PETROLOGICAL AND MINERALOGICAL STUDIES OF THE JOAN LAKE AGPAITIC COMPLEX CENTRAL LABRADOR

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by

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ABSTRACT

The Joan Lake area includes a zoned alkalic, largely agpaitic pluton (approximately 12 sq. miles). This pluton is in obscured contact with Precambrian volcanic, sedimentary, metasomatic rocks, thermally metamorphosed diorites and gabbros. The alkalic complex is subdivided from the core to the periphery as follows:

The Core (Ijolite-urtite)

Non-agpaitic rocks essentially composed of nepheline and Na-amphiboles with minor Na-pyroxene, lamprophyllite, phlogopite, ramsayite, apatite and pectolite. These rocks are generally interlayered with Type I.

Type I (Lujavrite)

Agpaitic rocks essentially composed of Na-pyroxene, K-feldspar, arfvedsonite, variable nepheline and minor eudialyte. Texture varies from hypidiomorphic granular to laminated and gneissose.

Type II

Agpaitic rocks essentially composed of K-feldspar, nepheline, arfvedsonite, lesser amounts of aenigmatite and eudialyte with minor Na-pyroxene. Texture varies from trachytoid, laminated to layered.

Type III

Agpaitic rocks essentially composed of K-feldspar, nepheline and eudialyte, appreciable aenigmatite and arfvedsonite and minor Na-pyroxene. Texture varies from poikilitic, pegmatoid to gneissose.

Type IV (Eudialytite)

Agpaitic rocks essentially composed of eudialyte (60-80%) with the remainder

K-feldspar, arfvedsonite, aegirine and nepheline. These rocks occur as veins and patches of granular segregations within the Type III rocks.

Fenites

Metasomatic rocks mainly composed of K-feldspar, albite, quartz and appreciable Na-amphiboles with minor Na-pyroxene, biotite and complex Zr, Ti, rare earth, Nb and beryllium silicates. They show a variety of textures. These were country rocks that have been intruded by the pluton.

Dykes and sills of ijolite-urtite and Type I rocks intrude and metasomatize the Seal Lake Group to the north of the Joan Lake agpaitic pluton.

The initial alkalic magma could have been derived from a volatile-(Cl,F,H) and hydrocarbon-rich but water-deficient ijolite-urtite parent. Geophysical evidence is in accord with the origin of ijolite-urtite by processes of partial melting of mantle rocks. During crystallization the magma became peralkaline. Geochemical and mineralogical complexities may be due to variable P_{O_2}. The concentration of Zr, Ti, rare earth , Nb and other rare metals can be ascribed to the role of volatile transport.

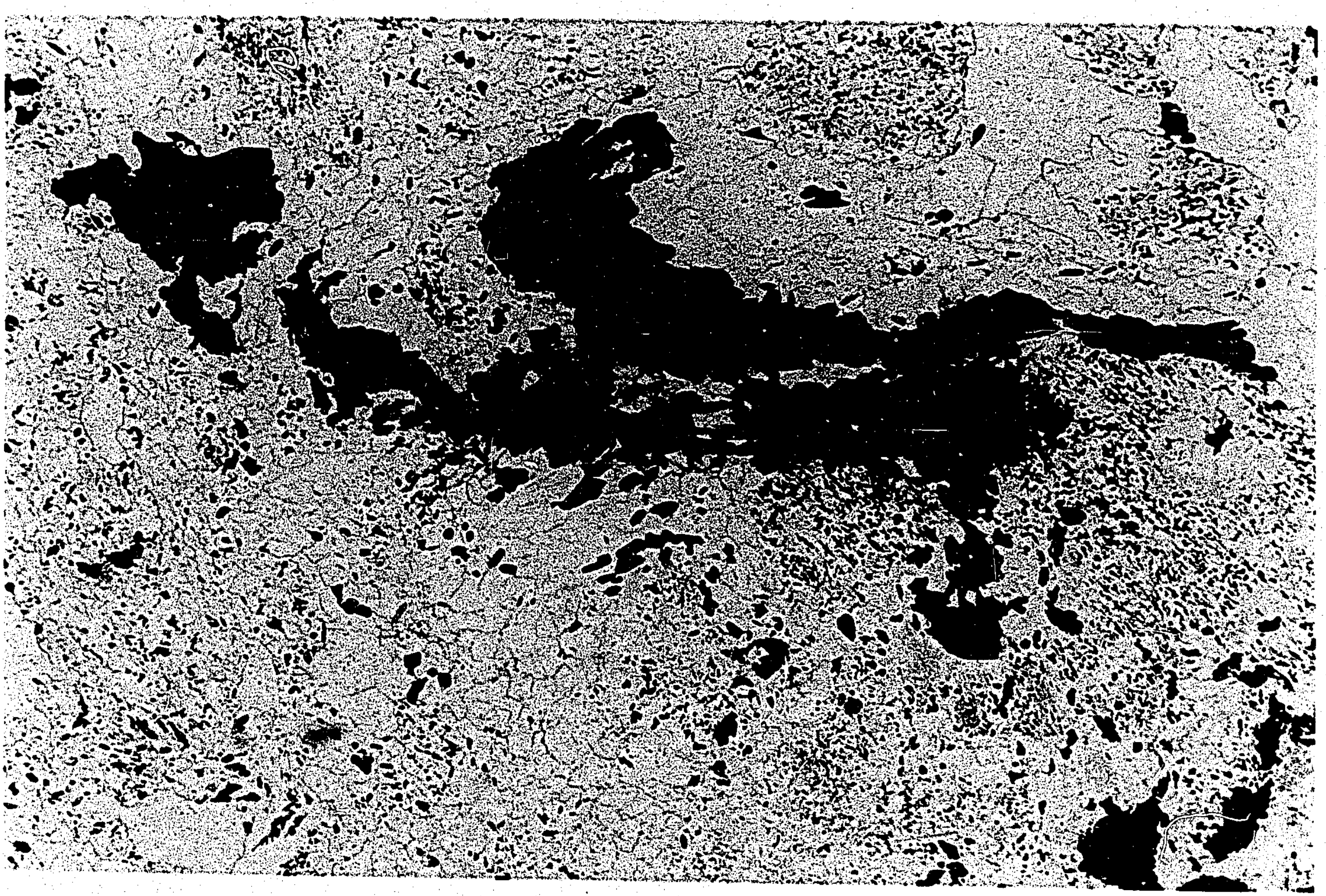
K-Ar ages on nepheline and amphiboles vary from about 1000 m. y. in the core to 1400 m. y. in the margin of the pluton. It is suggested that the true age of emplacement of the pluton may lie in the range of 1000-1400 m. y.

Twenty-five minerals have been recorded for the first time from Central Labrador and twenty six minerals or mixtures of minerals could not be identified.

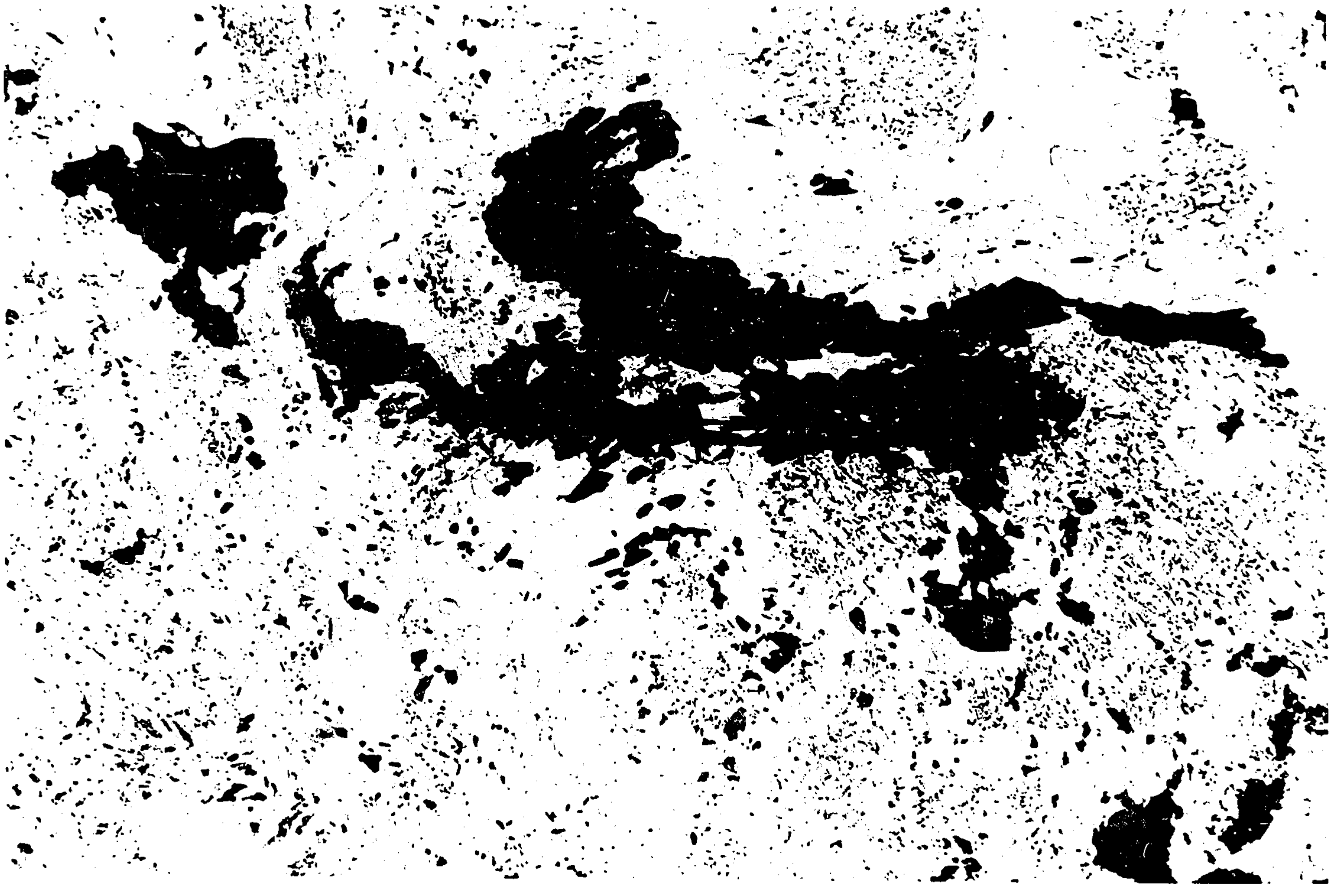
Infrared absorption shows little structural water in the amphiboles, however Fe^{3+} is attached with OH in the M(3) site while Fe^{3+} in the M(2) site is probably completely linked with Cl or F. Mössbauer resonance indicates that Fe^{2+} dominates over Fe^{3+} in Na-amphiboles. On the other hand, Fe^{3+} dominates over Fe^{2+} in Na-pyroxenes. Mössbauer resonance of aenigmatite suggests two basic units in the structure, namely: 1) an M-site comparable to those of amphiboles and pyroxenes, 2) a structural unit comparable with $Fe''Fe'''Fe'''O_4$ or $Fe\,Ti'''Ti'''O_4$ type of inverse spinel. The intense colours of aenigmatite may be ascribed to $O^{2-}\rightarrow Fe^{3+}$, $Ti^{3+}\rightarrow Ti^{4+}$, $Fe^{2+}\longrightarrow Fe^{3+}$ charge transfers and octahedral Fe^{2+}. The distinctive deep blue colour of Fe-Ti-omphacite in $E \parallel Z$ is probably due to octahedral Fe^{2+}. Infrared absorption analysis of eudialyte shows little structural water but indicates the presence of hydrocarbons. The patchy zoning in eudialyte grains may be due to varying amounts of hydrocarbons in different domains. Electron spin resonance of fluorapatite indicates that some O^{-2} resides in one of the F-sites and Mn^{2+} replaces Ca^{2+}.

"Nature in one of her playful moods, has scattered clues but pixie like. She seems to have delighted in giving just enough information to keep up the suspense."

-Sudesh-



FENITE : SHOWING ASTROPHYLLITE (GOLDEN YELLOW), AENIGMATITE (RED), UNKNOWN ALTERATION OF AENIGMATITE (DARK BROWN), RIEBECKITE, (R)AND AEGIRINE AUGITE (PALE TO YELLOWISH GREEN) IN A QUARTZO-FELDSPATHIC MATRIX. CLUSTERS OF AEGIRINE NEEDLES ARE CONFINED TO IRREGULAR K-FELDSPAR GRAINS. THE INCLUSION FREE ZONES ARE COMPOSED OF QUARTZ AND ALBITE. PLANE POLARIZED LIGHT., 100 X., SPECIMEN 287(54° 08'N AND 62° 32'W).



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LIST OF COMMON MINERALS

(agpaitic rocks)

Mineral	Chemical formula
Eudialyte	$Na_2Ca_4Zr\ Si_6O_{18}(F)_2$
Aenigmatite	$Na_4Fe_{10}Ti_2Si_{12}O_{40}$
Arfvedsonite	$Na_3Fe^{\prime\prime}_4Fe^{\prime\prime\prime}\ Si_8O_{22}(OH)_2$
Nepheline	$NaAlSiO_4$
Ramsayite	$Na_2Ti_2Si_2O_9$
Lamprophyllite	$Na_2(Sr,Ba)_2Ti_3(SiO_4)_4(O,OH)_2$
Pectolite	$Na\ Ca_2Si_3O_8(OH)$
K-feldspar	$KAlSi_3O_8$
Albite	$NaAlSi_3O_8$
Aegirine-augite	Solid soln. of acmite, hedenbergite,diopside and jadeite.

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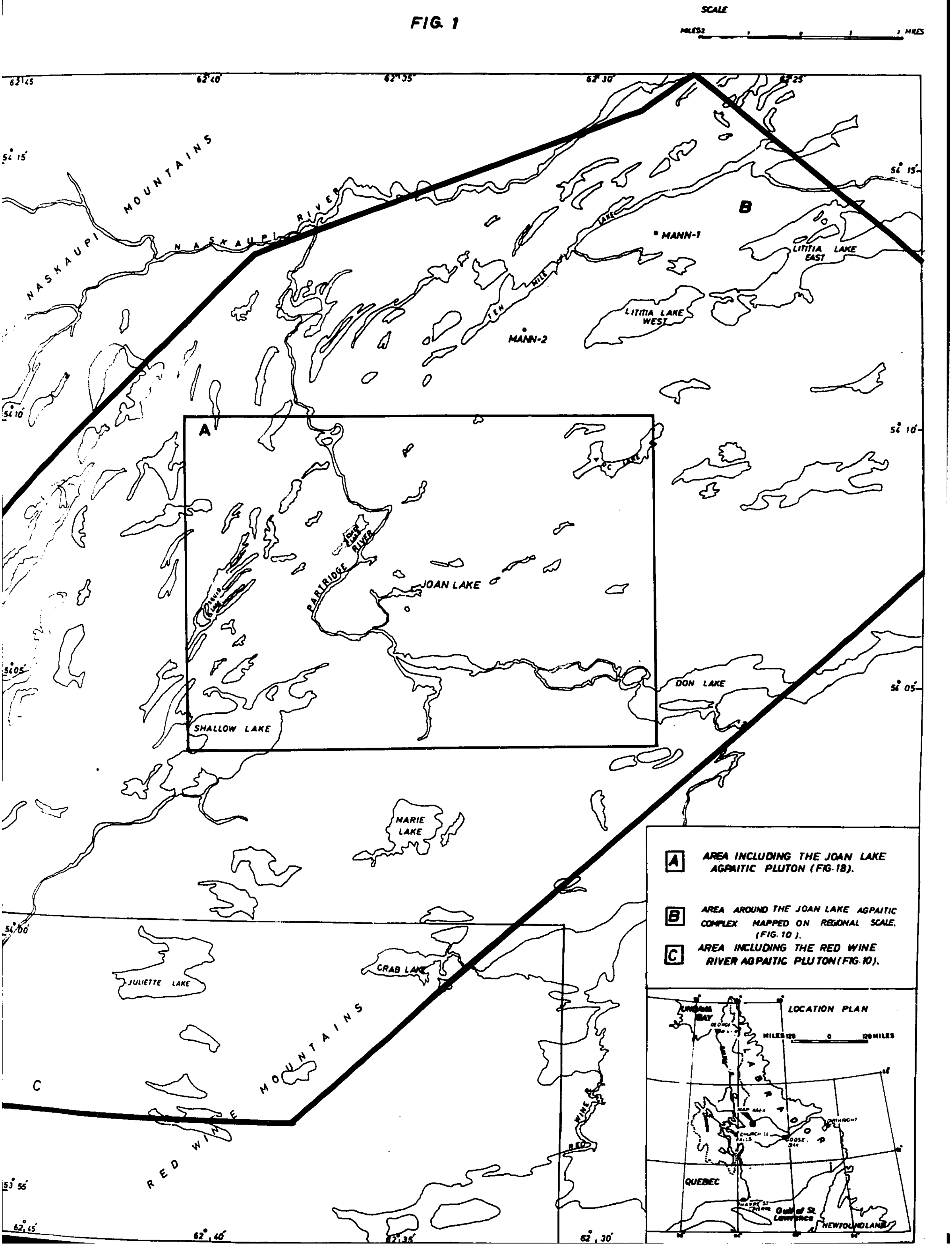
GEOGRAPHICAL NAMES ARE SUBJECT TO REVISION

GEOGRAPHICAL LOCATION OF THE GEOLOGICALLY INVESTIGATED AREAS
CENTRAL LABRADOR

FIG. 1



CHAPTER I

INTRODUCTION

The study area lies between 53°55' - 54°17' N and 62°24' - 62°46' W (Fig. 1). It consists of a portion of the well exposed rocks of the Naskaupi Mountains to the north and ill exposed rocks of the Red Wine River Valley to the south. In general the area is readily accessible by a float-equipped aircraft operating out of Goose Bay and Churchill Falls, Labrador; however, numerous flat, poorly drained and marshy regions are inaccessible except by helicopter or arduous ground traverse.

