z <sub>∞c</sub> degrees		20 <sup>+</sup>		19 <sup>±2</sup>		21		~23		22 <sup>±2</sup>		24?
n <sub>2</sub>		1.669		1.677		1.696		1.678		1.682		1.691
n <sub>1</sub>		1.654		1.668		1.685		1.669		1.672		1.681
Pleochroic X		pale yellow		pale yellow		pale yellow		pale yellow		pale yellow		pale yellow
Formula Y		light green		olive green		brown		green		green		brown
Z		greenish blue		bluish green		olive brown		bluish green		bluish green		olive green

1 Reduced to 100% because of impurity corrections.

2 Uncorrected analyses

3 Structural type: W<sub>2-3</sub>(X,Y)<sub>5</sub>(Z<sub>4</sub>O<sub>11</sub>) (OH,F,Cl)<sub>2</sub>

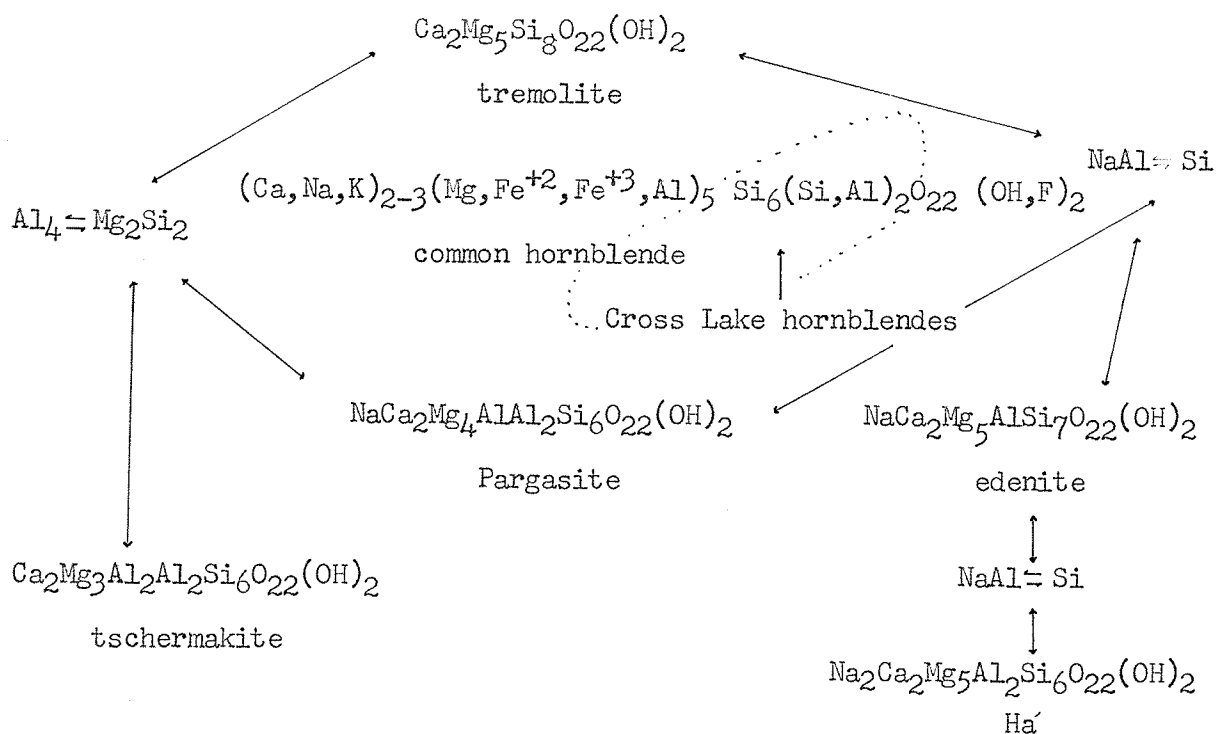
4 Ratio of atoms/unit formula,

Analyst: D. Brown, Manitoba Mines Branch

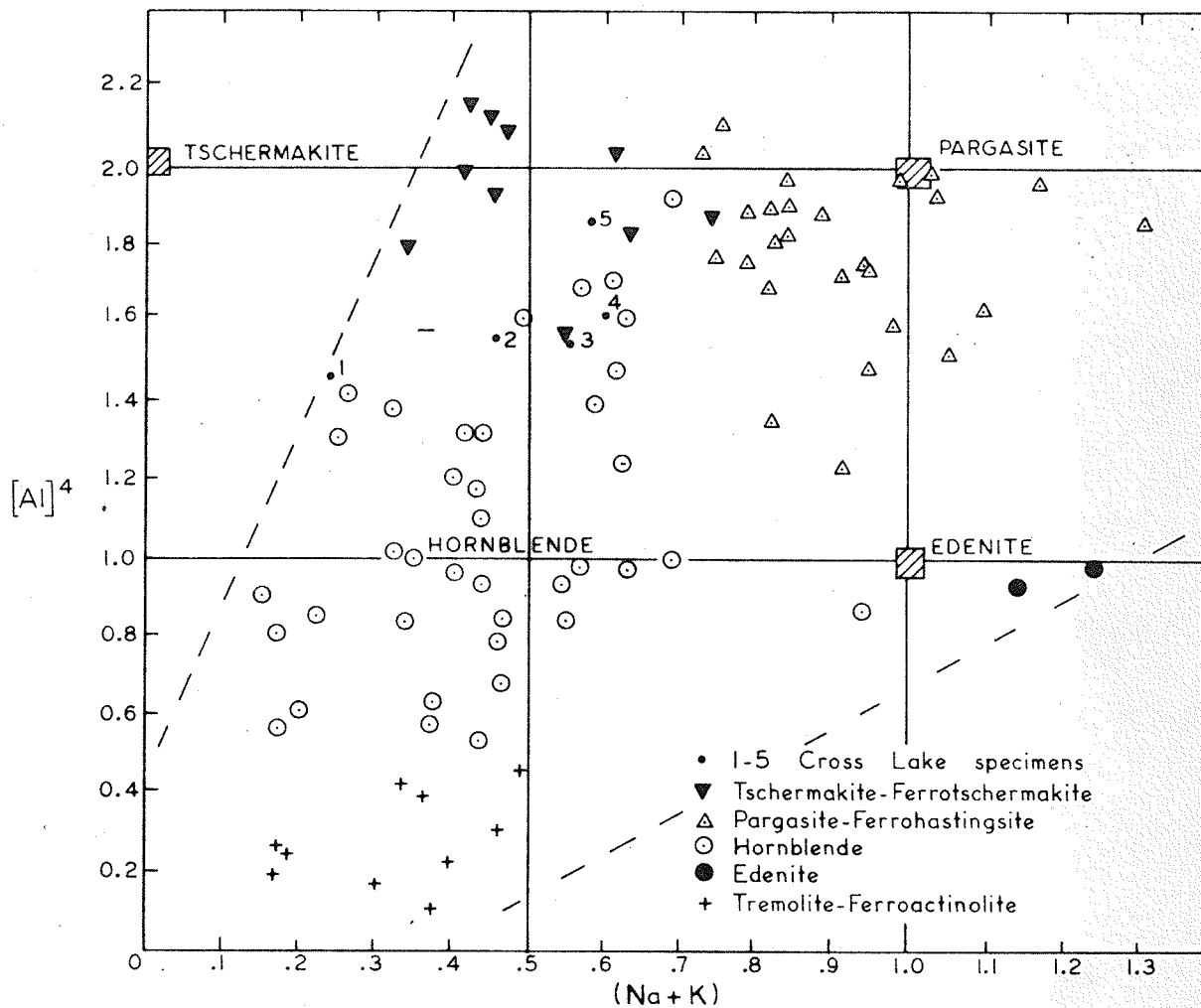
Hornblende is assigned a general formula and this is further divided into more specific end-members, one of which is called common hornblende. Tremolite, ferro-actinolite, basaltic hornblende, kaersutite, and barkevite are excluded from this "family". This is rather different from older classifications such as that of Winchell and Winchell (1961) where hornblende is used as a general term for all amphiboles except the anthophyllite-cummingtonite sub-group. The term common hornblende is applied to all members of the calcium-amphibole sub-group except oxy- or basaltic hornblende. The restriction of the name hornblende is desirable although workers are likely to continue to use it in the general sense. Amphiboles from Cross Lake basalts (2) are hornblendes in the sense of Deer et al. (1963).

The composition of hornblendes is best represented by the scheme presented by Hallimond (1943) and elaborated by Sundius (1946). Hallimond considered hornblendes as derived from substitution in the tremolite structure. Apart from complete  $Fe^{+2}$ -Mg diadochy, the edenite-ferroedenite series is regarded as derived from the tremolite structure by Na entering the otherwise vacant A site and this balanced by one Al replacing one Si. The tschermakite-ferrotschermakite series is derived from the replacement of Si by Al, balanced by Al replacing Mg. Sundius (1946) suggested that the pargasite-ferrohastingsite series is a combination of the two substitutions. Common hornblende might be considered as a combination of the two substitutions, closer to tremolite than pargasite, but with a formula of greater latitude than the other members. This scheme and the relationship of Cross Lake hornblendes to it is given

below.



Deer et al. (1963, Vol. II) have adopted and clarified this scheme. Their Figures 71 and 72 show plots of  $[\text{Al}]^4$  against  $(\text{Na}+\text{K})$  and  $[\text{Al}]^4$  against  $([\text{Al}]^6+\text{Fe}^{+3}+\text{Ti})$ , all in terms of atoms per unit formula. They are reproduced herein as Figures 3-8 (page 41) and 3-9 (page 42), and Cross Lake hornblendes are plotted on them. The  $[\text{Al}]^4$  content of Cross Lake hornblendes is less than that of theoretical tschermakite but is similar to some low  $[\text{Al}]^4$  tschermakites. The  $(\text{Na}+\text{K})$  content, #1 excepted, is greater than that of most tschermakites. The  $([\text{Al}]^6+\text{Fe}^{+3}+\text{Ti})$  content however is decidedly less than tschermakites. The  $([\text{Al}]^6+\text{Fe}^{+3}+\text{Ti})$  plot of Cross Lake hornblendes is generally within the pargasite field. Actually  $[\text{Al}]^6$  is less than in pargasite and  $(\text{Na}+\text{K})$  is much less. The composition of

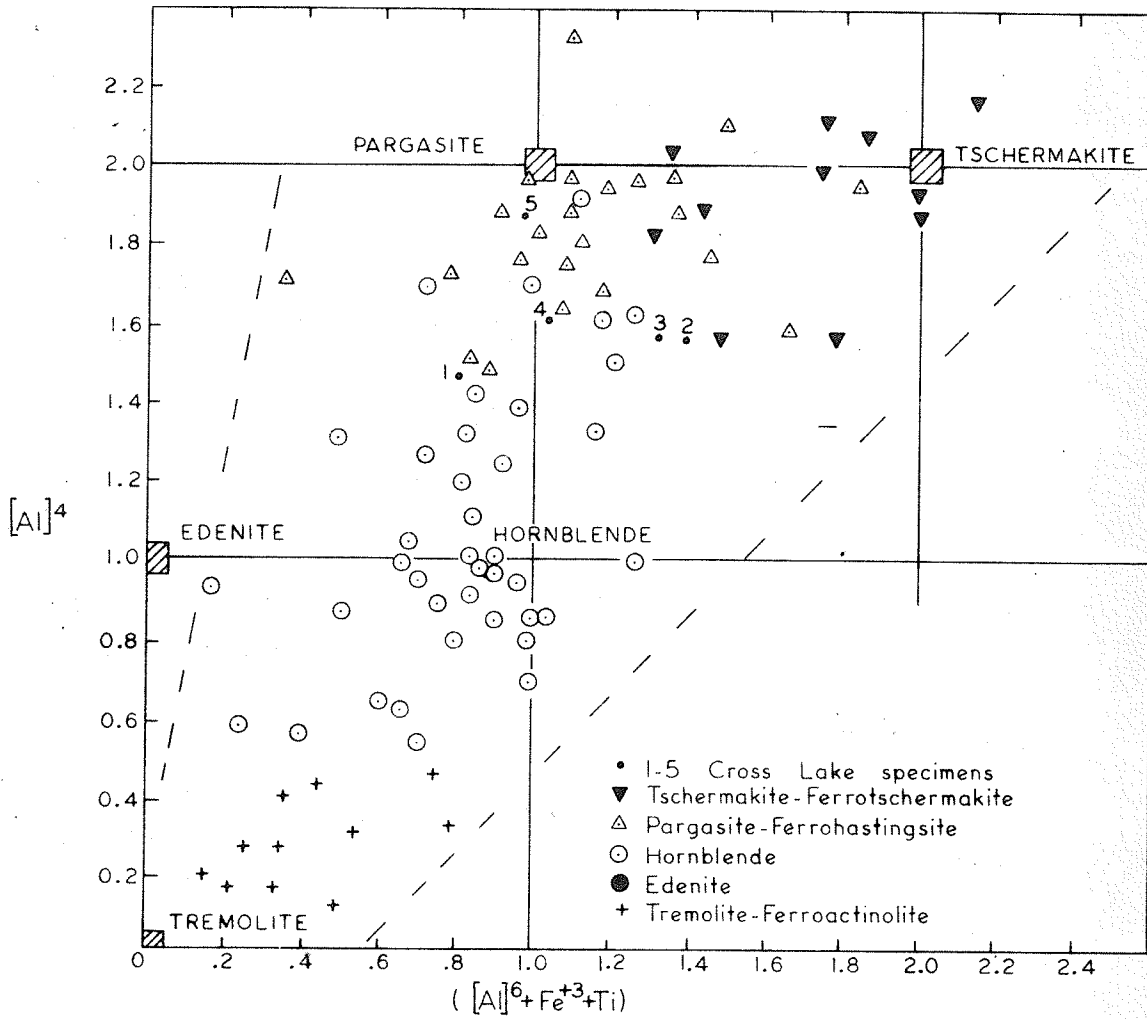


CHEMICAL VARIATION OF Ca-AMPHIBOLES.

Expressed as number of (Na+K) and  $[Al]^4$  atoms per unit formula.

(after Figure 71 Deer, Howie, + Zussman Vol. 2, 1963)

FIGURE 3-8



CHEMICAL VARIATION OF Ca-AMPHIBOLES.

Expressed as number of  $([Al]⁶ + Fe³⁺ + Ti)$  and  $[Al]⁴$  atoms per unit formula.

(after Figure 72 Deer, Howie, + Zussman Vol.2, 1963)

FIGURE 3-9

Cross Lake hornblendes resemble most closely the composition of common hornblendes in that ( $[Al]^{6+Fe^{+3}+Ti}$ ) and (Na+K) are approximately the same. Cross Lake hornblendes have a higher  $[Al]^{4}$  content and a correspondingly lower Si content than common hornblende.

Nineteen analyses of common hornblende were selected at random from Deer et al. (1963, Vol. II pp. 274 ) in order to compare the  $[Al]^{4}$  and  $[Al]^{6}$  contents with hornblendes from Cross Lake basalts. This data are plotted on Figure 3-10 in terms of atoms per unit formula. The  $[Al]^{4}$  content of Cross Lake hornblendes is higher than almost all of those taken from the literature. The  $[Al]^{6}$  content of Cross Lake hornblendes is also generally higher than those selected from the literature. The average  $[Al]^{6}$  content of 38 specimens from Deer et al. (1963, Vol. II) is 0.35 atoms per unit formula; it is 0.51 atoms per unit formula for Cross Lake hornblendes.

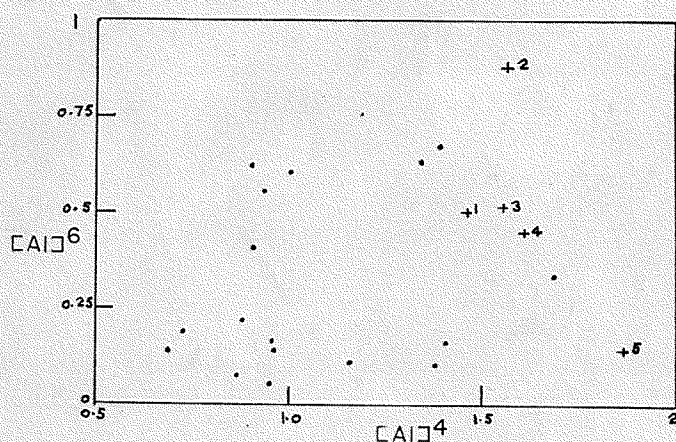


FIGURE 3-10. PLOTS RELATING CROSS LAKE HORNBLENDES (+) AND PUBLISHED COMMON HORNBLENDES (·) IN TERMS OF ATOMS PER UNIT FORMULA OF  $[Al]^{4}$  AND  $[Al]^{6}$ ; 1,2, ETC. IN ORDER OF INCREASING METAMORPHIC GRADE.

The  $Fe^{+3}$  content of Cross Lake hornblendes is small so that they do not approach oxy-hornblendes in composition. The elements K, Mn, Ti, P and Ba are present in only minor amounts. The  $Fe^{+2}/Mg$  ratios (Table 3-6) indicate these hornblendes are intermediate between Mg and Fe-rich end members.

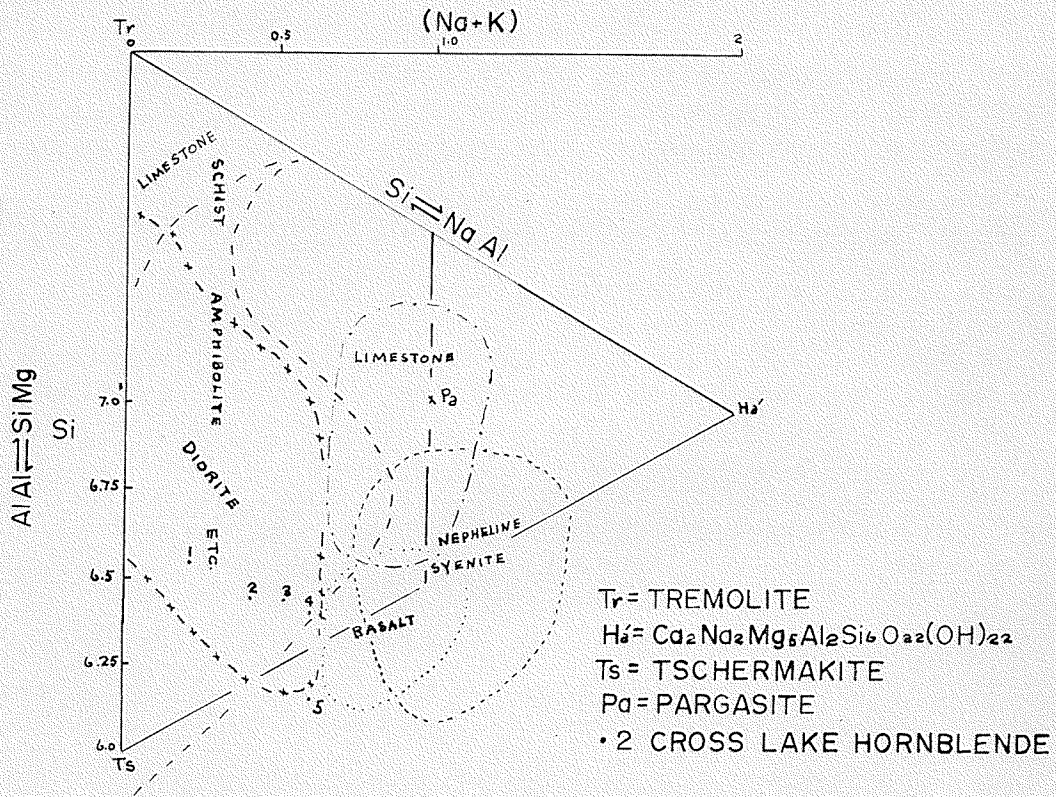
Hornblende Composition and Rock Composition

Hallimond (1943)

related the composition of hornblende to rock type. A plot of Si versus (Na+K) in terms of atoms per unit formula was made for 196 published hornblende analyses (Hallimond 1943, Figure 3). General fields of rock types were delineated. Hallimond (1943) suggested that there is an increased substitution in the tremolite structure with a higher temperature of formation. Figure 3-11, (Page 45) is modified after Hallimond's (1943) diagram. Hornblendes from Cross Lake basalts plot in the amphibolite field. The numbers adjacent to the plots are in order of increasing metamorphic grade (see Table 3-4) and progressive (Na+K) substitution is evident.

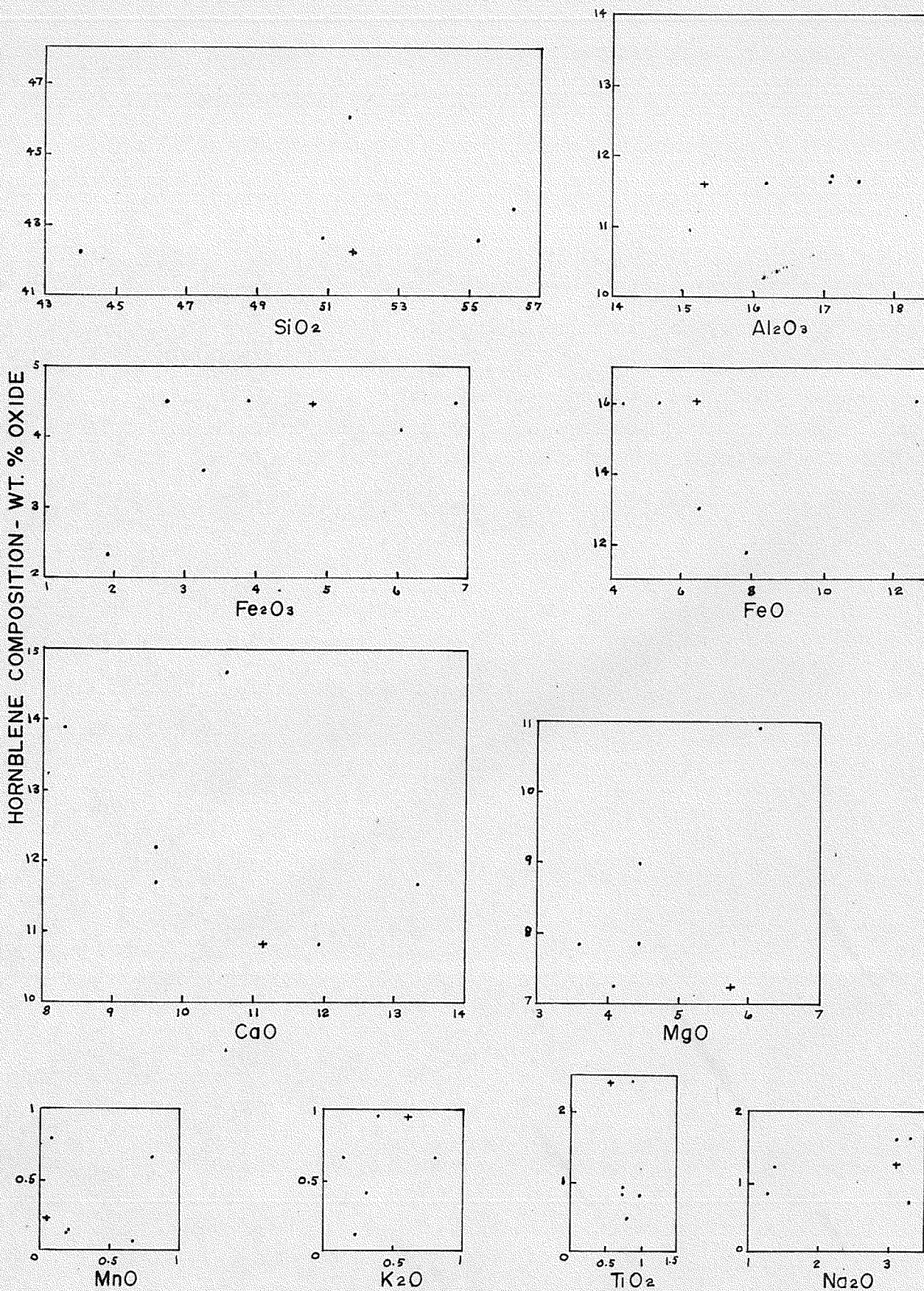
Figure 3-12 (page 46) shows plots of hornblende composition versus rock composition in terms of weight percent of oxides for Cross Lake basalts. A direct control of the hornblende composition by the rock composition is not apparent.

Other writers suggest hornblende composition is related to rock composition. Larsen and Draisen (1950) demonstrate that for a variety of rocks ranging from calcic gabbro to granite, the ratio  $FeO+MnO+Fe_2O_3/FeO+MnO+Fe_2O_3+MgO$  is about the same for the rocks.



COMPOSITION OF HORNBLLENDES AS ATOMS PER UNIT FORMULA RELATED TO ROCK TYPE (AFTER HALLIMOND, 1943)

FIGURE 3-II



+ not analyzed-assumed same as RE214

ROCK COMPOSITION - WT. % OXIDE

FIGURE 3-12. GRAPHS RELATING HORNBLENE COMPOSITION TO ROCK COMPOSITION OF BASALTS

as for the enclosed hornblende. These ratios for Cross Lake are:

	R478	R811	RA87	RE214	R563	RE130
Hornblende	0.73	0.56	0.65	0.72	0.72	-
Rock	0.70	0.62	0.69	0.83	0.66	0.66

The spread for the hornblende and enclosing rock is about the same as that of Larsen and Draisen. They find that the ratio for hornblende is always somewhat less than for the enclosing rock. Two of the hornblendes from Cross Lake have a higher ratio.

Engel and Engel (1963) attribute chemical changes in hornblendes from northwest Adirondack amphibolites to changes in rock composition. Changes in rock composition are due to progressive metamorphism.

Hornblende and Metamorphism      Constituent hornblendes of Cross Lake basalts (2) show variations in chemical and physical properties and these are considered to be largely a function of metamorphic grade.

Engel and Engel (1962) record the following changes in hornblendes from amphibolites of the northwest Adirondacks during metamorphism from the almandine-amphibolite to the hornblende granulite facies:

- (1) Decrease in amount;
- (2) Colour change from bluish green to brownish green;
- (3) Increase in density from 3.260 to 3.278.

Chemical changes are:

- (1) Increase in Ti, Na, and K content;
- (2) Decrease in (OH), F, Mn, and  $\text{Fe}_2\text{O}_3/\text{FeO}$  and Fe/Mg;
- (3) Si, Al, and Ca remain nearly constant.

Shidō and Miyashiro (1958) have investigated progressive regional metamorphism of basic rocks of the Abukuma plateau, Japan. Three zones were delineated using hornblende as an index mineral. In the lowest grade the amphibole is actinolite, in the intermediate grade a blue-green hornblende (γ) and in the highest zone hornblende is green, greenish brown or brown (δ). The alkali content is related to the host rock and maximum possible alkali content increases with increasing grade. They find hornblendes from the two upper zones are high in Al but a progressive relationship between the replacement of Si by Al and grade is not apparent. Wiseman (1934) on the other hand reports progressive replacement of Si by Al during progressive metamorphism of epidiorites from the Scottish Highlands.

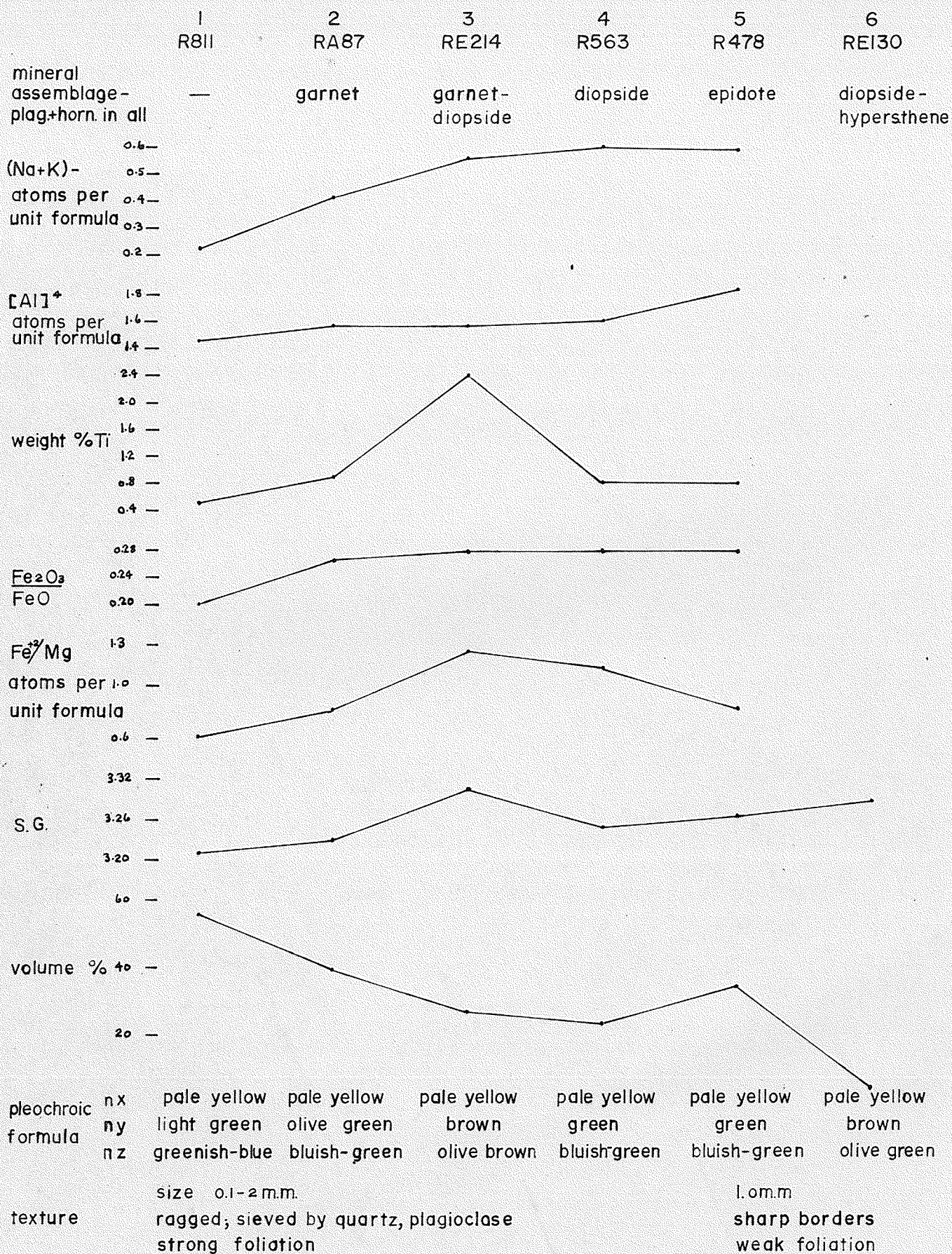
Work by many authors such as Dodge (1942) in the Black Hills, South Dakota, Eskola (1952) in Finland, and Milligan (1960) in Manitoba report increase in colour intensity of hornblende with increasing metamorphic intensity.

Hornblendes from the area selected for analysis are from basalt specimens each of which represents a distinct mineral assemblage (Table 3-4). There is a progressive increase in the amount of (Na+K) and  $[\text{Al}]^4$  in hornblendes with increasing

temperature of formation. This is generally compatible with the progressive appearance of garnet, diopside, and hypersthene. One assemblage (5 of Table 3-4) consists of hornblende, plagioclase, and epidote. It was thought this would represent the lowest grade but the (Na+K) and  $[Al]^{IV}$  content of hornblende suggests a considerably higher grade. Thus if the (Na+K) and  $[Al]^{IV}$  content is truly a function of metamorphic intensity, then one cannot always assign a metamorphic grade based solely on minerals present.

Figure 3-13 sets out the properties of hornblende relevant to metamorphism. Specimens are numbered in order of increasing metamorphic intensity (1 to 6). As stated above this is based on a progressive increase in (Na+K) and  $[Al]^{IV}$ . There is some suggestion that the Ti content increases with increased metamorphic intensity. Number 3 has a very high Ti content and this cannot be attributed to a high Ti content in the rock. The  $Fe_2O_3/FeO$  ratio increases then levels off and the  $Fe^{+2}/Mg$  ratio increases then decreases. The specific gravity increases with an increase in Fe and Ti content. Hornblende specific gravities show a progressive increase with increasing metamorphic intensity except for number 3 which is anomalously high. This is due to a high Ti content. The volume percent of hornblende in the rock decreases with increasing metamorphic intensity with the exception of number 5 which is high. Colours change from greenish blues to darker shades of olive and brown. Colours apparently become darker with an increase in Ti and Fe content.

metamorphic grade increases  $\longrightarrow$   
 almandine - amphibolite facies  $\longrightarrow$  granulite facies



HORNBLLENDE PROPERTIES AND METAMORPHIC GRADE

FIGURE 3-13

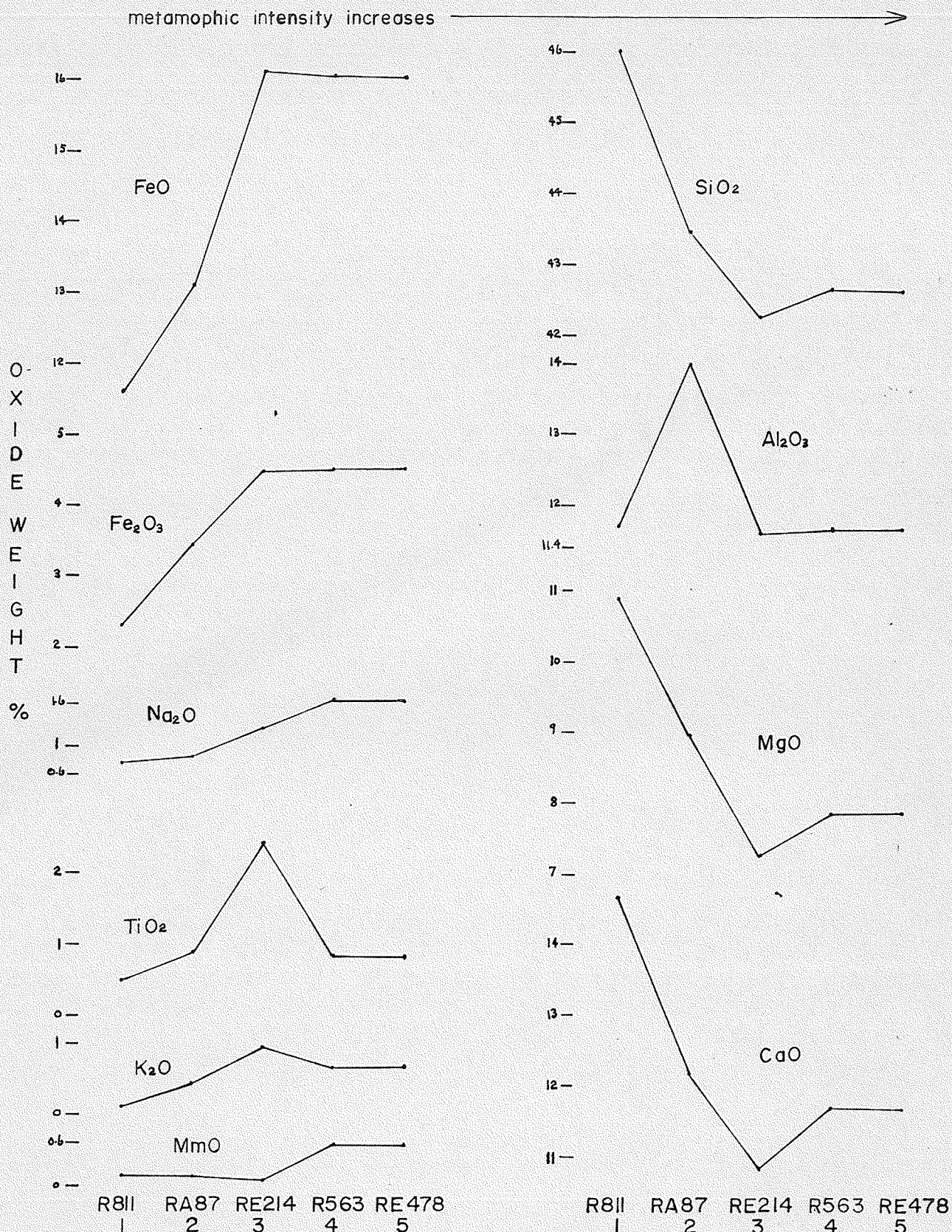
Figure 3-14 (page 52) illustrates the relationship between the chemical composition of hornblende and metamorphic grade. The oxides FeO, Fe<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O, and K<sub>2</sub>O (with the exception of K<sub>2</sub>O in No. 4) all show a similar variation. The oxides SiO<sub>2</sub>, MgO, and CaO also show a similar variation but it is opposite to the first group. Engel and Engel (1962) found little variation for SiO<sub>2</sub>, MgO, and CaO. For Cross Lake hornblendes elements of the first group largely replace those of the second during progressive metamorphism.

Light green to bluish green retrograde hornblende occurs in minor amounts in pyroxene-bearing rocks and replaces darker hornblende and pyroxenes. It was not chemically analyzed.