1. Physiography

The study area is glaciated with low to moderate relief. In the Naskaupi Mountains, it is marked by narrow valleys along the strike with intervening high cliffs. To the south, Red Wine River Valley constitutes marshes, patterned ground, boulder trains, drumlins and eskers. The rocks are poorly exposed in the Red Wine River Valley except for a few ridges and hummocky isolated hills emerging out of the glacial drift. The topography reflects, to a considerable degree, the character of the underlying bed rock; poorly drained areas being underlain by rather uniform gneisses and structureless massive intrusives whereas more rugged areas are underlain by basic rocks or agpaitic syenites.

The Joan Lake agpaitic complex forms a plateau-like range of peneplained hills with 10-15% outcrop, 10-15% vegetation cover, and the rest occupied by lakes and marshes. Fresh outcrop exposures are common along some of the lakes. The Partridge River follows the edge of the Joan Lake agpaitic stock.

2. Historical outline

Since 1843, the area has been visited by several prospectors and explorers interested in locating native copper and gold (Davies 1843, Knight 1925, Mann 1959) but the first attempt to prepare a geological map of the Seal Lake volcanics was made in 1946 (Halet 1946). In the late forties, the area to the west of Seal Lake was explored for iron ore (for details on early explorations, see Mann 1959) and the Photographic Services Corporation (Toronto) aerially covered the entire region. Subsequently, Scott and Conn (1950) prepared the first composite geological map for the entire region and ruled out the possibility of extending the Labrador iron-ore belt into the Seal Lake trough (a basin filled with sedimentary and volcanic rocks extending from Canairiktok River to Ten Mile Lake in a north-south direction).

From 1951 to 1954, geologists of Frobisher Exploration Company discovered more than 125 occurrences of native copper within the Seal Lake volcanics. Christie et al. (1953), representing the Federal Government of Canada, mapped a very large area extending up to the Labrador Coast. Robinson and Cruft (1958) found uranium mineralization in the Stormy Lake area of the Seal Lake region. Discoveries of copper and uranium triggered an intensive exploration in the area. Therefore, Brummer (1956, 1957) representing Kennco Ltd., carried out geochemical surveys to the south of Seal Lake and reported two radioactive showings (Mann - 1 and Mann - 2) in the Ten Mile Lake region (Fig. 1). Fahrig (1959) prepared a detailed geological map of Snegamook Lake area, to the south of the Seal Lake trough. Subsequently Mann (1959), in his doctoral dissertation, compiled all information then available and included the Joan Lake rocks in the Lititia* Lake Formation of the Seal Lake Group.

Mann (1959) and Robinson and Cruft (1958) referred to the presence of eudialyte in the amphibolitic schists and gneisses in the Joan Lake area. The radioactive zones located by Brummer (1956, 1957) gave high beryllium values (Evans and Dujardin 1961) and therefore Rio-Tinto Exploration Ltd., Canada, carried out drilling in the Mann - 1 region (the Ten Mile Lake area). The laboratory investigation of the core samples from Mann - 1 led to several mineralogical discoveries (Nickel and Charette 1962, Nickel 1963, Nickel <u>et al</u>., 1964, Nickel and Mark 1965, Heinrich and Deane 1962, Heinrich and Quon 1963). These discoveries led Heinrich (1966, p. 69 and pp. 88-89) to conclude that the fenites were well developed around the "agpaitic Seal Lake intrusive". His observation was not substantiated by the known geology (Brummer and Mann 1961, Moore 1968).

Barringer Air-Photos Corporation (Toronto) made detailed aerial coverage and Brinex Ltd., Montreal, covered the Seal Lake area radiometrically using an air-borne scintillation counter (Sutton 1967). Several areas of high radioactive values were checked in the following year (Smith 1968). Eudialyte was reported to occur in amphibolitic schists and pegmatite veins, in the Joan Lake area, where very high radioactivity was observed in the previous year.

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*Lititia has been spelt as "Letitia" since 1961, however, the author preferred the original spellings.

TABLE 1

Stratigraphy of the study area, Central Labrador

Christie et al.(1953)		Mann (1959)					Brummer and Mann (1961)		Stevenson (1969)		
Pleistocene: Glacial drift and sands		Pleistocene: Glacial drift and sands					Pleistocene: Glacial drift and sands		Pleistocene: Glacial drift and sands		
PROTEROZOIC	Diabase, gabbro and diorite with included sedimentary and volcanic rocks. Volcanic rocks: basalt, andesite, and acidic flows. Sedimentary rocks: quartzite, arkose, slate, agglomerate, dolomite, chert and included interbedded volcanic rocks.	PROTEROZOIC	SEAL LAKE GROUP 33000 ft.	UPPER RED QUARTZITE FORMATION 2600 ft.	Red quartzite becoming argillaceous at the base with scattered pebbly bands.				PRECAMBRIAN	HELIKIAN:	Diabase dykes, granites, quartz-monzonites, quartz diorite, syenite: generally coarse-grained to poorly foliated, foliated to massive rocks. They are locally intensely epidotised; altered by intrusion of granites.
				ADELINE ISLAND FORMATION 1600 ft.	Green, purple, and red slates, shales and quartzites.					SEAL LAKE GROUP (?):	Gabbroic, sedimentary, volcanic rocks, undivided white quartzite and fine-grained basaltic flows.
					Red shale						Mainly impure quartzite, sandstone, tuffs locally altered to epidote schists.
				SALMON LAKE FORMATION 3000 ft.	Red shales with intercalated amygdaloidal basalt flows with a few diabase sills.						Basic and ultrabasic rocks, undivided anorthosite, gabbroic rocks including gabbroic anorthosite, diorite, quartz gabbro, peridotite, pyroxenite and hornblendite.
				WHISKY LAKE FORMATION 3000 ft.	Red and grey slates and phyllites, red silty argillites and minor red quartzites.			Seal Lake Group division identical with Mann, 1959			Intermediate basic gneisses, undivided locally altered to amphibolite, commonly garnetiferous.
				WUCHUSK LAKE FORMATION 20000 ft.	Interbedded chert, variegated shales, phyllites, hornfels, argillites, fine grained quartzite and calcareous beds with thick, intrusive concordant sills of diabase, metadiabase and very coarse-grained diabase.	$\dot{5}$					Granite and related rocks of probably intrusive origin, massive to poorly foliated cut by numerous pegmatite veins.
				BESSIE LAKE FORMATION 4200 ft.	Blue, white and pink quartzites becoming feldspathic, gritty and conglomeratic at the base, intercalated with vesicular and amygdaloidal basalt which has been metamorphosed in the south to chlorite-epidote schist.	$\dot{4}$					Mainly feldspar-quartz-biotite-sillimanite gneiss with abundant pegmatitic material.
					UNCONFORMITY			UNCONFORMITY			White crystalline marble.
			PRE-SEAL LAKE GROUP	CROTEAU LAKE GROUP	Basal sedimentary formations overlain by porphyry, rhyolite tuffs and fragmentals intruded by younger granite.		BASEMENT	Lititia Lake Formation			
					RELATION UNKNOWN-POSSIBLY CONTEMPORANEOUS						
				LITITIA LAKE GROUP 8500 ft.	Schistose quartz-feldspar porphyry, rhyolite, tuffaceous rhyolite, banded tuff, argillites, and minor fragmental bands, intruded by aegirine syenite.	$\dot{3},\dot{9},\dot{10}$					
					Shear zones of banded feldspar, diopside and amphibolite schists.	$\underline{\dot{7},\dot{8},\dot{9},\dot{10}}$		Granitic gneisses			
					UNKNOWN RELATION						
ARCHEAN	Foliated to massive gabbros, anorthosite, and diorite.	ARCHEAN	BASEMENT	ANORTHOSITE	Medium to very coarse-grained anorthosite intruded by a few diabase dykes. The anorthosite and Seal Lake Formation contact is obscured by alluvium.	$\dot{2}$					
	Granitoid and massive granitic rocks.			GRANITE AND GRANITIC GNEISS	Hornblende granite, porphyritic granite and biotite granite with minor relict bands of sedimentary quartz sericite schist and chlorite-epidote schist cut by dykes of aplites, pegmatite and quartz veins.	$\dot{1},\dot{6}$					

<u>Note</u>: $\dot{1}$ to $\dot{10}$ refer to the map units used in Fig. 10.

As a result of continuing interest by the Geological Survey of Canada, the Red Wine River area was mapped under Operation North West River (Stevenson 1969). The writer in 1968, identified an agpaitic syenite composed of nepheline, eudialyte, aenigmatite, arfvedsonite, microcline and aegirine-augite, from the Red Wine Mountains, a range of hills about 10 miles south of Joan Lake (Dr. Stevenson's collection, Geological Survey of Canada). Subsequently, encouraged by Dr. I.M. Stevenson, he joined Brinex Ltd., Montreal, to evaluate the Joan Lake eudialyte occurrences. During his investigation in 1969, the writer not only discovered the two agpaitic plutons (Fig. 1, block A and block C) but found several inconsistencies in the geology of the area as described by the previous workers. An area of 200 square miles was mapped on 1 inch = 2 miles scale (Fig. 1, block B). In addition, an area of 45 square miles, including the Joan Lake pluton (Fig. 1, block A) was mapped on a scale of 1:20,000. After the petrographical study, the area was again visited in 1971 to check conclusions.

3. Geological setting of the study-area based on previous data

According to Christie et al. (1953) the study-area is composed of the Proterozoic volcanic to sedimentary rocks and Archean granitoids, gabbros, diorites and anorthosites (Table 1). Robinson and Cruft (1958), Mann (1959), Brummer and Mann (1961), Evans and Dujardin (1961), Shewman (1967) and Smith (1968) regard the northern portion of the area and part of the Naskaupi fold belt as belonging to the Lititia Lake Formation

(Pre-Seal Lake Group) and Bessie Lake Formation (Seal Lake) and the southern part as the basement complex. However, Mann (1959) included anorthosites and granitic rocks in the basement complex while Brummer and Mann(1961) considered the Lititia Lake Formation as a part of the basement.

Brummer and Mann (1961) consider that the Seal Lake syncline, a structure containing the Seal Lake volcanics and sedimentary rocks, has been overturned to the north and the contact between the southern granites and the Seal Lake Group is sheared and mylonitized. They propose a thrust contact between southern granites and the Lititia Lake Formation. Furthermore, they surmise that slices of granites and the older Seal Lake rocks are thrust over the younger formations to the north with partial or complete elimination of some of the lithological units. They suggest an unconformity between Lititia Lake and Bessie Lake Formations, but the contact between the two is obscure. Also they describe some sodium-rich syenite plugs in the Lititia Lake Formation which are conveniently included in the Lititia Lake Formations. Evans and Dujardin (1961) in their description of the geology of the Ten Mile Lake area, describe the structure of the Lititia Lake Formation as follows:

> "The volcanic rocks and the gneisses dip south at 50^{o}-70^{o} and strike generally east-west, but appear to wrap around the syenite in an arcuate pattern with its convex side to the north. Granulation in the gneisses suggests some movement parallel to the strike but other than this, no faulting of any consequence has been noted."

Baragar (1968) describes the Lititia Lake Group as an assemblage of schistose acid volcanic rocks but he does not discuss their relationship with the southern granites. According to Stockwell et al. (1970), the Seal Lake Group unconformably overlies the Lititia Lake Formation.

To the south of the Ten Mile Lake area, many geologists describe basement granites (Christie et al.1953, Brummer and Mann 1961) over which the Lititia Lake Group is supposed to lie. Brummer and Mann (1961) describe very slight degrees of regional metamorphism and a high degree of dynamic metamorphism present in these granites. Stevenson (1969) describes regional metamorphism of varying grades in the Red Wine River Valley (his units 7-8, greenschist and units 8-11, granulite facies). He concludes, "By far the greater proportions of the rocks in the area fall in the albite-epidote and the amphibolite facies of metamorphism, typical of medium to high grade regional metamorphism, common everywhere to rocks of Grenville province." Cumming et al. (1955) determined the age of a galena-bearing vein from Croteau Lake volcanics (outside the map area, and about 40 miles to the east) by Pb/U method, to be 1685 ± 160 m. y. Since Lititia Lake Formation was deduced to be equivalent of Croteau Lake Formation (Beavan 1958), they were not only considered time equivalent but were loosely placed in the Archean. Bearing in mind the uncertain relations, an unconformity between Lititia Lake Formation and southern rocks (granites and granitic gneisses) was suggested (Mann, 1959).

K-Ar age determinations carried out on biotite and hornblende from granititic gneisses overlain unconformably by the Seal Lake Group, gave

1430 m. y. and 1350 m. y. respectively (Stockwell et al. 1970). Muscovite, from quartzite collected three miles south of the thrust zone and considered to be the metamorphic equivalent of the Seal Lake Group, gave a K-Ar age of 975 m. y. Seal Lake amygdaloidal basalt gave 960 m. y. (whole rock quoted by Stockwell et al. 1970).

Therefore, the geological setting of the area remains uncertain until the following problems are resolved:

1) The relationship between Lititia Lake Formation and the Seal Lake Group.
2) The relationship between the so-called basement complex and Lititia Lake Formation.
3) The geological relationship of ijolite-urtite, agpaitic rocks and fenites (these units were not identified earlier).
4) The metamorphic history of the area. If regional metamorphism took place during the Grenvillian orogeny, why were the Seal Lake rocks not involved or partially involved, if Stevenson's correlation of rocks to the south (Stevenson 1969, units 7-8) is considered valid?

4. Purpose of the study

In view of the discoveries of agpaitic plutons and the lack of geological information of these and other rocks in the vicinity, the present investigation attempts to:

a) describe the petrographical and mineralogical relationships of various rock units observed in the Joan Lake area,
b) investigate the chronology of the agpaitic syenites, gabbros, fenites and diorites in the Joan Lake and surrounding areas,

c) establish the subdivisions of the agpaitic rocks,

d) record minerals from the Joan Lake pluton and surrounding fenites,

e) propose an origin for agpaitic rocks in general and the various units of the Joan Lake agpaitic complex in particular.

PART 1

GEOLOGY IN THE JOAN LAKE AREA, CENTRAL LABRADOR

CHAPTER 2

FIELD METHODS, OBSERVATIONS AND ISOTOPIC AGE DETERMINATION

1. Methods

The work was initiated in the Ten Mile Lake area on Bessie Lake Formation. This formation is composed of quartzite, slate, diabase, metavolcanics and phyllite. The field work was extended to the southern hills, first by making traverses parallel to Ten Mile Lake, then traversing across the southern hills described as Lititia Lake Formation (Brummer and Mann 1961). The available outcrops were investigated in detail along streams, lake shores and caribou trails. The main rocks encountered within these hills were classified as porphyritic rhyolites, trachytes, andesites, argillites (including slates, schists, etc.), lenticular bodies of ijolite-urtite and lujavrites. Helicopter flights were made to the south of the Ten Mile Lake area.

A reconnaissance survey revealed two agpaitic complexes in the Red Wine Mountain west of the Red Wine River Valley and near Joan Lake. As the Joan Lake agpaitic complex was well exposed, detailed investigation was carried out and geological data were collected during eleven camp shifts. In each region, traverses were made radiating from the camp site and rock specimens from fresh and representative outcrops were collected. Following the initial "boot and hammer" survey, detailed mapping was carried out along cut traverse lines and from drill core (3/4 inches diameter) information. Most of the geological data were plotted on aerial

Fig.2 is in pocket at the end of the thesis.

Fig. 3: Quartz veins in slates, acid volcanics and fenite. Remnants of slates in fenite.

Fig. 3A: Quartz veins parallel to the bedding cleavage in slates, (62°33′48″W and 54°12′10″N).

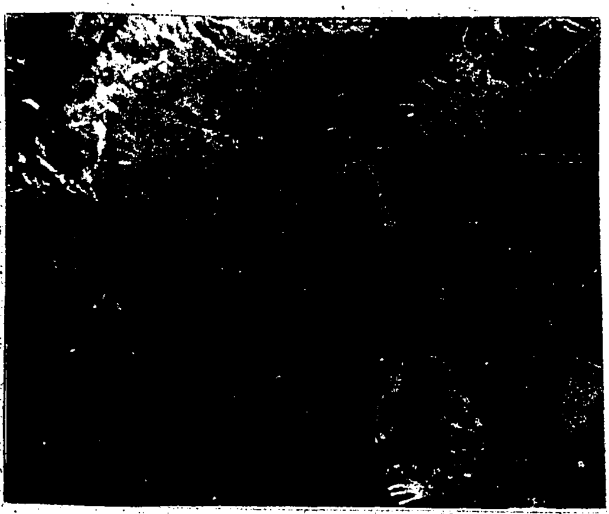

Fig. 3B: Interlacing quartz veins in acid volcanics at the southern bank of Ten Mile Lake, (62°30′W and 54°14′N).

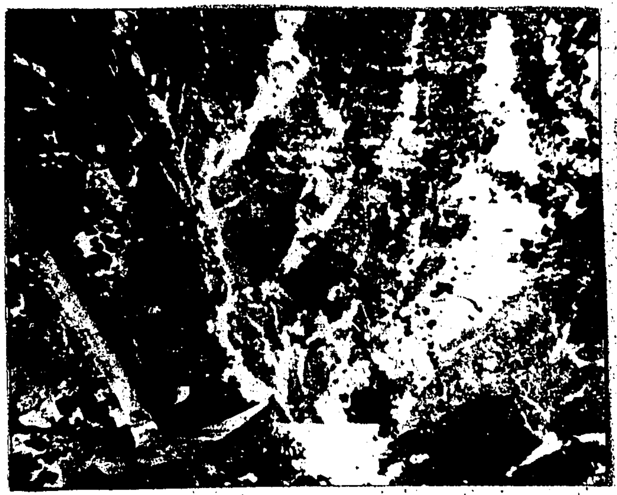

Fig. 3C: Branching, irregularly spaced quartz veins in fenite at the southern bank of Joan Lake, (62°34′W and 54°07′30″N).

Fig. 3D: Remnants of slates in fenite, (62°33′56″W and 54°05′30″N).

photographs (1:20,000) but part of the area was mapped on a scale of 1 inch = 100 feet (Singh 1969). The rocks encountered in the Joan Lake pluton were classified as layered ijolite-urtite, Type I (lujavrite), Type II (hypidiomorphic granular), Type III (pegmatoid) and quartzites, porphyritic meta-volcanics and fenites.

Several helicopter flights were made to collect more data from the surrounding areas. During the above detailed investigation, 650 rock specimens were collected but only 300 points could be plotted on the map (Fig. 2) due to difficulty in representing them on the present scale.

In total, fourteen weeks were spent in the field during 1969 and two weeks in 1971.

2. Observations

During the field investigation, the following observations were made:

a) The contact between the so-called Bessie Lake quartzites and the Lititia Lake Formation is conformable. At places, the quartzites contain gritty to conglomeratic and agglomeratic discontinuous lenses in the eastern portion of Ten Mile Lake.

b) The Lititia Lake volcano-sedimentary sequence is composed of porphyritic rhyolites, trachytes and andesites interbedded with argillites. The above sequence is metamorphosed under greenschist facies conditions and is composed of phyllites, slates and schists of different types. Within the so-called Lititia Lake Formation, quartz veins show different dispositions e.g., parallel to the bedding in slates (Fig. 3A), interlacing networks of rootless veins (Fig. 3B) in volcanics, and

Fig. 4: Mylonitized porphyritic rhyolite and brecciated fenite.

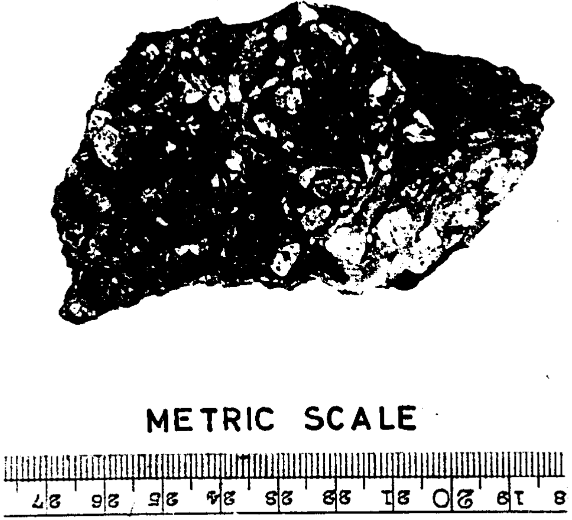

Fig. 4 A: Mylonitized porphyritic rhyolite from the Ten Mile Lake area. Specimen 115.

Fig. 4B: Microphotograph of the mylonitized porphyritic rhyolite from the Ten Mile Lake area. Specimen 115, Polarized light, x20.

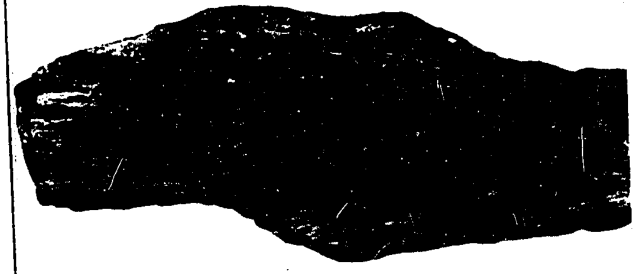

Fig. 4 C: Brecciated fenite from the Ten Mile Lake area. Specimen 126, x¼.

Fig. 4 D: Brecciated fenite with alternating bands of quartz and feldspar (gray) and aegirine and arfvedsonite (black). Specimen 126, Polarized light, x80.

Fig. 5: Lujavrite, interlayered ijolite and urtite, folded ijolite, and fragmented ijolite.

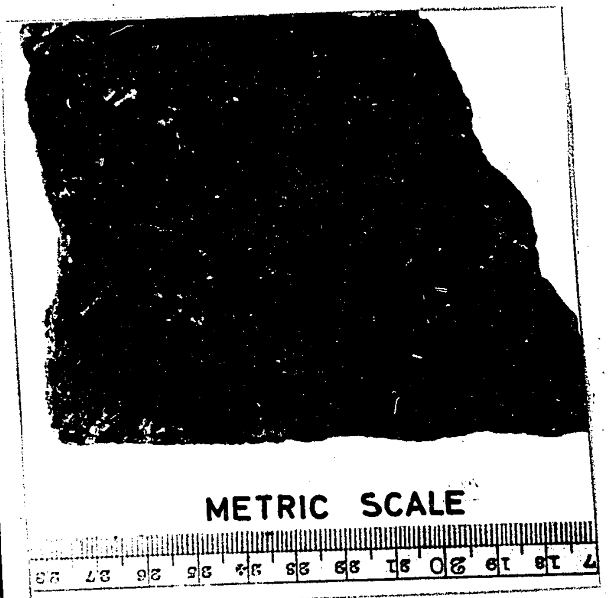

Fig. 5.A: Lujavrite from a dyke in fenites to the northeast of Esker Lake (Specimen 276).

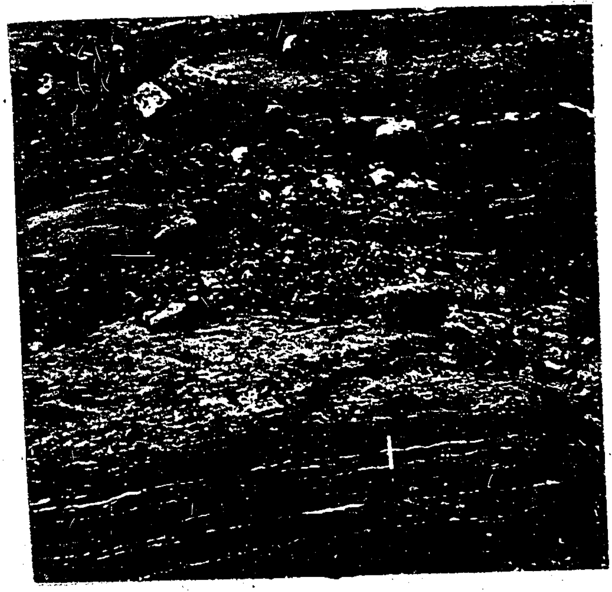

Fig. 5.B: Layered ijolite (dark gray) and urtite (light gray) to the south of Brian Lake (62°32′ 40W and 54°06′ 45N).

Fig. 5.C: Ijolite showing folding within dark bands. The folds are intruded by a refolded urtite (light gray) vein (62°34′30W and 54°06′05N)

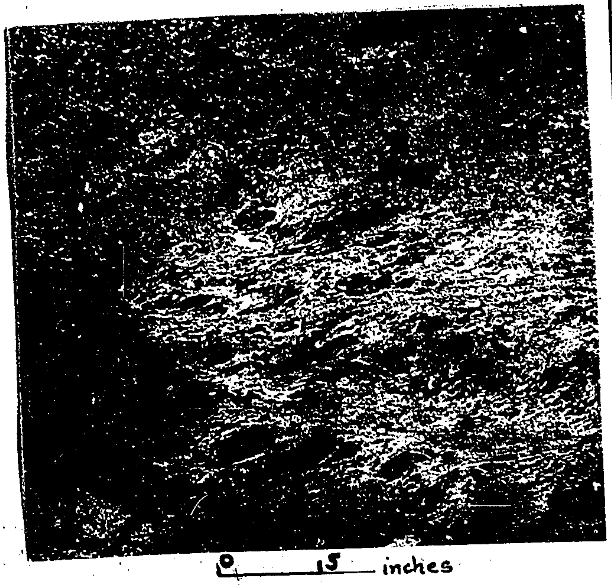

Fig. 5D: Dark bands of ijolite fragmented and converted into lujavrite to the south of Lac Henri (54°06′ 45N and 62°34′39W).

branching irregularly spaced veins in fenites (Fig. 3C). Both slates and volcanic rocks have been metamorphosed to gneisses (Fig. 3D), such that their original character is completely obliterated. Bessie Lake quartzites have been transformed into granitic gneiss on the northern and eastern shores of Shallow Lake.

c) No evidence of thrusting along the arcuate disposition of outcrops of the Lititia Lake Formation and the southern granites could be established; however, patchy mylonitic zones within acid volcanics and fenites can be seen (Fig. 4A, 4B, 4C, and 4D). A few minor faults cut across the Lititia Lake Formation.

d) At Mann 2, ijolite-urtite (essentially a nepheline, Na-amphibole and Na-pyroxene rock) intrudes the volcano-sedimentary sequence of the Lititia Lake Formation and metasomatizes the surrounding rocks. To the north of Esker Lake, lujavrite (alkali feldspar-nepheline-aegirine-arfvedsonite rock, Fig. 5A) forms a dyke-like intrusion into the highly metasomatized Lititia Lake volcanics. Besides the intrusions of ijolite-urtite and lujavrite, quartz-fluorite-ussingite and albitite veins are commonly developed in the fenites within the Lititia Lake Formation. Pegmatitic veins contain sphalerite-galena-pyrrhotite in barylite-rich fenites at Mann - 1.

e) The Joan Lake agpaitic pluton contains xenoliths of schist (Specimen 207), quartzite (Specimen 209) and volcanics (Specimens 204, 205 & 206) and apparently intrudes the volcano-sedimentary sequence of the Seal Lake Group and Lititia Lake Formation. The contact of the Joan Lake agpaitic pluton is not well marked as it is buried under glacial drift

Fig. 6: Megascopic features of Type III and Type IV (eudialytite) rocks.

Fig. 6A: Eudialyte-nepheline gneiss composed of eudialyte (pink), nepheline (gray), arfvedsonite and aenigmatite (black), feldspar (white) and aegirine (green) cut by a coarse arfvedsonite-feldspar vein (54°07′58″N and 62°31′58″W).

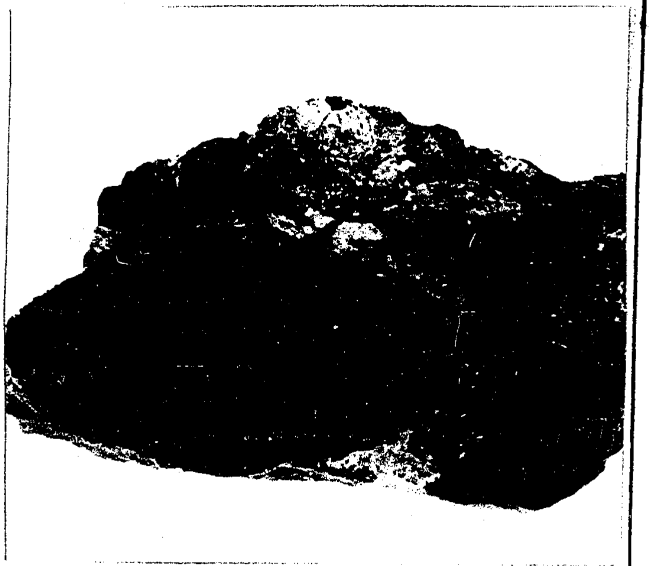

Fig. 6B: Megacrystal of arfvedsonite (black) developed in a eudialyte rich pegmatoid phase (Type III), Specimen 231, x ¼.

Fig. 6C: Pegmatoid eudialyte-nepheline-aenigmatite rock (Type III), (54°08′45″N and 62°33′15″W).

Fig. 6D: Eudialytite vein (white) in Type III rocks (54°07′58″N and 62°32′W).

on the northern side and is obscured by heavy vegetation to the west and south-west. To the south-east of the pluton, quartz-diorite was observed close to agpaitic rocks but their precise contact lies beneath a drift-filled, 5-feet wide stream course. In the centre of the Joan Lake pluton, the dark layers (Fig. 5B), composed of nepheline and ferrohastingsite (ijolite-urtite), gradually are fragmented (Fig. 5D), and converted into aegirine-lujavrite (Type I). At places, the ijolite-urtite bands are ruptured, deformed plastically, sealed and deformed again. (Fig. 5C). As one proceeds from the central core of the agpaitic pluton, the eudialyte content increases (Fig. 6A) and the rocks become coarse to very coarse grained with reduction in aegirine content. In the peripheral zone arfvedsonite and eudialyte vary in size from a fraction of an inch to several inches across (Fig. 6B). Aenigmatite becomes an essential constituent but the nepheline content shows quite marked fluctuations. The rock near the margin becomes pegmatoid in texture (Fig. 6C). In this zone, patches and veins of eudialytite (60-80% eudialyte) can occasionally be seen (Fig. 6D). In the southeast of the pluton, medium-grained alkali-feldspar and eudialyte-rich hypidiomorphic aenigmatite-nepheline rocks (Type II) intrude the pegmatoid Type III. At another place, Type III rocks occur with alternating black and pink layers. In such a case, the black layers consist of nepheline, arfvedsonite, aegirine and albite while pinkish layers contain eudialyte, arfvedsonite, aenigmatite and nepheline as essential constituents.

f) The Joan Lake agpaitic complex is surrounded by fenites on its northern, western and eastern sides while the rocks of quartz-diorite and gabbroic composition to the southeast are only thermally metamorphosed. Fenites in the immediate vicinity of the Joan Lake pluton are rich in perthites while they are enriched in albite in the Ten Mile Lake area. To the south of Joan Lake, the fenites are locally developed as metasomatic nebulous masses which look like separate intrusions.

g) South of Joan Lake, in the Red Wine River Valley, is another agpaitic complex (Fig. 1, block C) probably intruding schists and regionally metamorphosed rocks e.g., anthophyllite-grünerite-hornblende-feldspar gneisses and sillimanite-cordierite hornfelsic rocks.