In summary, hornblendes from Cross Lake basalts are classified as aluminous common hornblendes. Hornblendes are related to rock composition in so far as they plot within the amphibolite field and approach the basalt field in Hallimond's (1943) diagram. A more intimate relationship between total rock and hornblende composition is not apparent. Variations in mode, colour, specific gravity, texture and chemical composition of hornblendes are attributed mainly to changes in metamorphic intensity. Not all changes are systematic for all parameters or even for a single parameter.

### Garnet

The distribution of garnet-bearing basalts (2b) is shown in Figure 7-1 (page 128). Garnet is locally concentrated in bands and may comprise as much as 50 percent of the rock by volume.



CHEMICAL COMPOSITION OF HORNBLLENDE AND METAMORPHIC INTENSITY

FIGURE 3-14

Garnet is invariably seived with quartz and hornblende. Quartz is evidently a product of garnet formation because it occurs as inclusions where little or no quartz is present in the rock.

Two garnet specimens were analyzed by standard chemical methods. The relatively high manganese content caused some difficulty in the analyses. Chemical analyses, structural formulas, compositions in terms of end members and the refractive indices are all set out in Table 3-7 (page 54). Specimen RA87 is garnet from the assemblage hornblende-plagioclase-garnet and RE214 from the assemblage hornblende-plagioclase-garnet-diopside. The latter represents a higher metamorphic grade than the former. Impurities were: RA87 - 2.99 volume percent hornblende; RE214 - 4.78 volume percent hornblende. The chemical compositions of both hornblendes were known and both garnet analyses were corrected.

An attempt is made to evaluate changes in amount and composition of garnet in terms of rock composition and composition and amount of coexisting minerals. This may not be entirely valid because only two analyses are available and differences in composition are within the limits of analytical error.

Figure 3-15A (page 55) shows that from RA87 to RE214 weight percent of FeO in garnet decreases somewhat. There is an increase in the FeO content of hornblende and a greater increase in FeO in the total rock. Clinopyroxene appears in RE214 and this mineral takes up some FeO. Garnet increases in volume percent from 8.4 percent in RA87 to 32.0 percent in RE214. In the section on Cation

TABLE 3-7  
GARNET DATA

STRUCTURAL FORMULA  
BASED ON 12 OXYGEN ATOMS

				STRUCTURAL FORMULA BASED ON 12 OXYGEN ATOMS			
RA87		RE214		RA87	RE214		
SiO <sub>2</sub>	37.21	37.82	36.87	37.29	Si	2.90	2.90
Al <sub>2</sub> O <sub>3</sub>	24.16	24.24	23.57	23.23	Al	0.10	0.10
Fe <sub>2</sub> O <sub>3</sub>	1.63	1.7	2.46	2.57	Al	2.10	2.11
FeO	26.98	27.01	26.23	25.98	Fe	0.10	0.15
MgO	4.23	4.4 <sup>1.</sup>	2.08	2.3 <sup>1.</sup>	Ti	0.02	-
CaO	3.54	3.8 <sup>1.</sup>	7.22	7.4 <sup>1.</sup>	Fe	1.76	1.72
Na <sub>2</sub> O	0.02	0.04	-	0.03	Mg	0.49	0.25
K <sub>2</sub> O	0.20	0.21	-	0.02	Ca	0.30	0.61
TiO <sub>2</sub>	0.27	0.29	0.04	0.14	Mn	0.11	0.09
P <sub>2</sub> O <sub>5</sub>	0.09	0.09	0.07	0.07	K	0.02	-
MnO	<u>1.67</u>	<u>1.65</u>	<u>1.45</u>	<u>1.40</u>	P	0.01	-
	<u>100<sup>2.</sup></u>	<u>101.24<sup>3.</sup></u>	<u>100<sup>2.</sup></u>	<u>100.43<sup>3.</sup></u>			
					Almandine	66.2	64.4
R.1	1.800		1.792		Pyrope	18.4	9.4
					Grossularite	4.5	14.2
Vol. %	8.4		32.0		Andradite	6.8	8.6
					Spessartite	<u>4.1</u>	<u>3.4</u>
						<u>100</u>	<u>100</u>

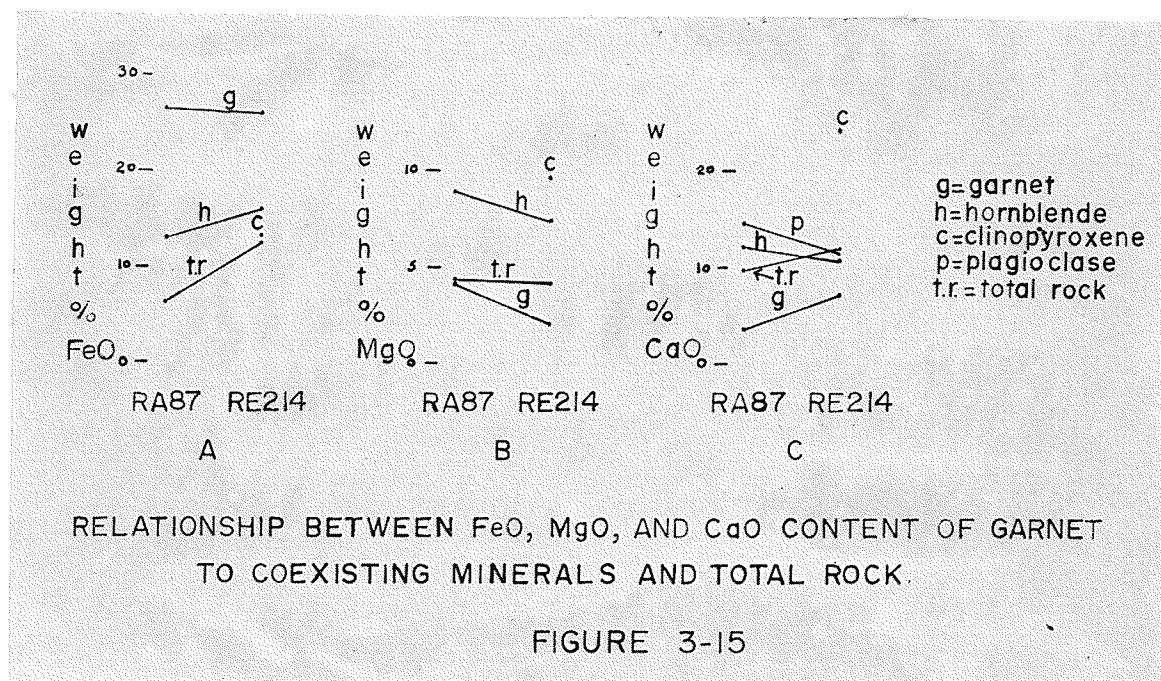
1. Possibly high due to Mn interference.

2. Corrected for impurities

3. Uncorrected analyses

Analyst: D. Brown, Manitoba Mines Branch

Distribution Figure 3-19 (page 70) shows that much of the  $Fe^{+2}$  in RA87 is taken up by magnetite. The FeO content of garnet does not appear to be controlled by the FeO content of the total rock or coexisting minerals. An increase in total FeO results in an increase in the amount of garnet formed.



The difference in the MgO content of the total rock between RA87 and RE214 is negligible. (Figure 3-15B) Both garnet and hornblende decrease in MgO content and this appears to be due to the formation of clinopyroxene in RE214.

The CaO content of garnet and total rock increases from RA87 to RE214 while that in hornblende and plagioclase decreases (Figure 3-15C). Clinopyroxene is developed in RE214 and more total

Ca is taken up in this mineral than any other (Figure 3-21, page 71). As shown in the section on clinopyroxene, the development of this mineral does not depend on a high Ca content of basalt. The Ca content of garnet varies inversely with the Mg content. An increase in CaO in garnet may be due to an increase in total CaO in the rock or a complex relationship with coexisting minerals.

### Clinopyroxene

The distribution of clinopyroxene-bearing basalts (2b, 2c) is shown in Figure 7-1 (page 129). Clinopyroxene occurs in three mineral assemblages which are in order of increasing metamorphic grade: clinopyroxene-garnet-hornblende plagioclase; clinopyroxene-hornblende-plagioclase; and clinopyroxene-hypersthene-hornblende-plagioclase. The metamorphic grade increases from southeast to northwest across the area. Clinopyroxene is light green in color and consists of subhedral grains from 0.5 to 1 mm. in diameter.

Table 3-8 (page 57) sets out some physical and optical properties for three clinopyroxenes representative of the three assemblages described above. One of these was analyzed chemically. Refractive indice determinations on grains lying on their cleavage faces were made on the other two specimens. The percent hedenbergite was obtained by applying this data to Parker's (1961) curves. Optic angle and  $Z \wedge c$  measurements were made with a 3-axis Universal stage.

TABLE 3-8  
CLINOPRYOXENE DATA

R563

		Structural Formula Based on 6 Oxygen Atoms	
*SiO <sub>2</sub>	50.16	Si	1.93
Al <sub>2</sub> O <sub>3</sub>	2.55	Al	0.07
Fe <sub>2</sub> O <sub>3</sub>	2.43	Al	0.04
FeO	10.4	Fe <sup>+2</sup>	0.33
MgO	10.73	Fe	0.06
CaO	21.37	Mg	0.61
Na <sub>2</sub> O	0.47	Ca	0.88
K <sub>2</sub> O	0.05	Na	0.04
H <sub>2</sub> O <sup>+</sup>	0.90	Ti	0.02
TiO <sub>2</sub>	0.28	Mn	0.03
P <sub>2</sub> O <sub>5</sub>	0.10		
MnO	0.72		
	<u>100.16</u>		

<u>PROPERTY</u>	<u>RE214</u>	<u>R563</u>	<u>RE130</u>
Mineral Assemblage (-Plag.+Horn. in all)	garnet	-	hypersthene
Vol. %	15.0	25.2	17.4
Density	3.44	3.52	3.43
2V	58½	59½	59
Z <sub>ac</sub>	24±2	21±2	23
n <sub>2</sub>	1.724		1.718
n <sub>1</sub>	1.700		1.696
Colour	pale green	pale green	pale green
% Hedenbergite	48 (salite)	35 (salite)	43 (salite)

—————→ Metamorphism Increases

\*Analyst: D. Brown, Manitoba Mines Branch

The ratio  $\frac{\text{Fe}^{+2}}{\text{Mg}+\text{Fe}^{+2}} \times 100$  for clinopyroxene and total rock

are compared below:

	RE214	R563	RE130
Clinopyroxene	48	35	43
Total Rock	63.5	40.1	38.8

An obvious relationship does not exist.

The average CaO content of 15 analyzed Cross Lake basalts is 10.47 weight percent. The average for the three clinopyroxene-bearing rocks of this group is 10.66; two are below average. Thus basalts containing clinopyroxene are no richer in CaO than those without clinopyroxene.

The formation of clinopyroxene in basalts at Cross Lake seems largely controlled by metamorphic grade. Specimens in Table 3-8 are arranged so that metamorphism increases from left to right. Systematic changes in clinopyroxene composition as a function of metamorphic grade cannot be demonstrated. The composition of clinopyroxene appears to be a complex function of kinds and amounts of coexisting minerals.

### Hypersthene

Hypersthene-bearing basalts (2c) occur only in the northwest part of the area. Plagioclase, brown hornblende, and clinopyroxene are coexisting minerals. Hypersthene consists of nearly round anhedral grains averaging 0.4 mm. in diameter.

One specimen was analyzed chemically and the data together with some physical properties are given in Table 3-9 (page 60). The composition determined from chemical analysis is in close agreement with that obtained by applying refractive indices to Parker's curves (1961). Hypersthene contains a higher percentage of the iron end-member than does coexisting clinopyroxene and this conforms to the relationship found by Binns (1962). Basalts containing hypersthene are within the hornblende-granulite facies of metamorphism.

#### Minor Minerals

Basalts (2) contain small amounts of quartz, epidote, biotite, chlorite, calcite, magnetite, sphene, and tremolite (see modal analyses, Table 2-2). None of these minerals were analyzed chemically.

### CATION DISTRIBUTION

#### Introduction

A new method of evaluating changes in kind, composition, and amount of coexisting minerals developed by progressive metamorphism of basalt (2) is presented in terms of cation distribution. The development of this method was prompted by the fact that most studies consider only changes in kinds and composition of minerals and neglect the important factor of quantity. Six specimens of basalt from the area were selected for this study (Table 3-4, p. 28). Each possesses a distinct mineral assemblage that formed under

TABLE 3-9  
HYPERSTHENE DATA

REL30

<u>Weight %</u>		<u>Structural Formula Based on 3 Oxygen Atoms</u>			
*SiO <sub>2</sub>	49.56	Si	0.96	} 1	
Al <sub>2</sub> O <sub>3</sub>	1.79	Al	0.04		
Fe <sub>2</sub> O <sub>3</sub>	3.61	Fe <sup>+3</sup>	0.05		
FeO	27.61	Fe <sup>+2</sup>	0.45		
MgO	15.72	Mg	0.45		} 0.985
CaO	0.98	Ca	0.02		
Na <sub>2</sub> O	0.13	Ti	0.005		
K <sub>2</sub> O	0.10	Mn	0.01		
TiO <sub>2</sub>	0.46				
P <sub>2</sub> O <sub>5</sub>	0.10				
MnO	0.69				
	<u>100.75</u>				
		<u>Composition</u>			
N <sub>2</sub>	=	1.729	Chemical Analysis:	Fs <sub>50</sub> En <sub>50</sub>	
N <sub>1</sub>	=	1.720	Parker's Curve:	Fs <sub>52</sub> En <sub>48</sub>	
2V	=	59°(?)			
Density	=	3.58			
Colour	=	pink			

\*Analyst: D. Brown, Manitoba Mines Branch.

different conditions of metamorphic intensity. Variations in bulk composition between specimens are real, but relatively small.

#### Method of Calculation

Ideally, the volume percent, chemical composition, and specific gravity for each mineral in all assemblages should be known. Table 3-10 (page 62) outlines the kind of data available for the calculation. Most major minerals were analyzed chemically. Specific gravity determinations were made on all hornblende, garnet, clinopyroxene, and hypersthene specimens. The specific gravities of plagioclase were obtained from standard curves using the chemical analysis.

The 2V of epidote was determined on the universal stage and the composition obtained from Figure 343 of Winchell and Winchell (1961). The ny of biotite was determined and Figure 257 of Winchell and Winchell (1961) employed to obtain the chemical composition and specific gravity. Although this composition is only an approximation, biotite occurs in negligible amounts. Sphene, calcite, and magnetite never exceeded 2 percent by volume and were assigned standard compositions and specific gravities. The opaque mineral appeared to be magnetite and was considered as such in all cases.

The volume percent was determined by the average of point counts on two thin sections per specimen with 1000 counts on each. Sections were cut perpendicular to foliation.

TABLE 3-10

DATA AVAILABLE FOR CATION DISTRIBUTION CALCULATIONS

		R811	RA87	RE214	R563	R478	RE130
Quartz	Comp.		SiO <sub>2</sub>				
	S.G.		2.65				
Plagioclase	Comp.		Chem. Analysis				
	S.G.		Calculated from Analysis				
Hornblende	Comp.		Chem. Analysis				Same as RE214
	S.G.		Determined				
Garnet	Comp.	-	Chem. Analysis		-	-	-
	S.G.	-	Determined		-	-	-
Clinopyroxene	Comp.	-	-	Ref. Index	Chem. Analysis	-	Ref. Index
	S.G.	-	-	Determined		-	Determined Chem. Analysis
Hypersthene	Comp.	-	-	-	-	-	Chem. Analysis
	S.G.	-	-	-	-	-	Determined
Biotite	Comp.	Based on R.I.	Negligible	-	-	Based on R.I.	-
	S.G.	Graphs*	"	-	-	Graphs*	-
Epidote	Comp.	Based on 2V	-	-	2V	Based on 2V	-
	S.G.	Graphs*	-	-	Graphs*		-
Sphene	Comp.		CaTiSiO <sub>3</sub>	-	CaTiSiO <sub>3</sub>		-
	S.G.		3.48	-	3.48		-
Magnetite	Comp.		Fe <sub>2</sub> O <sub>3</sub>			-	Fe <sub>2</sub> O <sub>3</sub>
	S.G.		4.96			-	4.96
Calcite	Comp.	-	-	-	CaCO <sub>3</sub>		-
	S.G.	-	-	-	2.7		-

- Mineral not present

\* S.G. obtained from graphs relating S.G. to composition

Table 3-11 (pages 64 and 65) outlines the calculations involved for specimen R563 and this serves to illustrate the procedure. Constituent minerals are listed. The product of specific gravity and volume percent for a given mineral gives the mass which is converted to weight percent. The chemical composition in terms of oxide weight percent for each mineral is listed in column 7. The oxide weight percent is multiplied by the weight percent of the mineral in the total rock. This product is shown in column 9 and represents the bulk weight percent of each oxide in each mineral and is a function of mineral composition and weight percent of the mineral in the total rock.

The figures in column 9 are converted to cation molecular proportion in column 10 and reduced in column 11 to bulk cation percent. This later figure means that there are 100 cations in the total rock of which 47.1 percent are Si cations. Of this 47.1 percent, total plagioclase contains 23.6 percent, total hornblende 10.1 percent, total clinopyroxene 12.3 percent, and so on, summing to 47.1 percent.

This information is summarized for each of the six specimens in Tables 3-12 to 3-17 (pages 66, 67, and 68 inclusive). The row for each cation gives the bulk cation percent for each mineral (i.e. column 11 above). The summation of each row, shown in the third column of the tables, gives the percent of each cation in the total rock determined from the above calculations. The second column of the tables gives the percent of each cation determined from total rock analysis. Discrepancies occur but they

TABLE 3-11 (cont'd on next page)

## OUTLINE OF METHOD FOR CALCULATION OF CATION DISTRIBUTION

<u>R563</u>					
1	2	3	4	5	
<u>Mineral</u>	<u>Specific Gravity</u>	<u>Vol. %</u>	<u>Mass</u>	<u>Wt. %</u>	
Quartz	2.65	0.5	1.325	0.44	
Plagioclase	2.67	50.0	133.500	44.16	
Hornblende	3.25	24.0	78.000	25.80	
Clinopyroxene	3.52	23.0	80.960	26.78	
Epidote	3.48	0.3	1.044	0.34	
Calcite	2.7	0.4	1.080	0.36	
Magnetite	4.96	0.1	0.496	0.16	
Sphene	3.48	1.7	5.916	1.96	
		100.0	302.321	100.00	

6	7	8	9	10	11
<u>Mineral</u>	<u>Chem. Analysis</u> <u>Wt. %</u>	<u>Wt. % of</u> <u>Mineral</u>	<u>Bulk Wt.</u> <u>%</u>	<u>Cation Mol.</u> <u>Prop x 1000</u>	<u>Bulk</u> <u>Cation %</u>
Quartz					
SiO <sub>2</sub>	100	0.0044	0.44	7.32	0.4
Plagioclase					
SiO <sub>2</sub>	58.41	0.4416	25.79	429.92	23.6
Al <sub>2</sub> O <sub>3</sub>	26.42	"	11.67	228.91	12.6
CaO	8.09		3.57	63.59	3.5
Na <sub>2</sub> O	6.95		3.07	99.05	5.4
K <sub>2</sub> O	0.13		0.06	1.27	0.1
			44.16		
Hornblende					
SiO <sub>2</sub>	42.62	0.258	11.00	183.06	10.1
Al <sub>2</sub> O <sub>3</sub>	11.66	"	3.01	59.04	3.2
Fe <sub>2</sub> O <sub>3</sub>	4.52		1.15	14.53	0.8
FeO	16.07		4.14	57.62	3.2
MgO	7.85		2.02	50.09	2.8
CaO	11.69		3.01	53.67	3.0
Na <sub>2</sub> O	1.62		0.42	13.55	0.7
K <sub>2</sub> O	0.66		0.17	3.61	0.2
H <sub>2</sub> O	1.75		0.45	24.98	(1.4)
TiO <sub>2</sub>	0.81		0.21	2.63	0.1
P <sub>2</sub> O <sub>5</sub>	0.17		0.06	0.85	0
MnO	0.58		0.15	2.11	.1
	100		25.80		

TABLE 3-11

Mineral	Chem. Analysis Wt. %	Wt. % of Mineral	Bulk Wt. %	Cation Mol. Prop x 1000	Bulk Cation %
Clinopyroxene					
SiO <sub>2</sub>	50.08	0.2678	13.41	223.32	12.3
Al <sub>2</sub> O <sub>3</sub>	2.54	"	0.68	13.34	0.7
Fe <sub>2</sub> O <sub>3</sub>	2.43		0.65	8.14	0.4
FeO	10.38		2.78	38.69	2.1
MgO	10.71		2.87	71.18	3.9
CaO	21.34		5.71	101.82	5.6
Na <sub>2</sub> O	0.47		0.13	4.19	0.2
K <sub>2</sub> O	0.05		0.01	0.21	0
H <sub>2</sub> O <sup>±</sup>	0.90		0.24	13.29	(0.7)
TiO <sub>2</sub>	0.28		0.08	11.00	0.1
P <sub>2</sub> O <sub>5</sub>	0.10		0.03	0.42	0
MnO	0.72		0.19	2.68	0.2
	<u>100.0</u>		<u>26.78</u>		<u>25.5</u>
Epidote					
SiO <sub>2</sub>	36.97	0.0034	0.13	2.16	0.1
Al <sub>2</sub> O <sub>3</sub>	22.28	"	0.07	1.37	0.1
Fe <sub>2</sub> O <sub>3</sub>	14.25		0.05	0.63	0
CaO	23.01		0.08	1.43	0.1
H <sub>2</sub> O	3.49		0.01	0.56	
			<u>0.34</u>		
Magnetite					
Fe <sub>2</sub> O <sub>3</sub>	69.0	0.0016	0.11	1.38	0.1
FeO	31.0	"	0.05	0.70	0
			<u>0.16</u>		
Sphene					
SiO <sub>2</sub>	30.6	0.0196	0.60	9.98	0.6
CaO	28.6	"	0.56	9.99	0.6
TiO <sub>2</sub>	40.8		0.80	10.01	0.6
			<u>1.96</u>		
Calcite					
CaO	56	0.0036	0.20	3.57	0.2
CO <sub>2</sub>	44	"	0.16	3.64	0.2
			<u>0.36</u>		
			<u>100</u>	<u>1819.50</u>	<u>100</u>

TABLE 3-12

## SUMMARY OF CATION DISTRIBUTION DATA FOR R811

CATION	CATION % TOTAL ROCK	CATION % MODE	QUARTZ	PLAGIOCLASE	HORNBLLENDE	BIOTITE	MAGNETITE
Si	47.5	45.8	(1) 5	(43) 19.6	(56) 25.7	0	
Al	18.6	17.4		(56) 9.7	(44) 7.7	0	
Fe <sup>+3</sup>	1.3	2.2			(45) 1.0		(55) 1.2
Fe <sup>+2</sup>	6.1	6.0			(90) 5.4		(10) 0.6
Mg	8.4	9.1			(100) 9.1		
Ca	10.5	11.1		(21) 2.3	(79) 8.8		
Na	5.8	5.8		(86) 5.0	(14) 0.8		
K	0.3	0.1		(33) 0	(67) 0.1		
H <sub>2</sub> O	0.6	2.2			(100) 2.2		
Ti	0.6	0.2			(100) 0.2		
P	0.1	0			0		
Mn	0.2	0.1			(100) 0.1		
	100.0	100.0					

TABLE 3-13

## SUMMARY OF CATION DISTRIBUTION DATA FOR RA87

CATION	CATION % TOTAL ROCK	CATION % MODE	QUARTZ	PLAGIOCLASE	HORNBLLENDE	GARNET	MAGNETITE
Si	52.7	51.4	(37) 19.0	(21) 10.8	(30) 15.4	(12) 6.2	
Al	17.8	18.8		(44) 8.2	(31) 5.9	(25) 4.7	
Fe <sup>+3</sup>	2.3	1.7			(53) 0.9	(12) 0.2	(35) 0.6
Fe <sup>+2</sup>	5.1	8.0			(49) 3.9	(47) 3.8	(4) 0.3
Mg	6.2	5.9			(81) 4.8	(19) 1.1	
Ca	9.6	8.7		(44) 3.5	(53) 4.6	(7) 0.6	
Na	2.4	1.9		(68) 1.3	(32) 0.6		
K	0.4	0.3		(33) 0.1	(67) 0.2		
H <sub>2</sub> O	2.6	2.6			(100) 2.6		
Ti	0.5	0.3			(100) 0.3		
P	0.2						
Mn	0.2	0.4			(25) 0.1	(75) 0.3	
	100.0	100.0					



## SUMMARY OF CATION DISTRIBUTION DATA FOR REL30

CATION	CATION %		QTZ.	PLAG.	HORN.	BIOT.	EPIDOTE	CARB.	SPHENE
	TOTAL ROCK	MODE							
Si	50.3	49.7	(23)11.2	(37)18.6	(31)15.2	(1)0.6	(7)3.6		(1)0.5
Al	19.1	18.0		(57)10.2	(28) 5.1	(1)0.2	(14)2.5		
Fe <sup>+3</sup>	2.7	2.7			(63) 1.7		(37)1.0		
Fe <sup>+2</sup>	3.3	4.6			(93) 4.3	(7)0.3			
Mg	4.9	5.5			(95) 5.2	(5)0.3			
Ca	9.4	10.2		(28) 2.9	(42) 4.2		(23)2.4	(2)0.2	(5)0.5
Na	5.5	4.8		(83) 4.0	(17) 0.8				
K	0.9	1.0		(20) 0.2	(60) 0.6	(20)0.2			
H <sub>2</sub> O <sup>±</sup>	3.1	2.4			(46) 1.1	(8)0.2	(46)1.1		
Ti	0.5	0.7			(30) 0.2				(70)0.5
P	0.2	0.1			(100)0.1				
Mn	0.1	0.1			(100)0.1				
CO <sub>2</sub>		0.2				(100)0.2			
	100.0	100.0							

TABLE 3-17

## SUMMARY OF CATION DISTRIBUTION DATA FOR REL30

CATION	CATION %		QUARTZ	PLAGIOCLASE	HORNBLLENDE	CLINOPY.	ORTHOPLY.	MAG.
	TOTAL ROCK	MODE						
Si	47.9	48.1	(1)0.2	(54)26.1	(13)6.4	(21)9.9	(11)5.5	
Al	16.7	15.7		(87)13.6	(8)1.3	(4)0.6	(1)0.2	
Fe <sup>+3</sup>	3.3	2.6			(19)0.5	(15)0.4	(12)0.3	(54)1.4
Fe <sup>+2</sup>	5.0	7.4			(28)2.1	(27)2.0	(35)2.6	(10)0.7
Mg	7.9	7.3			(23)1.7	(41)3.0	(36)2.6	
Ca	11.0	10.3		(36) 3.7	(17)1.8	(46)4.7	(1)0.1	
Na	5.6	6.6		(91) 6.0	(6)0.4	(3)0.2	0	
K	0.7	0.4		(50) 0.2	(50)0.2		0	
H <sub>2</sub> O <sup>±</sup>	1.3	1.1			(100)1.1			
Ti	0.4	0.3			(100)0.3	0	0	
P					0		0	
Mn	0.2	0.2				(50)0.1	(50)0.1	
Ba					0			
	100.0	100.0						

are not alarmingly great. Most specimens are banded and greatest differences are in assemblages containing garnet.

A final calculation takes variations in the total rock composition into account so that the various specimens may be compared. Thus for specimen R563 (Table 3-15) there are 47.1 Si atoms of which total plagioclase contains 23.6. Total plagioclase contains:  $236/471 \times 100 = 50$  percent of total Si atoms. Hornblende contains 22 percent of total Si, clinopyroxene 26 percent, etc. These numbers are shown in brackets in Tables 3-12 to 3-17 and are the ones plotted on the graphs showing cation distribution.

#### Discussion of Results

Figure 3-16 to 3-25 (pages 70, 71, 72) present the cation distributions for Si, Al, Fe<sup>+3</sup>, Fe<sup>+2</sup>, Mg, Ca, Na, K, Ti, and Mn respectively. The upper curve indicates the relative amount of the particular cation in the total rock in terms of cation percent (column 3 in Tables 3-12 to 3-17). The lower series of curves show the bulk distributions of the cations between coexisting minerals. Throughout the discussion bulk distributions are referred to as bulk Si in hornblende, bulk Ca in garnet, etc. in order to avoid confusion with actual mineral compositions.

The reader should refer to Figure 3-26 (page 73) and 3-27 (page 74) in conjunction with the cation distribution graphs. Figure 3-26 gives the mineral content as volume percent and weight percent. Figure 3-27 summarizes the composition of the major minerals as cation percent.