3. Isotopic age determination of the Joan Lake rocks

K-Ar age determinations were carried out by Dr. K. Bell of Carleton University. Calculations are based on the following constants;

$$\lambda_e = 0.585 \text{ x } 10^{-10} \text{yr}^{-1},$$

$$\lambda_a = 5.30 \text{ x } 10^{-10} \text{yr}^{-1},$$

$$K^{40}/K = 0.0119 \text{ atom percent.}$$

The age of the mineral was determined by using the following relation:

$$t(\text{time in m.y. }) = {}^{1}/_{\lambda_o} \ln(1 + {}^{\lambda_o}/_{\lambda_e} \text{ x } Ar^{40}/ K^{40}).$$

The dates determined on various minerals are summarized in table 2.

The K-Ar age determinations lead to the following observations:

1. the dates on nepheline give younger ages than those of coexisting amphiboles,
2. the pluton shows older ages towards the periphery, and
3. the Joan Lake pluton might have been emplaced between 1000 and 1400 m. y.

TABLE 2

K-Ar dates for minerals in
the Joan Lake pluton

Sample No	Rock type	Sample type	Date in m. y.
202	Ijolite	Nepheline	978±62
202	Ijolite	Amphibole	1,000±65
230	Type I	Amphibole	1,078±65
274	Type III	Nepheline	1,207±75
274	Type III	Amphibole	1,334±84
272	Type III	Amphibole	1,417±102

The differences in the dates of coexisting nepheline and amphiboles may be ascribed to the following factors;

1. crystallo-chemical differences of the minerals,
2. loss of argon from the nepheline structure and entrapment of excess argon in crystal imperfections and along the low angle grain boundaries in amphiboles,
3. differences in degree of hydration of individual minerals (more hydrated minerals such as zeolites after nepheline, may show younger ages due to loss of argon during hydration, as suggested by Kaneoka, 1972) and
4. non-uniform rates of argon diffusion in different mineral phases.

The differences in ages of various rocks of the pluton may be attributed to the combination of the following factors:

1. differences in potassium metasomatism relative to argon in various regions of the pluton

2. in certain parts of the pluton, diffusion proceeded at different rates as compared to other parts.
3. folding and fracturing in the centre was more intense than at the periphery of the pluton leading to the loss of radiogenic argon, and
4. the central portion of the pluton being reheated after emplacement.

Field evidence suggests a higher intensity of folding in the central portion of the pluton. Differences in the structures of amphiboles (Specimens 202 and 274) are quite clear from their Mössbauer and optical spectra (Part 3). These differences might have been caused by reheating of amphiboles of ijolite, however, it is difficult to envisage metamorphism affecting the central portion of the pluton but not the rim.

Considering the factors outlined above and the field disposition of the Joan Lake pluton, it will be advisable to suggest that the K-Ar dates do not necessarily determine the true age of the pluton. The age of emplacement of the entire pluton may lie in the range of 1000-1400 m. y. provided radiogenic argon was not added from another source or did not escape after its emplacement.

CHAPTER 3

PETROGRAPHY OF THE ROCKS NEAR JOAN LAKE

*1. Quartz-cordierite-sillimanite-plagioclase and quartz-anthophyllite-grünerite-hornblende gneisses

These rocks are exposed as elongated ridges and isolated hills in the Red Wine River Valley. Generally, they are surrounded by glacial drift. Commonly these rocks are medium-to coarse-grained, knotty, porphyroblastic and augen gneisses of brown, buff to dark colours. At places, they are profusely intruded by quartz-muscovite-tourmaline-microcline pegmatitic veins.

a) Quartz-sillimanite-cordierite gneiss

These are dark brown, medium-grained slightly foliated knotty rocks composed of cordierite, microcline-microperthite, sillimanite, magnetite and plagioclase. Muscovite, biotite, apatite, rutile and a green isotropic mineral (unidentifiable, probably spinel) are present as minor constituents.

Anhedral to subhedral grains of cordierite (MgO = 11.77% and FeO = 3.30%) are confined to magnetite-biotite rich bands. Generally, cordierite grains form poikiloblasts enclosing magnetite anhedra, biotite flakes, and dendrites of magnetite. Both twinned and untwinned anhedra of cordierite with biaxially positive and negative optics are present within the same thin section. The optic angle

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* Numbers correspond to map units in the geological map (Fig. 10).

Fig. 7: Petrographic features of sillimanite-cordierite rocks.

Fig. 7A: Sillimanite-cordierite rocks showing poikiloblastic grains of microcline-microperthite with myrmekitic andesine, cordierite and magnetite inclusions, Specimen 381, x100., +nicols.

Fig. 7B: Cordierite showing sector twinning. Specimen 381, x80, + nicols.

Fig. 7C: Plagioclase showing twisted lamellae along the composition plane. Speciment381, x80, +nicols.

Fig. 7D: Quartz-orthoclase vein-like intergrowth in cordierite. Speciment381, x235, +nicols.

varies from 65^{o} to 75^{o}. Untwinned anhedra of cordierite sometimes give rise to myrmekite structure when enclosed by microcline-microperthite poikiloblasts (Fig. 7A). In a few cordierite grains, sector twinning (Fig. 7B) is also observed while in other grains lamellar twinning is seen. Sillimanite needles grow as fibrolites and show epitaxial growth with biotite flakes, but, at places, they also grow as distaxial needles on cordierite. A few anhedral grains of corundum are observed in the vicinity of magnetite, sillimanite and cordierite. Myrmekitic to cauliflower-like plagioclase subhedra form inclusions in microcline-microperthite poikiloblasts. Antiperthitic andesine (An_{37} Ab_{62} Or_{1}, electron microprobe determination) subhedra are found in the main matrix along with other grains which do not show any evidence of myrmekitization, or formation of antiperthite. Andesine commonly shows complex twins or combinations of albite and pericline laws. However, some grains are twinned on the simple albite law but in such cases, the twin lamellae are twisted along the composition plane (Fig. 7C). Quartz is generally confined to cordierite subhedra as veins and subhedral grains (Fig. 7D). X-ray analysis of such quartz veins from within cordierite grains gave quartz and orthoclase lines.

Small anhedra of apatite, zircon, sphene and rutile occur as inclusions in cordierite, plagioclase and microcline-microperthite grains. Muscovite is as an alteration of biotite. Microcline-microperthite is compositionally close to $Or_{80.5}$ $Ab_{18.1}$ $An_{1.4}$, and forms poikiloblasts.

b) Quartz-anthophyllite-grünerite gneiss

These are medium to coarse-grained porphyroblastic mesocratic gneissose rocks composed of anthophyllite, grünerite, quartz, oligoclase-andesine (An_{28}-An_{32}), biotite, sphene, chlorite, epidote, garnet, chloritoid, ilmenite, hornblende, muscovite, magnetite, perthite and microcline.

Anthophyllite ($2V_x = 78^o$) occurs as large grains but occasional composite grains are also observed. In composite grains, the core is anthophyllite while margin is formed by bluish green hornblende ($2V_x = 74^o$). Generally, anthophyllite grains show lamellar twinning and occur in association with biotite and magnetite. At places, anthophyllite co-exists with grünerite ($2V_z = 84^o$, $Z \wedge c = 14^o$). Occasionally light green patches of hornblende (reaction centres) within anthophyllite grains are observed. Generally plagioclase (An_{28-32}) is twinned on albite law but a few grains show twinning on combination laws. Biotite flakes appear to be in the phlogopite range and commonly show arrangement of magnetite along the shear planes such that shear folds are developed within these flakes. Garnets vary from non-spongy to spongy, colourless subhedra and occur as inclusions in biotite and plagioclase. Chlorite flakes generally occur as alteration products of biotite. Grünerite ($2V_x = 84^o$) occurs as colourless, radiating flaky aggregates in association with anthophyllite. Muscovite flakes co-exist with epidote in plagioclase grains. Microcline and perthite subhedra form porphyroblastic grains in some rocks. Sphene ($2V_z = 30^o$) occurs as pinkish polysynthetically twinned subhedra.

Fig. 8: Petrographic features of quartz-diorite, quartz-aegirine-muscovite schist and quartzite.

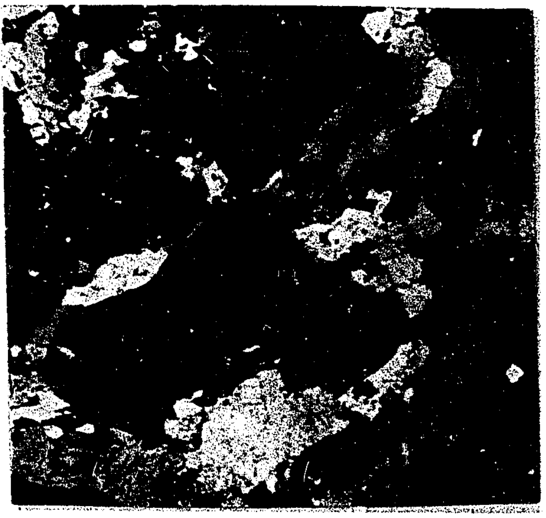


Fig.8A: Quartz-diorite showing diffused oscillatory zoning in plagioclase. At the upper right corner, the plagioclase is partly fused. Specimen 289, x 50, +nicols.

Fig.8B: Highly kinked quartz-aegirine-muscovite schist with well developed shear cleavage. Specimen 207, Polarzed light, x50.

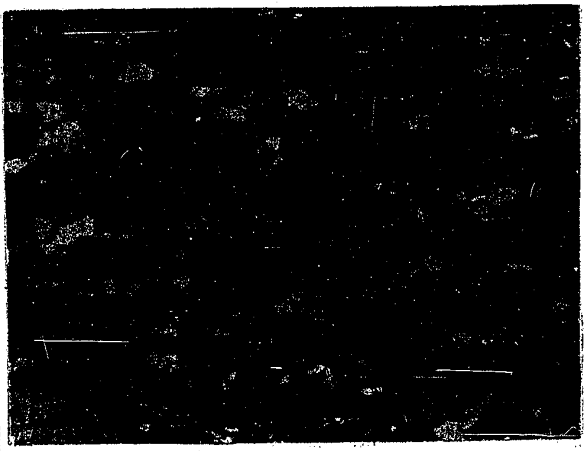


Fig. 8C: Bessie Lake quartzites grading into mylonitized porphyroblastic quartzitic schists with porphyroblasts of quartz. Specimen 331, x 50, +nicols.

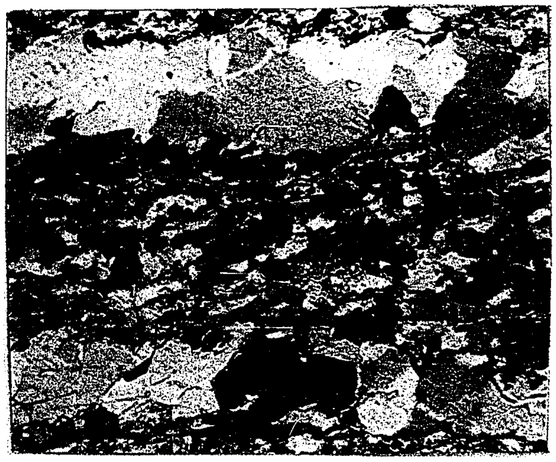


Fig.8D: Quartzite xenolith of recrystallized and banded rock with quartz and albite (colourless) and aegirine, albite, riebeckite(black) as alternating bands. Specimen 209, Polarized light, x50.

2. Metamorphosed gabbro and quartz-diorite

Medium to coarse-grained melanocratic rocks, mostly composed of plagioclase (45%), hornblende, biotite and augite (45%), magnetite, ilmenite and pyrite (7%) and quartz (3%). At places they include ilmenite-hematite-pyrite lenses up to 2 ft. x 2 ft. x 5 ft. size. These rocks occasionally acquire gneissosity and are intruded by veins of aplite. Near the Joan Lake agpaitic syenite, they are changed into epidiorites with hornfelsic texture. Biotite-schist xenoliths are common in these rocks.

Microscopically they are medium-grained hypidiomorphic, mesocratic rocks composed of andesine-labradorite (An_{45} - An_{54}), biotite, amphibole, quartz, apatite, magnetite, sphene, augite, muscovite and traces of pyrite. Plagioclase is altered to epidote and sericite. Some plagioclase forms poikilitic grains enclosing hornblende anhedra. Generally albite, albite-carlsbad, albite-pericline twins and twins of unidentified laws are observed in plagioclase. Biotite flakes contain inclusions of magnetite, hornblende, apatite, and sphene. Occasionally, some needles of rutile, arranged parallel to pseudohexagonal faces of biotite, give an impression of three directions of cleavage in basal-section. Some flakes of biotite show evidence of twisting such that shear cleavage develops and iron oxides form an irregular shear fold pattern. Amphiboles are generally hornblendic in composition but enclose colourless pyroxenes (diopsidic-augite) in the core. Quartz forms a very minor phase.

At places, the plagioclase shows oscillatory zoning with An_{36} at the margin and An_{48} at the core. In such cases, the boundaries of respective zones are quite diffused (Fig. 8A). In those rocks, the plagioclase grains fuse to form veins filling the cracks. Biotite and sphene develop in the cracks within plagioclase. Some quartz grains show deformation lamellae while others are clear. Oxyhornblende forms the margins of pyroxene cores.

3. Quartz-muscovite-biotite schist, slate and porphyritic acid volcanics

Fine-grained olive-green to black, spotty to slightly phyllitic schists and metavolcanics. The unmetamorphosed, cataclastic, porphyritic acid volcanics form ridges in the Esker Lake and Ten Mile Lake areas. These rocks were described as members of the Lititia Lake Formation by earlier authors.

a) Phyllite and slate

Fine-grained, black, banded rocks showing slaty and shear cleavages. They are chiefly composed of hematite needles (arranged parallel to the slaty cleavage), quartz, chlorite, magnetite, sericite and muscovite. To the west of Ten Mile Lake, they contain numerous quartz veins parallel to their bedding (Fig. 3A). Brecciation has affected the slates to the west of Ten Mile Lake (Specimen 140) and the slates at that locality are composed of olive-brown biotite flakes, magnetite granules, limonite, pyrite, quartz and sericite.

b) Schist

Fine to coarse-grained, black to mesocratic micaceous rocks composed of quartz, muscovite-biotite, epidote, chlorite and sericite.

They are locally kinked. Epidote and sphene anhedra are found in the vicinity of biotite and muscovite flakes. Quartz aggregates are interlaced with micas. Magnetite anhedra are randomly distributed throughout the matrix. In some rocks, these anhedra are distributed in bands alternating with quartz and sericite. When xenoliths occur in agpaitic rocks, needles of aegirine and riebeckite are found parallel to their foliation (Fig. 8B). Fluorite forms larger grains (4-5mm) in such schistose rocks.

c) Cataclastic, porphyritic, acid volcanics

Green to brown, commonly porphyritic with phenocrysts of blue quartz, plagioclase and K-feldspar embedded in a fine-grained matrix (Figs. 4A and 4B). Most of them are rhyolite to trachyte in composition but a few outcrops have tuffaceous appearance.

Highly cracked phenocrysts of quartz, plagioclase and K-feldspar are embedded in a quartzo-feldspathic matrix. Limonite and hematite fill the cracks. Quartz, perthite, sanidine ($2V_x$=10-15°)and plagioclase occur as phenocrysts. Rarely mylonitised matrix enters the cracks. Some plagioclase phenocrysts break down to albite and calcite. In such rocks homogeneous sanidine grades into sanidine perthite.

4. Quartz-epidote-sericite schist and banded quartzite

(Bessie Lake quartzite)

Alternating olive-green to flesh-coloured banded quartzite. Less commonly these quartzites grade into quartzitic schists (Fig. 8C).