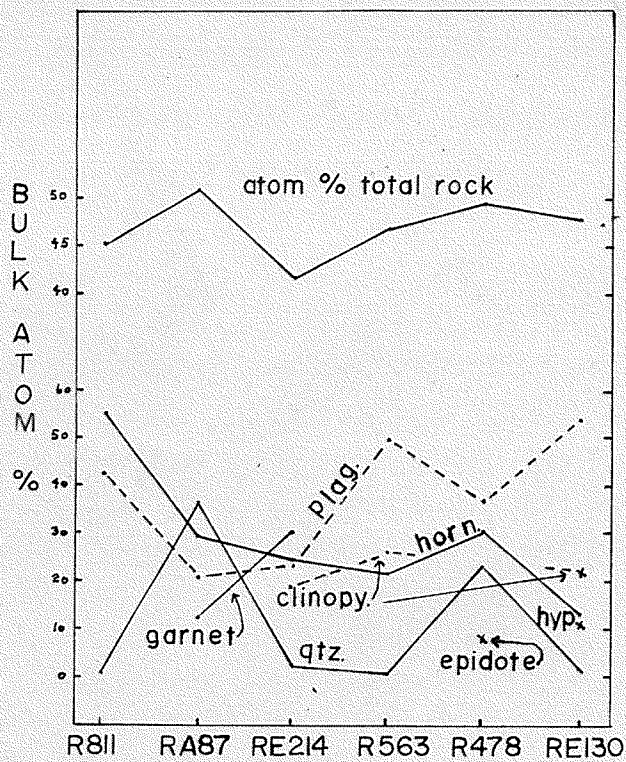


FIGURE 3-16 BULK DISTRIBUTION OF Si IN COEXISTING MINERALS OF BASALT

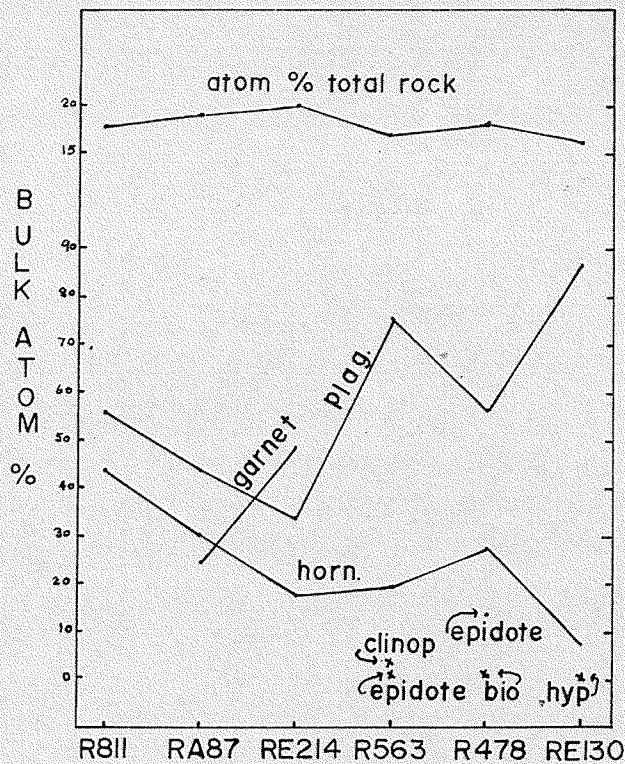


FIGURE 3-17 BULK DISTRIBUTION OF AL IN COEXISTING MINERALS OF BASALT

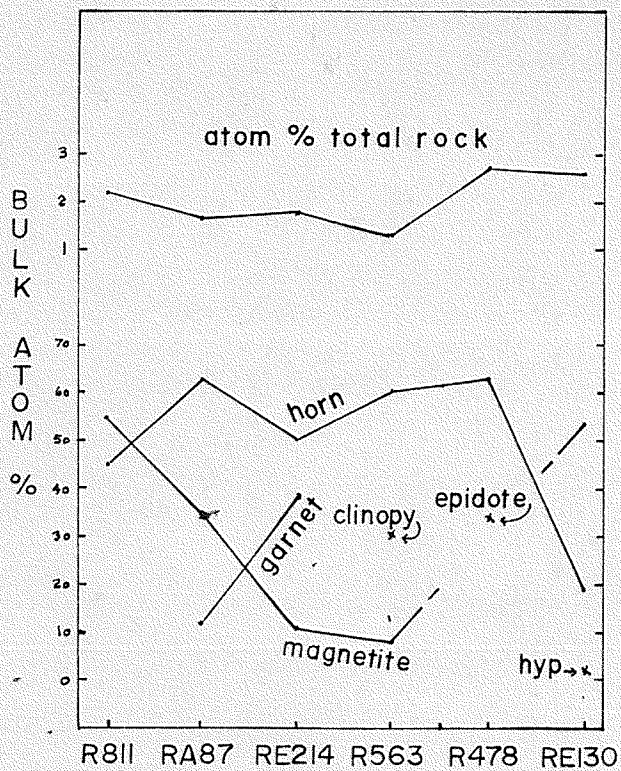


FIGURE 3-18 BULK DISTRIBUTION OF Fe<sup>3+</sup> IN COEXISTING MINERALS OF BASALT

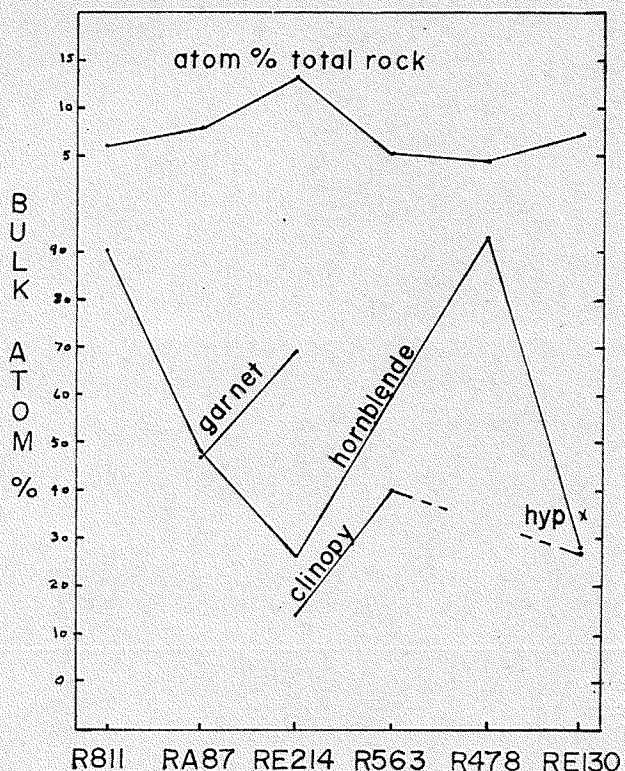


FIGURE 3-19 BULK DISTRIBUTION OF Fe<sup>2+</sup> IN COEXISTING MINERALS OF BASALT

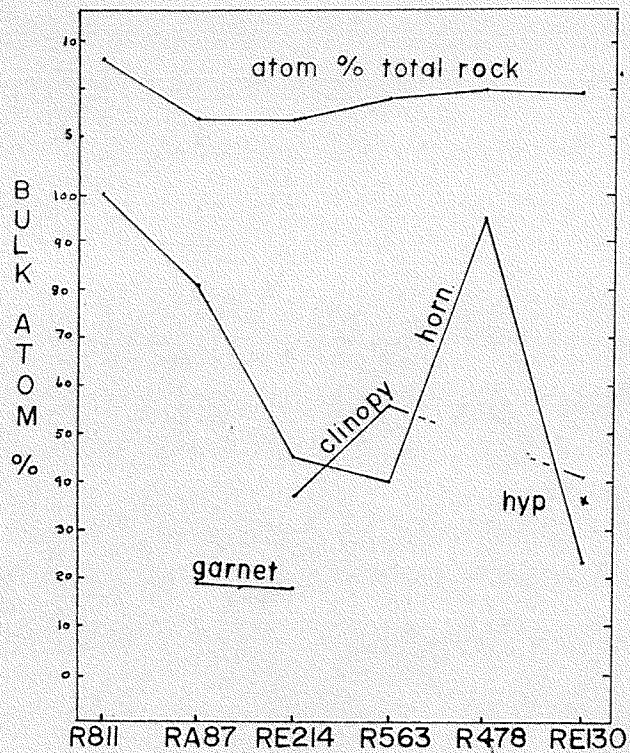


FIGURE 3-20 BULK DISTRIBUTION OF Mg IN COEXISTING MINERALS OF BASALT

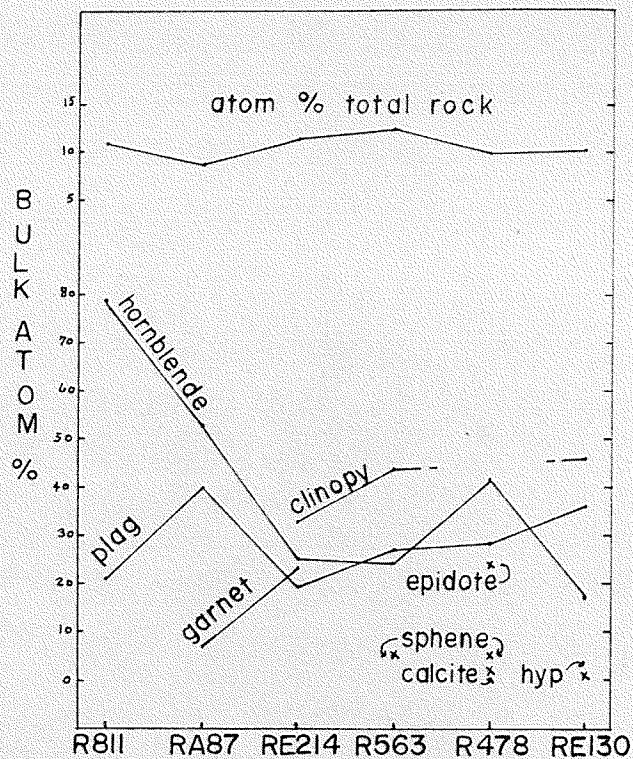


FIGURE 3-21 BULK DISTRIBUTION OF Ca IN COEXISTING MINERALS OF BASALT

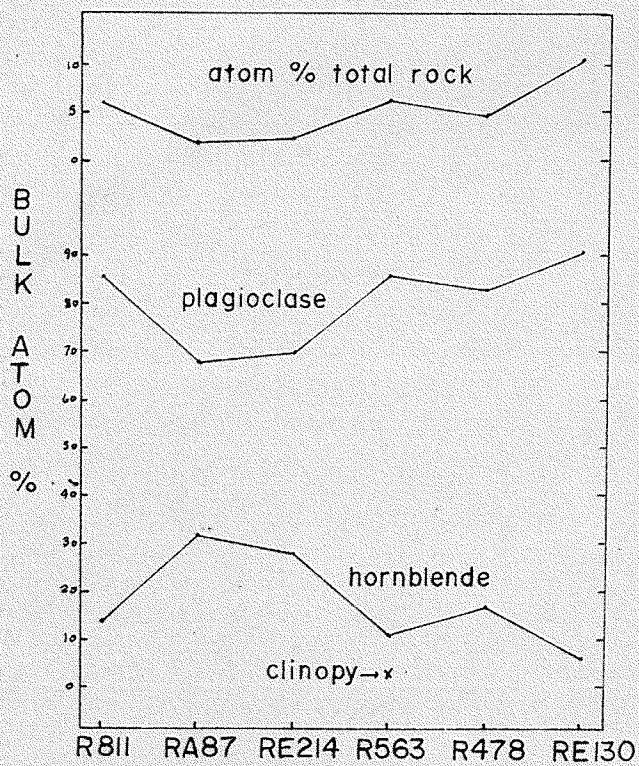


FIGURE 3-22 BULK DISTRIBUTION OF Na IN COEXISTING MINERALS OF BASALT

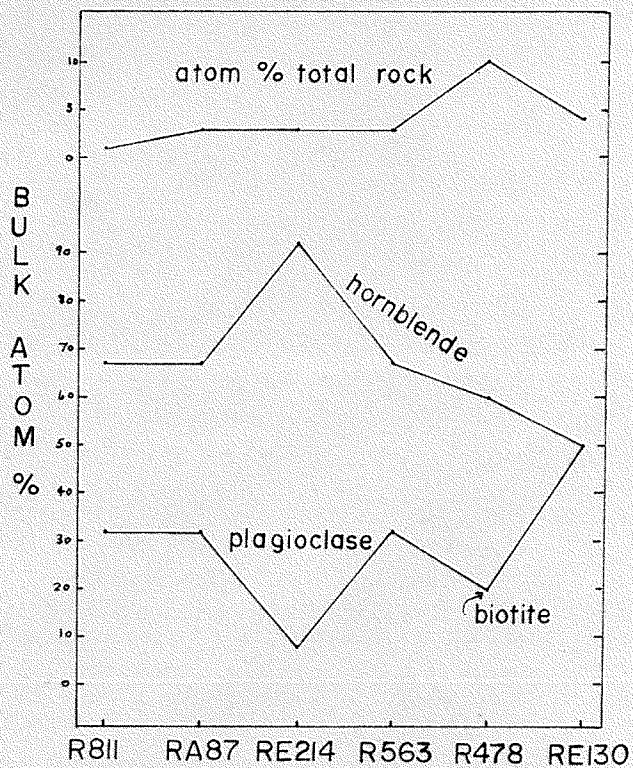


FIGURE 3-23 BULK DISTRIBUTION OF K IN COEXISTING MINERALS OF BASALT

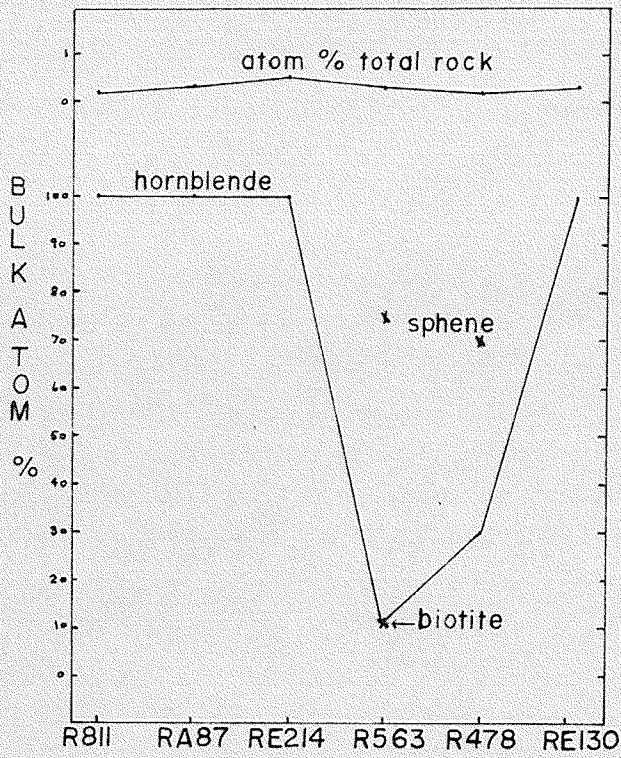


FIGURE 3-24 BULK DISTRIBUTION OF TI IN COEXISTING MINERALS OF BASALT

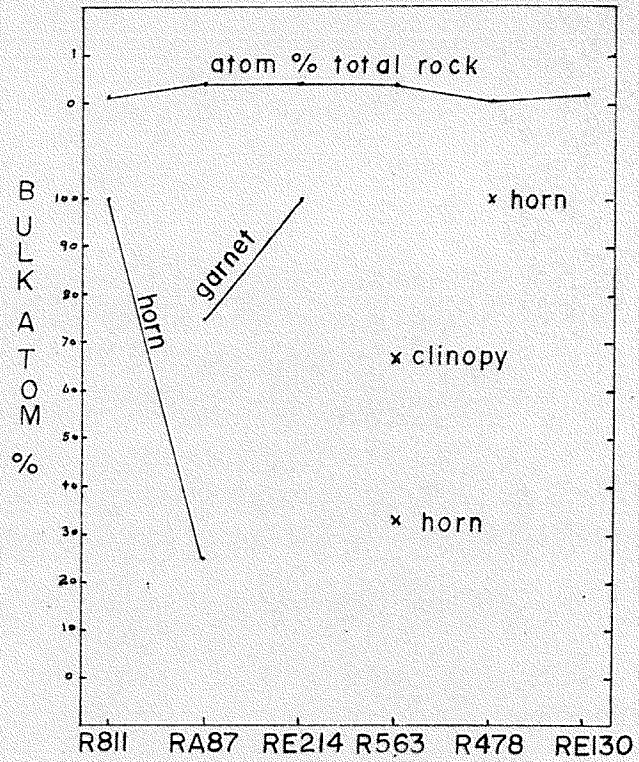


FIGURE 3-25 BULK DISTRIBUTION OF Mn IN COEXISTING MINERALS OF BASALT

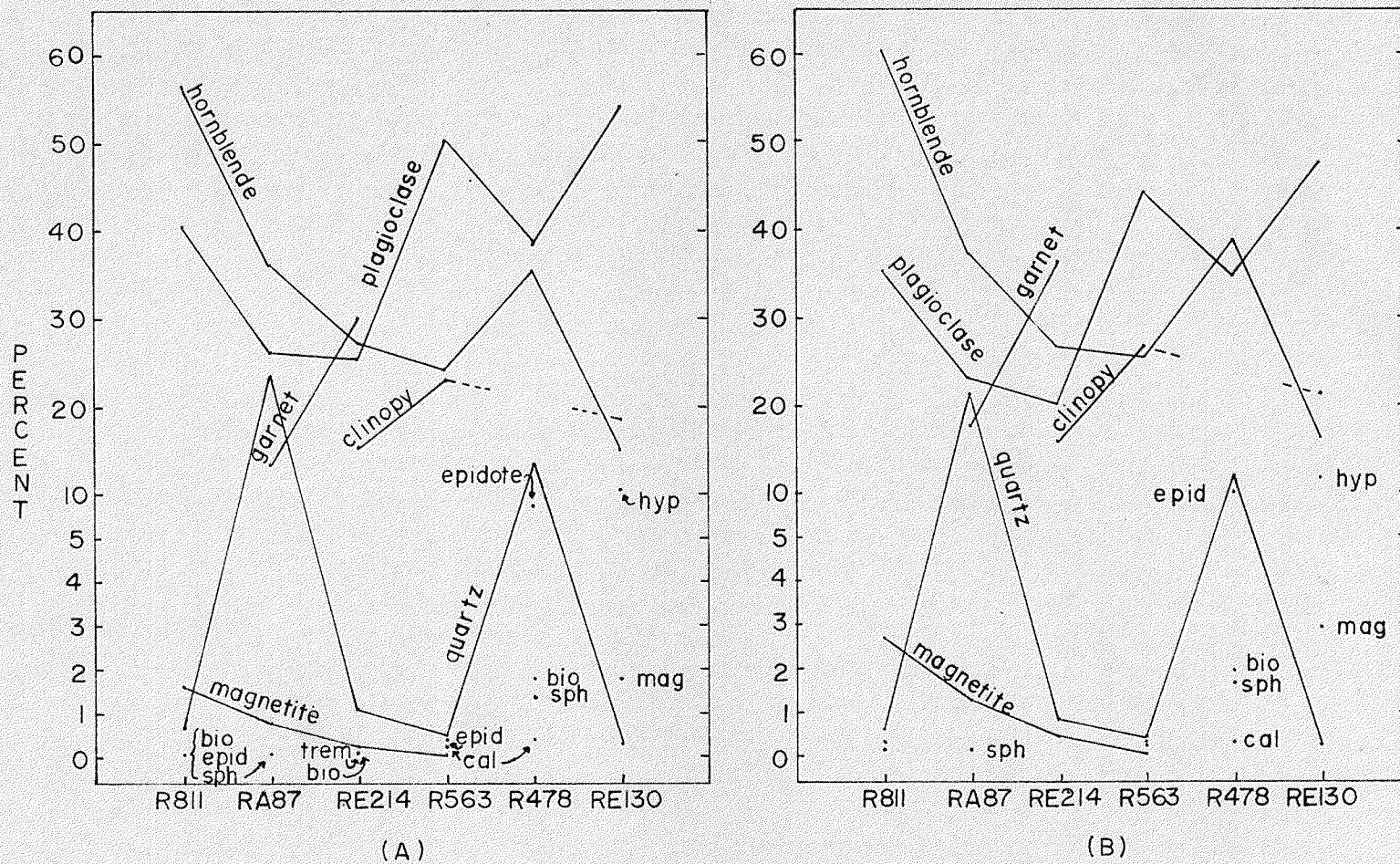
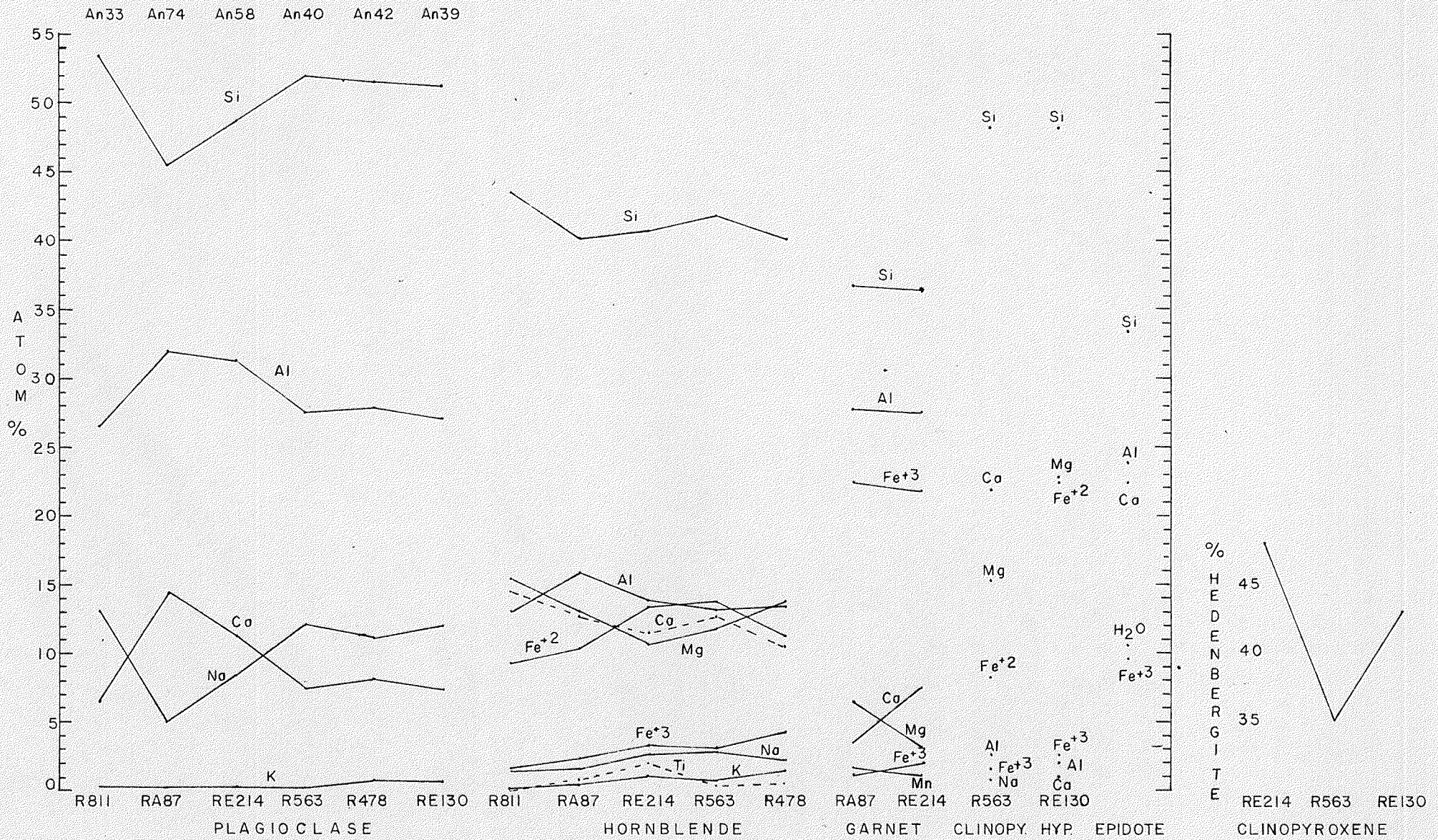


FIGURE 3-26. MINERAL CONTENT IN (A) VOLUME PERCENT AND (B) WEIGHT PERCENT FOR SPECIMANS IN CATION DISTRIBUTION STUDY OF BASALT



COMPOSITION OF MINERALS IN CATION DISTRIBUTION STUDY

FIGURE 3-27

Silicon Si distribution (Figure 3-16) follows the weight percent curve rather closely. Plagioclase has a higher Si content than hornblende. For this reason bulk Si in plagioclase may exceed that in hornblende, even though hornblende has the higher weight percent (R478).

Aluminum Most of the Al is distributed between plagioclase, hornblende, and garnet. Bulk Al in plagioclase exceeds that in hornblende even where the weight percent of hornblende is nearly twice that of plagioclase (R811) because plagioclase has a higher Al content than hornblende. The Al content of garnet is approximately the same as plagioclase between An<sub>33</sub> and An<sub>42</sub>. The more calcic the plagioclase, the higher the Al content. Bulk Al relationships between plagioclase and garnet are similar to the weight percent curves. In the hornblende granulite facies (RE130) 85 percent of the Al is concentrated in plagioclase. This is because of the low Al content of hypersthene and clinopyroxene and the low weight percent of hornblende. The high bulk Al content of plagioclase is due to the high weight percent of plagioclase and not, as might be expected, because of a high Al content due to a more calcic plagioclase. Thus in the hornblende granulite facies, characterized by the development of Al-poor minerals, a high weight percent of plagioclase might be expected.

Ferric Iron The most remarkable feature of Figure 3-18 is the bulk Fe<sup>+3</sup> content of magnetite. Specimen R811 contains only 2.65 percent magnetite by weight (1.6 vol. percent) but due to its

high  $\text{Fe}^{+3}$  content (69 atom percent) the bulk  $\text{Fe}^{+3}$  content is 55 percent. Specimen RE130 shows a similar relationship. Where the magnetite content is low, bulk hornblende contains most of the  $\text{Fe}^{+3}$ .

Ferrous Iron Most of the  $\text{Fe}^{+2}$  is concentrated in hornblende and only a little in biotite and magnetite where hornblende is the dominant mafic mineral. Garnet has a higher  $\text{Fe}^{+2}$  content than hornblende. In assemblages with garnet and hornblende, the bulk  $\text{Fe}^{+2}$  content of garnet will approach or exceed that of hornblende, even when the weight percent of garnet is less than hornblende.

The relationship between the bulk  $\text{Fe}^{+2}$  content of hornblende and clinopyroxene depends on weight percent and compositions. The weight percent of hornblende is greater than clinopyroxene in RE214 and slightly less in R563. However the bulk  $\text{Fe}^{+2}$  contents of hornblende and clinopyroxene maintain about the same proportions between RE214 and R563 with more bulk  $\text{Fe}^{+2}$  in hornblende than clinopyroxene. This is because clinopyroxene from RE214 is more  $\text{Fe}^{+2}$ -rich than clinopyroxene from R563. In specimen RE130 the weight percent of clinopyroxene exceeds hornblende but the bulk  $\text{Fe}^{+2}$  contents are nearly equal. Hypersthene has a higher bulk  $\text{Fe}^{+2}$  content than any other coexisting mineral, even when the weight percent of hypersthene is less.

Magnesium Hypersthene contains the highest cation percent Mg and garnet the least; hornblende and clinopyroxene are intermediate. The bulk Mg distribution is shown in Figure 3-20. The high bulk Mg content for clinopyroxene of R563 is due to the high Mg content of this specimen.

Calcium Clinopyroxene and epidote contain about the same atom percent Ca and this is higher than in other coexisting minerals. Hornblende contains more calcium than plagioclase up to a plagioclase composition of calcic labradorite. Garnet is low in Ca and the Ca content of hypersthene is negligible. Thus the bulk Ca content of epidote and diopside is high even when the weight percent of these minerals is relatively low. Figure 3-21 shows the bulk Ca content for plagioclase of specimen RA87 is large, although the weight percent is comparatively low. This is a reflection of the high Ca content of this plagioclase.

The calcium distribution curves may shed some light on composition changes of plagioclase with progressive metamorphism. New minerals are developed and these appear to govern the composition and quantity of plagioclase. The development of garnet from an assemblage consisting of hornblende and plagioclase (R811) is largely through the destruction of hornblende. Because the Ca content of garnet is relatively less than hornblende, a more Ca-rich plagioclase develops (RA87). When epidote or clinopyroxene is present (R478, R563), plagioclase is less calcic because Ca is taken up by these minerals. Plagioclase increases in amount in

assemblages containing clinopyroxene and hypersthene (R563, RE130) because these minerals are Al-poor (see section on Al distribution). Weight percent clinopyroxene decreases between R563 to RE130. The plagioclase does not become more calcic; the amount of plagioclase increases and hence the bulk Ca content of plagioclase. An assemblage representing the hornblende granulite facies consisting essentially of plagioclase and hypersthene might be expected to contain a more calcic plagioclase and a greater amount of plagioclase than in any of the lower grades.

Sodium Figure 3-22 shows that Na is largely distributed between plagioclase and hornblende. The bulk Na content of plagioclase is larger than hornblende and the two curves are a mirror image.

Potassium Like Na, K is largely confined to hornblende and plagioclase (Figure 3-23). Hornblende contains a higher bulk K content than plagioclase.

Titanium Titanium is distributed mainly between hornblende and sphene (Figure 3-24). Sphene, when present even in small amounts, may contain a large proportion of the total amount of Ti in a rock.

Manganese The total Mn content is very low and does not exceed 0.5 cation percent. Most Mn is concentrated in garnet if present or in clinopyroxene and hypersthene.

### BASALT MIGMATITE (6)

The term migmatite is applied to a megascopically composite rock that once consisted of a geochemically mobile material and immobile material (Dietrich and Mehnert in Sørrensen, 1960). Basalt (2) is the immobile phase and introduced quartzo-feldspathic material is the mobile phase. Basalt migmatites (6) are extensively developed in the area and represent a transition phase in the change from basalt (2) to rocks of the gneiss complex (9).

A banded migmatite (6) is produced as shown in Plate 3 (page 80) where quartzo-feldspathic material is injected in lit-par-lit fashion along schistosity planes. Migmatite (6) most commonly occurs as agmatite (Sørrensen, 1960) or, using a more descriptive term, injection breccia (Goodspeed, 1948). Plate 4A and 4B (page 81) are photographs of this type. Angular blocks of basalt (2), a few feet wide, are set in a matrix of pegmatite, biotite granodiorite gneiss (9a), or hornblende tonalite gneiss (9b). Blocks show rotation at a large angle to the dominant foliation suggesting the enclosing rocks were once mobile.

Basalt inclusions in migmatite (6) were "granitized" due to a metasomatic reaction with the injected quartzo-feldspathic material. The term granitization is used for this process although the end-product is biotite granodiorite gneiss (9a) (trondjemite). This is because sodium is the dominant alkali element of the injected quartzo-feldspathic material and potassium is subordinate. Petrologic studies indicate that the granitization of basalt produces the following

mineralogical changes in basalt: a replacement of hornblende by biotite; a decrease in the content of mafic minerals; an increase in the plagioclase content; a more sodic plagioclase; and an increase in the quartz content.

Three samples were selected to illustrate the mineralogical and chemical changes produced by the progressive granitization of basalt inclusions. These data are shown graphically in Figure 3-28 (page 82). The volume percent is based on 1000 point counts per specimen. Each specimen was analyzed chemically. The composition of plagioclase from R434-1 was determined by chemical analysis and that of the other two by measuring extinction angles on the universal stage. The samples were collected across an outcrop width of approximately 10 feet. The basalt sample, (R434-3, was collected from an inclusion that appeared unaffected by the quartzo-feldspathic material. Sample R434-2 is from a partially granitized inclusion and R434-1 is from a more completely granitized inclusion.

The progressive granitization of basalt (2) due to the introduction of quartzo-feldspathic material produces a marked increase in  $\text{SiO}_2$  and a more modest increase in  $\text{Al}_2\text{O}_3$  and  $\text{Na}_2\text{O}$ . There is an increase in  $\text{K}_2\text{O}$  in tonalite (9b), then a decrease in granodiorite (9a). All the other oxides show a progressive decrease in amount.

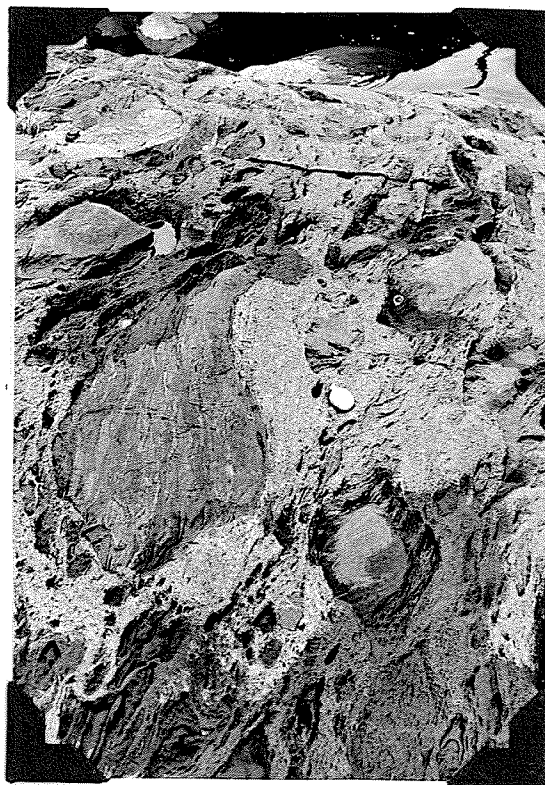
The main mineralogical changes are an increase in quartz and plagioclase and a decrease in hornblende. Plagioclase shows a progressive decrease in calcium content and the composition changes from



Plate 3. Banded Basalt Migmatite.

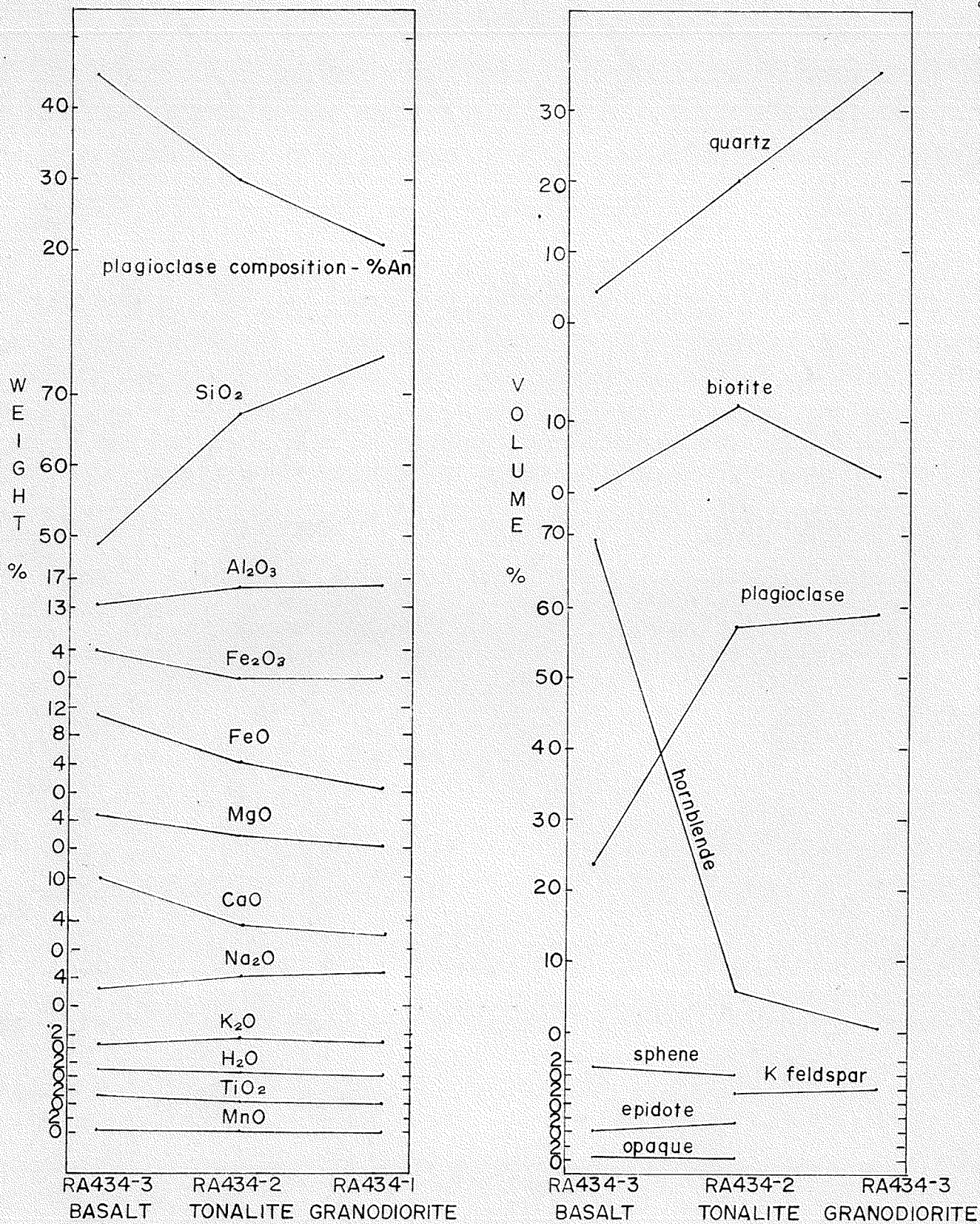


A



B

Plate 4. Basalt Migmatite - Agmatite or Injection Breccia.



Analysis - D.F. Brown Man. Mines Branch

CHEMICAL AND MINERALOGICAL CHANGES ACCOMPANYING BASALT GRANITIZATION

FIGURE 3-28

An<sub>45</sub> to An<sub>30</sub> to An<sub>21</sub>. The increase in biotite content from basalt (2) to tonalite (9b) is because biotite replaces hornblende. The decline in the biotite content from tonalite (9b) to granodiorite (9a) is due to the removal of basic elements. Some of the liberated K<sub>2</sub>O forms K feldspar as suggested by the slight increase in this mineral from tonalite (9b) to granodiorite (9a). Some K<sub>2</sub>O is apparently removed because the total K<sub>2</sub>O content decreases from tonalite (9b) to granodiorite (9a).

Many of the basalt inclusions in migmatite, near the contact between migmatite and basalt, show little or no effects of granitization. As the distance from the contact increases, the inclusions show a greater degree of granitization and migmatite grades into hornblende tonalite gneiss (9b). Tonalite contains scattered inclusions of partially granitized basalt. Still further from the contact tonalite grades into biotite granodiorite gneiss (9a). The granodiorite locally contains ghost-like remnant inclusions.

## CHAPTER IV

### SEDIMENTARY ROCKS

#### INTRODUCTION

Sedimentary rocks, consisting of conglomerates (3) and sandstones (4) comprise 20 percent of the exposed rocks of the area. Their distribution is shown in Figure 4-1 (page 85). Metamorphism has recrystallized sediments into paragneisses and locally schists consisting essentially of quartz, plagioclase, and biotite. The general terms sandstone and conglomerate however are used throughout the discussion rather than paragneiss, schist, meta-sandstone or meta-conglomerate. Sediments of the western two-thirds of the area were locally injected by pegmatite and granite and these rocks are mapped as sedimentary migmatites (7, 8).

Although sedimentary rocks are intensely folded, recrystallized, and injected by pegmatite, primary structures are locally well preserved. Cross-bedding\* is common and provides a useful criterion for determining tops of beds. Graded bedding is locally present and was used for top determinations where there is an obvious change from fine sediments to coarse sandstone and grit.

\* Cross-bedding appears to be mainly the "planar" type; see McDowell (1957, page 14).

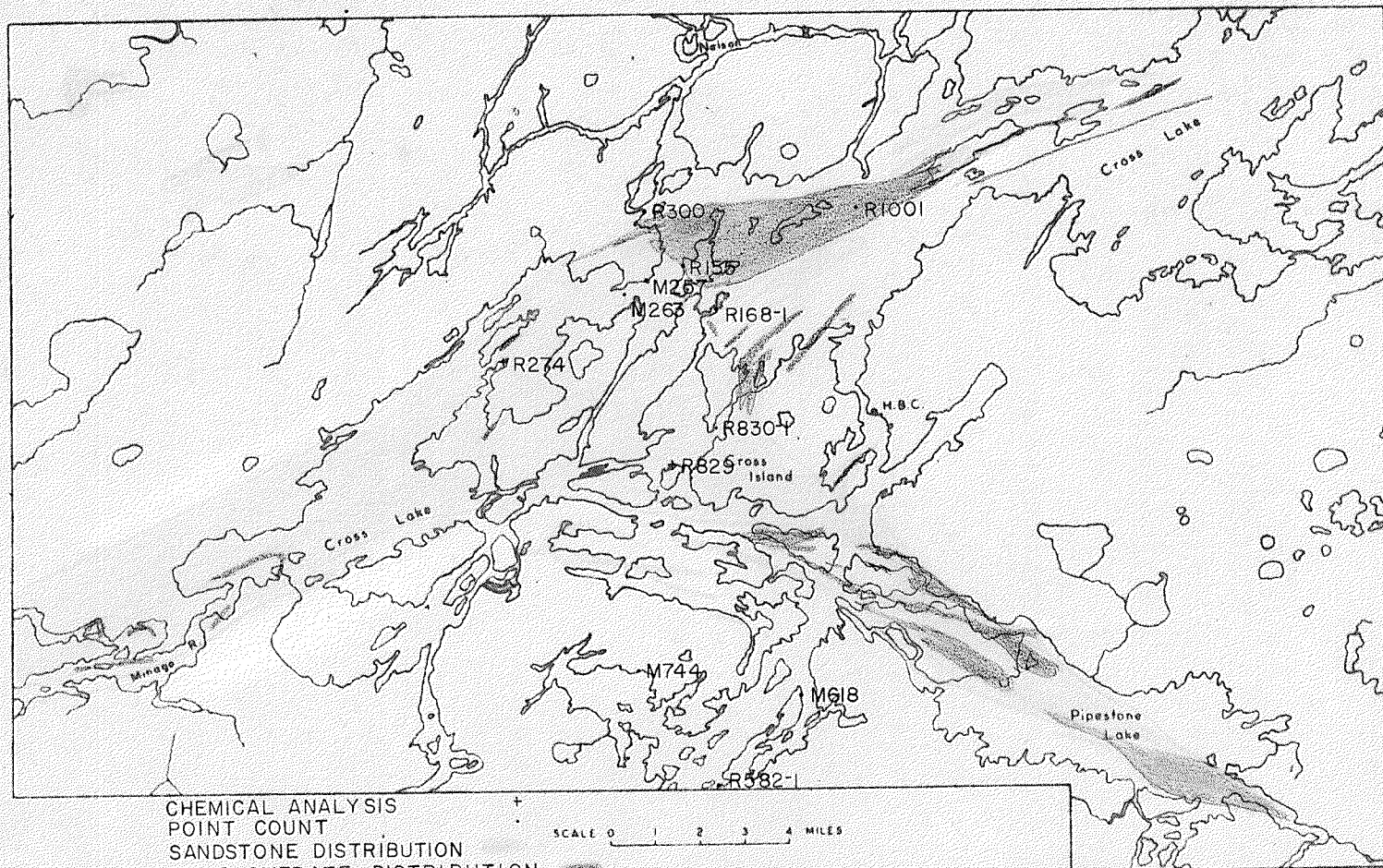


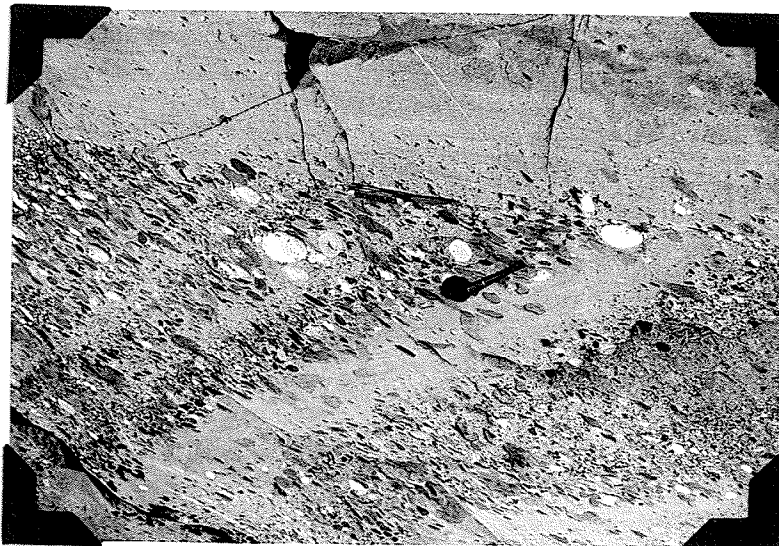
FIGURE 4-1. DISTRIBUTION OF SEDIMENTARY ROCKS AND LOCATION OF CHEMICAL AND MODAL ANALYSES

Recrystallization can produce anomalous tops especially in shales and silts. Scour-and-fill and channelling also occur. Plate 5A (page 87) is a photograph showing an unconformity located on an island between Cross Lake and Pipestone Lake. Features such as this do not represent major time breaks but rather a local interruption in sedimentation. Primary bedding, due to variations in the proportion of light and dark minerals is illustrated by Plate 5B (page 87). This exposure, near the west end of Cross Lake, is one of the rare examples in the area of shallow dipping beds.