Generally, these quartzites are composed of polygonal quartz, muscovite, microcline, albite-oligoclase (An_8 to An_{14}) but quartzitic schists contain chlorite, talc, epidote and rarely biotite flakes. Zircon, magnetite, and hematite occur as minor constituents.

Some quartzite xenoliths are found in the Joan Lake agpaitic complex. The xenolithic quartzites show recrystallization within quartz-rich bands (Fig. 8D) and the mafic bands are composed of riebeckite, acmite, sphene and lamprophyllite. Bands rich in mafic minerals are discontinuous within felsic matrix. They swell and pinch out within short distances.

5. Diabase sills

Sills of melanocratic, coarse-grained rocks with ophitic texture, occur within the Seal Lake Group interlayered with tuffs, quartzites and argillites.

These rocks are composed of large laths of altered labradorite (An_{55-58}) and subcalcic-augite. Augite commonly alters to chrysotile but, at places, antigorite also develops. Plagioclase alters to granules of epidote and needles of sericite. Leucoxene, magnetite and hematite are quite common. The degree of alteration of diabase increases towards the south. The altered diabase contains lenses of chlorite which gives it a spotty appearance.

6. Granite and granitic gneiss

Medium-grained, leucocratic, gneissose rocks composed of quartz, biotite, microcline, aegirine-augite, magnetite and muscovite (Figs.9A, 9B).

Fig. 9: Petrographic features of aegirine granite, Type II, aegirinite, and Type III rocks.

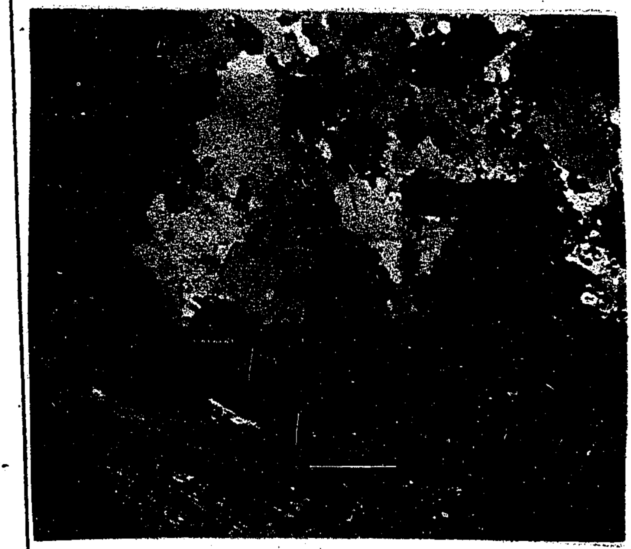


Fig. 9A: Aegirine granite showing the relation of aegirine-augite (black), microcline (gray) and quartz (light gray to gray). Specimen 363, x50, +nicols.

Fig. 9B: Aegirine granite with typical rectangular joints at the southwestern shore of Shallow Lake (62°40′10″W and 52°02′50″N).

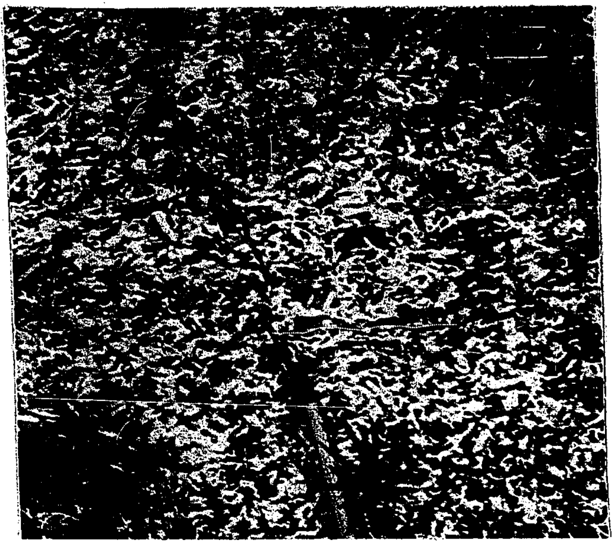


Fig. 9C: Unfoliated nepheline-eudialyte-aenigmatite (Type II) rock(62°30′30″W and 54°06′10″N).

Fig. 9D: Aegirinite composed of aegirine (light gray), arfvedsonite (black) and albite (colourless). Specimen 266, Polarized light, x50.

Fig. 9: Petrographic features of aegirine granite, Type II, aegirinite, and Type III rocks.

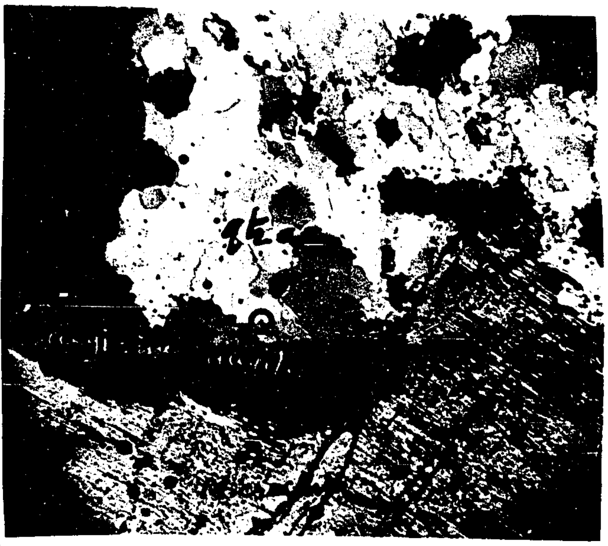


Fig. 9A: Aegirine granite showing the relation of aegirine-augite (black), microcline (gray) and quartz (light gray to gray). Specimen 363, x50, +nicols.

Fig. 9B: Aegirine granite with typical rectangular joints at the southwestern shore of Shallow Lake (62°40′10″W and 52°02′50″N).

Fig. 9C: Unfoliated nepheline-eudialyte-aenigmatite (Type II) rock(62°30′30″W and 54°06′10″N).

Fig. 9D: Aegirinite composed of aegirine (light gray), arfvedsonite (black) and albite (colourless). Specimen 266, Polarized light, x50.

Quartz occurs as anhedral aggregates while microcline and perthite form porphyroblasts. Biotite occurs in lenticular aggregates of flakes while aegirine-augite develops as anhedral to subhedral grains (Fig. 9A). Oligoclase (An_{22-26}) forms a few scattered laths.

7. Layered ijolite-urtite and lujavrite

Fine-grained, melanocratic to leucocratic, layered rocks. The melanocratic rocks are composed of nepheline, ferrohastingsite, barytolamprophyllite, ramsayite, lamprophyllite, apatite, phlogopite, pectolite, traces of hydrosodalite and zeolites (unidentified). Their chemical composition is similar to the ijolite-urtite of Galakhov (1967a). The leucocratic rocks consist of nepheline, alkali-feldspar, arfvedsonite, biotite, and aegirine-augite. Compositionally they are close to the lujavrite of Sørensen (1969). The melanocratic layers are deformed and fragmented until they grade into lujavrite completely.

The lenticular body of ijolite-urtite and lujavrite in the hills to the south of Ten Mile Lake shows variation in mineralogical composition within short distances both across and along the strike. In such a case the ijolitic rocks are composed of nepheline, arfvedsonite, ramsayite, lamprophyllite, aenigmatite, blue clinopyroxene (Fe-Ti-omphacite), pectolite, natrolite, alkali-feldspar, loparite, aegirine-augite, Li-mica, innelite and several unidentified minerals.

Detailed petrographic description of the above rocks is covered in Part 2.

8. Type I (Lujavritic gneiss)

Mesocratic to leucocratic, medium-to coarse-grained gneissose, highly folded rocks composed of nepheline, alkali-feldspar, arfvedsonite, aegirine-augite and plagioclase. They also occur as hypidiomorphic granular rocks forming dykes and sills which intrude the Lititia Lake Formation.

They are composed of both zoned and unzoned aegirine-augite, nepheline, pectolite, astrophyllite, arfvedsonite, vinogradovite, eudialyte (eucolite, mesodialyte varieties), microcline, natrolite, albite, titanian lavenite, sphalerite, apatite, fluorite, biotite, hematite, lithian-mica, pyrrhotite and several unidentified minerals.

Since these rocks form the major part of the Joan Lake agpaitic complex, they are described in detail in the next part.

9. Pegmatoid (Type III) and other unfoliated eudialyte-aenigmatite-nepheline syenites (Type II)

Mesocratic, medium-grained to pegmatoid and unfoliated rocks (Fig. 9C), commonly developed as marginal phases of the agpaitic complex at Joan Lake. In pegmatoid Type III, the grain size varies from a few millimeters to several centimeters, while Type II rocks are finer grained. The Type III rocks show poikilitic texture and are intruded by the eudialytite veins. At some places, these rocks become sufficiently rich in aegirine (Fig. 9D) to resemble aegirinites described from Kola Peninsula, U.S.S.R. (Vlasov <u>et al</u>. 1966).

A variety of mineral associations has been noted but eudialyte, nepheline, aenigmatite and arfvedsonite are major constituents in all types; however apatite, pectolite, acmite, natrolite, pyrrhotite, galena, albite, oligoclase, fluorite, lamprophyllite, biotite, steenstrupine(?), mesodialyte, bastnaesite, schizolite and several other mineral species occur in varying proportions. Detailed mineralogy and petrography of these rocks will be discussed in Part 2.

10. Fenite and quartz-aegirine syenite

Fine to medium-grained schistose to gneissose and unfoliated rocks developed in the metasomatic aureole around the Joan Lake agpaitic pluton. The texture of these rocks varies within short distances. Mineralogically, they are hosts to several uncommon minerals, such as eudialyte, neptunite, astrophyllite, niobophyllite, barylite, joaquinite, eudidymite and loparite (perovskite). Generally, they show clear evidence of pervasive migration of fluids from the Joan Lake agpaitic pluton into the volcano-sedimentary sequence of the Seal Lake Group.

Commonly, these rocks are composed of arfvedsonite, aegirine, K-feldspar and albite and can be divided into different classes on the basis of type and amount of feldspars, as follows:

1) Perthite-rich approaching perthosite;
2) Albite-rich approaching albitite;
3) Intermediate type, nearly equal amounts of both the feldspars.

Detailed petrography of these rocks is described in the next part.

11.Glacial drift and sands

Glacial drift,composed of large boulders, tillites and sands of various grain sizes. Generally, the boulders in the drumlins are not transported far from their source. They are therefore good indicators of the outcrops nearby.

Discussion

Sillimanite-cordierite and anthophyllite-grünerite gneisses along with metagabbro, schists and slates indicate that the units 1-6 had undergone regional metamorphism under greeschist to upper amphibolite facies. The presence of quartz and orthoclase veins in cordierite, dendritic-magnetite of the type illustrated by Spry(1969, p. 153), corundum, antiperthite, microcline-microperthite, complex twins in cordierite(Venkatesh 1954), and destruction of albite twins in plagioclase, can be explained by a superimposed contact metamorphism on a regionally metamorphosed assemblage of sillimanite-cordierite rocks(Singh and Kamineni 1971). The superimposition of thermal metamorphism on regional metamorphic assemblages is also supported by several features observed in anthophyllite -hornblende-grünerite gneisses, metagabbros and metamorphosed diorites.

The occurrence of quartz-muscovite schists,slates and other low grade regionally metamorphosed rocks as xenoliths(Seal Lake Group) in the Joan Lake agpaitic complex suggests that the agpaitic pluton is younger than the Seal Lake Group.Age determinations indicate that the Joan lake pluton may be 1000 to 1400 m. y. in age. Both ijolite - urtite and lujavrite(Type 1)

Fig.10 is in pocket at the end of the thesis.

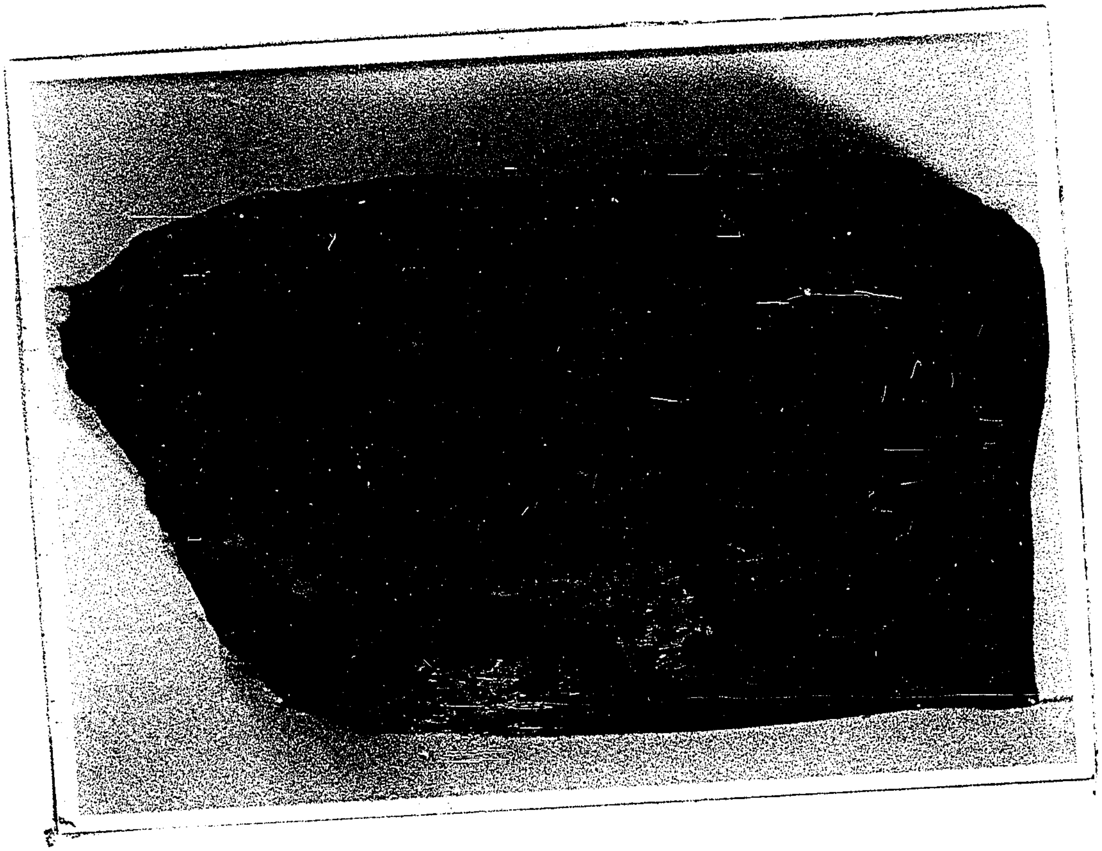
intrude the Lititia Lake and Seal Lake volcano-sedimentary sequences, therefore agpaitic rocks are younger than the Seal Lake Group. Fenites show evidence of mylonization and therefore cataclastic activity may be post-fenitization and later than or contemporaneous to the Joan Lake agpaitic intrusion.

The new interpretation based on petrographic study and field investigations is presented on the regional map (Fig. 10). In this map, Seal Lake and Lititia Lake Groups (Units 1-5) are included in "Precambrian" but the terms Seal Lake and Lititia Lake Groups have not been used in the legend because of their imprecise definitions.