### CONGLOMERATE (3)

Conglomerates (3) in the area vary from massive beds greater than 100 feet in thickness to thin lenses enclosed by sandstone (4). The kind and size of pebbles and the nature of the matrix were recorded in detail in the field but only the major features are described here. Conglomerates (3) are characterized by pebbles tectonically elongated into the shapes of triaxial ellipsoids. This phenomenon is described further in the section in Chapter VIII on lineations.

A boulder conglomerate (3a) unconformably overlies basement biotite granodiorite gneiss (1) at the north end of Cross Island (Plate 1, page 13). Most of the boulders consist of granodiorite gneiss which appear identical in the field and in thin section to the underlying basement biotite granodiorite gneiss (1). The intermediate axes of the boulders are as much as 2 feet in length. Pebbles of greenish grey schist are present. The matrix



A. Local Unconformity

Note non-parallel primary and secondary foliation.



B. Bedding in Shallow Dipping Sediments

is dark grey schist and consists of mica, garnet, quartz and plagioclase.

A conglomerate (3a) consisting of granodiorite boulders of extraordinary size occurs at the east end of Pipestone Lake, where the easternmost arm of the Nelson River enters the lake. The largest boulder recorded was 6 feet by 4 feet and the unexposed axis is probably the longest. Some diorite pebbles are present together with unusual light green chloritic pebbles.

The most extensive exposures of conglomerate (3a) occur along islands in Cross Lake north of Cross Island. Massive beds consist of 75 percent granodiorite pebbles and boulders together with 25 percent pebbles of quartz, quartzite, basalt, diorite and siltstone. The maximum size is approximately one foot in diameter. The matrix is a dark schist consisting of biotite, plagioclase, quartz, garnet and hornblende.

Pebbles of quartz and quartzite are prominent in conglomerates (3b) located at the west end of Cross Lake and along the Minago River.

Lenticular beds of conglomerate (3b) interbedded with coarse sandstones (4) and basalt (2) occur on the islands between Pipestone and Cross lakes. Boulders average 6 inches and are as much as one foot in diameter. The pebble content is variable and consists of basalt, quartz, quartzite, granodiorite, siltstone, and brown and black argillite. The matrix is arkosic and

associated sandstones have a composition similar to that of the conglomerate.

#### SANDSTONE (4)

Rocks mapped as sandstones (4) contain minor beds of argillite, siltstone, grit, conglomerate and limey sediments. Sandstones are recrystallized to buff to brown paragneisses and where the mica content is relatively high, to schists. Granitization has resulted in the addition and subtraction of material which is not always obvious in outcrop or in thin section.

The mineral content of a selected suite of sandstones (4) is set out in Table 4-1 (page 90). Quartz, plagioclase, biotite and muscovite are the principal minerals and are present in most sandstones (4a). Quartz usually possesses undulatory extinction and is banded and embays and replaces plagioclase. Plagioclase may be twinned or untwinned and is anhedral. The composition is variable and ranges from sodic oligoclase to calcic andesine with sodic andesine the commonest composition. Biotite is dark brown and is locally replaced by muscovite. Both these minerals occur as idiomorphic grains up to several mm. in length. Garnet is a common constituent of sandstone (4). It consists of irregular or euhedral porphyroblasts poikilitically enclosing quartz. The foliation both wraps around and abuts against garnet. Clinozoisite, magnetite, hornblende, chlorite, tourmaline and calcite are all minor constituents of sandstone. Potash feldspar

TABLE 4-1

## MINERAL CONTENT OF SELECTED SANDSTONES

SPECIMEN NO.	QUARTZ	PLAG.	BIOTITE	MUSC.	GARNET	SILLIMANITE	K-SPAR	ZOISITE	OPAQUE	HORN. & CHLORITE	CALCITE	OTHERS
R155	69.1	12.9	3.8	7.5	0.2	6.2				0.3		
R168-1	43.4	22.4	22.7	6.9				2.7	0.7		1.2	
RR274	50.7	34.4	12.7		1.1		1.1					
R300	36.9	34.0	18.4	0.6	8.8				1.0	tr	0.4	
R582-1	35.8	44.0	6.1			9.4			0.3	4.4		
R829	34.7	39.6	21.1	2.6						1.6		0.4
R830-1	27.7	28.8	0.1	0.6				0.7		42.1		
R1001	55.6	20.2	13.8	7.4					0.2	1.8	1.0	
M257	63.2		9.6	0.4		25.8		1.0				
M263	60.5	24.6	6.9	1.1			6.6		0.1	0.2		
M618	65.2	21.8	10.1	1.6				0.5	0.5			0.3
M744	32.3	60.3	7.0				0.2	0.1				0.1

1000 point counts per specimen.

is locally present in small amounts and it may have been introduced in part. The grain size of most sandstones is 1 - 2 mm. in diameter; some are as fine-grained as 0.2 mm.

Sillimanite gneiss (4b) occurs west of Cross Island. Plate 6 (page 92) shows sillimanite knots concentrated along what are apparently aluminum-rich beds. Sillimanite may locally comprise as much as 50 percent of the rock by volume.

A band of staurolite schist (4c) occurs at the north end of Cross Island. Horwood (1934) reported staurolite schist from a bay on Cross Island southwest of the Hudson's Bay Post. The writer was unable to locate this exposure.

An uncommon and distinctive rock type consists of white plagioclase phenocrysts set in a tough, fine-grained matrix of quartz and biotite. The rock is probably a metamorphosed argillite (4d) and the plagioclase phenocrysts are porphyroblasts. In some places, the rock is sheared and plagioclase grains are round. Examples of this rock occur on the islands south of the western exit of the Nelson River from Cross Lake.

Siltstone with well-preserved delicate bedding occurs on an island in Pipestone Lake  $1\frac{1}{2}$  miles east of the large mafic dyke. Narrow limey bands occur locally and consist of 90 percent pale tremolite and 10 percent plagioclase, hornblende and quartz. Plate 15B (page 148) shows such a band deformed into a pinch-and-swell structure. Neither of these two rock types are sufficiently extensive to be shown separately on the geologic map.

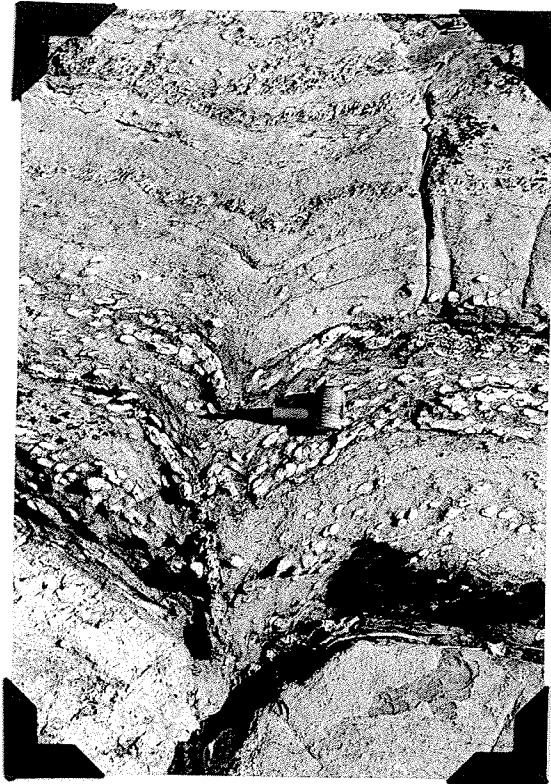


PLATE 6. Sillimanite Gneiss

Chemical analyses of two sandstones are set out in Table 4-2 (page 94) together with that of average arkose and greywacke. Both specimens consist largely of quartz, plagioclase, and biotite (Table 4-1). Specimen R274 represents the commonest sandstone type in the area and R829 is a rather more biotite-rich or "greywacke" type. As suggested above, recrystallization has produced a mineral assemblage that may differ from the original.

Specimen R274 chemically most closely resembles an arkose or subgreywacke (Pettijohn, 1956, Table 48). It is not possible to determine whether rock fragments or feldspar grains predominated before recrystallization. According to Pettijohn (1956) the feldspar in arkose is potash feldspar. This is probably because most arkoses studied were derived from a granite terrain. The feldspar in R274 and by far the dominant one in all sandstones of the area is plagioclase. This is because sediments were derived from gneisses containing little or no potash feldspar.

Texture is the most important single criteria of greywacke. Recrystallization has produced new textures in Cross Lake sandstones. Although arkose and greywacke do not differ greatly chemically, specimen R829 is a lithic or feldspathic greywacke. The MgO and Al<sub>2</sub>O<sub>3</sub> content is higher than the average arkose and closer to that of the average greywacke. The SiO<sub>2</sub> content is closer to greywacke than arkose (compare with Archaean greywackes, Table 7, Pettijohn, 1943).

TABLE 4-2

## CHEMICAL COMPOSITION OF SANDSTONES

	R274* Arkose	Average Arkose (Pettijohn,1956)	R829* Greywacke	Average Greywacke (Pettijohn,1956)
SiO <sub>2</sub>	74.5	76.37	68.77	64.7
Al <sub>2</sub> O <sub>3</sub>	12.87	10.63	15.78	14.8
Fe <sub>2</sub> O <sub>3</sub>	0.81	2.12	0.85	1.5
FeO	4.09	1.22	3.52	3.9
MgO	0.91	0.23	1.76	2.2
CaO	1.78	1.30	2.16	3.1
Na <sub>2</sub> O	2.25	1.84	3.47	3.1
K <sub>2</sub> O	2.00	4.99	2.17	1.9
H <sub>2</sub> O <sup>±</sup>	0.75	0.83	0.82	3.1
CO <sub>2</sub>	Nil	0.54	-	1.3
TiO <sub>2</sub>	0.27	-	0.40	0.5
P <sub>2</sub> O <sub>5</sub>	0.08	0.21	0.12	0.2
MnO	0.15	0.25	0.08	0.1
	100.46	100.94	99.90	100.4
K <sub>2</sub> O/Na <sub>2</sub> O	0.84		0.63	

\* Analysts: A. M. MacKay and D. F. Brown,  
Manitoba Mines Branch.

According to Middleton (1960) sandstones belonging to the eugeosynclinal clan have a  $K_2O/Na_2O$  ratio that is less than unity and this chemical characteristic sets them apart from other sandstones. Specimen R274 and R829 have a  $K_2O/Na_2O$  ratios of 0.84 and 0.63 respectively (Table 4-2). As shown previously (Chapters II and III). they were deposited in an orogenic basin rather than a eugeosyncline. The basement biotite granodiorite gneiss (1) has a  $K_2O/Na_2O$  ratio of 0.61 (Table 5-1, page 98). The mean  $K_2O/Na_2O$  ratio of 15 analyzed basalts (2) from Cross Lake is 0.25. Sandstones (4) from the area were mainly derived from the basement gneiss (1) and to a lesser extent from basalt (2). The low  $K_2O/Na_2O$  ratio in the sandstones (4) is due to the low  $K_2O/Na_2O$  ratio in the source rocks together with conditions of rapid erosion and deposition and little chemical weathering.

In summary, most Cross Lake sandstones are arkoses or subgreywackes with lesser associated greywackes. Sandstones containing greater than 75 percent quartz, protoquartzites or feldspathic sandstones, are rare. Sandstones with greater than 95 percent quartz, orthoquartzites, are absent.

#### SEDIMENTARY MIGMATITES (7, 8)

Sediments of the western 2/3 of the area were locally injected by pegmatite and granite. It was not possible to map sediments and pegmatite separately on the scale of the mapping. These composite rocks were mapped as conglomerate migmatite (7) and sandstone migmatite (8) (agmatite of Bell, 1962). The sediments en-

closed by pegmatite do not appear to be permeated by pegmatite and little introduced potash feldspar occurs in the sediments. Sandstones are thoroughly permeated by granite at a location approximately 5 miles east of Cross Island.

Horwood (1934) presented a lengthy discussion on the granitization of arkose at Cross Lake. This was based on modes, and oxide compositions calculated from the modes, from seven specimens collected along a north-south section located at the western end of Cross Lake. The only significant mineralogical change was an increase in potash feldspar and a decrease in quartz. Chemically there was an increase in  $Al_2O_3$  and  $K_2O$ , and a decrease in  $SiO_2$ . In the writer's opinion it is most difficult to select specimens from the gneiss complex (9) and be certain they were derived from arkose.

Arkose and greywacke chemically resemble biotite granodiorite gneiss (9a) more than the other rock types of the gneiss complex (9). (Compare Table 4-2, page 94 and Table 5-2, page 102). The main chemical changes necessary to convert arkose and greywacke to biotite granodiorite gneiss are: an addition of  $Na_2O$ ; and a removal of  $FeO$ ,  $Fe_2O_3$ ,  $MgO$  and, depending on the composition of the sandstone,  $SiO_2$ . This process was not studied in detail. Table 4-1 (page 90) indicates the variability of the mineral content of the sandstones. Recrystallization with little or no addition and subtraction of materials could convert some sandstones to biotite granodiorite gneiss. In summary, it seems reasonable to assume that some of the rocks of the gneiss complex were derived from sedimentary rocks, even though this cannot be firmly substantiated.

CHAPTER VACID AND INTERMEDIATE ROCKSBASEMENT BIOTITE GRANODIORITE GNEISS (1)

The basement biotite granodiorite gneiss (1) underlies the unconformity at the north end of Cross Island. Exposures near the Hudson's Bay post gave an age date of 2500 m.y (Table 9-2, page 164) and are thought to be basement biotite granodiorite gneiss (1). Horwood (1935) believed that the basement was tonalite, although no unconformity was ever observed by him. In this report, hornblende tonalite gneiss (9b) is part of the gneiss complex (9).

Basement biotite granodiorite gneiss (1) is a grey, medium-grained, strongly foliated rock which locally contains quartz eyes and quartz veins. The presence of skialiths suggest it is a hybrid rock. Thin section examinations show plagioclase (An14) to be anhedral and mainly untwinned. Quartz has undulatory extinction and occurs as bands. Muscovite locally replaces dark brown biotite. A modal analysis is given in Table 5-1 (page 98).

Table 5-1 (page 98) sets out a chemical analysis of the basement biotite granodiorite gneiss (1) (see Figure 5-1, page 99, for sample location) and analyses of the average plutonic granite, granodiorite, and quartz diorite (tonalite). The  $\text{SiO}_2$  content of the basement gneiss (1) is between that of granite and granodiorite;  $\text{K}_2\text{O}$  is less than in these two rocks. The  $\text{Na}_2\text{O}$  and  $\text{Al}_2\text{O}_3$  content of the basement gneiss (1) is higher than that of

TABLE 5-1

## CHEMICAL AND MINERAL CONTENT OF BASEMENT GNEISS

	Plutonic Granite*	Plutonic Granodiorite*	Plutonic Quartz Diorite*	Basement Gneiss (1) R1029-1**
SiO <sub>2</sub>	70.18	65.01	61.59	68.26
Al <sub>2</sub> O <sub>3</sub>	14.47	15.94	16.21	16.48
Fe <sub>2</sub> O <sub>3</sub>	1.57	1.74	2.54	0.98
FeO	1.78	2.65	3.77	2.26
MgO	0.88	1.91	2.80	1.07
CaO	1.99	4.42	5.38	2.24
Na <sub>2</sub> O	3.48	3.70	3.37	4.35
K <sub>2</sub> O	4.11	2.75	2.10	2.65
H <sub>2</sub> O <sup>±</sup>	0.84	1.04	1.22	0.83
TiO <sub>2</sub>	0.39	0.57	0.66	0.38
P <sub>2</sub> O <sub>5</sub>	0.19	0.20	0.26	0.20
MnO	0.12	0.07	0.10	0.05
	100	100	100	99.75
K <sub>2</sub> O/Na <sub>2</sub> O				0.61

<u>R1029-1</u>	<u>Volume %</u>
Quartz	33.5
Plagioclase (An14)	34.3
K-feldspar	5.1
Biotite	11.9
Epidote & Allanite	1.8
Muscovite	12.2
Calcite	0.5
Apatite	0.7
	<u>100</u>

\* Taken from Barth (1952) after Daly.

\*\* Analyst: A. M. MacKay, Manitoba Mines Branch.

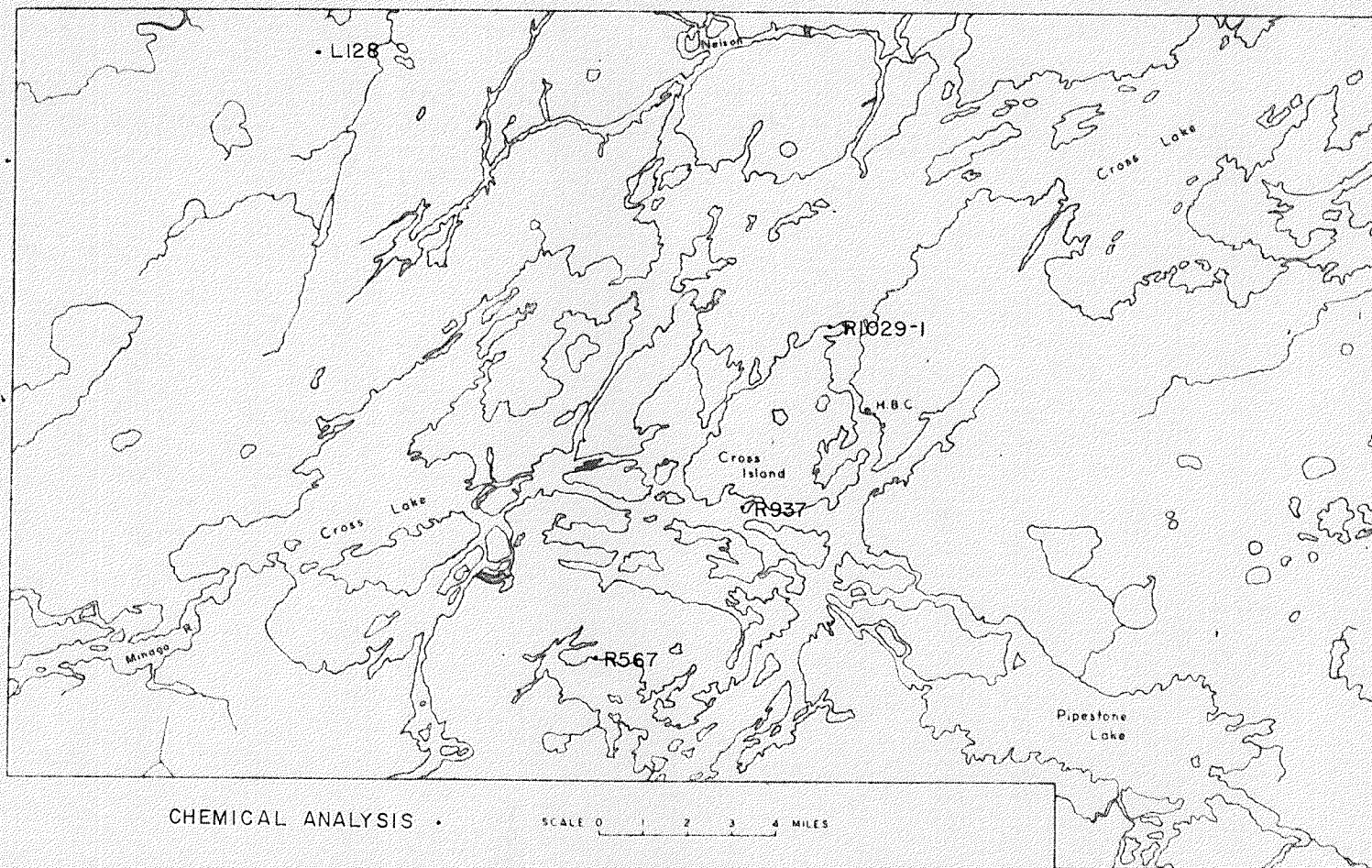


FIGURE 5-1 LOCATION OF ANALYZED SPECIMANS OF ACID AND INTERMEDIATE ROCKS

granite, granodiorite, and quartz diorite. Thus the basement gneiss (1) exposed at the unconformity on Cross Island is a sodium-rich granodiorite.

### GNEISS COMPLEX (9)

#### Introduction

Approximately 60 percent of the area is underlain by rocks of the gneiss complex (9). The gneiss complex (9) is subdivided on the basis of whether the dominant mafic mineral present is biotite, hornblende, or hypersthene; the ratio of microcline to plagioclase; and the presence of plagioclase phenocrysts. This subdivision gives the following rock types: biotite granodiorite gneiss (9a); hornblende tonalite gneiss (9b); adamellite (9c); feldspar porphyry gneiss (9d); and hypersthene gneiss (9e). Pegmatite, aplite, and quartz veins occur but are too small to be shown separately on the geologic map. More than one rock type may occur in the same exposure and the contacts are usually gradational. The location of chemically analyzed specimens from the gneiss complex (9) are shown in Figure 5-1 (page 99).

It was shown in Chapter III that some of the rocks of the gneiss complex (9) were produced by the granitization of basalt (2) by injected quartzo - feldspathic material. In Chapter IV it was suggested that recrystallization and granitization of sedimentary rocks (3, 4) could produce biotite granodiorite gneiss (9a). Some adamellites (9c) appear to be intrusive while others may have

formed by the potassium metasomatism of pre-existing rocks.

Biotite Granodiorite Gneiss (9a)

This is the commonest rock type of the gneiss complex (9) and comprises rocks in which biotite is the dominant mafic mineral and microcline is less than two-thirds of the total feldspar. Biotite granodiorite gneiss (9a) is a grey to pinkish grey medium-grained rock. It is usually gneissic but may be locally massive and locally may contain plagioclase phenocrysts. The average mineral content based on twelve specimens is set out in Table 5-2 (page 102). Plagioclase, quartz, and biotite are the main minerals. Microcline is locally present in small amounts or is absent. Plagioclase is anhedral, partly twinned, and from 0.1 to 0.5 mm. in diameter. Although it is usually fresh, some alteration to white mica, clinozoisite, and calcite occurs. Quartz shows undulatory extinction and is interstitial and appears to replace plagioclase in almost every thin section examined. Microcline also appears to replace plagioclase. Hornblende, where present, is partly replaced by brown biotite.

Antiperthitic feldspar was observed in six specimens, all but one of which are located east and west of Eve's Falls. Patches of microcline in plagioclase are less than 0.1 mm. in diameter and are either parallel to (010) or are randomly oriented. This texture is due to exsolution rather than replacement. Where microcline does replace plagioclase, it does so at grain boundaries.

TABLE 5-2

## CHEMICAL AND MINERAL CONTENT OF BIOTITE GRANODIORITE GNEISS

Mineral Content of Biotite Granodiorite Gneiss

	<u>Average*</u>	<u>Max.</u>	<u>Min.</u>	<u>Plagioclase Composition</u>
Quartz	33.8	35.6	23.8	(Tsuboi curves and/or U stage extinction angles)
Plagioclase	54.6	59.5	46.6	
Biotite	6.7	14.4	2.3	Average = An22
Microcline	3.5	7.4	0	Max. = An32
Hornblende	0.6	3.8	0	Min. = An14
Others	0.8			
	<u>100</u>			Others - apatite, sphene, epidote, muscovite, magnetite, calcite, chlorite, garnet, allanite.

\* Average of 12 specimens, 1000 point counts each.

<u>Chem. Analysis**</u>	<u>M112-1**</u>	<u>R434-1**</u>	<u>Mineral Content</u>	<u>M112-1</u>	<u>R434-1</u>
SiO <sub>2</sub>	74.32	75.53	Quartz	31.2	35.6
Al <sub>2</sub> O <sub>3</sub>	15.59	15.77	Plagioclase	56.7(An19)	59.4(An21 <sup>+</sup> )
Fe <sub>2</sub> O <sub>3</sub>	0.32	0.14	Biotite	3.1	2.3
FeO	0.70	0.16	Microcline	7.1	2.0
MgO	0.19	0.43	Muscovite	0.8	
CaO	1.82	2.16	Chlorite	0.7	0.7
Na <sub>2</sub> O	4.25	4.66	Magnetite	0.4	
K <sub>2</sub> O	2.25	1.08		<u>100</u>	<u>100</u>
H <sub>2</sub> O <sup>±</sup>	0.28	0.34			
TiO <sub>2</sub>	0.09	0.09			
MnO	0.05	0.02			
	<u>99.86</u>	<u>100.82</u>			

\*\* Analysts: D.F. Brown and A.M. MacKay,

Manitoba Mines Branch.

None of the antiperthitic specimens showed this.

Several specimens of biotite granodiorite gneiss (9a) showed evidence of shearing when examined in thin section. They consist of porphyroclasts of quartz and plagioclase in a matrix of fine quartz. Apart from the known fault at Eve's Falls, the rocks at the other localities showed no evidence of shearing in the outcrop.

Two chemical analyses of biotite granodiorite gneiss (9a) are set out in Table 5-2 (page 102). The analysis shown in Table 5-5 (page 109) is from a biotite granodiorite but it is included elsewhere because it makes up part of the feldspar porphyry gneiss (9d). The weight percent  $\text{Na}_2\text{O}$  is two to four times that of  $\text{K}_2\text{O}$ . The  $\text{SiO}_2$  content is greater than that of the average granodiorite and granite (Table 5-1). Biotite granodiorite gneiss (9a) approaches the composition of a trondjemite. (See for example Turner and Verhoogen, 1960, Table 34.)

#### Hornblende Tonalite Gneiss (9b)

Hornblende tonalite gneiss (9b) occurs in the form of mafic-rich bands enclosed by biotite granodiorite gneiss (9a) or it grades into basalt migmatite (6). A photograph of typical hornblende tonalite gneiss (9b) is shown in Plate 7 (page 104). The average mineral content of three specimens is given in Table 5-3 (page 105). Hornblende is the dominant mafic mineral, may be as much as 20 percent by volume, and is replaced in varying

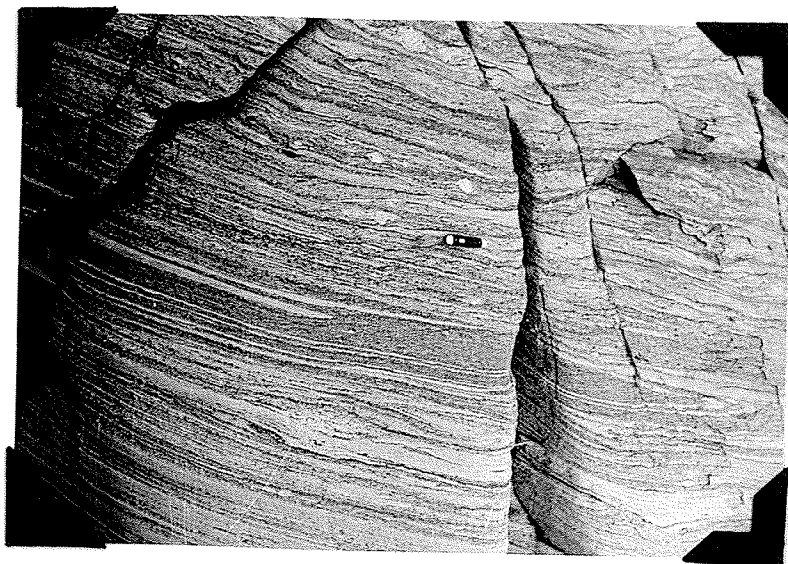


PLATE 7. Hornblende tonalite gneiss.

TABLE 5-3

## MINERAL CONTENT OF HORNBLLENDE TONALITE GNEISS

	Average* Mineral Content Hornblende Tonalite Gneiss
Quartz	23
Plagioclase (An34)	59
Hornblende	11
Biotite	4
Microcline	1
Others	2
	100

\* Average of 3; 1000 point counts each.

Others = clinozoisite, sphene, magnetite, apatite.

degrees by biotite. Plagioclase is sodic andesine.

#### Adamellite (9c)

Adamellite (quartz monzonite) is a quartz-rich rock in which from one-third to two-thirds of the total feldspar is microcline. Adamellites (9c) are not common at Cross Lake. They occur as bands in other rocks of the gneiss complex most of which are too small to be shown on the geologic map, or as small bodies intruding the Cross Lake Group (2, 3, 4). Adamellite that comprises part of the feldspar porphyry gneiss (9d) is described in the next section.

Adamellite (9c) locally occurs as a distinctive light grey leucocratic rock but elsewhere it may so resemble biotite granodiorite gneiss (9a) that it is impossible to separate them in the field. Structurally, adamellite varies from distinctly gneissic to nearly massive.

Table 5-4 (page 107) gives the average mineral content of adamellite (9c) and sets out one chemical analysis. Plagioclase is anhedral, has irregular grain boundaries, and is locally twinned. Microcline is interstitial and appears to replace plagioclase. Both plagioclase and microcline locally occur as phenocrysts. Quartz is interstitial, has undulatory extinction and replaces both microcline and plagioclase. Muscovite occurs as small grains that replace plagioclase and biotite and as large, discrete laths.

TABLE 5-4

## CHEMICAL ANALYSIS AND MINERAL CONTENT OF ADAMELLITES

Mineral Content - Adamellites

	<u>Average*</u>	<u>Max.</u>	<u>Min.</u>	<u>Plagioclase Composition</u>
Quartz	35.2	39.8	26.6	(Tsuboi curves and/or U stage extinction angles)
Plagioclase	34.9	50.9	28.3	
Microcline	20.2	27.9	15.4	Average = An16
Biotite	4.4	7.7	1.8	Max. = An20
Muscovite	3.1	6.8	0	Min. = An10
Others	<u>2.2</u>			Others = sphene, clinozoisite, magnetite, hornblende, calcite, apatite, chlorite, allanite.
	<u>100</u>			

\* Average of 7 specimens; 1000 point counts each.

<u>Chemical Analysis**</u>	<u>R931</u>	<u>Mineral Content</u>	<u>R931</u>
SiO <sub>2</sub>	73.92	Quartz	33.1
Al <sub>2</sub> O <sub>3</sub>	14.83	Plagioclase (An14)	31.9
Fe <sub>2</sub> O <sub>3</sub>	0.28	Microcline	26.2
FeO	0.99	Biotite	2.8
MgO	0.11	Muscovite	5.6
CaO	0.80	Apatite, epidote	0.4
Na <sub>2</sub> O	3.55		
K <sub>2</sub> O	4.47		<u>100</u>
H <sub>2</sub> O <sup>+</sup>	0.36		
TiO <sub>2</sub>	0.06		
P <sub>2</sub> O <sub>5</sub>	0.01		
MnO	0.03		
	<u>99.40</u>		

\*\* D. F. Brown, Manitoba Mines Branch.

### Feldspar Porphyry Gneiss (9d)

The main occurrence of feldspar porphyry gneiss (9d) is east and west of the Nelson River where it enters the southwestern end of Cross Lake. Elsewhere, feldspar porphyry gneiss (9d) occurs as small bodies. A chemical analysis and the mineral content of a feldspar porphyry gneiss (9d) specimen is given in Table 5-5 (page 109).

The feldspar porphyry gneiss (9d) varies in composition from granodiorite to adamellite. It is generally gneissic and is locally banded. Bands consist of microcline pegmatite, even-grained gneiss, and relic mafic bands. Phenocrysts of plagioclase and microcline seldom exceed one inch in diameter. Phenocrysts of microcline in pegmatite contain scattered inclusions of plagioclase in optical continuity. This suggests replacement of plagioclase by microcline. Phenocrysts in narrow pegmatite bands locally coalesce to form a single phenocryst which extends across the width of the band.

### Hypersthene Gneiss (9e)

Hypersthene gneiss (9e) occurs in the northwest part of the area. It is characterized by brown plagioclase which may be mistaken for weathering or iron stain. Quartz, locally distinctly blue in colour, occurs as elongate lenses that are oriented parallel to the foliation.

TABLE 5-5

CHEMICAL ANALYSIS AND MINERAL CONTENT OF  
FELDSPAR PORPHYRY GNEISS

R567\* - Porphyritic Biotite Granodiorite

<u>Analysis</u>		<u>Mineral Content</u>	
SiO <sub>2</sub>	71.63	Quartz	30.5
Al <sub>2</sub> O <sub>3</sub>	15.60	Plagioclase (An23)	52.2
Fe <sub>2</sub> O <sub>3</sub>	0.56	Microcline	0.7
FeO	2.68	Biotite	15.5
MgO	0.47	Muscovite	0.5
CaO	2.24	Others	0.6
Na <sub>2</sub> O	4.35		<hr/>
K <sub>2</sub> O	1.60		100
H <sub>2</sub> O <sup>+</sup>	0.47		<hr/>
TiO <sub>2</sub>	0.29		
P <sub>2</sub> O <sub>5</sub>	0.12	Others = apatite, clinzoisite, magnetite	
MnO	0.03		
	<hr/>		
	100.04		
	<hr/>		

\* Analysts: A.M. MacKay and D.F. Brown,  
Manitoba Mines Branch

The chemical composition together with the mineral content of a typical hypersthene gneiss (9e) is set out in Table 5-6 (page 111). Plagioclase is the dominant mineral and is anhedral, partly twinned and averages 1 mm. in diameter. Quartz varies from 10 to 40 percent by volume, shows undulatory extinction, occurs as grains or bands, and replaces plagioclase. Hypersthene is light pink in colour and seldom exceeds 10 percent by volume. Some specimens contain only traces of hypersthene. There is minor replacement of hypersthene by biotite and bluish green hornblende along tiny cracks. Elsewhere reddish brown biotite and olive green hornblende occur as stable minerals rather than products of hypersthene alteration.

#### Pegmatite, Aplite, Quartz Veins

Pegmatite dykes, aplite dykes, and quartz veins are all too small to be shown separately on the geologic map. Pegmatites are common and consist essentially of microcline, quartz, biotite and muscovite with minor black tourmaline, garnet, magnetite and apatite. Beryl-bearing pegmatites were found in eight localities (see geologic map) and are all confined to sedimentary rocks. To the writer's knowledge, this is the first report of beryl at Cross Lake. Crystals may be several inches long, are light green in colour and are not of gem quality. A pegmatite body south of Cross Island contains individual crystals of spodumene several feet long. Associated white mica has a greenish hue and may be lithium bearing.

TABLE 5-6

CHEMICAL ANALYSIS AND MINERAL CONTENT OF  
HYPERSTHENE GNEISS

<u>Chemical Analysis*</u>	<u>L-128</u>	<u>Mineral Content</u>	<u>L-128</u>
SiO <sub>2</sub>	67.4	Quartz	19.2
Al <sub>2</sub> O <sub>3</sub>	16.4	Plagioclase (An29)	74.4
Fe <sub>2</sub> O <sub>3</sub> } FeO }	4.4	Hypersthene	4.9
		Hornblende	0.1
MgO	2.05	Opaque	1.2
CaO	5.10	Apatite	0.2
Na <sub>2</sub> O	3.96		100
K <sub>2</sub> O	<u>0.42</u>		
	<u>99.73</u>		

\*X-Ray Fluorescence - K. Ramlal, Univ. of Manitoba.

CHAPTER VIMAFIC AND ULTRA-MAFIC INTRUSIVE ROCKSANORTHOSITE AND GABBRO (5)Minago River Gabbro

The northern edge of a large gabbro body occurs south of the Minago River and the southwest end of Cross Lake. It is exposed  $7\frac{1}{2}$  miles in an easterly direction and pinches out west of the Nelson River. It extends beyond the western margin of the area. Within the area, it is exposed for 2 miles in a southerly direction and extends for at least 15 miles south of the area, almost to Kiskitto Lake.

Gabbro (5) stands out as a topographic high and forms an escarpment at the contact with rocks of the gneiss complex (9) and paragneiss (4a). The presence of shears and quartz veins in the gabbro near the contact suggests that the contact may be a fault. Gabbro is concordant with the surrounding gneisses (4a, 9) and is cut by mafic dykes (10) and pegmatite.

Gabbro (5) is a grey, medium to coarsely crystalline rock which varies from foliated to massive. Gabbro was mapped as hornblende gabbro (5b) where hornblende is the dominant mafic mineral and biotite gabbro (5a) where biotite is the dominant mafic mineral. Mafic minerals seldom exceed 10 percent by volume and usually comprise 5 percent by volume. Hornblende gabbro (5b)

locally contains mafic bands a few inches across which may contain up to 75 percent hornblende. Plagioclase is the main mineral in gabbro (5a, 5b) and occurs as a mosaic of well-twinned anhedral grains as large as 5 mm. in diameter. Some diffuse zoning is present. Bent or fractured grains occur, but are not common. The compositions of plagioclase from six specimens were determined by measuring extinction angles on the Universal stage. Five are calcic labradorite and one is sodic labradorite.

The Minago River gabbro is cut by mafic dykes (10) and pegmatite. The plagioclase of the gabbro is not granulated and several interpretations can be made for this. Gabbro could have been emplaced as a hydrous melt rather than a partly crystalline mass after the regional folding. On the other hand, the gabbro could have been emplaced before folding. Recrystallization might have eliminated the effects of granulation produced either by folding or emplacement as a partly crystalline mass. Other rocks of the area (2, 3, 4) were intensely folded and recrystallized and show little or no evidence of granulation and shearing. There is also the possibility that the gabbro was emplaced before folding and acted as a buttress.