PART 2

THE JOAN LAKE AGPAITIC COMPLEX

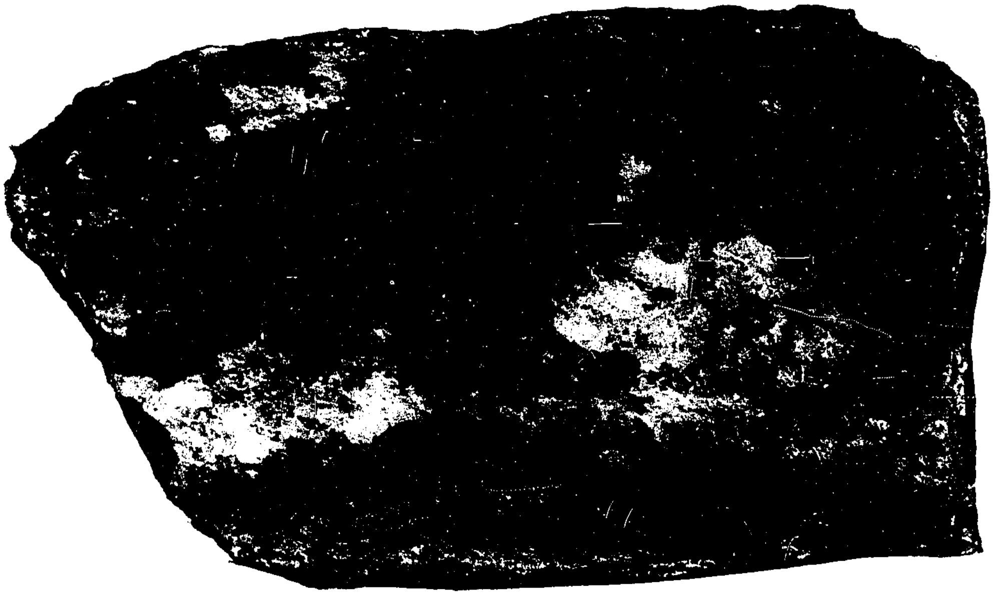
THE JOAN LAKE AGPAITIC SYENITE
(TYPE III)



AN AGPAITIC SYENITE FROM THE JOAN LAKE AREA, LABRADOR, COMPOSED OF EUDIALYTE (PINK), AENIGMATITE (REDDISH BROWN), ARFVEDSONITE (BLACK), AEGIRINE-AUGITE (GREEN), NEPHELINE AND FELDSPAR (WHITE)., 1/4 X.

THE JOAN LAKE AGPAITIC SYENITE

(TYPE III)



AN AGPAITIC SYENITE FROM THE JOAN LAKE AREA, LABRADOR, COMPOSED OF EUDIALYTE (PINK), AENIGMATITE (REDDISH BROWN), ARFVEDSONITE (BLACK), AEGIRINE-AUGITE (GREEN), NEPHELINE AND FELDSPAR (WHITE)., 1/4 X.

CHAPTER 4

CLASSIFICATION AND PETROGRAPHY

1. The agpaitic rocks, nomenclature and classification

The agpaitic rocks have been defined as peralkaline eudialyte-nepheline or sodalite-syenites with $Na_2O + K_2O/Al_2O_3 > 1$ (Gerassimovsky 1956), and characteristic mineralogy (Sørensen 1960, Gerassimovsky et al. 1966). The most typical minerals are eudialyte, aenigmatite, soda-amphiboles, rinkite and aegirine (Sørensen 1960). The most important characteristics that distinguish the agpaitic rocks from the common nepheline syenites are summarized in Table 3.

Since the discovery of eudialyte syenite from Greenland, the nomenclature and classification of the agpaitic rocks have been based on the name of the locality e.g., lujavrite from Lujavre Urt, Lapland (Ramsay 1890), chibinite from Kola peninsula, U.S.S.R. (Fersman 1923), kakortokite from Kakortok, Greenland (Ussing 1911) and naujaite from Naujakasik, Tunugdliarfik Fjord, Greenland. Rocks with similar mineralogy were given different names by different petrologists i.e., lujavrite and chibinite, kakortokite and khibinite (both layered types). Geologists studying rocks from Greenland retained the terminology of Ussing (1911) but redefined the terms as summarized in Table 4. On the other hand, Russian geologists used the term lujavrite (Vlasov et al. 1966) and redefined it as a rock containing equal amounts of alkali-feldspar, nepheline and aegirine.

TABLE 3

Comparison of agpaitic and non-agpaitic rocks

Agpaitic syenites	Non-agpaitic syenites
Chemical	
1. $\frac{Na_2O + K_2O}{Al_2O_3} > 1$	1. $\frac{Na_2O + K_2O}{Al_2O_3} \leqslant 1$
2. $\frac{Fe_2O_3}{FeO + Fe_2O_3}$ decreases with crystallization	2. $\frac{Fe_2O_3}{FeO + Fe_2O_3}$ increases with crystallization
3. $Na_2O \gg 2K_2O$	3. commonly $Na_2O \leqslant 2K_2O$
4. ZrO_2 greater than in any other known terrestrial rocks.	4. ZrO_2 always present in traces.
5. $TiO_2 \geqslant 1\%$	5. TiO_2 in traces
6. $(CaO + MgO) < 6\%$	6. $(CaO + MgO) > 6\%$
Mineralogical and Petrological	
7. Complex zirconium and titanium silicates are essential. Zircon and sphene are rare.	7. Complex zirconium and titanium silicates are absent, instead zircon and sphene are present.
8. Generally, ilmenite and magnetite are absent.	8. Ilmenite, magnetite and other oxides are common.
9. Ijolite-urtite is commonly associated with agpaitic rocks.	9. Ijolite-urtite is not an essential rock type.
10. Texture and mineralogy commonly vary within the same pluton.	10. Textures and mineralogical composition are generally consistent within the same pluton.
11. Reversal of normal mineral paragenesis is commonly observed i.e. amphiboles predate pyroxenes.	11. Such reversals are not common.
12. Alkali-feldspar shows characteristic chessboard and braided twins.	12. Combinations of twinning on albite and pericline laws are common.
Experimentally observed	
13. Large melting intervals, typically 400° - 500° C.	13. Small melting intervals, typically 200° - 250° C.

TABLE 4

Classification of agpaitic rocks used in Greenland

Name	Texture	Alkali-Feldspar	Nepheline	Sodalite	Na-Pyroxene	Na-Amphiboles	Eudialyte	Other (except oxides)
Lujavrite	Medium to coarse layered trachytoid massive	15-45 %	5-35 %	0-tr.	5-35 %	20-60 %	2-10 %	0-5 %
Kakortokite	Medium grained laminated to trachytoid	15-60 %	5-70 %	0-1 %	1-20 %	1-40 %	4-45 %	2-30 %
Naujaite	Very coarse grained poikilitic	5-40 %	2-20 %	35-70 %	2-15 %	0-10 %	1-25 %	0-5 %

Data taken from Johannsen 1939; Sørensen 1960, 1969, 1970; Ferguson 1964, 1970b.

Further, they divided the Lovozero agpaitic massif into differentiated rock complexes, poikilitic syenites and dykes, and abandoned the use of terms like kakortokite and naujaite. In Khibina intrusion, Galakhov (1961) described khibinite (trachytoid), laminated khibinite and massive khibinite along with the coarse-grained phase of rischörrite.

A cursory glance on table 4, convinces one that the terms kakortokite and lujavrite overlap compositionally. Therefore, Washington (1917) restricted the use of kakortokite to dark-coloured rocks while light-coloured rocks were classified as eudialyte-syenite (lujavrites).

From the above discussion of nomenclature and classification, it is clear that the names used for agpaitic rocks are not consistently defined.

Since the agpaitic rocks are formed under special environments (high alkalinity) and individual units do not show marked differences in chemical composition (Sørensen 1969, Gerassimovsky et al.,1966), they can be classified only on the basis of texture, mineral associations, and genesis. As aenigmatite is formed at low oxygen fugacity under high alkalinity (Ernst 1962, Abbott 1967), it can be used to separate mineral assemblages of essentially similar chemical composition and texture but contrasted mineralogy resulting from different oxygen fugacities. Furthermore, megascopic textural differences can be used to distinguish various rocks within an agpaitic complex.

In view of the confusion of nomenclature of agpaitic rocks and somewhat distinct mineral assemblage at Joan Lake, the writer has subdivided his alkalic rocks into 6 categories (Table 5) separable on the basis of texture and mineralogical composition.

TABLE 5

Classification of the rocks in the

Joan Lake Agpaitic Complex

		Aenigmatite	Name of the rock	Texture	Minerals	Range showing percent content
MAGMATIC	AGPATIC ROCKS	-	Type I (Lujavrite)	Gneissose Medium grained Laminated and hypidiomorphic Granular	Na-pyroxenes	20-50
					Na-amphiboles	10-40
					K-feldspar	10-45
					Nepheline	0-20
					Eudialyte	1- 5
					Others (No oxides)	0- 5
		+	Type II (Khibinite Kakortokite)	Trachytoid Laminated Layered Medium grained (Plutonic)	K-feldspar	15-60
					Na-amphiboles	4-45
					Aenigmatite	5-15
					Nepheline	5-70
					Eudialyte	5-30
					Na-pyroxene	1-10
					Sodalite	0- 5
					Others (No oxides)	1-15
		+	Type III (Rischorrite)	Poikilitic Pegmatoid to coarse Gneissose	K-feldspar	5-40
					Nepheline	2-20
					Eudialyte	5-25
					Aenigmatite	5-20
					Arfvedsonite	5-10
					Na-pyroxenes	1-15
					Others (No oxides)	0- 5
		±	Type IV (Eudialytite)	Vein Material Granular	Eudialyte	60-80
					Alkali-feldspar	0-25
					Nepheline	0-10
					Na-amphiboles	0-10
					Aegirine-augite	0-10
					Others (No oxides)	0- 5
	NON-AGPAITIC ROCKS	±	Ijolite-urtite	Gneissose Medium grained Laminated	Na-amphiboles	40-60
					Nepheline	20-50
					Na-pyroxenes	1-10
					Pectolite Ramsayite Lamprophyllite Biotite Aenigmatite	0- 5
					Others (No oxides)	0- 5
METASOMATIC	ROCKS	±	Fenites	Fine to coarse grained Schistose to gneissose	K-feldspar	10-90
					Plagioclase	10-90
					Quartz	2-10
					Na-amphiboles	10-25
					Na-pyroxenes	5-10
					Others	2- 5

N.B.: Rock types are not listed in chronological order.

Fig. 11: Petrographic features of Type I and Type III rocks.

Fig. 11A: Zoned aegirine-augite in Type I (lujavrite) with $Ac_{56}Di_{44}$ (core) and $Ac_{78}Di_{22}$(rim). Nepheline (ne), albite (ab) and eudialyte (eu). Specimen 242. Polarized light, x50.

Fig. 11B: Ferrohastingsite showing arfvedsonite, possibly as an exsolved phase. Nepheline (ne) occurs as inclusions while aegirine-augite forms independent subhedra. Specimen 254, Polarized light, x80.

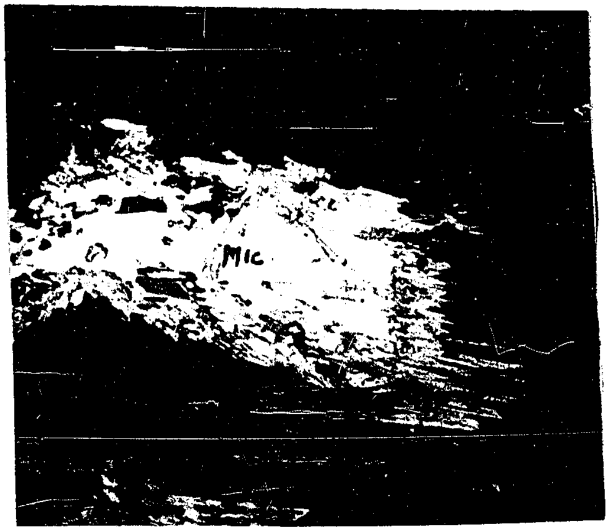


Fig. 11C: Arfvedsonite replaced by aegirine (aeg). Microcline (Mic) occurs as anhedral grains. Specimen 272. Polarized light, x50.

Fig. 11D: Eudialyte (eud) showing patchy zoning. Arfvedsonite (black) is replaced by aegirine-augite (dark gray) and nepheline (colourless). Specimen 226, x50, +nicols.

a) Type I (lujavritic rocks)

Leucocratic to mesocratic, medium-grained trachytoid, gneissose to schistose rocks composed of aegirine-augite, nepheline, alkali-feldspar and arfvedsonite.

Aegirine-augite occurs as both zoned and unzoned anhedral to subhedral grains (Fig. 11A). The powder from zoned aegirine-augite(X-ray analysis, see page 112) gave a composition close to $Ac_{66}Di_{34}$ and unzoned aegirine-augite, compositions ranging from $Ac_{75}Di_{25}$ to $Ac_{85}Di_{15}$. Optical analysis of aegirine-augite gives $Ac_{56}Di_{44}$ with a rim of $Ac_{78}Di_{22}$ while unzoned aegirine-augite falls close to $Ac_{75}Di_{25}$ in composition. Both zoned and unzoned aegirine-augites contain inclusions of nepheline, microcline, albite and eudialyte.

Arfvedsonite is generally intergrown with aegirine-augite. Occasionally, arfvedsonite anhedra occur as inclusions in aegirine-augite poikilites. At places, large ferrohastingsite subhedra show centres of exsolution to probably arfvedsonite (Fig. 11B) while in some grains they alter to aegirine ($Ac_{85}Di_{15}$, Fig. 11C).

Nepheline forms anhedral to subhedral grains, commonly altered to natrolite. In some grains albite occurs as inclusions but other grains are transected by bands of an unidentified material. Aegirine-augite, eucolite, eudialyte and arfvedsonite also form inclusions in the nepheline subhedra.

Microcline occurs as poikilitic (2mm - 6mm) anhedral to subhedral grains and shows cross-hatched to chessboard twinning. Occasionally, the anhedra grade into patch perthite.

Eudialyte grains are rounded to subrounded, zoned (Fig. 11D) and highly cracked. Commonly, they alter into Un-5, fluorite, unidentifiable yellow flakes (0.05 - 0.08mm dia.) and gray grains (0.02 - 0.05mm dia.), white mica and pectolite. Aegirine-augite, arfvedsonite, nepheline, microcline, albite, apatite and other alteration products form inclusions in eudialyte grains.

Schizolite, lamprophyllite, ramsayite, sphalerite, lavenite, pyrrhotite, biotite, sodalite, and several unidentified minerals (Un-12 to Un-24) are accessories.

b) Type II (eudialyte-aenigmatite-nepheline syenite)

Leucocratic to mesocratic, (pink, black to white), medium-grained, trachytoid to layered rocks composed of eudialyte, alkali-feldspars, aenigmatite, nepheline, arfvedsonite and aegirine. Eudialyte is usually confined to the interstices of alkali-feldspar and plagioclase euhedral grains which form a mesh-like network. Commonly, these rocks show alternate pink to white and dark-coloured layering. Pink to white layers are composed of nepheline, eudialyte, alkali-feldspar and albite while dark layers contain aegirine-augite, bastnaesite, arfvedsonite and nepheline.

Microscopically, they are composed of euhedral to subhedral grains of zoned eudialyte, aenigmatite, vein perthite, braided microcline, albite, arfvedsonite, aegirine-augite (both zoned and unzoned), bastnaesite, mesodialyte, vinogradovite, steenstrupine(?), fluorite, apatite, pectolite, natrolite, hydromuscovite, pyrrhotite, britholite, nepheline and several unidentified minerals (Un-1 to Un-20).

Fig. 12: Petrographic features of Type II and Type III rocks.

Fig. 12A: Eudialyte subhedra (eud) altering to steenstrupine(?) near the margins. Arfvedsonite (arf), aegirine-augite (aeg), aenigmatite (aen) and nepheline (ne) are other minerals. Specimen 44, (Type II), x50, +nicols.

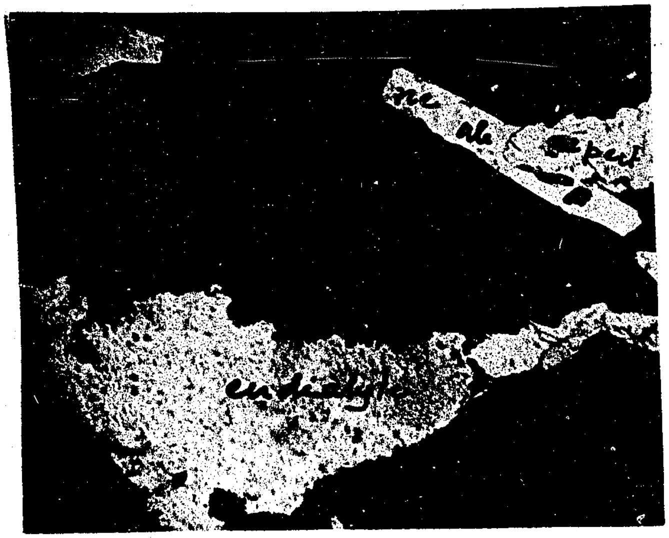


Fig. 12B: Aenigmatite (aen) subhedra, arfvedsonite (arf), eudialyte (eud), microcline (mic), albite (ab), nepheline (ne) and pectolite (pect) form the major constituents of Type II rocks. Specimen 743, x50, +nicols.