#### Minor Bodies of Ovoid Gabbro (5d)

Small bodies of ovoid gabbro (5d) a few feet across are enclosed in basalt (2) and occur in the northeastern part of the area and approximately  $1\frac{1}{2}$  miles south of Cross Island. They consist of 70 percent plagioclase ovoids one to three inches long and

30 percent matrix of fine-grained hornblende and plagioclase. The matrix appears identical to basalt (2) so that the ovoid gabbro (5d) simply fades into basalt. These bodies appear to have formed by the metasomatic growth of plagioclase crystals.

#### Pipestone Lake Sill

A sill consisting of gabbro (5b, 5d) and anorthosite (5c) occurs south of Pipestone Lake. The sill separates basalt (2) on the north from rock of the gneiss complex (9) on the south. Isolated lenses of sill rocks are locally enclosed by basalt and the gneiss complex. The sill dips 80°N to vertical, is concordant with the surrounding rocks, and forms a sinuous pattern that extends in a generally easterly direction for approximately 10 miles. It pinches out at both ends and seldom exceeds 1000 feet in thickness. In the central part of the sill, 2000 feet of sill rocks are overlain to the north by 1000 feet of basalt (2) followed by 40 feet of sill rocks.

Hornblende gabbro (5b) is the commonest rock type of the sill and it is similar to that described for the Minago River gabbro. Locally it contains hornblende-rich bands a few inches to several feet wide.

Ovoid gabbro (5d) consists of ovoids of plagioclase which average 6 inches long and are as much as one foot long set in a hornblende-rich matrix. A photograph of ovoid gabbro is shown in Plate 8A (page 115). Thin section examination indicates the ovoids



A. Ovoid Gabbro



B. Anorthosite enclosing Band of Ovoid Gabbro

consist of either of a few plagioclase crystals that are fractured and offset or a mosaic of irregular, finely-twinning grains. The latter are less than 0.1 mm. in diameter, possess very undulatory extinction, and appear to represent a more extreme granulation than the former. Plagioclase is calcic labradorite. Numerous tiny needles of hornblende and grains of clinozoisite outline the fractures and are enclosed by plagioclase. Hornblende with a maximum diameter of 0.5 mm. is the main mineral of the matrix. The pleochroic formula is:  $n_x$ : colourless;  $n_y$ : light green; and  $m_z$ : bluish green. Approximately 10 percent of the matrix consists of plagioclase which averages 0.1 mm. in diameter. Magnetite in the form of clots and bands may make up as much as 20 percent of the matrix.

Ovoid gabbro (5d) locally grades into massive anorthosite (5c) by the coalescence of ovoids and the decrease in the hornblende content. Plate 8B (page 115) is a photograph which shows a band of ovoid gabbro (5d) enclosed by anorthosite (5c). Note that the ovoid outline persists in the anorthosite (5c). In outcrop anorthosite (5c) is light grey, coarsely crystalline, and appears to be virtually 100 percent plagioclase. Thin section examination reveals plagioclase in anorthosite (5c) has the same fine twinning, fracturing and granulation as plagioclase in ovoid gabbro (5d). Hornblende and magnetite together with secondary chlorite, clinozoisite, biotite and muscovite may comprise up to 10 percent of the rock.

A zone of massive and disseminated magnetite occurs along the south shore of Pipestone Lake. Massive beds are as much as 10 feet thick. According to Bell (1962) a zone some 100 feet wide and thousands of feet long has been traced with a ground magnetometer.

Hornblende gabbro (5b) is the dominant rock type within the main body of the sill. Locally, hornblende gabbro (5b) grades into anorthosite (5c) and the latter occurs as lenses or bands tens of feet wide. Ovoid gabbro (5d) occurs within these rocks (5b, 5c) as bands a few feet wide. Contacts are gradational. Relationships are best seen along the shoreline of Pipestone Lake where isolated bands of sill rocks occur enclosed in basalt (2). There, basalt (2) grades into sill rocks through an increase in plagioclase and a decrease in hornblende content. Rocks become anorthosite (5c) and ovoid gabbro (5d) some 10 feet from where this change begins. Basalt (2) contains phenocrysts of plagioclase near the contact with the sill rocks and there are bands of porphyritic basalt (2) some 2 feet wide within the sill rocks.

This same banding with gradational contacts occurs at the most easterly exposure of the sill. There are several bands 20 feet wide and one band 50 feet wide of sill rocks. All are separated by basalt (2) and there are thin bands of basalt (2) within bands of sill rocks.

The time and mode of emplacement of the Pipestone Lake sill is not precisely known. Mafic dykes (10) were not observed cutting the sill. A fault contact between sill rocks and hornblende tonalite gneiss (9b) is exposed at the eastern end of the sill. Several other contacts between sill rocks and those of the gneiss complex (9) were observed, but they are not diagnostic.

Lineated hornblende occurs in hornblende gabbro (5b) exposed at the western end of the sill. The trend and plunges of these lineations are similar to that of lineated hornblende in nearby basalts (2). This suggests the sill was emplaced before or during folding, but not after, because the lineations were produced by the folding.

The sill occurs on the south limb of a syncline. (See Figure 8-6, page 153.) This together with top determinations based on pillowed basalt (2) suggests that the top of the basalt (2) immediately north of the sill is to the north. Hence the top of the sill faces north if it were emplaced in a horizontal or nearly horizontal position and later tilted by folding. If the sill were emplaced after folding, then the top could face north or south. Bell (1962) believed the top faced south.

Isolated bands of sill rock occur in basalt (2). Contacts are gradational and the plagioclase content of basalt increases and plagioclase becomes porphyritic near the contacts. This suggests, at least locally, that sill rocks were emplaced as a hydrous melt rather than a partly crystalline mass and that metasomatic transfer of ions occurred. The magnetite bands are enclosed by

basalt and this indicates differentiation prior to emplacement.

Plagioclase of sill rocks is locally extremely granulated. This suggests the sill was either injected as a dry crystal mush (Bell, 1962) or the granulation was produced by folding. In the first case, the sill could have been emplaced after folding, in the second case, before or during folding. Other rocks of the area (2, 3, 4) were folded but show no evidence of granulation because they are recrystallized. Sill rocks are also recrystallized but this did not completely eliminate the effects of granulation.

The kinds of evidence and the conclusions drawn therefrom concerning the time and mode of emplacement of the Pipestone Lake sill are summarized as follows: (1) lineations: emplacement before or during folding; (2) top: faces north if emplacement before or during early stages of folding; faces north or south if emplacement after folding; (3) gradational contacts, porphyritic basalt: hydrous melt, migration of ions; (4) magnetite, bands of sill rocks enclosed in basalt: differentiation prior to intrusion; (5) granulation: emplacement before, during, or after folding; if (3) is true then emplacement before or during folding; and (6) recrystallization: emplacement before or during folding.

Evidence indicates that the Pipestone Lake sill was differentiated prior to emplacement as a hydrous melt. It was emplaced before or during folding. The top of the sill faces north. The petrologic similarities between the Pipestone Lake sill, the Minago River gabbro, and the minor bodies of ovoid gabbro

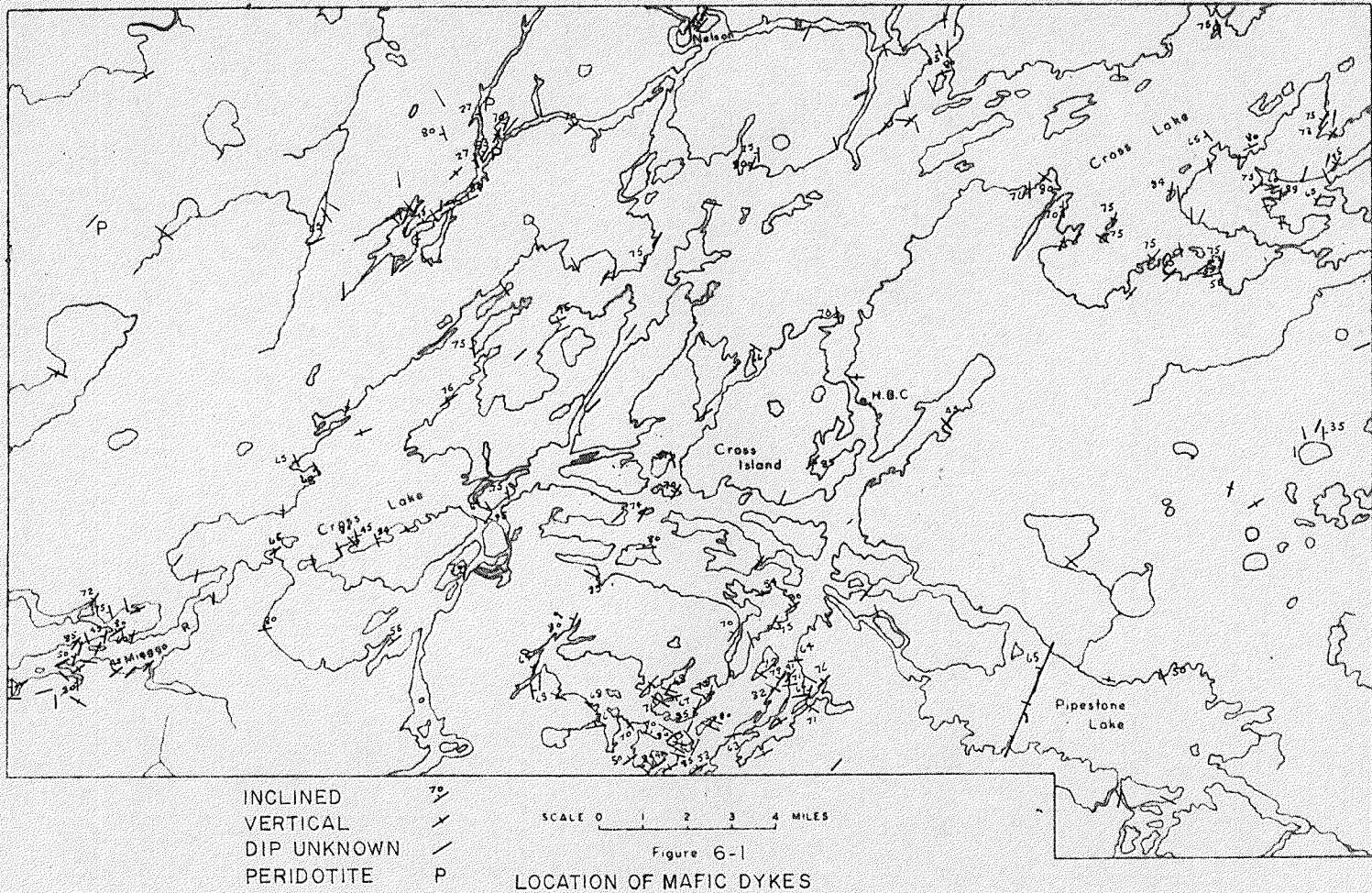
suggest they may have been emplaced at the same time even though they are spacially separate.

#### MAFIC AND ULTRA-MAFIC DYKES (10)

Approximately 245 mafic dykes (10) were recorded in the area and their locations are shown on Figure 6-1 (page 121). The extent of the large dyke cutting across Pipestone Lake is as shown on Figure 6-1; for the remainder the length of the plotted line is the same, regardless of the actual length of the dyke. Mafic dykes (1) are largely but not wholly confined to the gneiss complex (9). The apparent absence of mafic dykes in some parts of the area is due to lack of exposure.

Figure 6-2 (page 122) shows the thickness distribution for 213 mafic dykes (10). The data used were maximum observed thicknesses. Sixty-eight percent of the dykes are less than 5 feet thick and 6 percent are greater than 100 feet thick. Only a few small dykes are exposed over their entire length. The largest dyke observed is located at the western end of Pipestone Lake. It is 500 feet thick and at least  $2\frac{1}{2}$  miles long.

Hornblende gabbro and diorite dykes (10a) are the most common type and they consist essentially of hornblende and plagioclase. Some have a diabasic texture. Hypersthene-bearing dykes (10b) range in composition from hypersthene gabbro to norite. Hypersthene is usually more or less completely altered to hornblende and biotite. The plagioclase content varies from 0 to 30



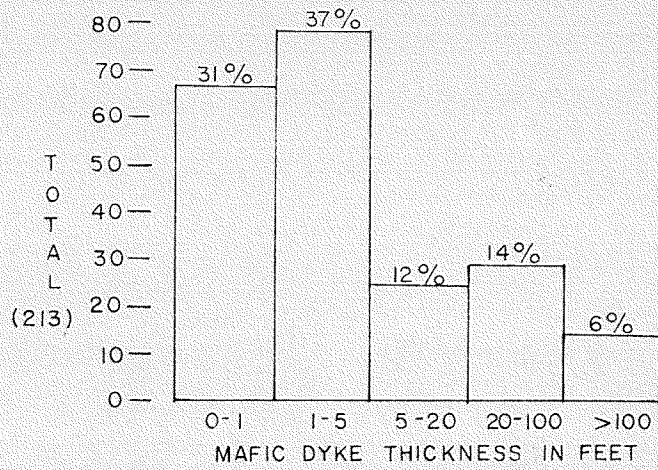


FIGURE 6-2 THICKNESS DISTRIBUTION OF MAFIC DYKES



CONTOUR DIAGRAM OF POLES TO 198 MAFIC DYKES  
CONTOUR INTERVAL IN % 4

FIGURE 6-3

percent by volume. Hypersthene cannot be positively identified in hand specimen so that some dykes mapped as hornblende gabbro and diorite (10a) may be hypersthene-bearing dykes (10b). Peridotite dykes (10c) were found in three localities (Figure 6-1). They consist of approximately 75 percent hypersthene, 20 percent olivine partly altered to serpentine, and 5 percent calcic labradorite.

Figure 6-3 (page 122) is a contour diagram based on poles to 198 mafic dykes (10). Dips were not recorded for approximately 20 percent of the dykes and these were not plotted. The diagram shows three main trends of mafic dykes. These are, in order of importance:  $N40^{\circ}E$ ; N; and  $N60^{\circ}W$ . Dykes trending  $N40^{\circ}E$  conform closely to the trend of the major linear features ( $N35^{\circ}E$ ). (Compare Figure 6-1 page 121 and Figure 8-3, page 146.) Some dykes occur along the major linear features. The largest dyke in the area trends  $N35^{\circ}E$ . Dykes trending N and  $N60^{\circ}W$  may be controlled by fractures related to the major linear features but fractures in these directions were not observed. The main trend of joints in the area is  $N35^{\circ}W$  and they do not appear to control the orientation of mafic dykes. Several examples of joints and small faults cutting mafic dykes were observed. In one case, a fault displaced a dyke 9 feet.

Baadsgaard et al. (1963) found two or more distinct periods of mafic dyke emplacement in rocks of the Yellowknife geologic province. This was based on age dates. It is possible that there was more than one period of mafic dyke emplacement at Cross Lake, but no age dates were made on mafic dykes. One example

of a dyke cutting another was observed ( $N75^{\circ}E$  cuts  $N18^{\circ}W$ ).

## CHAPTER VII

### METAMORPHISM

#### INTRODUCTION

The classical metamorphic zones were based on pelitic schists. Later attempts to apply these to other rock types presented difficulties especially where associated pelitic schists were lacking. Pelitic rocks are not common in the area. The metamorphic grade in the area is based on index minerals developed in basalts (2) and sedimentary rocks (3, 4) and relict minerals present in the gneiss complex (9). Basalts (2) and sedimentary rocks (3, 4) are completely recrystallized and primary minerals are not present. Rocks of the gneiss complex (9) were formed by the granitization of basalts (2) and sedimentary rocks (3, 4). Relict minerals are those that escaped alteration by the granitization process.

#### BASALT

Judging from a review by Poldervaart (1953) geologists have not agreed on the metamorphic trends of basalt. According to Sutton and Watson (1951) who worked in the northwest Highlands of Scotland "... no metamorphic rock can be looked upon as abnormal or anomalous because it fails to conform to types shown to exist in other areas."

Basalts (2) of the area consist of the following mineral assemblages, listed in order of increasing metamorphic grade:

(1) hornblende-plagioclase; (2) hornblende-plagioclase-garnet; (3) hornblende-plagioclase-garnet-diopside; (4) hornblende-plagioclase-diopside; and (5) hornblende-plagioclase-diopside-hypersthene.

This sequence is supported by progressive changes in hornblende composition. One assemblage, consisting of hornblende-plagioclase-epidote and thought to represent the lowest grade, appeared "anomalous". The hornblende composition suggested a grade between 4 and 5 above. Epidote is secondary. The mineral assemblage is not apparently an infallible criteria of metamorphic grade. The value of the various minerals as indicators of metamorphic grade is discussed below.

#### Plagioclase

Currie (1947), from a study of specimens from the Morton Lake area, Manitoba, correlated metamorphic changes in volcanic rocks with the metamorphic zones in the surrounding sedimentary rocks. He believed that the composition of plagioclase in volcanic rocks progressively changed from An<sub>26</sub> to An<sub>42</sub> from the biotite to the sillimanite zone. Plagioclase composition was determined by "optical methods" and no further discussion is given. It is difficult to evaluate his findings because some optical methods do not yield precise data. Milligan (1960) applied Currie's data to the Lynn Lake area.

In Chapter III it was shown that the composition and quantity of plagioclase in basalt (2) depends on kind, quantity, and composition of coexisting minerals. For isochemical rocks, these later parameters depend on metamorphic intensity. For non-isochemical rocks, differences in bulk composition also affect

these parameters. Plagioclase does not become progressively more calcic from the lower part of the almandine-amphibolite facies to the granulite facies. Changes in plagioclase composition could not be used to define metamorphic zones in this range.

### Hornblende

The principal progressive changes shown by hornblende under conditions of increasing metamorphic intensity are: (1) increase in (Na+K) and  $[Al]^{4-}$ ; (2) a general darkening in colour intensity from pale green and greenish blue to olive and brown; and (3) decrease in volume percent.

### Garnet

Garnet is widely distributed in basalts (2) of the area (Figure 7-1, page 128). It is absent in the northeast-trending bay east of the settlement, and along the north shore and most of the south shore of Pipestone Lake.

Many writers have cited the control of bulk composition on the development of garnet. Suzuki (1930), for example, suggested garnet in amphibolites does not necessarily imply a higher metamorphic grade but may be due to a suitable bulk composition. Of the three garnet-bearing basalts from the area analyzed chemically (almandine dominant end member), two have a comparatively high  $Fe^{+2}$  content, and one a rather low  $Fe^{+2}$  content. The writer found the amount of garnet increased with an increase in bulk  $Fe^{+2}$  content.

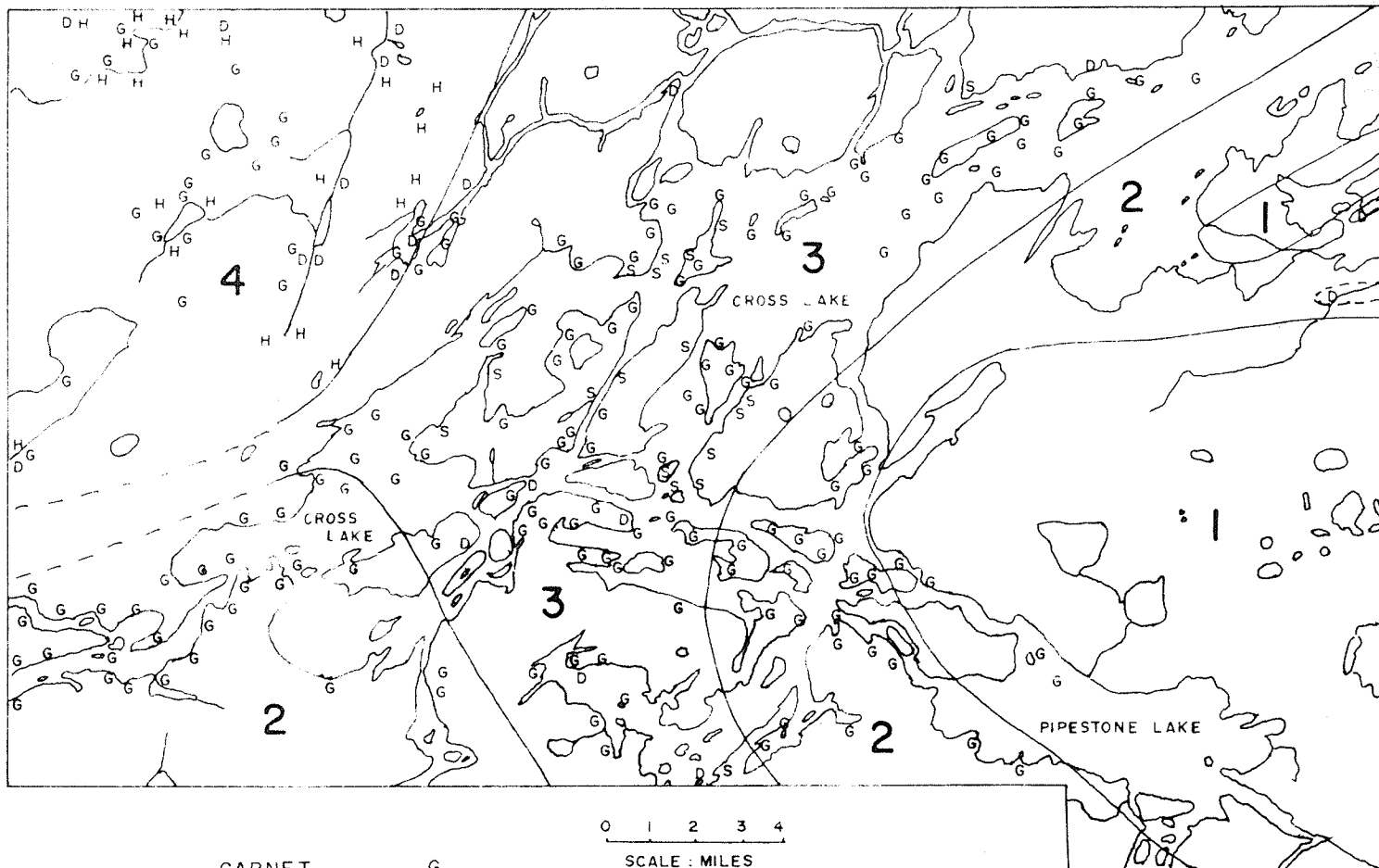


FIGURE 7-1 METAMORPHIC MAP AND DISTRIBUTION OF INDEX MINERALS

According to Turner and Verhoogen (1960, page 540) the assemblage for basic schists of the quartz-albite-epidote-almandine subfacies of the greenschist facies is hornblende-albite-epidote with or without almandine. Wiseman (1934) found that garnet does not necessarily appear at the almandine isograd. A similar conclusion was reached by Engel and Engel (1962). Plagioclase is andesine in basalts of the area consisting essentially of plagioclase and hornblende and lacking garnet. The grade is apparently higher than the almandine zone. Hornblende shows the progressive changes cited above from the assemblages hornblende-plagioclase to hornblende-plagioclase-garnet. This of course is based on only two analyses. Garnet is used as an index mineral because it cannot be demonstrated that differences in bulk composition exist between garnet and non-garnet bearing basalts, and because of changes in composition of coexisting hornblende. The writer realizes this may not be fully justified.

#### Diopside

Wiseman(1934) found in the "normal" trend of amphibolite metamorphism that the appearance of diopside corresponds to the sillimanite zone of pelitic schists. Hypersthene may also be present. Engel and Engel (1962) were able to relate the appearance of diopside to a temperature isograd of  $\sim 540^{\circ}\text{C}$ . The distribution of diopside in basalt (2) and sillimanite in paragneisses (4b) in the area are similar.

### Hypersthene

The appearance of hypersthene in basalts (2c) and in the gneiss complex (9e) is considered to mark the granulite facies boundary (Turner and Verhoogen 1960, page 553). These rocks are within the hornblende granulite subfacies of the granulite facies because hornblende and biotite persist in them. In Wiseman's (1934) abnormal granulite trend, original augite is replaced by diopside and hypersthene. Original minerals are not present at Cross Lake. According to Poldervaart and Backström (1949), from studies in the Kakamas area, South Africa, meta-basalts of both the granulite and amphibolite facies occur within the almandine and sillimanite zones of associated pelites. They offer the explanation that either granulites or amphibolites form under the same metamorphic intensity depending on wet or dry conditions.

### SEDIMENTARY ROCKS

Plagioclase, biotite, and muscovite occur in virtually all assemblages. Staurolite occurs in only one and perhaps two localities. Garnet and sillimanite appear to be the only diagnostic minerals.

Garnet in sedimentary rocks (3, 4) is controlled in part by a suitable bulk composition. It is widely distributed and the only place it is scarce is on the large island between Cross and Pipestone lakes.

Sillimanite in the form of knots is easily recognized in the field. Where it occurs as single grains, it can only be identified in thin section. Thus sillimanite may be somewhat more widely distributed than indicated on Figure 7-1. Bulk composition must in part control sillimanite development because sillimanite is concentrated in bands.

#### METAMORPHIC ZONES

Four metamorphic zones are recognized in the area and they are shown in Table 7-1 (page 132). Zones 1 and 2 represent a grade higher than the greenschist facies and lower than the sillimanite zone of the almandine-amphibolite facies. The division into two zones is based on the presence or absence of garnet in basalt (2). Garnet may occur in sedimentary rocks (2, 3) in Zone 1. The sillimanite zone 3 is marked by the appearance of sillimanite in sediments (3, 4) and diopside in basalts (2). The highest zone, 4, is within the hornblende granulite subfacies of the granulite facies and is based on the development of hypersthene in basalts (2c) and the gneiss complex (9e).

The location of the metamorphic zones is shown on the map in Figure 7-1 together with the distribution of index minerals. The dividing lines are generalized and the pattern may be far more complex in detail. For example all basalt bands in Zone 4 do not contain hypersthene and all basalts in Zone 3 do not contain diopside. The highest grade of metamorphism occurs in the northwest part of the area and the lowest in the southeast.

TABLE 7-1

## METAMORPHIC ZONES

FACIES	ALMANDINE-AMPHIBOLITE			HORNBLENDE- GRANULITE
ZONE	STAUROLITE - 1	KYANITE 2	SILLIMANITE 3	HYPERSTHENE 4
BASALT	Plagioclase: not diagnostic			
	Hornblende Pale-green, greenish blue green, bluish green			brown, olive-green
			Garnet	
			Diopside	
				Hypersthene
SEDIMENTS			Garnet	
			Sillimanite	
GNEISS COMPLEX				Hypersthene

The zones of the metamorphic map should not be regarded as absolute isopleths of metamorphic intensity. Yoder (1955) has demonstrated the role of water in metamorphism. Variations in the bulk water content may produce facies ranging from the greenschist to the eclogite under constant temperature-pressure conditions. Differences in water pressure may produce reversals in the normal isograd sequence.

## CHAPTER VIII

### STRUCTURAL GEOLOGY

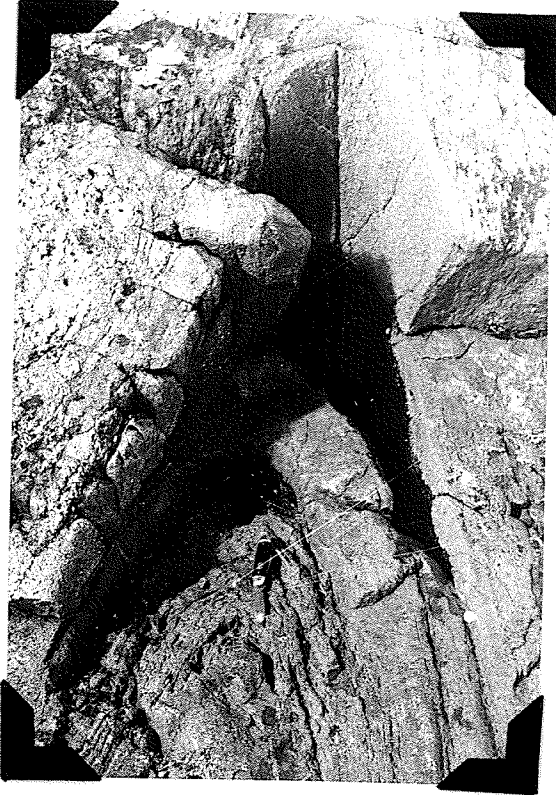
The various structural elements of the area are discussed. These elements are integrated and the structure of the area is described by means of maps and contour diagrams. Theories concerning the origin of the structure are presented.

### STRUCTURAL ELEMENTS

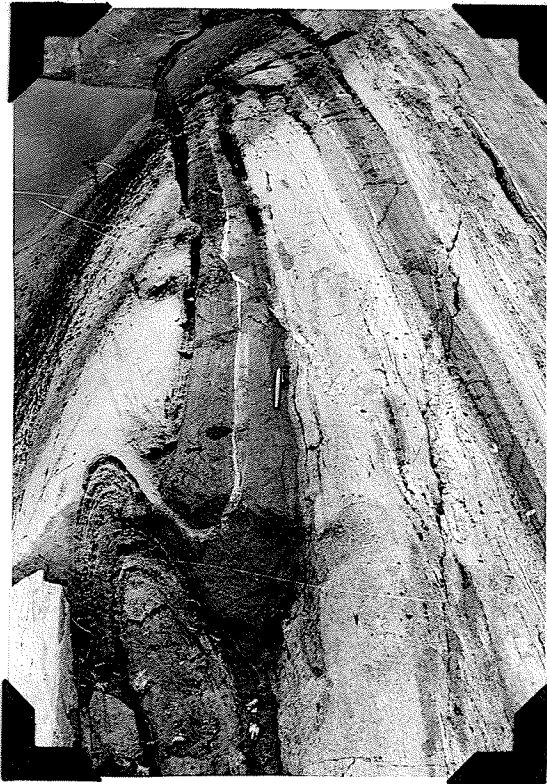
#### Mesoscopic Folds

Mesoscopic<sup>1</sup> folds of the S and Z types were noted but many folds are so irregular that the sense of movement could not be determined. Most mesoscopic folds are steeply-plunging, high-amplitude, and isoclinal or nearly so (Plate 9A,B, page 135). Less than 10 percent of approximately 234 recorded folds are distinctly non-isoclinal. Low-amplitude mainly non-isoclinal folds in paragneiss migmatite (8) are shown in Plate 10A (page 136). Some folds have attenuated or sheared-off limbs (Plate 10B, page 136). Crenulations in conglomerate (3) are shown in Plate 11A (page 137). Relatively soft pebbles of siltstone and basalt are folded whereas folds wrap around resistant granodiorite pebbles. Basalt (2) is rarely folded and presumably it yielded by shearing.

<sup>1</sup> The writer uses this term in the sense of Turner and Weiss (1963, page 76). Mesoscopic structures are those visible in hand specimens and exposures.



A.



B.

PLATE 9. Typical Mesoscopic Folds



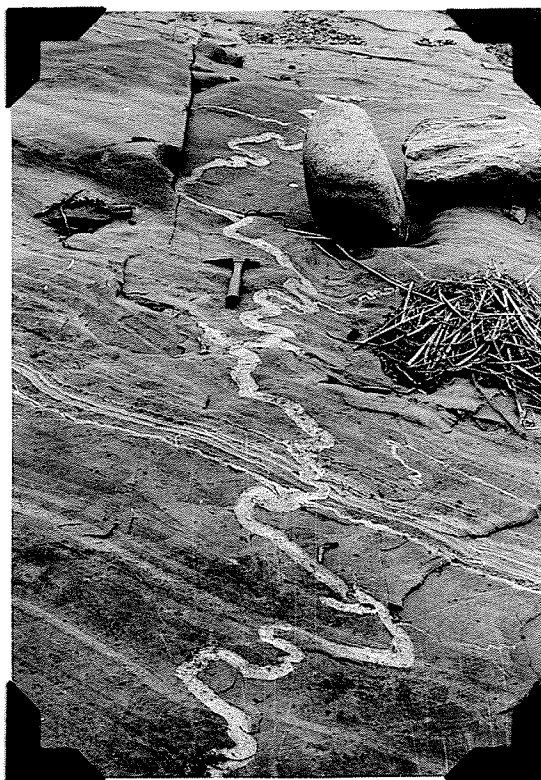
A. Low Amplitude Folds in Paragneiss.



B. Fold showing Shearing on Limb.



A. Crenulated Conglomerate.



B. Ptygmatic Folds.

Most mesoscopic folds observed in the area appear to be concentric<sup>1</sup> folds and some folds may be in part similar<sup>1</sup> folds. Folds shown in Plate 9A and 9B are concentric folds. The folds shown in Plate 10A are thicker along the axes than on the limbs and may be in part shear folds. The fold shown in Plate 10B indicates shearing on one limb. Some of the crenulations shown in Plate 11A appear to be similar folds because of the apparent thickening in the axial region. This is due to the resistant granite pebbles about which the folds are draped. Movement in concentric folds is parallel to bedding planes; movement in similar folds takes place along planes which may make any angle with the bedding. Shear planes transverse to the bedding planes were seldom observed at Cross Lake, but this effect may be more common than apparent.

Plate 11B (page 137) shows a ptygmatic fold consisting of quartzo-feldspathic material cutting across paragneiss (4). Ptygmatic folds occur locally in the area. The origin of ptygmatic folds is discussed by Dietrich (1960).

### Lineations

Lineations were mainly observed along shorelines because most exposures inland do not show a vertical section. Lineations are common in some parts of the area, scarce in others. All lineations are parallel to mesoscopic fold axes and are therefore b lineations in relation to these folds. This conclusion is substantiated by numerous examples where the various lineations occur

<sup>1</sup> Concentric and similar are used in the sense of Carey (1962, p. 96.)

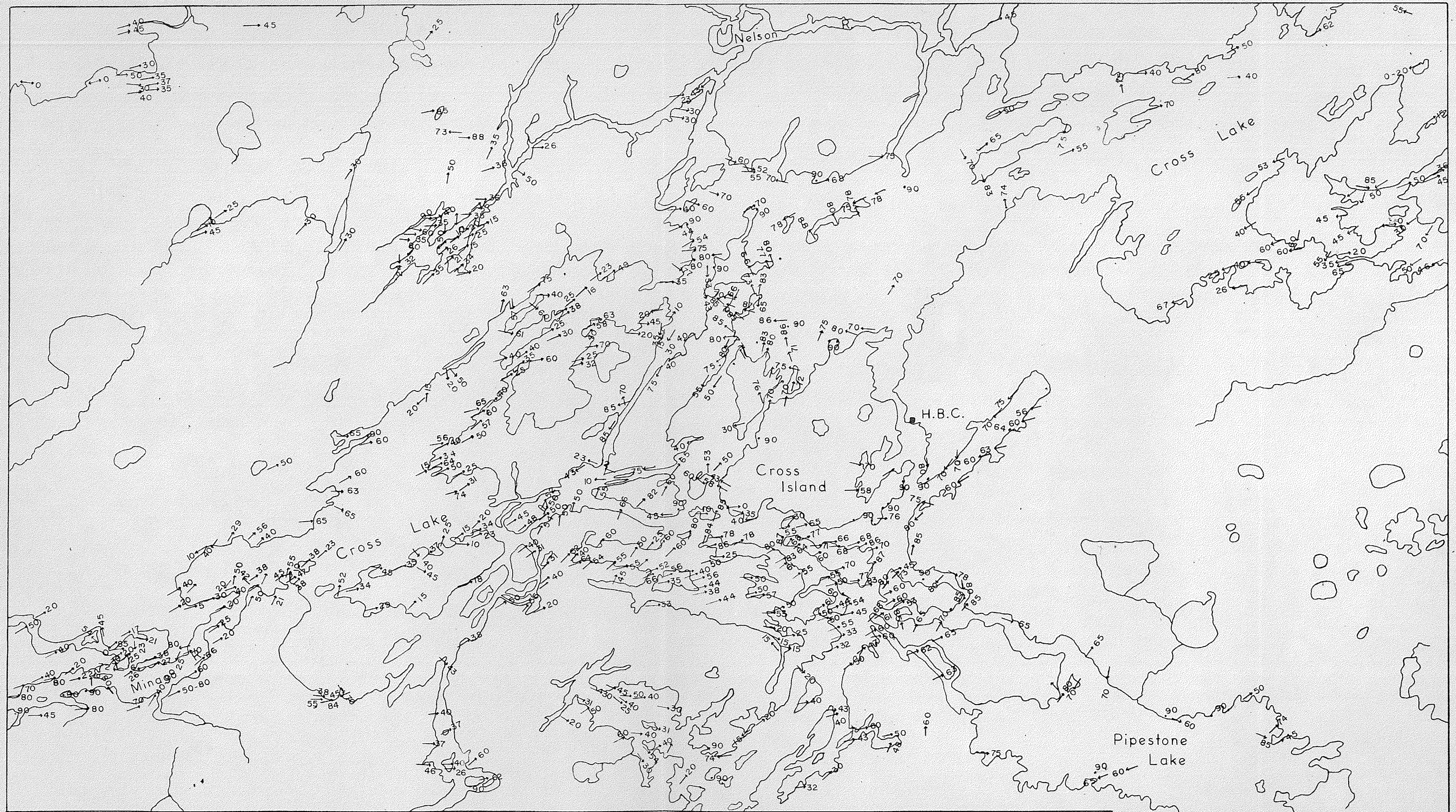
in the same outcrop or nearby localities. One of the theories of the origin of the structure (vertical uplift theory) suggests that these lineations are not parallel to the axes of the northeasterly- and southeasterly-trending major synclines and associated macroscopic<sup>1</sup> folds. The directions and plunges of the lineations are shown on Figure 8-1 (Page 140). The types of lineations are described below.

The directions and plunges of the axes of the mesoscopic folds described above were measured (except ptygmatic folds). Corrugations (Plate 12A, page 141) are restricted to paragneisses (4) and paragneiss migmatites (8). Corrugations are small-scale folds.

Lineated hornblende is common in basalt (2) (Plate 13A, 13B, page 142) and occurs locally in gabbro (5b) (Plate 12B, page 141). The long axes of quartz ellipsoids were measured in hypersthene gneisses (9e). These rocks are restricted to the northwestern part of the area. Rodding consists of pencil-like lineations (Plate 14A, page 143) that are restricted to paragneisses (4) and paragneiss migmatites (8).

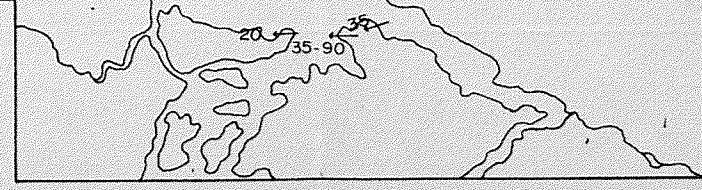
Pebbles in conglomerate (3) were tectonically elongated into the shapes of triaxial ellipsoids (Plate 14B, page 143). The amount of elongation depends on the degree of deformation and the pebble composition; basalt and siltstone pebbles are elongated more than quartz, quartzite, and granite. The ratios of the short to

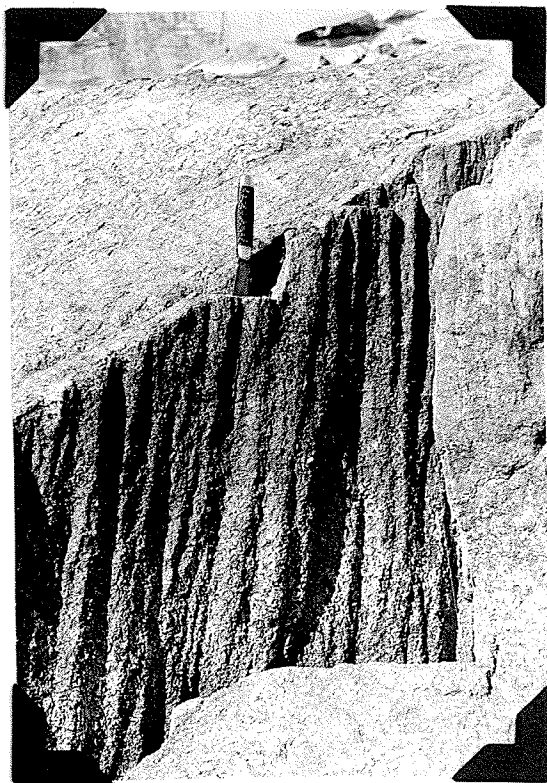
<sup>1</sup> Macroscopic folds are those too large to be observed in a single exposure and whose form and orientation can only be established by geologic mapping (after Turner and Weiss 1963, page 144).



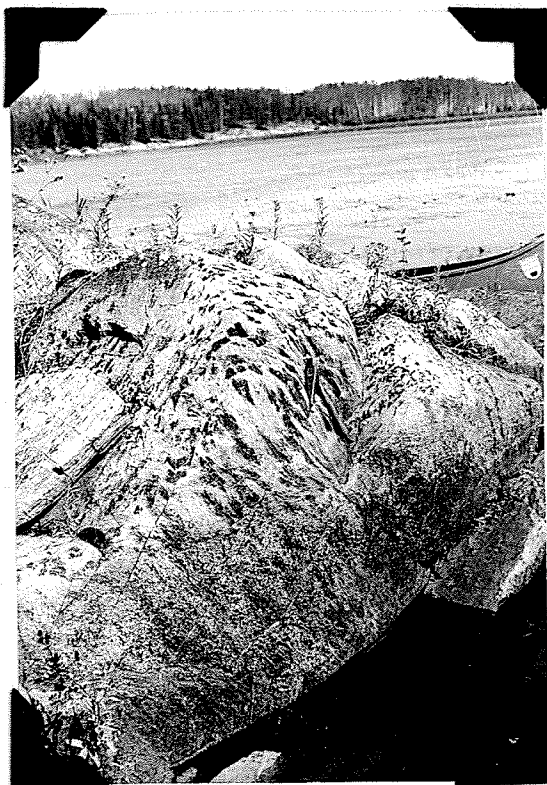
SCALE 0 1 2 3 4 MILES

Figure 8-1  
LINEATION MAP

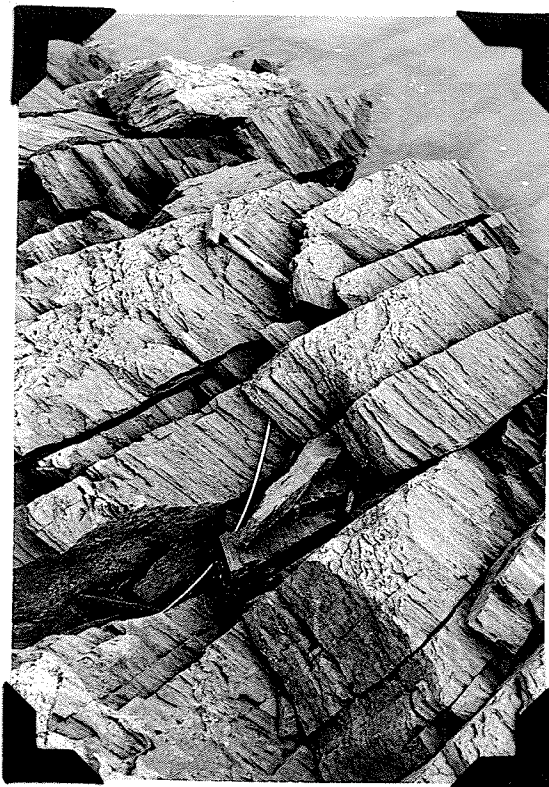




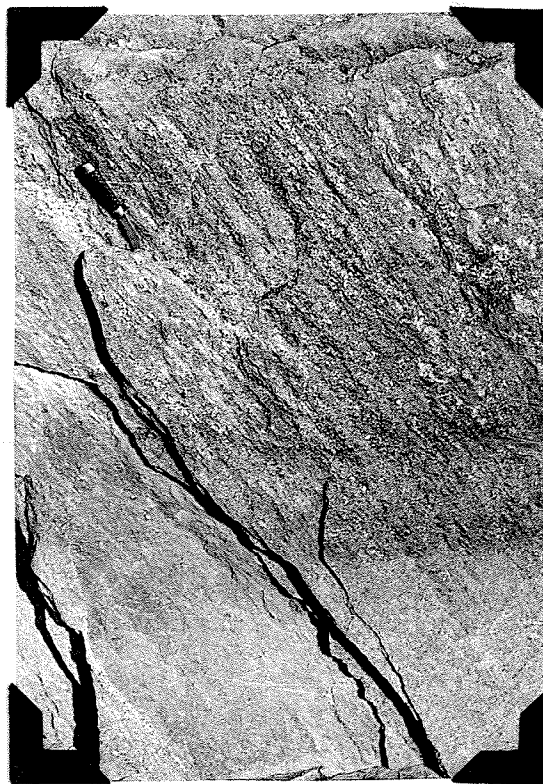
A. Corrugations in Paragneiss.



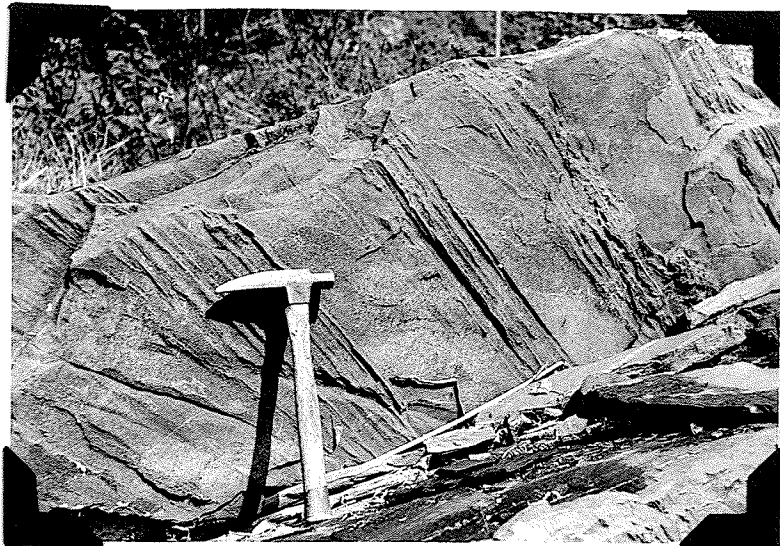
B. Hornblende Lineations in Gabbro.



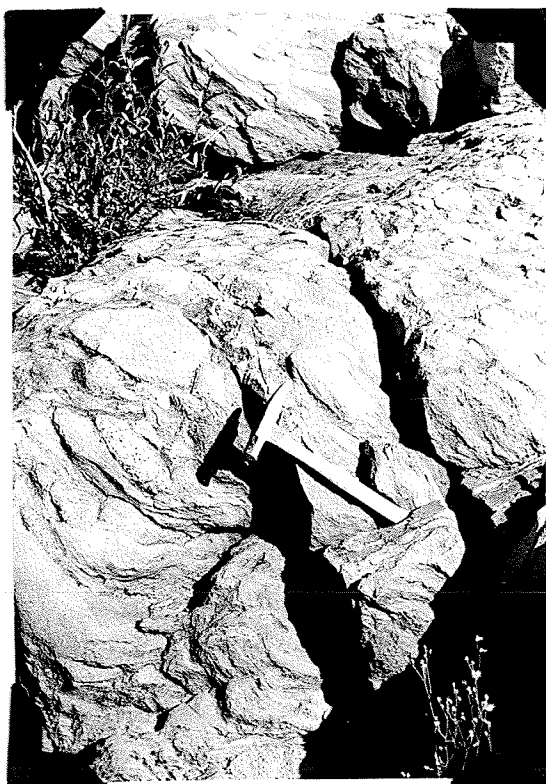
A. Hornblende Lineation Parallel to Hammer Handle; note jointing.



B. Hornblende Lineation.



A. Rodding



B. Elongated Pebbles - hammer handle along long axis.

intermediate to long axes vary from 1:3:10 to 1:3:50. The intermediate and long axes lie in the foliation planes. The lineations recorded were the directions and plunges of the long axes.

### Joints

Joints are common in the area and a single exposure may possess a bewildering number of them. Nevertheless, when considered statistically, they show a remarkably consistent orientation. Figure 8-2 (page 145) is a contour diagram of poles to joints based on one per square mile. They have a maximum orientation in the direction N35°W with dips vertical to 80°. Joints seldom show movement. Those that do are dealt with in the section on faults.

### Faults and Linear Features

The locations of faults and linear features are shown on Figure 8-3 (page 146).

Faults are not common in the area and the writer observed a total of only 24 faults. These were, with one exception, local and extended only a few tens of feet. One, at Eve's Falls, was traced about one mile. Of the 24 faults, 6 show a left-lateral and 8 a right-lateral component of displacement; the sense of the remainder could not be determined. The amount of horizontal slip was determined on only 3 faults and this was 9 feet in one case and less than one inch in the other two. The small faults appear to be genetically related to the joints as they are oriented in the same general direction.



CONTOUR DIAGRAM OF POLES TO 301 JOINTS  
GRID = ONE PER SQUARE MILE  
CONTOUR INTERVAL IN % = 8

FIGURE 8-2

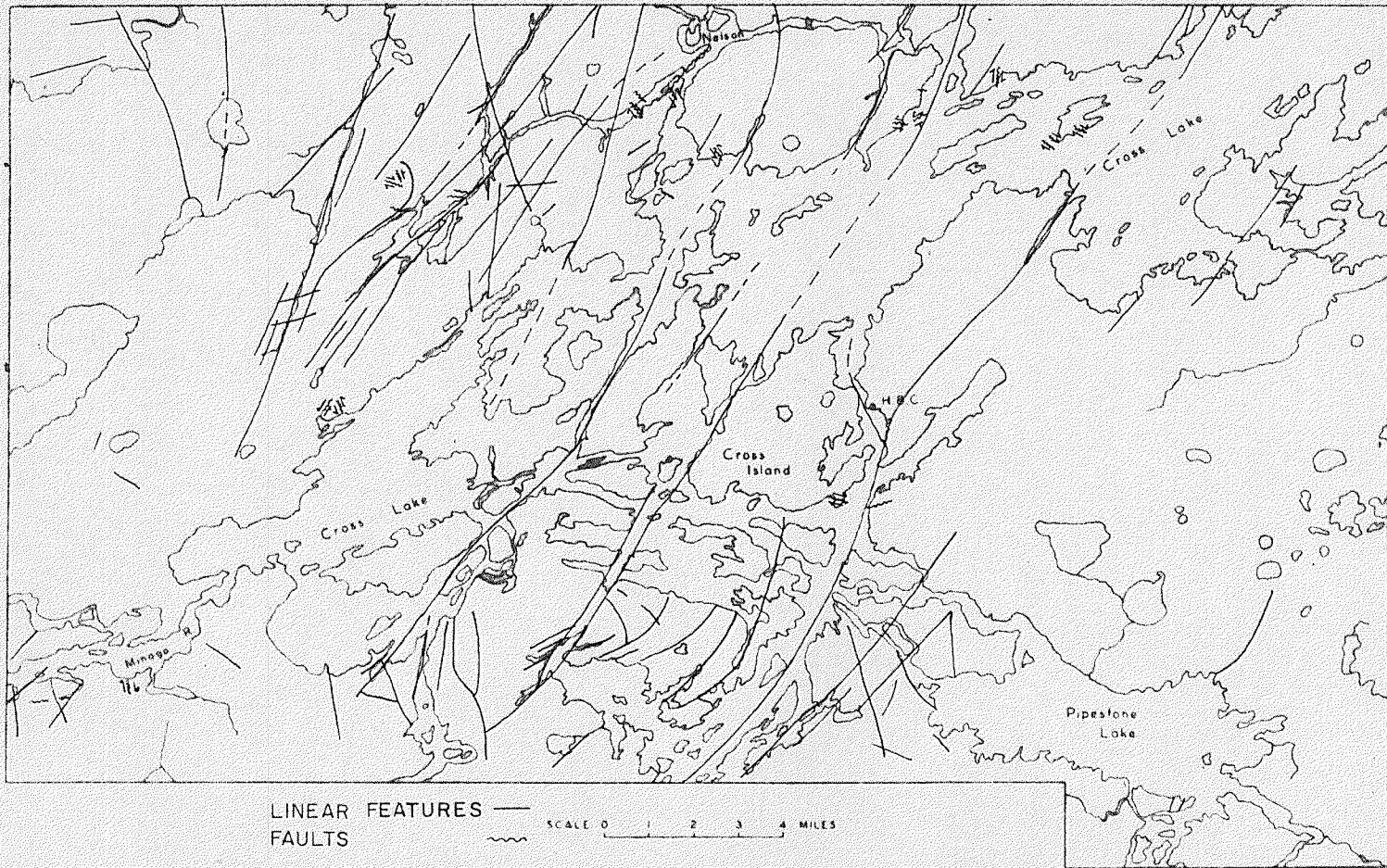


FIGURE B-3. LOCATION OF FAULTS AND LINEAR FEATURES

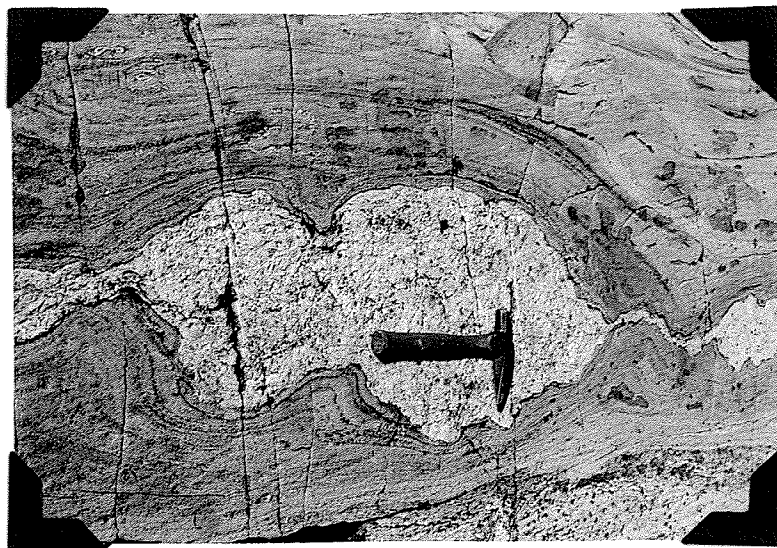
A number of prominent linear features were traced on the airphotos. The main trend is N35°E. Three can be followed approximately 21 miles until they pass out of the area. The linear features cut across structural trends without any apparent horizontal displacement and are therefore not strike-slip faults. They appear to be steep tensional fractures because some mafic dykes are aligned along them. Vertical displacement is not evident. The writer prefers the term linear feature rather than fault because there is no evidence for displacement. It seems unlikely that the joints and the linear features are genetically related. The former trend N35°W and extend only a few feet; the latter trend N35°E and can be traced for miles.

#### Boudins

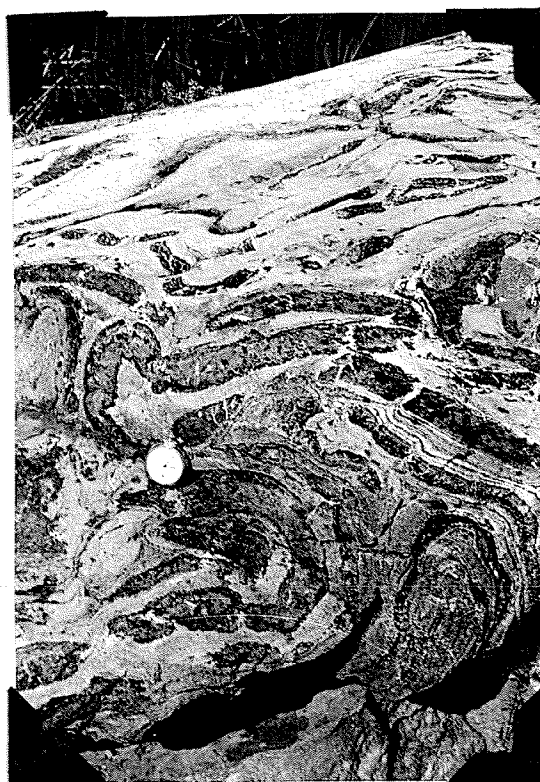
Plate 15A (page 148) shows a typical boudin of pegmatite in paragneiss migmatite (8). Note the presence of cross-cutting tension fractures. This type is identical to that shown in Plate 1D of Ramberg (1955). The long axes of boudins are parallel to the lineations in the area. Lineations classified as rodding appear to be micro-boudins. Pinch-and-swell structures are shown in Plate 15B (page 148). The dark "sausages" represent limey bands. These structures may be compared to those shown in Plate 2D of Ramberg (1955).

#### Foliation

Rocks of the area are strongly foliated. Foliation produced by tectonic processes has generally developed parallel to



A. Pegmatite Boudin in Sandstone - note tension fractures.



B. Pinch-and-swell Structures.

bedding planes in sedimentary rocks (3, 4) and primary layering in basalts (2). Rare examples of foliation not parallel to bedding are shown in Plate 5 (page 87) and Plate 16 (page 150). Layering in migmatites (6, 7, 8) and gneissosity in rocks of the gneiss complex (9) appear to be generally parallel to bedding in sedimentary rocks (3, 4) and banding in basalts (2).

#### STRUCTURE OF THE AREA

The general fold geometry of the area may be revealed in part by the orientation of the lineations if it is assumed that the lineations (including mesoscopic fold axes) are parallel to the axes of the major folds. It must be re-emphasized that one theory of the origin of the structure (vertical uplift theory) suggests that the lineations are not parallel to the axes of the major folds. Hence the orientation of the major fold axes would not correspond to the orientation of lineations.

Figure 8-4 (page 151) is a contour diagram derived from the plots of the trends and plunges of all recorded lineations. Lineations show a concentration about a girdle which lies in a plane that trends N62°E and dips vertically. The maximum pole concentration indicates plunges of 80° to 90° in the direction N62°E. There is a lesser concentration of poles plunging 30° to 60° in the direction N62°E. The diagram also shows poles that plunge steeply to the southwest. This may be explained by either a rotation of northeasterly-plunging lineations in the plane of the girdle to the vertical and beyond or a rotation of southwesterly-

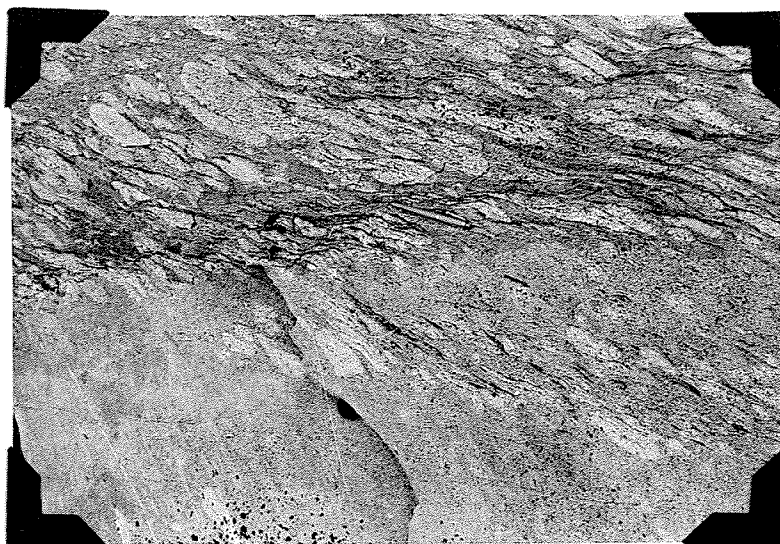
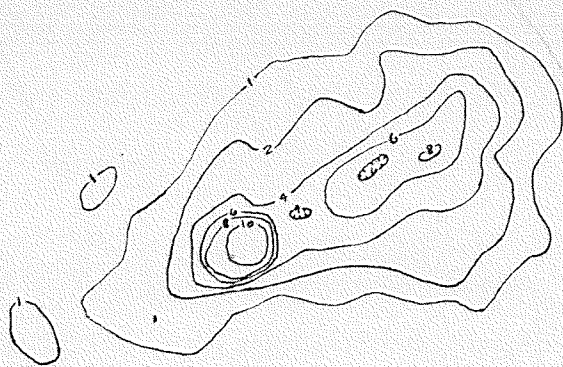
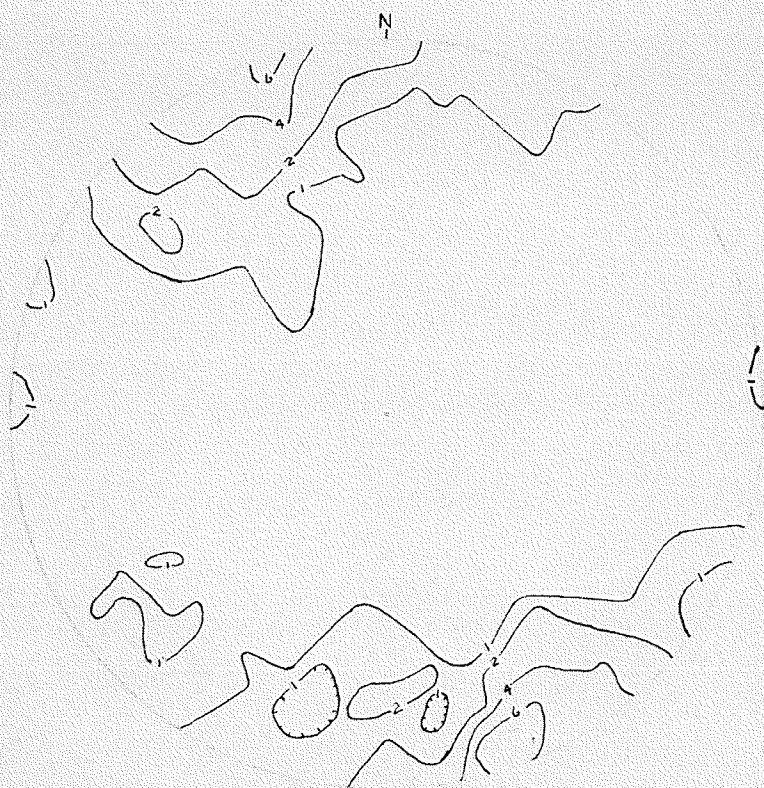


PLATE 16. Non-parallel Primary and Secondary Foliation.



CONTOUR DIAGRAM OF 609 LINEATIONS  
 CONTOUR INTERVAL IN % -6-

FIGURE 8-4



CONTOUR DIAGRAM OF POLES TO 476 FOLIATION PLANES  
 GRID = ONE PER SQUARE MILE  
 CONTOUR INTERVAL IN % -4-

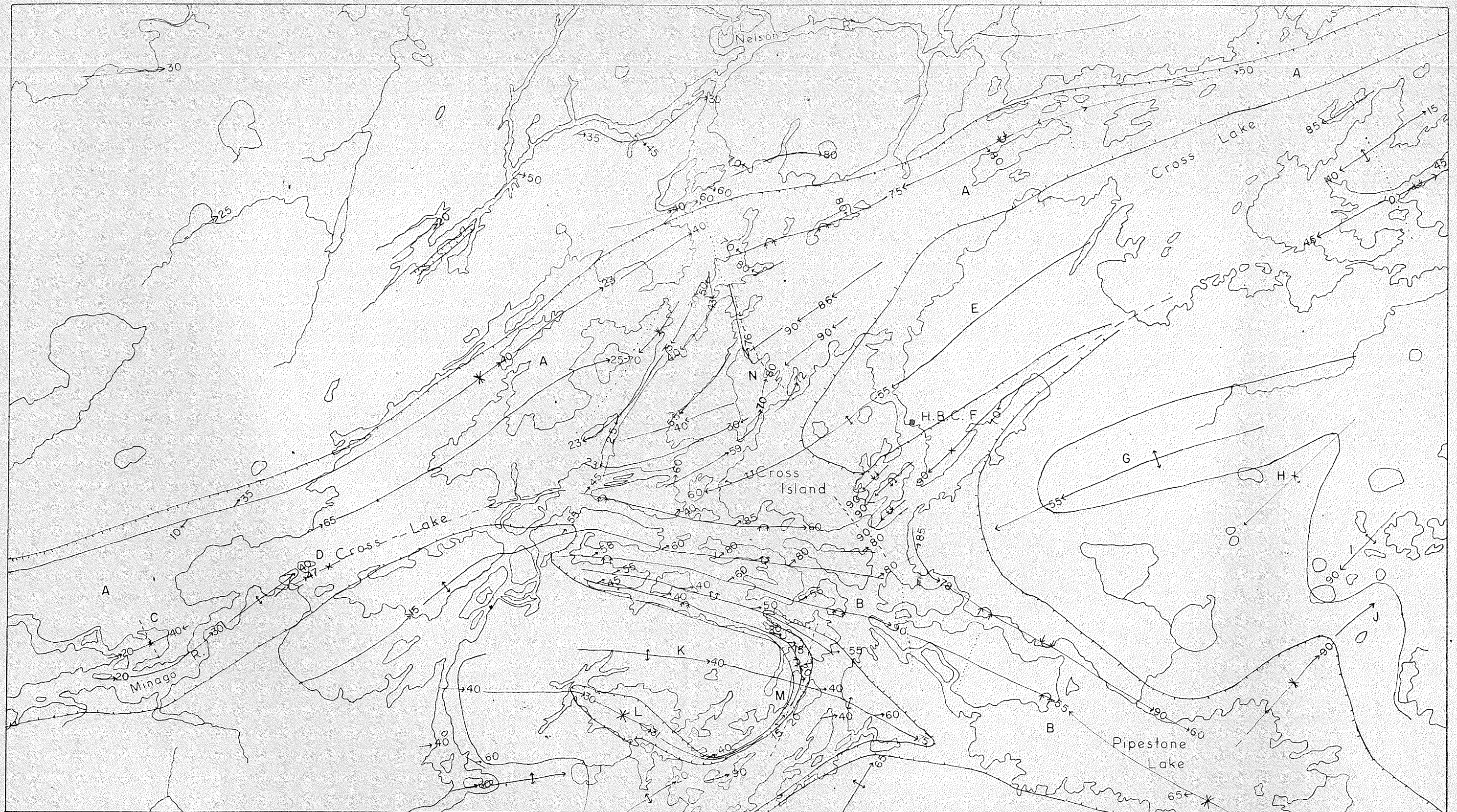
FIGURE 8-5

plunging lineations to the vertical position. Both cases may be correct. The former case suggests the presence of synformal anticlines and antiformal synclines.

The general fold geometry of the area is shown in part by a statistical analysis of foliation. Figure 8-5 (page 151) is a contour diagram based on plots of one pole to foliation per square mile. It suggests that the mean axial plane strikes  $N70^{\circ}E$  and dips  $84^{\circ}$  south. The absence of an AC girdle (i.e. one perpendicular to fold axes) suggests that folds are isoclinal. The angle between the strike of the mean axial plane of the folds ( $N70^{\circ}E$ ) and the trend of the horizontal projection of the fold axes ( $N62^{\circ}E$ ) is only 8 degrees. This may suggest that the amount of overturning of folds is not great.

The main structural features of the area are shown on Figure 8-6 (page 153). Sedimentary and volcanic rocks (2, 3, 4) occupy structural synclines and rocks of the gneiss complex (9) occupy structural anticlines. This is based on outcrop patterns and foliation attitudes. Three main structural trends are apparent and these are, in order of importance: northeast; southeast; and north northeast to north northwest respectively.

The dominant structural feature consists of a northeasterly-trending major syncline (A on Figure 8-6). This syncline is bifurcated near the central part of the area. There, one arm (A) trends northeasterly while the other arm (B on Figure 8-6) swings and trends in a southeasterly-direction.

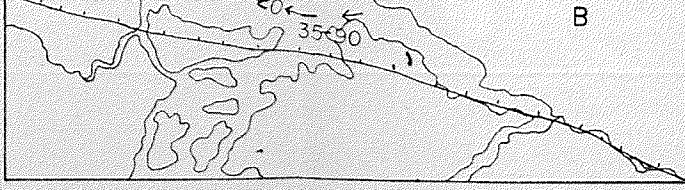


LEGEND

- AXIAL TRACE AND PLUNGE OF ANTICLINE, OVERTURNED ANTICLINE     $\uparrow$  55     $\cup$  80
- AXIAL TRACE AND PLUNGE OF SYNCLINE; OVERTURNED SYNCLINE     $\ast$  20     $\uparrow$  78
- CROSS FOLDS: REAL; POSSIBLE     $\cdots$      $\cdots$
- DIRECTION AND PLUNGE OF LINEATION     $\rightarrow$  40
- FEATURE REFERRED TO IN TEXT    A, B ETC.
- AREA ENCLOSED BY SEDIMENTARY AND VOLCANIC ROCKS     $\epsilon$

SCALE 0 1 2 3 4 MILES

Figure 8-6  
STRUCTURAL MAP



Outcrop patterns and foliation attitudes indicate that a number of macroscopic folds are superimposed on the major synclines. The axial traces of the macroscopic folds are shown on Figure 8-6 and they have the same trends and plunges as those of the major synclines. The amount of plunge of the macroscopic folds located along the Minago River (C and D on Figure 8-6) is based on the dips of bedding at the noses of the folds. Elsewhere, the amount of plunge of macroscopic folds is based on the plunge of lineations. This relationship is valid for the horizontal compression theory, but not for the vertical uplift theory.

The structure between the two major synclines (A and B) is a dominately anticlinal one, but in detail consists of several anticlines (E, G, I) and synclines (F, H, J) which trend and plunge to the southwest. An anticline (K) and a syncline (L) occur south of syncline B and these trend and plunge to the southeast. Trends south of syncline L are to the northeast.

Cross folds trend from north northwest to north northeast. Those shown as "real" on Figure 8-6 (C, M, N, O) were traced by means of outcrop pattern and the transverse trend of foliation. Those shown as "possible" on Figure 8-6 are located where lineations converge or diverge. They appear as culminations and depressions on the axial traces of the major northeasterly- and southeasterly-trending structures. Figure 8-7 (page 155) is a vertical section approximately parallel to the axis of major syncline B and shows the culminations and depressions along the axis. The "possible"

cross folds do not exist if the lineations are not parallel to the major fold axes.

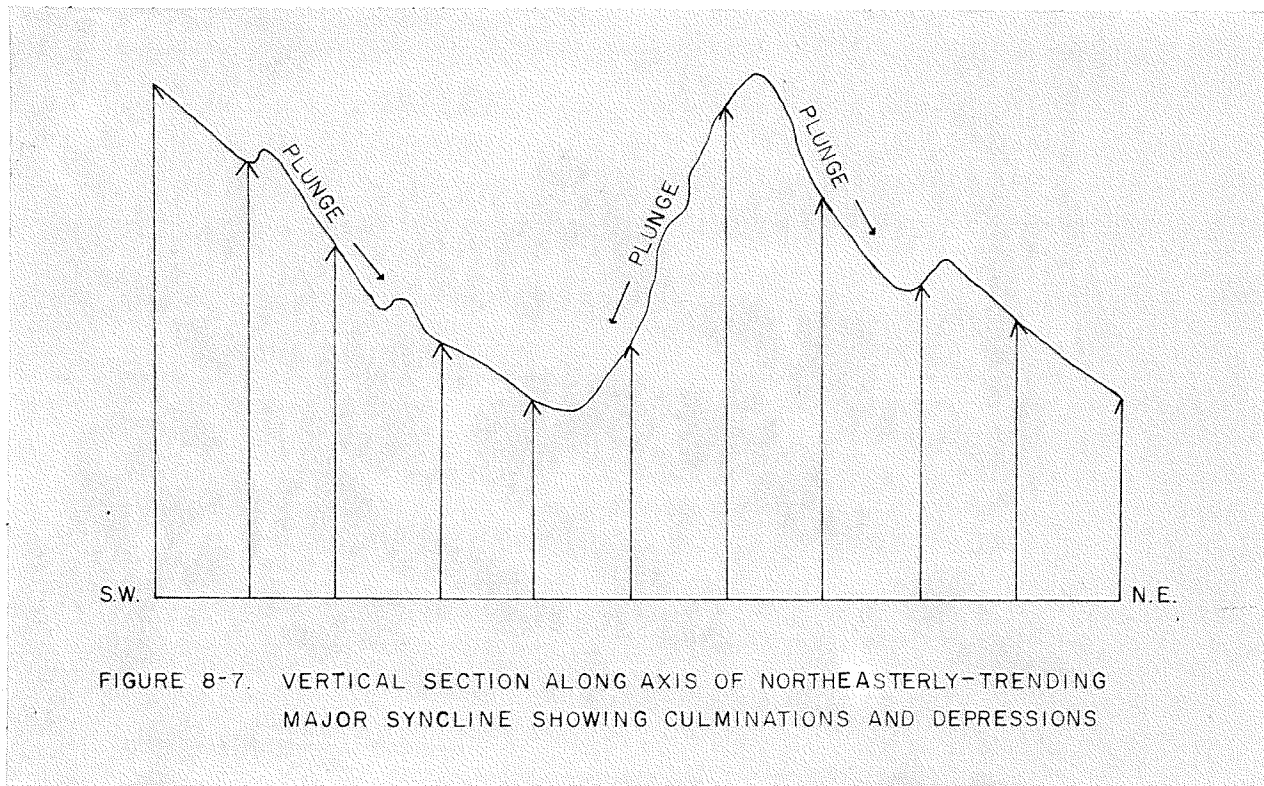


FIGURE 8-7. VERTICAL SECTION ALONG AXIS OF NORTHEASTERLY-TRENDING MAJOR SYNCLINE SHOWING CULMINATIONS AND DEPRESSIONS

### ORIGIN OF THE CROSS LAKE STRUCTURE

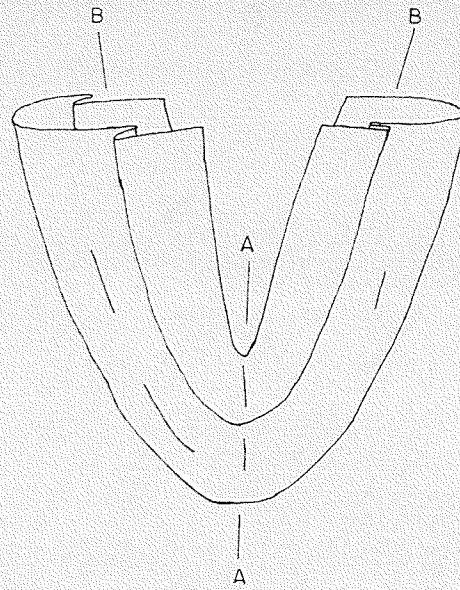
#### Horizontal Compression Theory

This theory requires two and perhaps three periods of folding to account for the structure. The maximum compressive stress acted in an east-west direction during the first period of folding.