Fig. 12C: Poikilitic arfvedsonite (arf) subhedra containing inclusions of nepheline (ne), aenigmatite (aen), microcline (mic) and albite (ab). Specimen 274, (Type III) Polarized light, x50.

Fig. 12D: Aenigmatite (red) growing epitaxially on arfvedsonite (green) in Type III rocks. Specimen 271, Polarized light, x80.

Eudialyte occurs as intensely cracked euhedral to subhedral grains. Almost all the grains show patchy zoning grading into hourglass structure. Generally, the lighter portions in eudialyte grains are associated with cracks. At places, eudialyte alters into mesodialyte and eucolite. Needles of aegirine form inclusions in eudialyte along the cracks and steenstrupine(?) develops in the peripheral zones (Fig. 12A).

Aenigmatite occurs as independant euhedral (Fig. 12B) to subhedral grains some of which show poikilitic texture and enclose aegirine, arfvedsonite, albite, and a few nepheline grains. Some aenigmatite grains grow epitaxially on arfvedsonite (Fig. 12D). Rarely schizolite, biotite and unidentifiable yellowish grains, are seen within aenigmatite subhedra.

Microcline grains are poikilitic, anhedral to subhedral and enclose eudialyte, arfvedsonite, nepheline, albite, and aegirine-augite.

Besides occurring as inclusions in other minerals, nepheline grains are confined to patchy aggregates. Some of the grains are altered to a sheaf-like aggregate of hydromuscovite and natrolite. Some grains of nepheline are intergrown with microcline.

Arfvedsonite forms large subhedra which sometimes enclose aenigmatite, albite, microcline and grade into aegirine at the margins.

Bastnaesite, pectolite, apatite, pyrrhotite, sphalerite, vinogradovite and britholite are accessories.

c) Type III (eudialyte-aenigmatite-arfvedsonite-K-feldspar- nepheline syenitic gneisses and pegmatoid rocks)

Coarse to very coarse-grained gneissose to pegmatoid rocks in which arfvedsonite and eudialyte grow from 5 millimeters to several centimeters

Fig. 13: Petrographic features of Type III rock, Type IV rock and schistose ijolite.

Fig. 13A: Intergrowth of microcline and nepheline in Type III rock. Specimen 272, x50, +nicols.

Fig. 13B: Eudialytite containing eudialyte (eud) and interlocking grains of aegirine (aeg) and albite (ab). Specimen 215, x50, +nicols.

Fig. 13C: Ijolite-urtite rock composed of nepheline (ne) and ferrohastingsite (fer) anhedral to subhedral grains. The ferrohastingsite anhedra show slipping along the cleavage traces. Specimen202, x50, +nicols.

Fig. 13D: Nepheline phenocryst showing overgrowth in schistose ijolite. Specimen 202A, x50, +nicols.

(10-15 centimeters) across. Aenigmatite anhedra also vary from a few millimeters to several centimeters in length. The nepheline content varies within short distances. Alkali-feldspar grows in large crystals interlocked with arfvedsonite and eudialyte.

Microscopically, arfvedsonite occurs as poikilitic subhedra which enclose numerous grains of aenigmatite, eudialyte, nepheline and microcline (Fig. 12C). Microcline and nepheline intergrow to give rise to a texture resembling pseudoleucite (Fig. 13A). White mica, pectolite, apatite and fluorite occur as inclusions in eudialyte grains. Commonly nepheline forms polygonal aggregates. Steenstrupine(?), sphalerite, lamprophyllite, biotite (phlogopite), sodalite, albite, eucolite, mesodialyte, lithium-mica, karnasurtite, pyrrhotite, galena and several unidentified minerals (Un-1 to Un-20) are accessories (Part 3).

d) Type IV (eudialytite)

Medium-to coarse-grained pink rocks forming veins and lenses in Type II and Type III rocks. They generally are composed of 60-80% eudialyte and 20-40% of other light and dark minerals (Table 5). Microscopically, the rocks are medium grained, hypidiomorphic granular (Fig. 13B) composed of subhedral to anhedral cracked grains of eudialyte, anhedra of sodalite, rinkite, albite, microcline, nepheline, arfvedsonite and a few grains of aegirine.

Eudialyte alters into submicaceous flakes of lithium-mica which are confined to interstices. Microcline, albite, rinkite, cryptocrystalline quartz aggregates(probably chalcedony), a dark brown isotropic mineral (unidentified, Un-23) and, more rarely, other minerals form the matrix.

2. Non-agpaitic rocks and lujavrite sills and dykes

a) Ijolite-urtite

Fine to medium-grained, mesocratic to melanocratic, schistose to non-foliated rocks, composed of ferrohastingsite, nepheline, barytolamprophyllite, apatite, lamprophyllite, ramsayite and pectolite.

Microscopically, these rocks are fine grained to slightly schistose, composed of ferrohastingsite ($2V_x = 5\text{-}10^{\circ}$, X = greenish yellow, Y = brownish green, Z = smoky blue, $Z \wedge c = 34^{\circ}$) subhedra. Some ferrohastingsite subhedra show twinning on (110) and generally the cleavage traces are curved. Also some slipping along the cleavages is seen (Fig. 13C). Commonly ferrohastingsite grains are zoned.

Nepheline occurs as euhedral to anhedral grains and forms clusters within the ijolite. In schistose ijolite-urtite, it develops as long prismatic grains (Fig. 13D) which sometimes show zonal overgrowth. Generally, nepheline grains alter to natrolite but rarely to other unidentifiable zeolites and hydrosodalite. Most nepheline grains contain ramsayite, lamprophyllite and apatite inclusions.

Lamprophyllite flakes, bright yellow to golden yellow, are confined to the main matrix along with pectolite, nepheline, phlogopite, ramsayite and aegirine-augite (traces).

Pectolite as anhedral to subhedral grains, is intergrown with ferrohastingsite but rarely encloses ramsayite and lamprophyllite.

b) Ijolite-urtite and lujavrite sills and dykes in the Ten Mile Lake area

Fine-grained mesocratic to melanocratic, schistose to layered, foliated to unfoliated, sills and dykes composed of nepheline,

2. Non-agpaitic rocks and lujavrite sills and dykes

a) Ijolite-urtite

Fine to medium-grained, mesocratic to melanocratic, schistose to non-foliated rocks, composed of ferrohastingsite, nepheline, barytolamprophyllite, apatite, lamprophyllite, ramsayite and pectolite.

Microscopically, these rocks are fine grained to slightly schistose, composed of ferrohastingsite ($2V_x = 5\text{-}10^0$, X = greenish yellow, Y = brownish green, Z $\approx$ smoky blue, $Z \wedge c = 34^0$) subhedra. Some ferrohastingsite subhedra show twinning on (110) and generally the cleavage traces are curved. Also some slipping along the cleavages is seen (Fig. 13C). Commonly ferrohastingsite grains are zoned.

Nepheline occurs as euhedral to anhedral grains and forms clusters within the ijolite. In schistose ijolite-urtite, it develops as long prismatic grains (Fig. 13D) which sometimes show zonal overgrowth. Generally, nepheline grains alter to natrolite but rarely to other unidentifiable zeolites and hydrosodalite. Most nepheline grains contain ramsayite, lamprophyllite and apatite inclusions.

Lamprophyllite flakes, bright yellow to golden yellow, are confined to the main matrix along with pectolite, nepheline, phlogopite, ramsayite and aegirine-augite (traces).

Pectolite as anhedral to subhedral grains, is intergrown with ferrohastingsite but rarely encloses ramsayite and lamprophyllite.

b) Ijolite-urtite and lujavrite sills and dykes in the Ten Mile Lake area

Fine-grained mesocratic to melanocratic, schistose to layered, foliated to unfoliated, sills and dykes composed of nepheline,

Fig. 14: Ijolite specimens containing Fe-Ti-omphacite, lamprophyllite and ramsayite and fenite with film perthite porphyroblast.

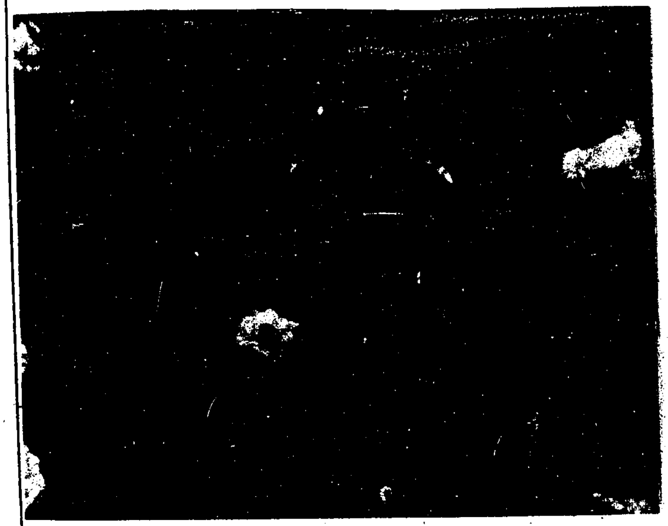


Fig. 14A: Ijolite with aenigmatite (red) Fe-Ti-omphacite (blue) and arfvedsonite (pale to yellowish green). Nepheline and feldspar (colourless) form other constituents. Specimen 125, Polarized light, x80.

Fig. 14B: Schistose ijolite with lamprophyllite (yellow), ramsayite (flesh coloured, lower left ↓), pectolite (pink), Na-amphiboles (gray to green) and nepheline anhedra. Specimen J_4 - 6, x50, +nicols.

Fig. 14C: Schistose ijolite with well twinned perovskite (loparite). Specimen 127. Polarized light, x80.

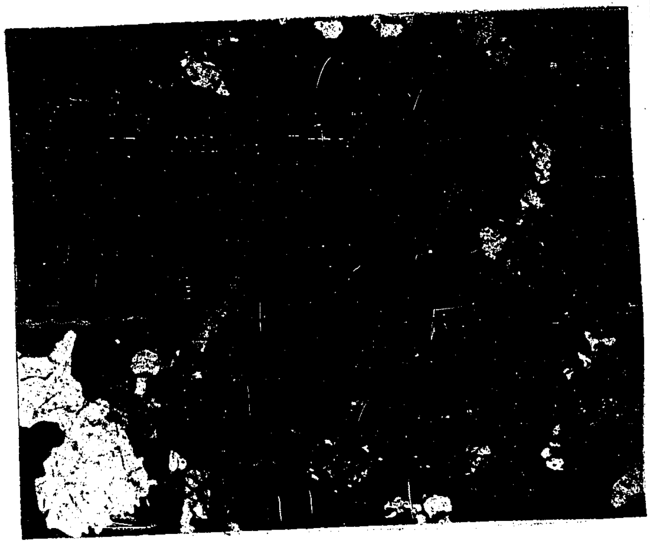


Fig. 14D: Fenite with porphyroblast of film perthite and recrystallized quartz anhedra in a quartzo-feldspathic matrix. Specimen 289, x50, +nicols.

arfvedsonite, alkali-feldspar, ramsayite, barytolamprophyllite, aegirine-augite, Fe-Ti-omphacite, pectolite, eudialyte, aenigmatite, phlogopite, sodalite, innelite, natrolite, perovskite (loparite), plagioclase (An_{16}) and several other accessory minerals (see Part 3).

Nepheline occurs as cracked anhedral to subhedral grains and is commonly associated with microcline and oligoclase (this unit resembles ijolite-urtite described from Khibina, U.S.S.R.). In lujavrite dykes the nepheline content is reduced so that it becomes an accessory mineral. The nepheline grains alter to natrolite. Arfvedsonite and ferrohastingsite are found as anhedral to subhedral grains, normally unaltered but near the margins of the sill at Mann-2, arfvedsonite alters into aegirine-augite. In another rock (Specimen 127), arfvedsonite is mantled by Fe-Ti-omphacite (Fig. 14A). In this case aenigmatite is associated with arfvedsonite.

Ramsayite and lamprophyllite form the other main minerals in arfvedsonite-rich schistose rocks (Fig. 14B) but they become accessories in aenigmatite-bearing zones. Aegirine-augite grains are generally rare but, at places within the same sill, they dominate other minerals. In lujavritic rocks they occur as the main mafic minerals. Alkali-feldspar develops profusely near the margins of the ijolite sills but it is more common as perthite in lujavrite.

Besides the various minerals reported above, perovskite (Fig. 14C), biotite, barytolamprophyllite, pectolite, apatite, hydromuscovite, albite, lithium-mica, galena, white mica, vinogradovite, leucoxene, sphalerite, innelite and Un-10 to Un-23 (unidentified), occur in various proportions.

3. Metasomatic rocks (fenites)

Rocks affected by liquid and vapour phases of the Joan Lake agpaitic pluton have been described earlier (Chapter 3). The preliminary study of such rocks leads to their classification based on the amount and type of feldspar developed. The following three classes are prominant.

a) K-feldspar-rich fenites

Texturally these rocks include a host of enigmatic varieties ranging from gneissose to hypidiomorphic granular, medium-to coarse-grained. Compositionally they comprise granite, syenite and perthosite. Megascopically, all of these rocks are stained red and resemble the fenites described by Heinrich and Moore (1970).

In the Joan Lake area, it is hard to categorize them as they were, in other areas, by Fawley and James (1955), James (1958) Fick and Van der Hyde (1959), Bailey (1960)and Sutherland (1965, 1967). In general, they can be described as non-fragmental to fragmental alkali-feldspar fenites.

Microscopically, these gneisses are composed of quartz (10%), microcline + perthite (50%), albite (10-15%), arfvedsonite and aegirine (25-30%) as principal minerals while astrophyllite, biotite, sphene, apatite, zircon, neptunite, ilmenite, hematite, thread-like needles (unidentified, not X-rayed) and red pigmentary stains (unidentified, not X-rayed).

Perthite occurs as porphyroblasts (Fig. 14D) and generally contains inclusions of quartz, albite, arfvedsonite and aegirine. Commonly the perthite anhedra are highly fractured and show all variations from

Fig. 15: Petrographic features of perthosite, porphyritic trachyte and albitite.

Fig. 15A: Perthosite composed of recrystallized perthite (per) interlocked with quartz (qtz) and aegirine-augite (aeg). Specimen 289, x50, +nicols.

Fig. 15B: Rods of alternating perthite and aegirine-augite in perthosite. Specimen 307, nicols crossed at an oblique angle, x50.

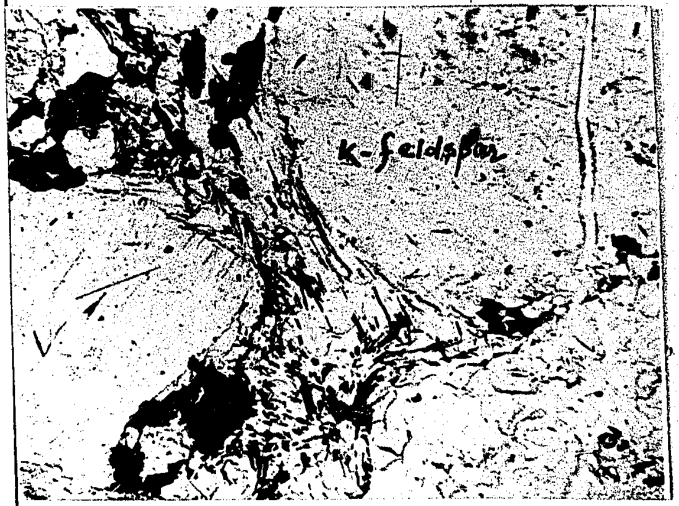


Fig. 15C: Porphyritic trachyte with intergranular acicular aegirine-augite and aenigmatite (both dark). K-feldspar forms the main phenocrysts. Specimen 158, Polarized light, x50.

Fig. 15D: Albitite composed of albite laths commonly with more than three twin lamellae. Aegirine (aeg) and barylite (bar) occur as interstitial minerals. Specimen 142, x50, +nicols.

rib and band, vein to cauliflower perthites. Generally, the patterns of structure observed in perthites can be related to the extent of cataclastic events. As the alkali-feldspar content increases, the rock tends to be monomineralic, such that the other minerals form 10-15% of the rock (Fig. 15A). Such a rock could be called perthosite (Johannsen 1939). In some grains, perthite develops a marginal phase of microcline with cross-hatched twinning. Occasionally, microcline grains contain veins of fine albite. Evidence of brecciation in perthites is very conspicuous as the sealed cracks produce rib and band structure with ribs branching out and converging within the same grain. These ribs show a series of combinations of concave and convex patterns but occasionally they give rise to "cauliflower like" patterns of dendritic tentacles. In some perthosites rods of perthite and aegirine-augite alternate (Fig. 15B) while other varieties show recrystallized margins.