This produced folds that trend from north northwest to north northeast and includes both the "real" and "possible" cross folds shown on Figure 8-6.

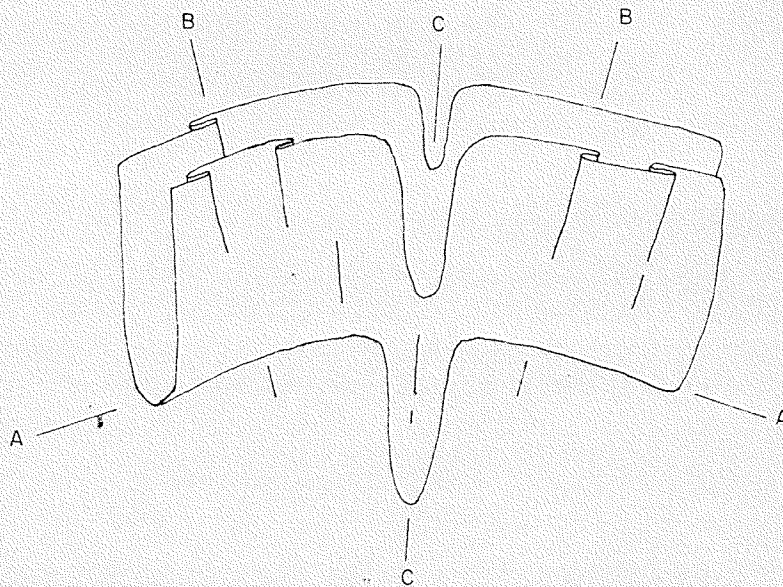
Possibly two periods of folding occurred in order to produce the southeasterly- and northeasterly-trending folds. Maximum stress directions for the second and third periods would be southwest-northeast and southeast-northwest respectively. It is also possible that the southeasterly- and northeasterly-trending folds were produced by a single period of folding. The north-easterly and southeasterly-trending major synclines (A and B in Figure 8-6) lie on the flanks of a large regional anticline whose axis trends easterly to slightly north of east (see Bell, 1962). Only the nose of this anticline lies within the area of study (shown as "major anticline" in Figure 8-6). Perhaps the maximum compression stress acted normal to this axis in a regional sense and local variations occurred.

Figure 8-8a (page 157) is a diagrammatic sketch of the fold geometry based on the horizontal compression theory. The axis labelled A is that of the cross folds produced by the first period of folding. This includes north northwesterly- and north northeasterly-trending folds such as those at M and N on Figure 8-6. The axis labelled B corresponds to fold axes produced by the second (and third) period of folding. The latter includes the major synclines and anticline, the macroscopic folds, and the associated lineations. The second period of folding was more intense than the first.



A-A AXES OF CROSS FOLDS AND LINEATIONS  
 B-B AXES OF MACROSCOPIC FOLDS, LINEATIONS,  
 AND MESOSCOPIC FOLDS

(a)



A-A AXES OF MACROSCOPIC FOLDS  
 B-B AXES OF MESOSCOPIC FOLDS AND LINEATIONS  
 C-C AXES OF CROSS FOLDS

(b)

FIGURE 8-8 FOLD GEOMETRY : (a) HORIZONTAL COMPRESSION THEORY; (b) VERTICAL UPLIFT THEORY

### Vertical Uplift Theory

Belousov (1962) is one of the most currently active proponents of folding produced by forces acting in a vertical direction. He refers to this type of folding as deep or metamorphic, supports his ideas with scale models and field studies, and draws strong analogies to salt dome tectonics. According to Belousov (1962) this type of folding results when sedimentary rocks are buried to such considerable depths that the underlying crystalline basement melts. This gives rise to a granite magma which rises because it is less dense than the overlying sedimentary rocks. The magma uplifts and folds the overlying rocks. Fold axes are horizontal or inclined, depending on the amount of differential uplift. Sedimentary rocks caught between steep-walled columns of rising granite are squeezed by horizontal forces and flow into areas where these granite columns are furthest apart. This will produce folds with vertical axes superimposed on the folds with horizontal or inclined axes.

Carey (1962, page 128) also discusses folding in terms of vertical forces. Vertically rising tongues of magma or salt gives rise to folds associated with mantled gneiss domes or salt domes. Sedimentary beds which were originally horizontal are forced to flow in a vertical direction by the rising magma. Sedimentary beds are folded and Carey (1962) refers to this process as paraboloidal folding. It is actually similar (i.e. shear) folding because sedimentary beds maintain a constant thickness in the

direction of flow. As the beds flow upward, the flow lines may diverge. This causes an expansion in the cross-section surface. When the flow lines converge again the cross-section surface does not shrink back to the size before expansion in an elastic manner; it converges through the development of wrinkles and mullion-like folds. These structures are characteristic of rocks that have flowed long distances. The axes of the wrinkles are parallel to the direction of flow not normal to them. The axes of the similar folds are normal to the flow directions. The wrinkles and mullion structures of Carey (1962) are apparently the same as the vertical folds described by Belousov (1962). They describe their formation in a somewhat different manner.

Figure 8-8b shows diagrammatically the fold geometry at Cross Lake if the structure had been produced by vertical uplift. The axis labelled A corresponds to the axes of the major synclines (A and B, Figure 8-6) the major anticline, and the macroscopic folds. All these are similar folds. The axis labelled B corresponds to the axes of the lineations, including the mesoscopic folds. The axes of the lineations are parallel to the flow directions and perpendicular to the axes of the similar folds.

Areas occupied by rocks of the gneiss complex (9) are structurally high and were uplifted relatively more than the structural synclines occupied by the sedimentary and volcanic rocks (2, 3, 4). Plunging similar folds such as the major anticline and those located at the cross folds indicated as "real" on Figure

8-6 are produced by differences in vertical uplift along the axial planes. The axis labelled C on Figure 8-8b corresponds to these cross folds. Cross folds shown as "possible" on Figure 8-6 are located where the plunges of lineations converge or diverge. Places where the plunges of lineations converge simply represent places where vertical flow lines diverge and diverging lineations are where the flow lines converge.

#### Combined Theory

This theory is a combination of the first two theories presented. Two alternatives are possible. The first suggests that the "real" cross folds were produced by a horizontal compression during an initial period of folding. The northeasterly- and southeasterly-trending structures were produced by vertical uplift during a second period of folding. The fold geometry will resemble that shown on Figure 8-8b except that any lineations produced during the first period of folding will be parallel to the axes of the cross folds.

The second alternative is that the "real" and "apparent" folds were produced by vertical uplift during an initial period of folding. The northeasterly- and southeasterly-trending folds were produced by a horizontal compression during a second period of folding. The fold geometry will resemble that shown on Figure 8-8a, except that any lineations produced during the first period of folding will be perpendicular to the axes of the cross folds.

## Discussion and Conclusions

The northeasterly- and southeasterly-trending major folds are similar folds if produced by a vertical uplift and concentric folds if produced by a horizontal compression. The major folds are too large to be observed in a single outcrop. Statistical data (Figure 8-5, page 151) suggests that the major folds are isoclinal folds. Shear planes will be parallel to bedding planes except in the axial regions if the major folds are isoclinal similar folds. Shear planes transverse to bedding planes occur at Cross Lake but they are uncommon. Most mesoscopic folds are concentric folds. It does not necessarily follow that the major folds are concentric folds.

The axes of the major structures and lineations are parallel if they were produced by a horizontal compression and normal if produced by a vertical uplift. The outcrop pattern around the noses of the folds labelled E, F, and G on Figure 8-6 is arcuate. The plunges of these fold axes, determined from the dips of foliation planes, are essentially parallel to that of the associated lineations. This suggests that these folds are concentric folds.

Sedimentary and volcanic rocks (2, 3, 4) at Cross Lake were intruded lit - par - lit by quartzo-feldspathic material and granitized. These intrusions could have caused vertical uplift and the formation of similar folds. The origin of the horizontal forces is not readily apparent, but this does not negate their existence.

The major folds appear to have been superimposed upon

the north northeasterly- and north northwesterly-trending cross folds. If this is so, then the cross folds were produced before the major folds during an earlier period of folding. Evidence suggests that the major folds are mainly concentric folds. It was not possible to determine if the cross folds were the result of a horizontal compression or a vertical uplift.

In conclusion, the structure at Cross Lake was likely produced during two periods of folding. The nature of the forces which acted during the first period is not known. The major folds appear to be concentric folds that were formed by a horizontal compression. Nevertheless, it may be that the major folds are at least in part similar folds and that a complex interplay of stresses produced the structure at Cross Lake.

CHAPTER IXGEOLOGICAL HISTORY OF THE AREA AND REGIONAL CONSIDERATIONSGEOLOGICAL HISTORY

The sequence of geological events at Cross Lake are set out in Table 9-1 (page 163) and are based on age dates and structural and petrological information. Specimens from the area aged by the K-Ar method are listed in Table 9-2 (page 164) and their locations are shown on Figure 9-1 (page 170). The first three ages listed are from specimens collected by the writer, dated by the Department of Geology, University of Alberta and published by Burwash et al. (1962). The last three ages listed are all from the same specimen. Their data are given by Lowden et al. (1963, page 72). A second biotite age determination was made because of a large discrepancy between the biotite and muscovite ages obtained from earlier determinations.

Sample AK206 is from a biotite granodiorite gneiss which petrologically resembles the older basement biotite granodiorite gneiss<sup>1</sup> (1) more than the younger biotite granodiorite gneiss (9a). This sample was dated at 2500 m.y. and if it does represent a sample of the basement gneiss (1), then several alternatives are possible. These are: the basement gneiss (1) formed 2500 m.y. ago; it formed

<sup>1</sup> The basement biotite granodiorite gneiss (1) can be positively identified at only one locality; at the unconformity on Cross Island.

TABLE 9-1  
SEQUENCE OF EVENTS

EON	ERA	OROGENY	EVENT	REMARKS
P R O T E R O Z O I C	M I D D L E		8. Formation of joints and minor faults	Main trend - N.W.
	+		7. Mafic dyke (10) emplacement	May be more than one period
	U P P E R		6. Development of N.E. trending linear features	Tensional features
	?			
	L O W E R	HUDSONIAN 1700 m.y.	5. Metamorphism, folding, and granite intrusions; granitization of Cross Lake group rocks (2, 3, 4)	Development of migmatites (6, 7, 8) and gneiss complex (9); major folds
			4. Emplacement of anorthosite and gabbro (5)	During early stages of 5
A R C H A E A N		KENORAN 2500 m.y.	3. Deposition of Cross Lake group (2, 3, 4)	N.N.E and N.N.W.-trending folds produced
			2. Erosion of basement gneiss (1)	Possible uplift
			1. Formation or recrystallization of basement biotite granodiorite gneiss (1)	Skialiths in gneiss suggest earlier orogenic cycle

TABLE 9-2

## AGE DATES

SAMPLE NO.	LOCATION	MINERAL DATED	AGE M.Y.	ROCK TYPE
AK206	54°38'N 97°47'W	Biotite	2500	Basement biotite granodiorite gneiss (1) ?
AK207	54°36'N 97°56'W	Biotite	1840	Adamellite (9c)
AK213	54°35'N 97°45'W	Biotite	2080	Granodiorite pebble in conglomerate (3b)
GSC 60-84 *	54°39'15"N 97°58'00"W	Biotite	2065	Garnet paragneiss (4a)
GSC 61-124*	54°39'15"N 97°58'00"W	Biotite	2135	
			} average = 2100	
GSC 61-125 *	54°39'15"N 97°58'00"W	Muscovite	1680	Garnet paragneiss (4a)

\* Same specimen.

earlier and was recrystallized 2500 m.y. ago; or it formed prior to 2500 m.y. ago, was recrystallized by the Hudsonian orogeny and the date represents a survival value. The Cross Lake group (2, 3, 4) was deposited unconformably on the basement gneiss (1). The alternatives given above for the basement gneiss (1) suggest that the Cross Lake group (2, 3, 4) is Lower Proterozoic in the first case and either Lower Proterozoic or Archaean in the latter two cases.

The average of the two biotite ages from garnet paragneiss (4a) (GSC60-84, GSC61-124) is 2100 m.y.; the muscovite age (GSC61-125) is 1680 m.y. Lowden et al. (1963, page 72) believe that the muscovite date is closer to the true age of crystallization because argon was later added to biotite. Sample AK213 is a pebble from a conglomerate (3b) and it gave an age of 2080 m.y. Burwash et al. (1962) suggest that this represents a survival value. They believe that intermediate ages are due to the expulsion of radiogenic argon from minerals during the Hudsonian orogeny which had originally crystallized during the Kenoran orogeny. Stockwell (in Lowden et al., 1963, page 127) pointed out the uncertainties involved concerning age date discrepancies. Age dates from rocks of the Cross Lake group (2, 3, 4) suggest that they were either crystallized by the Kenoran orogeny and recrystallized by the Hudsonian orogeny or that they were crystallized at some intermediate time.

An adamellite (9c) sample (AD207) gave an age date of 1840 m.y. The adamellite could have been formed during the Kenoran orogeny and recrystallized by the Hudsonian orogeny in which case

the date is a survival value. The adamellite could also have been formed approximately 1840 m.y. ago. Age dates indicate the Cross Lake group (2, 3, 4) was either metamorphosed during the Hudsonian orogeny or at a time intermediate between that of the Kenoran and Hudsonian orogenies. Petrologic studies show that rocks of the Cross Lake group were granitized by injected quartzo-feldspathic material and that this occurred after the metamorphism. The age-dated adamellite may represent either granitized material or possibly a post-metamorphic intrusion.

Several theories concerning the origin of the Cross Lake structure were discussed in Chapter VIII. The evidence suggested that the area underwent two periods of folding and that these probably corresponded to the Kenoran and Hudsonian orogenies. Apart from producing the cross folds, the effects of the Kenoran orogeny are not well known. The Hudsonian orogeny metamorphosed and granitized the pre-existing rocks and produced the dominant structures. Evidence was presented in Chapter VI which suggested that the gabbro-anorthosite bodies (5) intrude the Cross Lake group (2, 3, 4). These bodies were emplaced prior to or during the earlier stages of the Hudsonian orogeny.

The northeasterly-trending linear features cut across structural trends produced by the Hudsonian orogeny. They are considered to be tensional features because mafic dykes (10) occur in them. Joints and small faults cut across mafic dykes (10) and their formation is the last recognizable Precambrian event at Cross Lake.

## REGIONAL CONSIDERATIONS

### Previous work

Based on variations in structural trends, Gill (1952) showed that a boundary between two geological provinces, Churchill and Superior, lay in northern Manitoba. He stressed that a shield-wide Archaean orogeny is a misconception and that blocks or provinces of the shield formed at different times. J. T. Wilson (1957) demonstrated that the granites of the Superior province are older than those of the Churchill province. The large number of age dates available within the last five years has generally confirmed this.

Stockwell (in Lowden, 1961) proposed the name Hudsonian orogeny for the last main orogeny to affect the Churchill province and gave a median age of 1700 m.y. for this orogeny. The Kenoran orogeny, with a median age of 2500 m.y., is considered to be the last main orogeny to affect the Superior province.

A Bouguer gravity anomaly high, called the "Nelson River High" by Innes (1960), trends parallel to the Nelson River and lies near the centre of a gneissic zone. Wilson and Brisbin (1961) refer to this zone as the "Nelson River gneissic zone". They suggest the gneissic zone is approximately 50 miles wide and that it separates the Churchill and Superior provinces. In a more recent paper, Wilson and Brisbin (1962) point out that although the gneissic zone as a unit trends northeasterly, there are remnant east-west trends

within the gneissic zone that correspond to those of the Superior province. Wilson and Brisbin (1961) suggest that the westerly-trending greenstone belts of the Superior province are truncated by the gneissic zone and that faulting occurs at this boundary.

Gravity work by Wilson and Brisbin (1961) has revealed a Bouguer gravity low. This negative strip is located along a zone of intense faulting and coincides with the Thompson-Moak Lake nickel deposits. They suggest that this zone marks the boundary between the Churchill and the Superior province (i.e. gneissic zone). Wilson and Brisbin (1961) believe that the whole pattern of gravity anomalies, faulting, and peridotites is analgous to an island arc-alpine structure. The negative gravity strip coincides with the roots of an ancient mountain system. The Superior block, lying on the concave side of the arc, represents the former continent. Graben structures occur on the concave side of some alpine-type mountain belts and form angles of about  $45^{\circ}$  with them. This interpretation has been given to the Cuthbert Lake lineament.

Detailed mapping by Patterson (1963) suggests that the Churchill-Superior (i.e. gneissic zone) contact does not follow the axis of the gravity low. Patterson (1963) separated the Thompson-Moak Lake area into three blocks: a western Proterozoic block; a central block; and an eastern Archaean block. The central block is a zone of dislocation. Patterson (1963, page 7) believes that the charnockites at Thompson-Moak Lake are Archaean in age and stated "That the pyroxenes were formed before the Proterozoic

orogeny is indicated by the gradual increase in the intensity of their alteration in the Archaean rocks from east to west toward the Proterozoic-Archaean contact".

Lowden et al. (1963, page 73) suggest that although the Cross Lake area is within the Superior province, it lies within a belt some 60 miles wide and 270 miles long that has been reworked by the Hudsonian orogeny.

#### Present Interpretation

The Cross Lake area is shown in a regional setting in Figure 9-1 (page 170). The contact between the Churchill province and the gneissic zone is shown as that of Patterson (1963). The writer has extrapolated this contact to the southwest on the basis of structural trends. The contact between the Superior province and the gneissic zone is shown to coincide with the northwestern limit of the Cross Lake sedimentary-volcanic belt. This is in the sense of Wilson and Brisbin (1961).

The Cross Lake sedimentary-volcanic belt is not truncated by the gneissic zone and faulting does not occur along this boundary. The northwesterly-trending arm of the belt turns to the southwest and parallels the trend of the gneissic zone. The southwesterly-trending arm continues southwest beyond the junction with the northwesterly-trending arm and also parallels the gneissic zone trend. The contact between the Cross Lake sedimentary-volcanic belt and the gneissic zone is a gradational one. Rocks of the Cross Lake

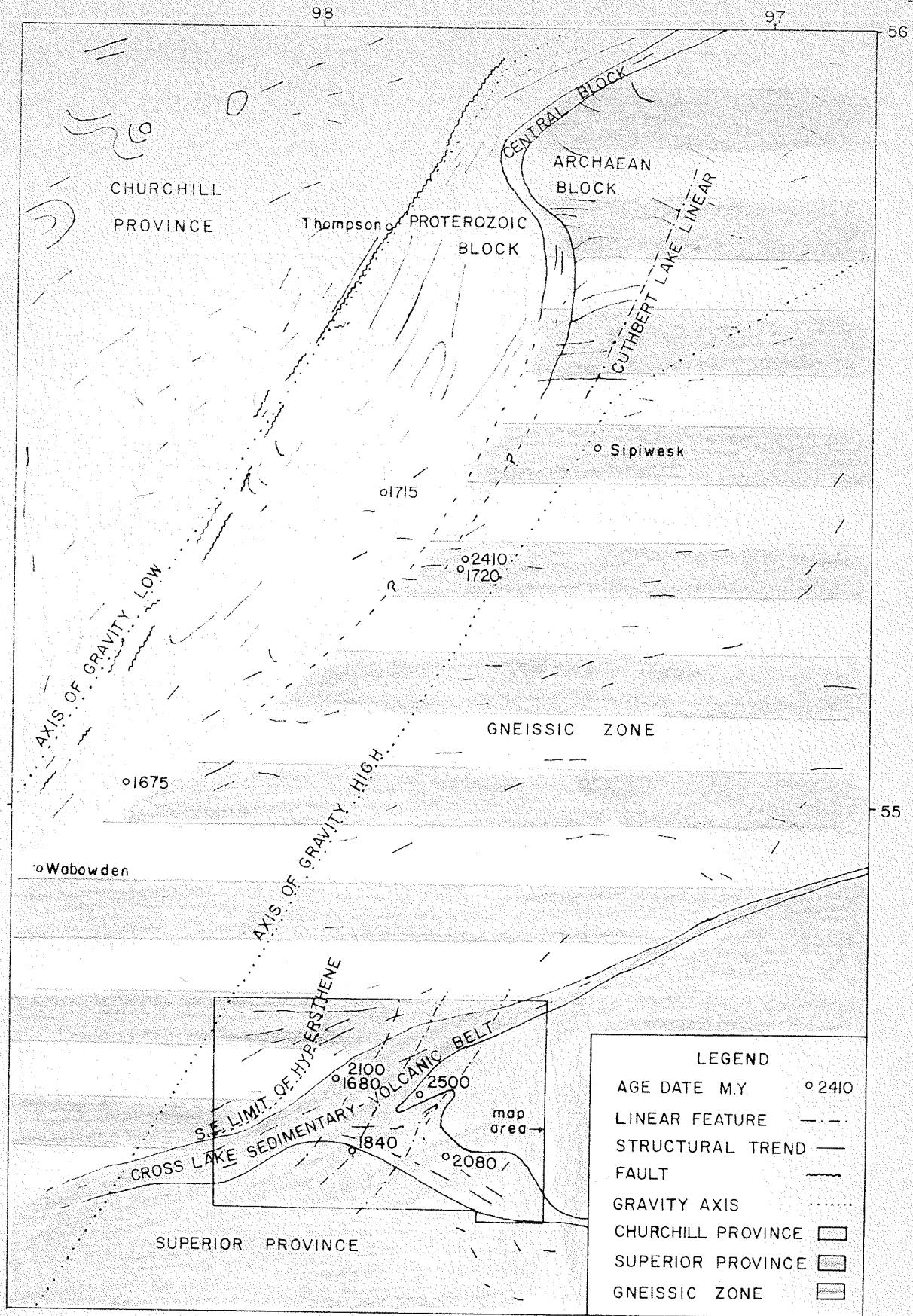


FIGURE 9-1 REGIONAL MAP

group (2, 3, 4) and some migmatites (6, 7, 8) derived from the group occur southeast of the contact. Migmatites (6, 7, 8) and rocks of the gneiss complex (9) derived from the granitization of Cross Lake group rocks (2, 3, 4) occur northwest of the contact.

The writer suggests that the charnockites of the Thompson-Moak Lake area may have been developed by the Hudsonian orogeny as were hypersthene-bearing gneisses (9e) at Cross Lake. The fault zone which Patterson (1963) considered to mark the Churchill-Superior boundary might be a post-Hudsonian feature. If this is so, then the gradual alteration of the pyroxenes in the charnockites westward toward this fault zone is not evidence that the charnockites are Archaean in age. Nevertheless, it must be pointed out that the charnockites in the Thompson-Moak Lake area are on strike with those at Dafoe Lake, approximately 30 miles to the east. These were dated at 2400 m.y. (GSC 60-83).

Available evidence suggests that the Hudsonian orogeny produced the intense folding, metamorphism, and granitization at Cross Lake. Age dates for the region are located on Figure 9-1. Dates which indicate Hudsonian effects on the "Superior" province immediately beyond this region are: quartz monzonite at Playgreen Lake (GSC60-85, 2190 m.y.); cordierite schist at Utik Lake (GSC 61-126, 2155 m.y.); microcline granite-gneiss 7 miles south of Robinson Portage (GSC61-127, 1970 m.y.); and porphyritic granite at Knee Lake (M.I.T. B3809, 1640 m.y.). If a shield province is defined by the last major orogeny to effect it, then the Cross Lake area is within the Churchill province. The grade

of metamorphism at Cross Lake decreases toward the southeast. The writer suggests that the boundary between the Churchill and Superior provinces lies somewhere south of Cross Lake. It is probably a gradational one where effects of the Hudsonian orogeny fade and disappear into the Superior province.

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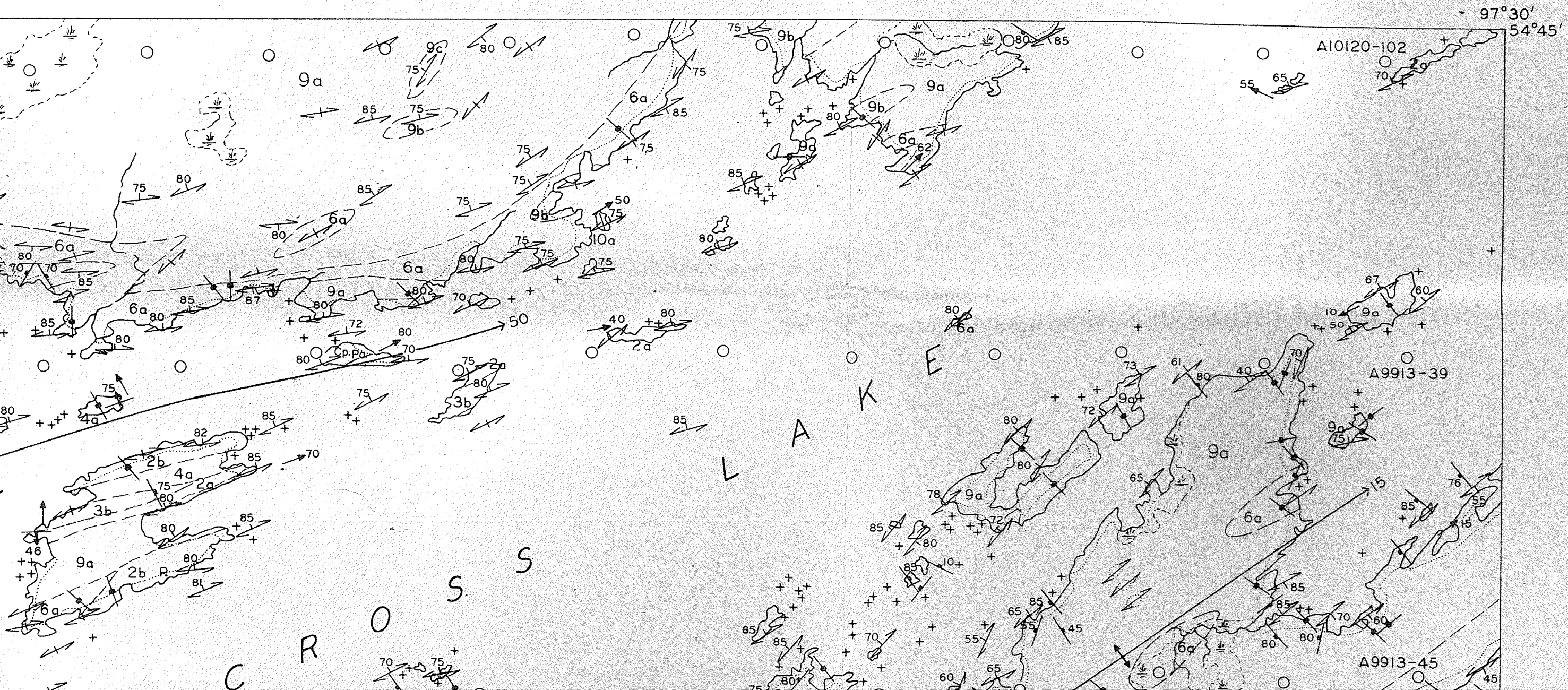
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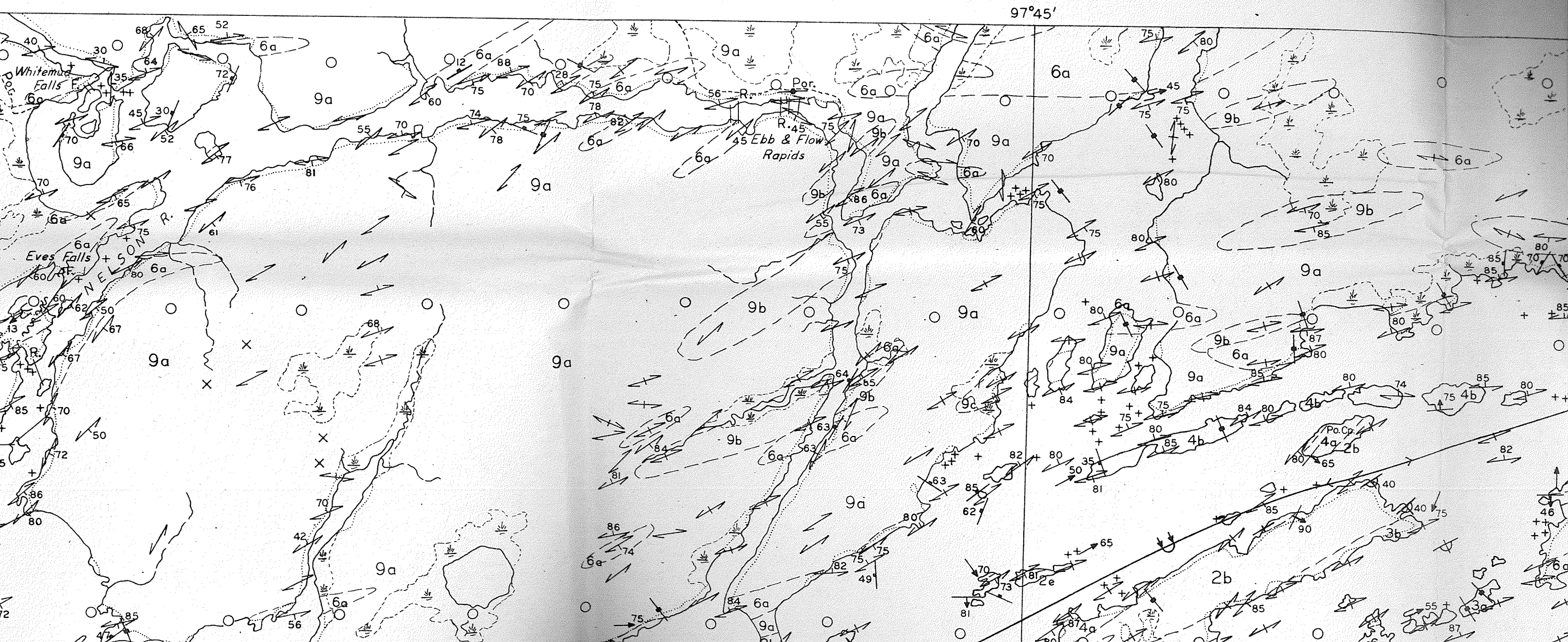
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# Manitoba

## Department of Mines and Natural Resources

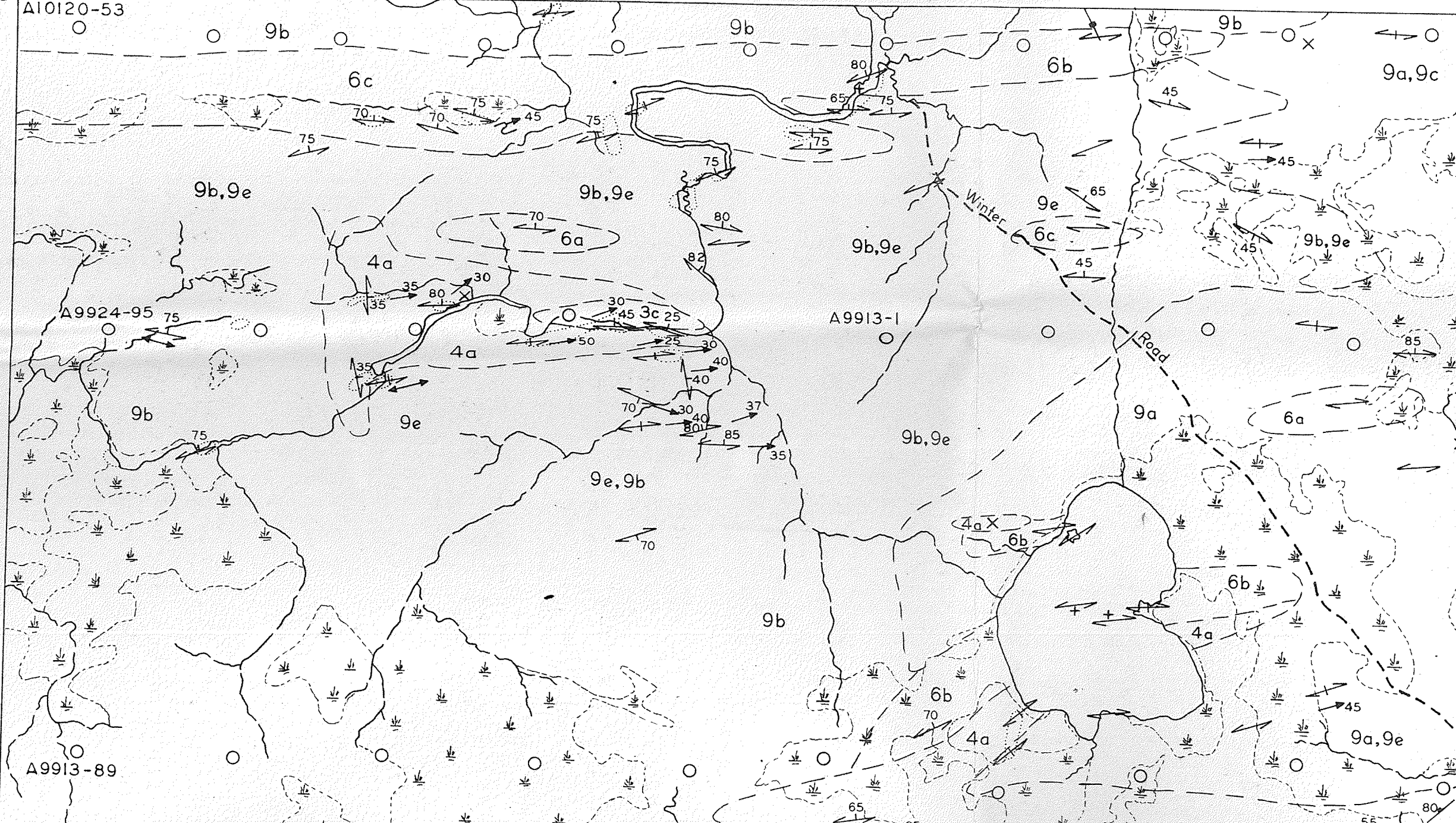
### MINES BRANCH





98°15'  
54°45'

A10120-53

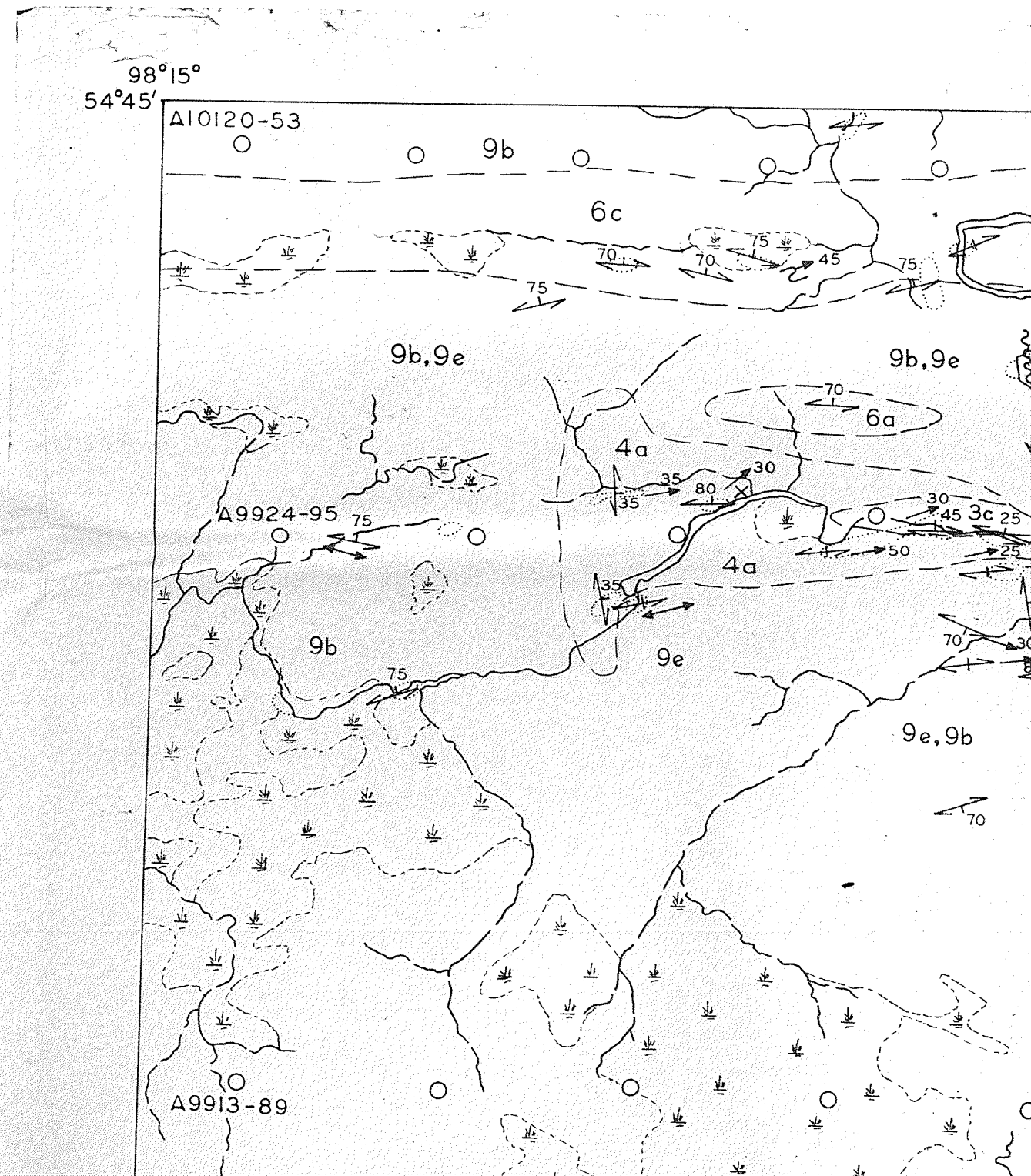


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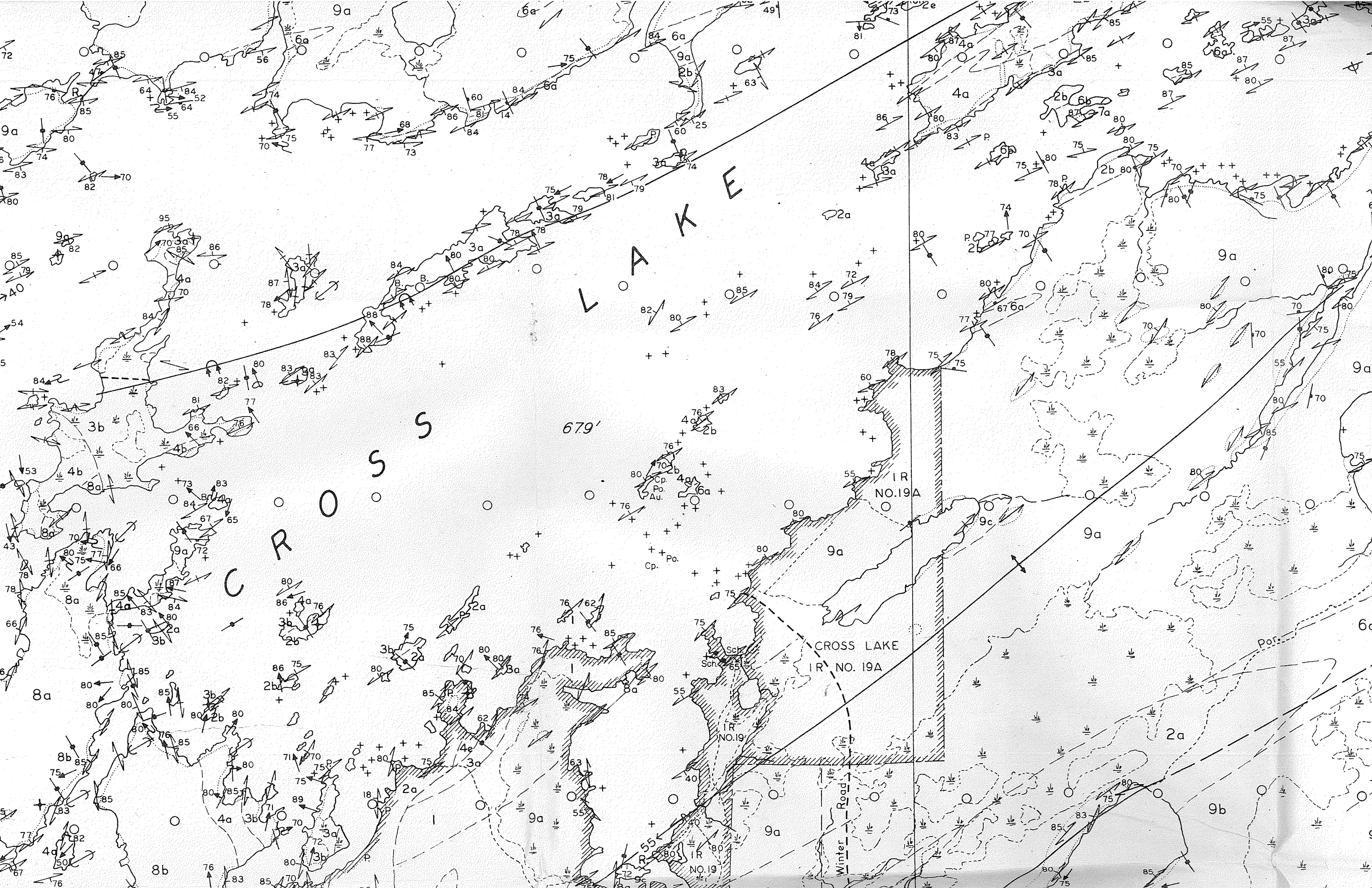
10. Mafic dykes: 10a, hornblende gabbro and diorite;  
 10b, hypersthene-bearing dykes;  
 10c, peridotite.

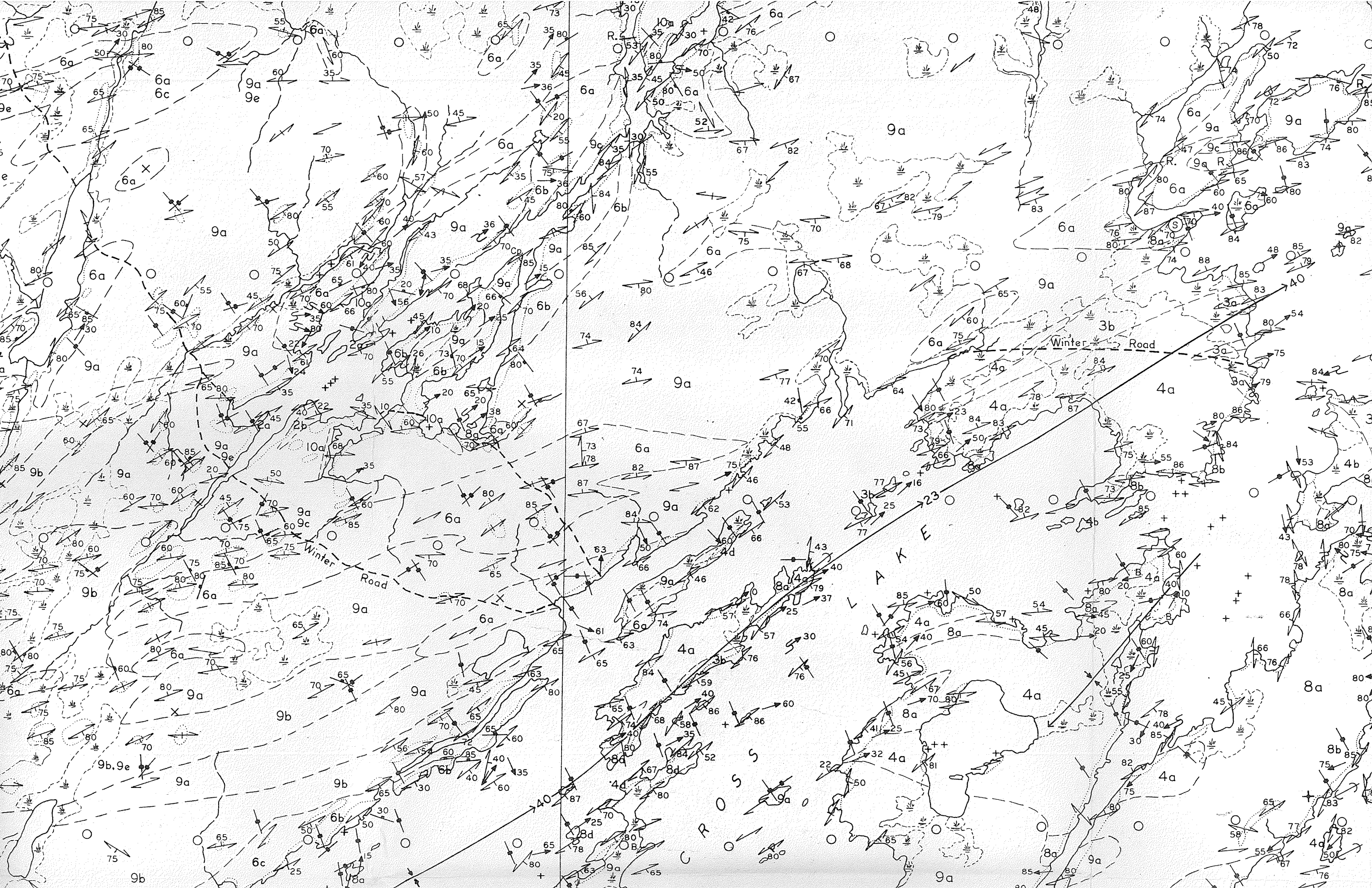
LEGEND

MIDDLE OR UPPER PROTEROZOIC ?









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giss;

an  
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wacke,  
ey shale.  
st)-  
schist;

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ned)

unknown)







A10029-4

10026-100

A10027-3

A9917-4

SEVENTEENTH BASE LINE

9b

9a

9b

9a

9a

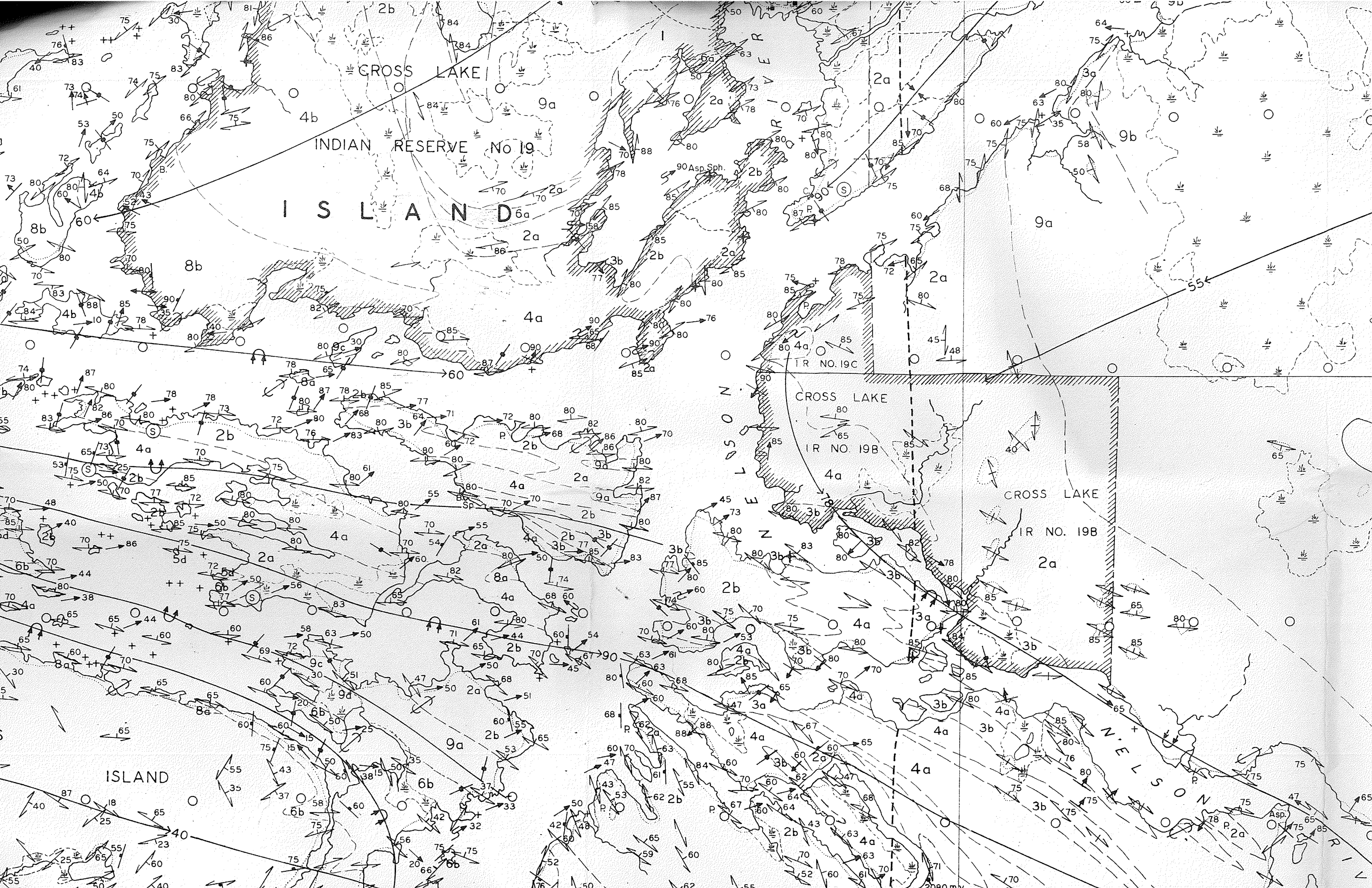
9a

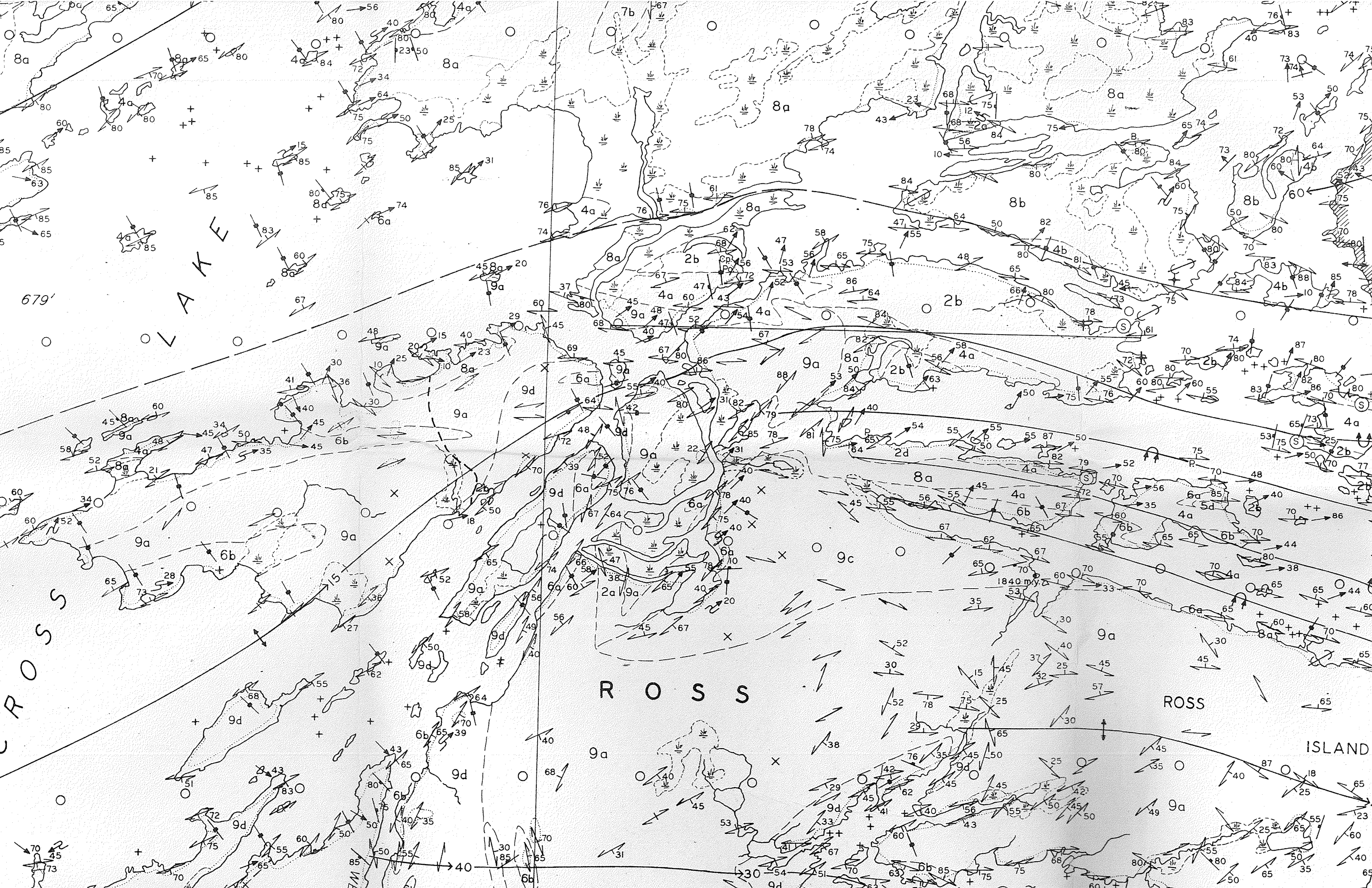
9a

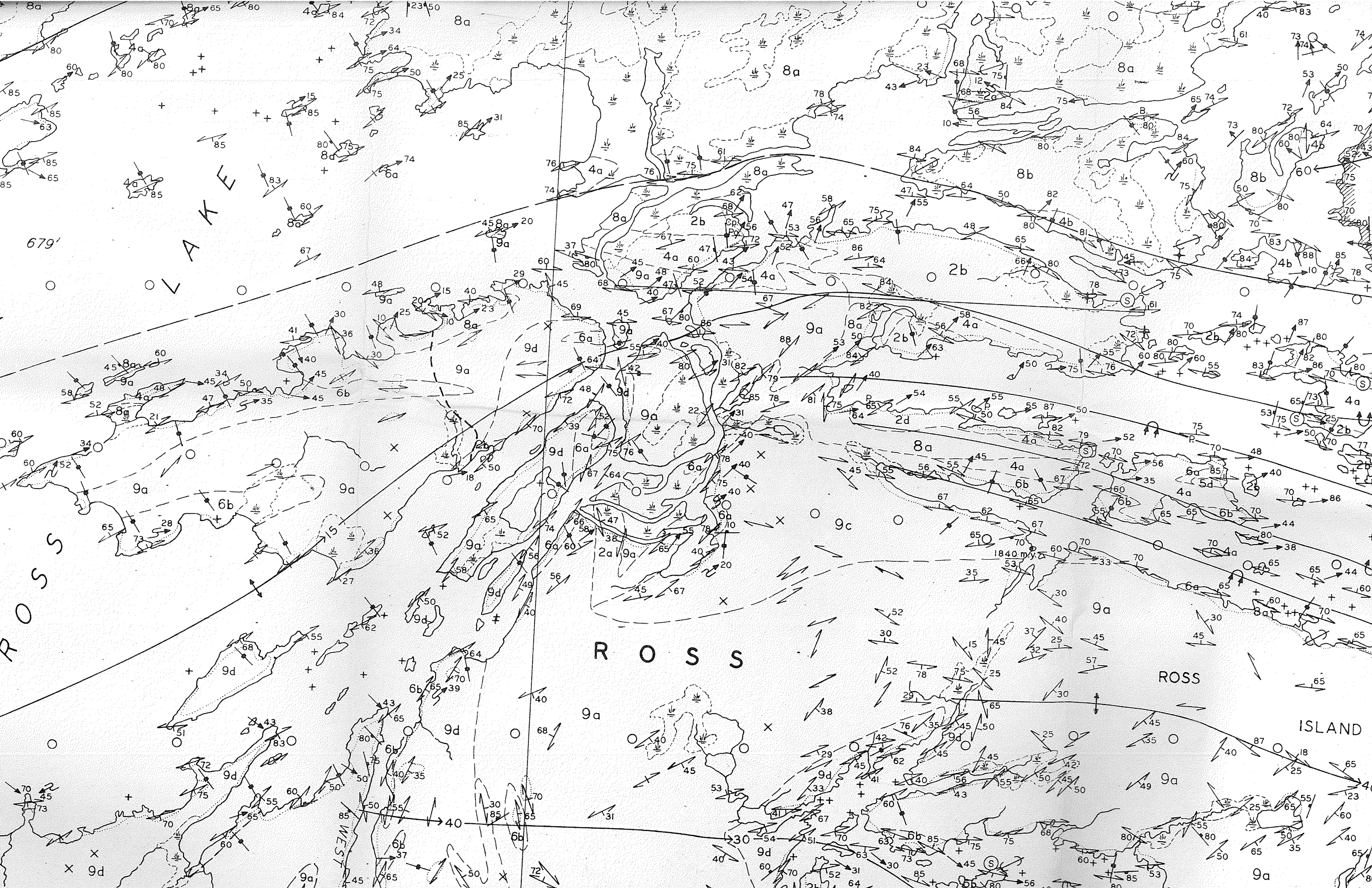
2a

9b

6a







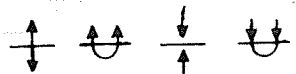

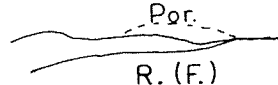

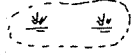



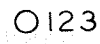
, upright

c.)

classified

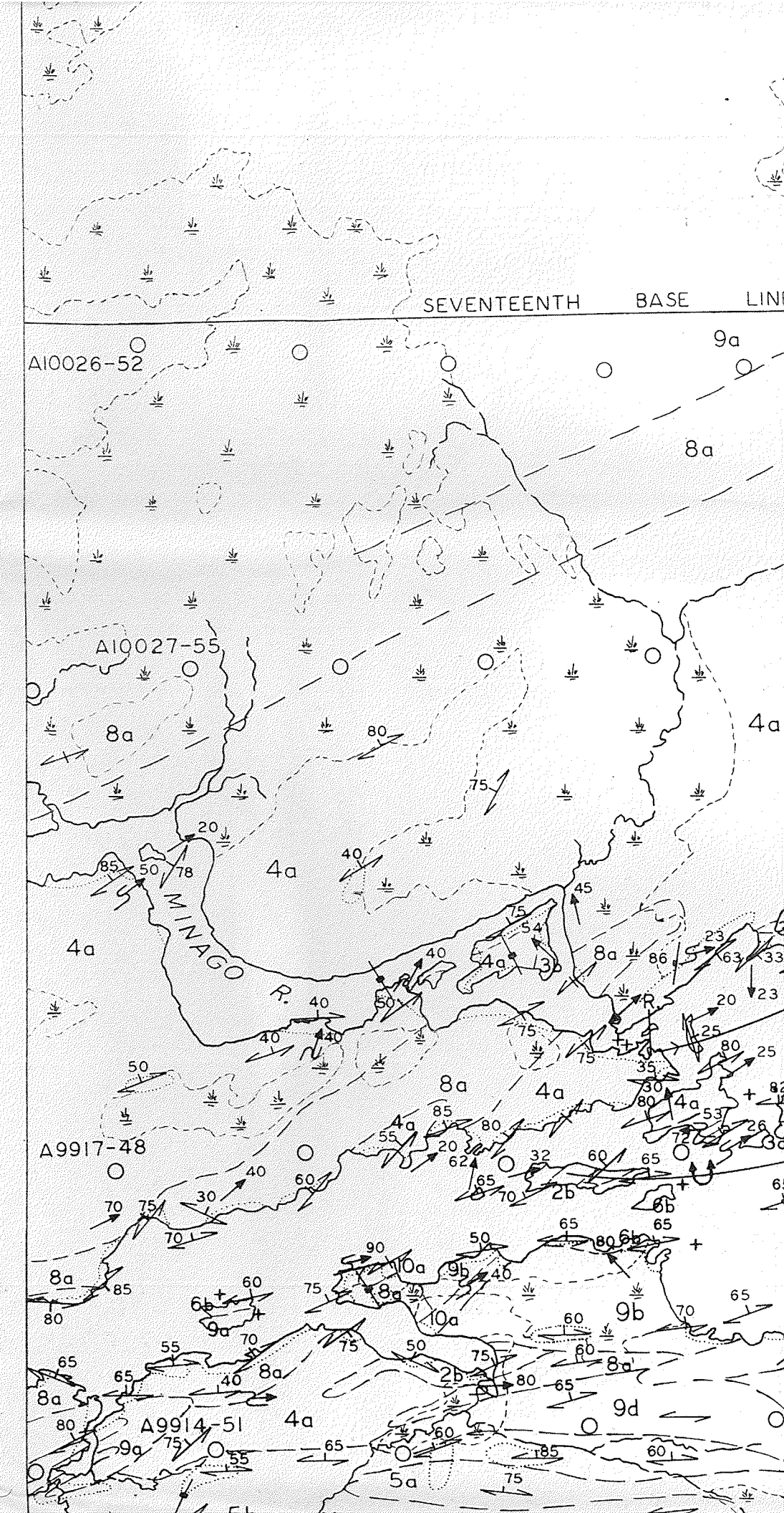
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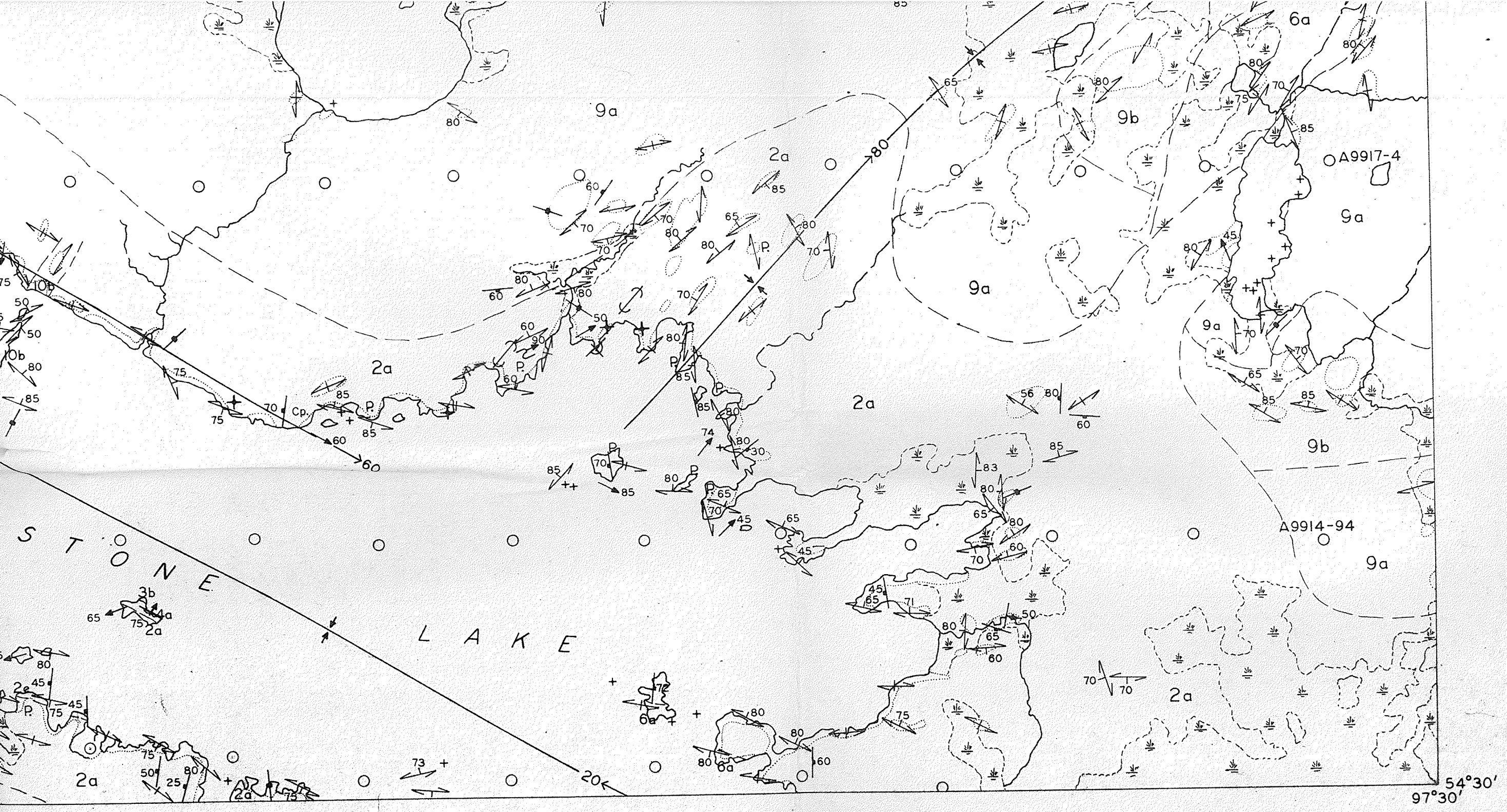


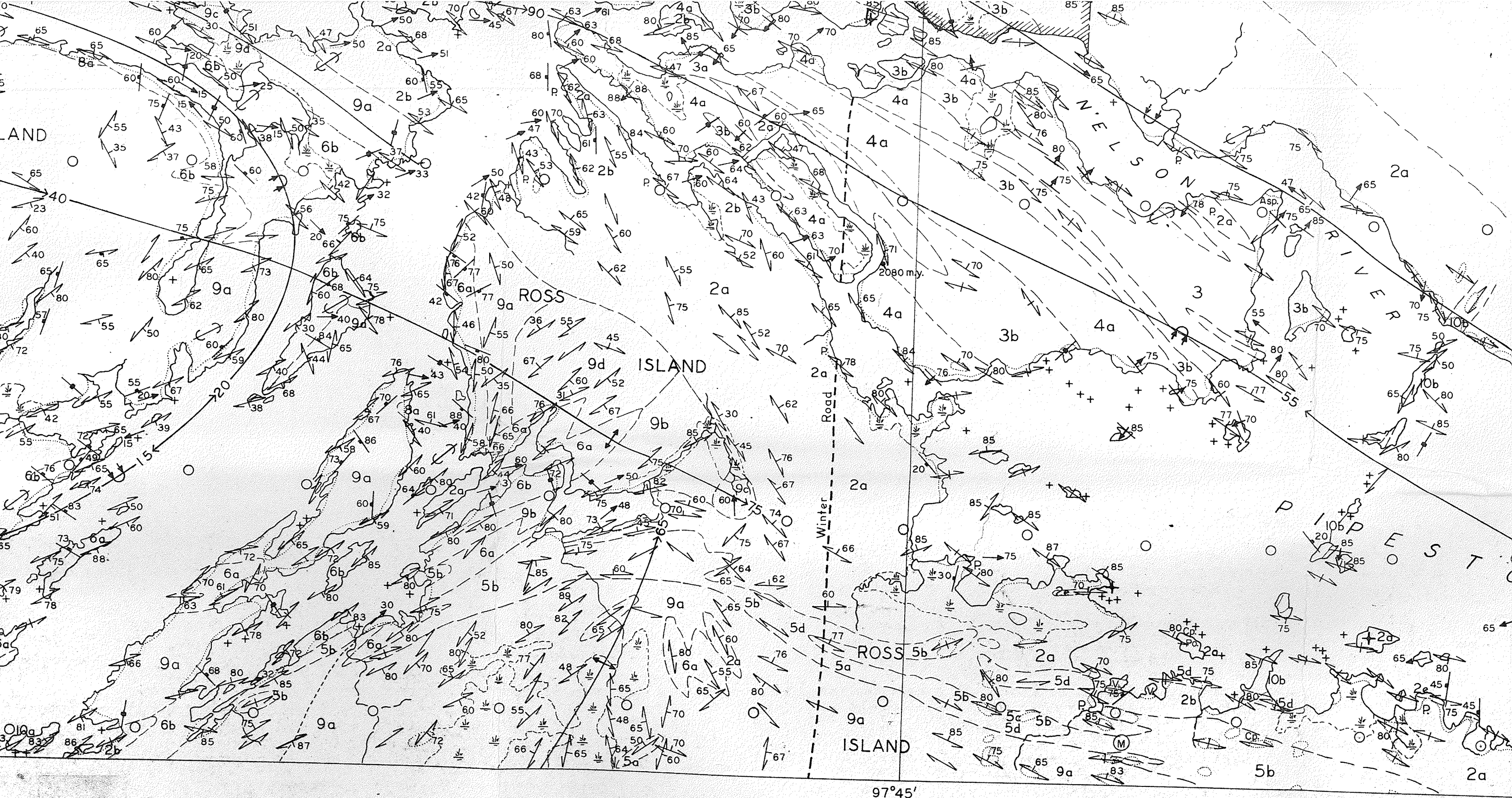
- ~~~~~ Fault
  - 
 Fold axes (upright anticline, overturned anticline, upright syncline, overturned syncline)
  - 
 Glacial striae (movement known, not known)
  - 2500 m. y. Age Date
  - 
 Fall, rapids, portage
  - 
 Reef
  - 
 Swamp (muskeg)
  - 
 Building (C. church, Sch. school, P. post office etc.)
  - 
 Area of magnetic disturbance
  - 
 Sulphides, largely pyrite and/or pyrrhotite, or unclassified
  - 
 Centre of aerial photograph
- Metallic Minerals**
- V vanadium-bearing magnetite
  - Py pyrite
  - Po pyrrhotite
  - Au gold
  - Ag silver
  - Sph sphalerite
  - Cp chalcopyrite
  - Gl galena
  - B beryl
  - Sp spodumene
  - Asp arsenopyrite

**Note:** This map is essentially a copy of the data compiled in the field during the mapping programme. It is not to be regarded as a final interpretation of the geology of the area, as only a broad lithologic classification and a minimum of structural information are shown.

Geology by D. H. Rousell, 1965



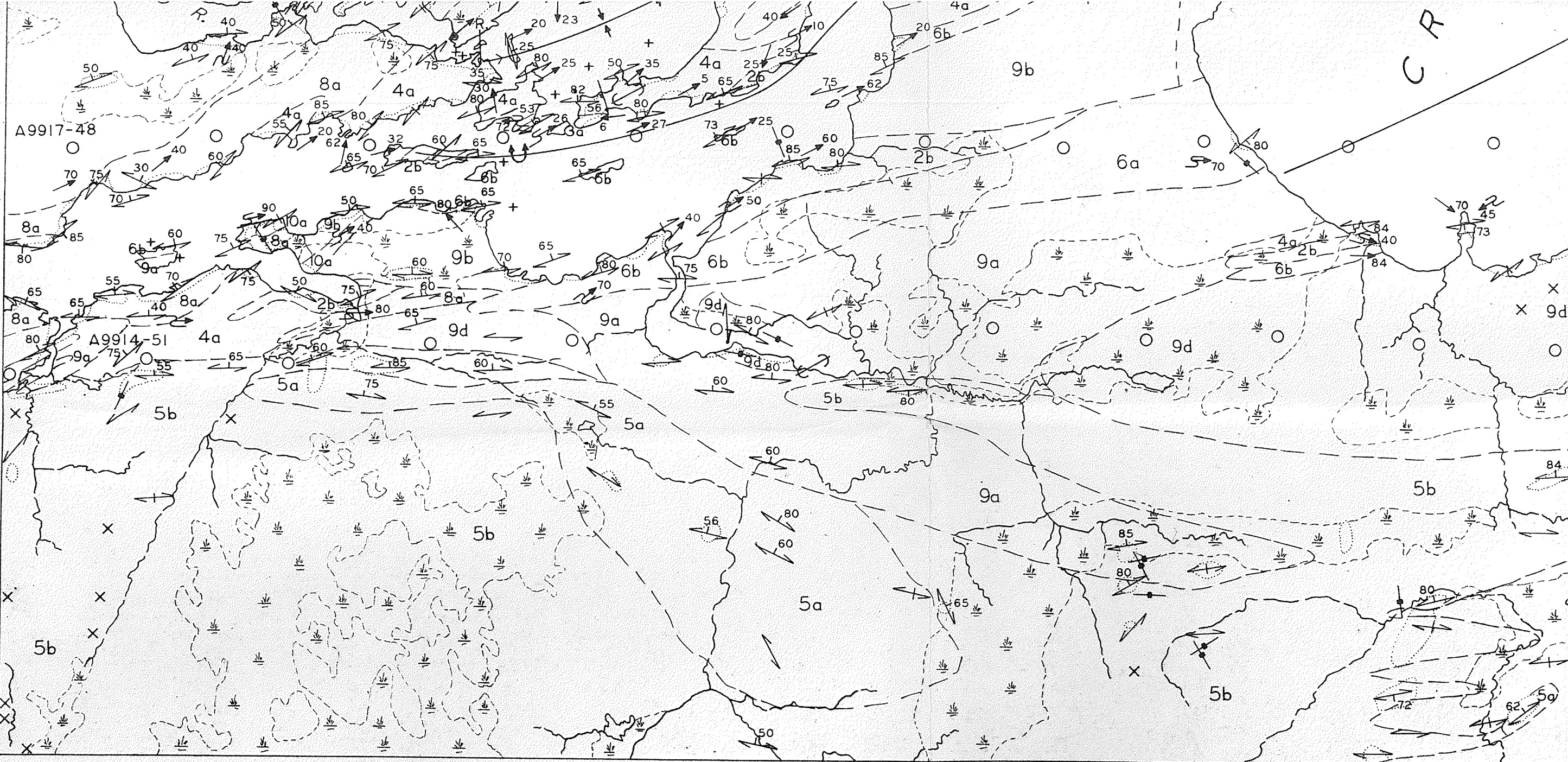




Lake Area  
and 63J/9. E



54°30'  
98°15'



B beryl  
Sp spodumene  
Asp arsenopyrite

Note: This map is essentially a copy of the data compiled in the field during the mapping programme. It is not to be regarded as a final interpretation of the geology of the area, as only a broad lithologic classification and a minimum of structural information are shown.

Geology by D. H. Rousell, 1965