Quartz occurs as independant anhedra and also as recrystallized inclusions in perthites. Riebeckite, aegirine-augite, magnetite, astrophyllite, hematite, oligoclase, zircon, pyrite, allanite, clinozoisite, eudialyte, sphene, apatite, leucoxene are accessories.

Riebeckite, aenigmatite and aegirine-augite occur as inclusions or follow the boundaries of porphyroblasts of alkali-feldspar (Fig. 15C) suggesting that an influx of liquids, rich in these inclusions, had invaded the trachytic rocks.

b) Albite-rich fenites

Albite-rich gneisses and schistose fenitesare described preliminarily in Chapter 3. They consist of fine-to medium-grained, leuco-to mesocratic,

Fig. 16: Petrographic features of fenites.

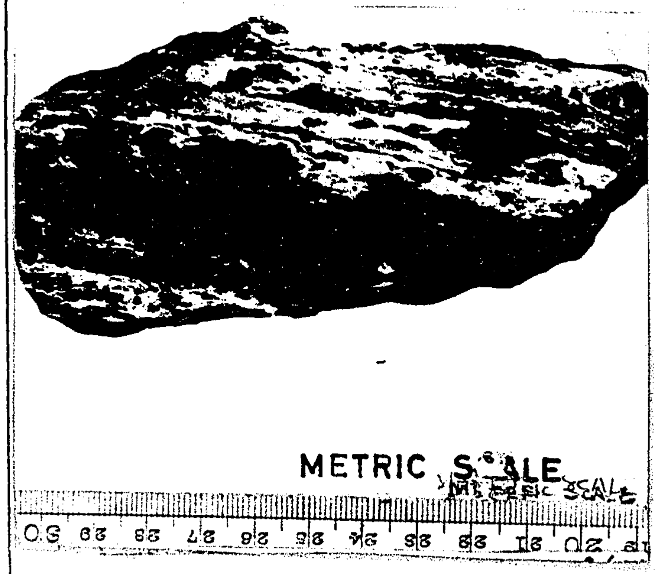


Fig. 16A: Layered fenitic gneiss with alternating layers of aegirine-augite, aenigmatite and arfvedsonite (black) and microcline, eudialyte, albite and quartz (light coloured). Specimen 288, x½.

Fig. 16B: Fenite, showing aenigmatite (aen), ilmenite (il), ramsayite (ram), quartz (colourless), biotite (biot) and an unidentified thread-like mineral. Specimen 235b Polarized light, x50.

Fig. 16C: Fenite with aegirine-augite (aeg), interlocked with joaquinite (joaq) in a quartzo-feldspathic matrix. Specimen 240, Polarized light, x50.

gneissose to schistose rocks. At places, they contain veins of albite with some sphalerite, galena, fluorite and pyrite. Generally, these gneisses develop around lenses of lujavrite in the southern hills of the Ten Mile Lake area. Like the K-feldspar-rich fenites, they also show a variety of textures.

1. Albitite

Mesocratic, with white-to flesh-coloured spots of albite in a hornfelsic matrix, At some places in Mann-1 area, pink to white veins of albitite cut across the gneisses. Generally, they are lenticular bodies a few feet long and a few inches wide.

Microscopically, they are composed of albite ($\approx$90%, Fig. 15D) and other minerals ($\approx$10%) like aegirine-augite, barylite, sphalerite, microlite-pyrochlore, quartz, leucoxene, fluorite, joaquinite and a few unidentified minerals (Un 12-19).

Albite occurs as concentric laths and shows the typical albite twin. Some patches of barylite occur with sphene and a few patches of leucoxene (Fig. 15D). Aegirine-augite forms anhedral aggregates. Riebeckite occurs as small needles enclosed in albite laths. Niobophyllite, sphene and arfvedsonite are intergrown. Sphalerite, galena, and joaquinite are rare.

2. Banded fenitic gneiss

Medium-to coarse-grained banded gneisses with commonly discontinuous mafic bands. The rocks are composed of pink barylite, dark green to black amphiboles and pyroxenes and white to slightly red feldspar.

Mineralogically, these rocks can be subdivided into the following associations:

Association 1

Fine-to medium-grained, banded gneisses with alternating discontinuous mafic and felsic bands. Mafic bands are composed of anhedra of neptunite (0.10 - 2mm.). Many of the neptunite grains are skeletal with numerous inclusions of other minerals, particularly albite. Larger grains of neptunite are associated with arfvedsonite, barylite, vinogradovite, pectolite and aegirine-augite. Eudialyte occurs as tiny rounded subhedra in the vicinity of neptunite grains. Light-coloured bands are composed of albite, eudialyte and some scattered barylite anhedra. At places, arfvedsonite acts as a substrate to neptunite. A few alteration products of barylite could not be identified (Un-10to Un-12). Sphene, apatite and hematite are accessories.

Association 2

Medium-grained, banded streaky gneisses containing neptunite, niobophyllite, barylite, sphalerite, albite, microcline, microlite-pyrochlore, joaquinite, aegirine-augite, hematite, pectolite and arfvedsonite.

Neptunite grains are generally intergrown with niobophyllite. Large neptunite grains contain inclusions of microlite-pyrochlore surrounded by radioactive halos. At other places, neptunite, barylite, niobophyllite and joaquinite are intergrown with arfvedsonite anhedra.

Elsewhere, sphene, apatite and fluorite are confined to felsic bands in which albite and microcline are the major minerals.

Association 3

Medium-grained, dark-coloured, gneissose rocks showing schlieren of mafic minerals which taper within the thin section. Generally mafic bands are composed of niobophyllite, arfvedsonite, sphene, aegirine-augite, barylite and leucoxene. Felsic bands contain albite, barylite, joaquinite and an alteration of barylite (unidentified Un-10). Aegirine-augite alters to a brownish, isotropic mineral (unidentified). Albite grains form the main matrix which is full of inclusions of aegirine-augite and prismatic grains of arfvedsonite.

c) Fenites rich in both alkali-feldspar and albite

Medium-grained gneisses (stained red) are composed of eudialyte, quartz, feldspars, astrophyllite, and aenigmatite.

These rocks are gneissose to porphyroblastic. At places, they show layering which separates aegirine-augite, arfvedsonite and aenigmatite-rich layers from feldspar, quartz and eudialyte-rich layers (Fig. 16A). Commonly, quartz, eudialyte, alkali-feldspar, aenigmatite, arfvedsonite and aegirine-augite occur as principal minerals with subordinate astrophyllite, apatite, ramsayite, oligoclase, biotite and a few unidentified minerals (Un-6 to Un-12).

Quartz occurs as lumped anhedral aggregates along with oligoclase (An_{26}) grains but astrophyllite, aenigmatite and aegirine-augite grow together (frontispiece). Perthite contains abundant aegirine needles concentrated in aggregates. In some rocks this perthite forms porphyroblasts and encloses aegirine-augite, aenigmatite, astrophyllite and ramsayite grains. Zircon is common in those rocks which do not contain eudialyte. In one of the rocks (Specimen 235) aenigmatite encloses ramsayite, biotite, arfvedsonite and ilmenite grains (Fig. 16B). Some brownish thread-like indeterminate mineral (not X-rayed) emanates from aenigmatite. At places, aenigmatite alters to an unidentifiable brownish material(not X-rayed). In another rock(Specimen 240) aegirine-augite and joaquinite are intergrown(Fig.16C).Microcline commonly grows as a network of interlacing veins but in some places, it also develops at the borders of microperthite grains.

Apatite,eucolite,hematite,nontronite and pectolite occur as accessory minerals.

CHAPTER 5

MINERAL ASSOCIATIONS

1. Mineral associations in agpaitic rocks

The agpaitic rocks have been known to contain a large number of mineral species in varying proportions (Vlasov et al. 1966, Semenov 1969, Sørensen 1960, 1962, 1969, 1970, Sørensen et al. 1970). Most petrologists interpreted the petrogenesis of these rocks according to the presence or absence of feldspar and nepheline (Sørensen 1969, 1970, Ferguson 1964, 1967, 1970a, b, Gerassimovsky 1966, Sood and Edgar 1970, Piotrowski and Edgar 1970). Mineralogical differences that distinguish agpaitic and miaskitic (including plumasitic) rocks have not been considered significant, perhaps due to lack of experimental evidence.

Experimental syntheses of the minerals common to agpaitic rocks, e.g., eudialyte (Michel - Lévy 1961, Hotun 1970) and aenigmatite, arfvedsonite (Ernst 1962, 1968) combined with thermodynamic studies of various geochemical problems involved in agpaitic rocks (Kogarko 1970) have revealed that agpaitic rocks are formed essentially under the following conditions:

a) high alkalinity,

b) low partial pressures of O_2, SO_2, SO_3, in the highly reducing vapour phase,

c) decreasing P_{O_2} as crystallization proceeds,

d) P_{O_2} conditions controlled by natural buffers,

e) high activity values of S, H_2S, CH_4, NH_3, CO, CO_2 and Cl.

Despite the above conditions of development, petrogenically agpaitic rocks have been compared with common nepheline syenites (Piotrowski and Edgar 1970, Sood and Edgar 1970). The processes envisaged for the formation of agpaitic rocks emphasize two factors:

1) Crystallization of a particular mineral or minerals under specific P_{H_2O} conditions (Sood and Edgar 1970) from basaltic magma.
2) High activity of volatiles.

Therefore, the processes proposed for the formation of nepheline-eudialyte rocks involve two factors only. Before the influence of various factors on the evolution of the mineral associations of agpaitic rocks is evaluated, it is necessary to review the occurrence of agpaitic minerals like eudialyte and aenigmatite in nature and the processes visualized for their formation.

a) Occurrence and origin of eudialyte

Eudialyte has been observed in tinguaites and phonolites (Karpoff 1953, Bordet et al. 1955, Stobbe and Murray 1956, Varet 1969); in pegmatites and veins within miaskitic complexes (Clabaugh 1949*, Brögger 1890, Williams 1891, Barth 1927, Landes 1931, Pecora 1942, Borodin and Nazarenko 1957, Agard 1960, Dusmatov et al. 1967, Efimov et al. 1970); in agpaitic rocks (Ramsay 1890, 1898, Ramsay and Hackmann 1894, Osann 1896, Ussing 1911, Lacroix 1911, Shand 1928, Adamson 1944); in quartz veins in limestone and aegirine granite dykes (Lacroix, 1911, 1915, 1922, Nockolds 1950) and in xenolithic blocks in agpaitic phonolitic volcanics (Dawson 1971).

Dependent on their occurrence, eudialyte-bearing rocks have been ascribed to magmatism (Pecora 1942, Ferguson 1964, 1970a, 1970b) and

* Dr D. S. Barker(personal communication) considers these occurrences as agpaitic syenites.

pneumatolytic autometasomatism (Eliseev et al. 1939, Eliseev and Fedrov 1953). However, the origin of eudialyte-bearing rocks is disputed (Gerassimovsky 1966, Borodin 1958, Vlasov et al. 1966, Sørensen 1958).

b) Occurrence and origin of aenigmatite

Aenigmatite has been recorded from alkalic volcanic rocks such as the pantellerites, pantelleritic trachytes and comendites of Pantellaria island, Mediterranian Sea (Foerstner 1881, Soellner 1909, Washington 1914, Gössner 1925, Gössner and Spielberger 1930, Carmichael 1962, Zies 1966), the phonolites of Haute Loire and Cantal, France (Lacroix 1910), the comendites of Mount Nimrud, Armenia (Prior 1928), the trachytes, phonolites, comendites and pantellerites of the Kenya Rift Valley (Smith 1931, Bowen 1937), the phonolites of Lupte Gorge in Portuguese East Africa (Teale and Smith 1923), the phonolites and trachytes of the Ahaggar, Sahara (Denaeyer 1923, Bouchart and Denaeyer 1925), the pantellerites of Afar, Ethiopia and French Somaliland (Arsandoux 1906), the phonolites of northwest Madagascar (Lacroix 1910, 1922), the comendites of Mayor Island, New Zealand (Marshall 1936), the alkalic lavas of Oki islands, Japan (Tomita 1934), the pantellerites of Santa Rosa, California (Williams et al. 1954) and the peralkaline trachytes of Nandewar Mountains, New South Wales, Australia (Abbott 1967).

Aenigmatite has also been reported from a wide variety of plutonic assemblages e.g., the nepheline and sodalite syenites of Kangerdluarfik, Greenland (Breithaupt 1865, Lorenzen 1881, Brögger 1890), microsyenite from south Boswell Bay, Kangerdluarfik, Greenland (Kelsey and McKie 1964),

TABLE 6

Mineral Associations in the Joan Lake Agpaitic Complex, Central Labrador

Rock name	Ijolite	Type I Lujavritic gneisses		Type II unfoliated-eudialyte-aenigmatite-arfvedsonite-nepheline rocks
Rock number	202,203	213,230,255	206,211,213,218 219,239,244,253 254,256,257,263 286,276	222B,442,743,223
Essential > 5%	Na-amphiboles Nepheline	Nepheline K-feldspar Arfvedsonite Eudialyte Aegirine-augite	K-feldspar Arfvedsonite Aegirine-augite Nepheline Albite-oligoclase	Eudialyte K-feldspar Arfvedsonite Aenigmatite Nepheline
Minor < 5%	Apatite Na-pyroxenes Phlogopite Ramsayite Pectolite	Pectolite Biotite Apatite Fluorite Albite	Eudialyte Lamprophyllite Sphalerite Ti-Lavenite Apatite Sodalite Pectolite Pyrrhotite Li-mica Karnasurtite Fluorite	Natrolite Aegirine-augite Hydromuscovite Pectolite Li-mica Pyrrhotite Bastnaesite Mesodialyte Albite Fluorite

TABLE 6 - Concluded

Type III pegmatoid, coarse-grained eudialyte-aenigmatite-arfvedsonite-nepheline rocks		Metasomatic rocks (fenites)	
270 - 274	224,225,233,227, 266,212,314,309	240,286,288, 287,318	207,209,235 287,318
Nepheline Arfvedsonite Aenigmatite Eudialyte	Eudialyte K-feldspar Arfvedsonite Aenigmatite Nepheline	K-feldspar Quartz Aegirine-augite Albite-oligoclase	Quartz Riebeckite Biotite K-feldspar
Pectolite Sodalite Li-mica Phlogopite Aegirine-augite	Aegirine-augite Pectolite, Eucolite Li-mica, Pyrrhotite Galena, Sphalerite Albite, Mesodialyte Schizolite, Steenstrupine(?) Fluorite	Apatite, Ramsayite Pectolite, Biotite Astrophyllite Aenigmatite, Zircon Lamprophyllite, Sphene Limonite, Joaquinite Niobophyllite	Aegirine-augite Fluorite, Aenigmatite Ramsayite, Lamprophyllite Astrophyllite, Zircon Ilmenite

the foyaite and khibinite pegmatites and the apatite rocks of the Khibina and Lovozero Tundras and Lujavrut, in the Kola Peninsula (Fersman 1923, 1926, 1937, Kostyleva 1929, Gerassimovsky 1936), in dykes at Langesunsfjord, Norway (Brögger 1890) in veins in the Languard Alp, Ober Engadin, Switzerland (Niggli <u>et al</u>.1940, Goldschmidt 1930) monzonites and syenites from the Moroto River, Sakhalin Island, Japan (Yagi 1953), in the nepheline syenites of Kassa in the Iles de Los (Lacroix 1911), in the Monte Chamaco alkali syenite, Angola (de Andre 1954), in the Mounic aegirine-microgranite in Sudan (Lacroix 1910), in the aegirine-syenite of Amphitrosy and the aegirine nepheline syenites of Fourche Mountains, in pulaskite from Arkansas (Williams 1891) and in nordmarkite from York, Maine (Woodard 1957).

In short, aenigmatite occurs in rocks rich in sodium and titanium and commonly depleted in silicon and is invariably associated with aegirine or sodic amphiboles.

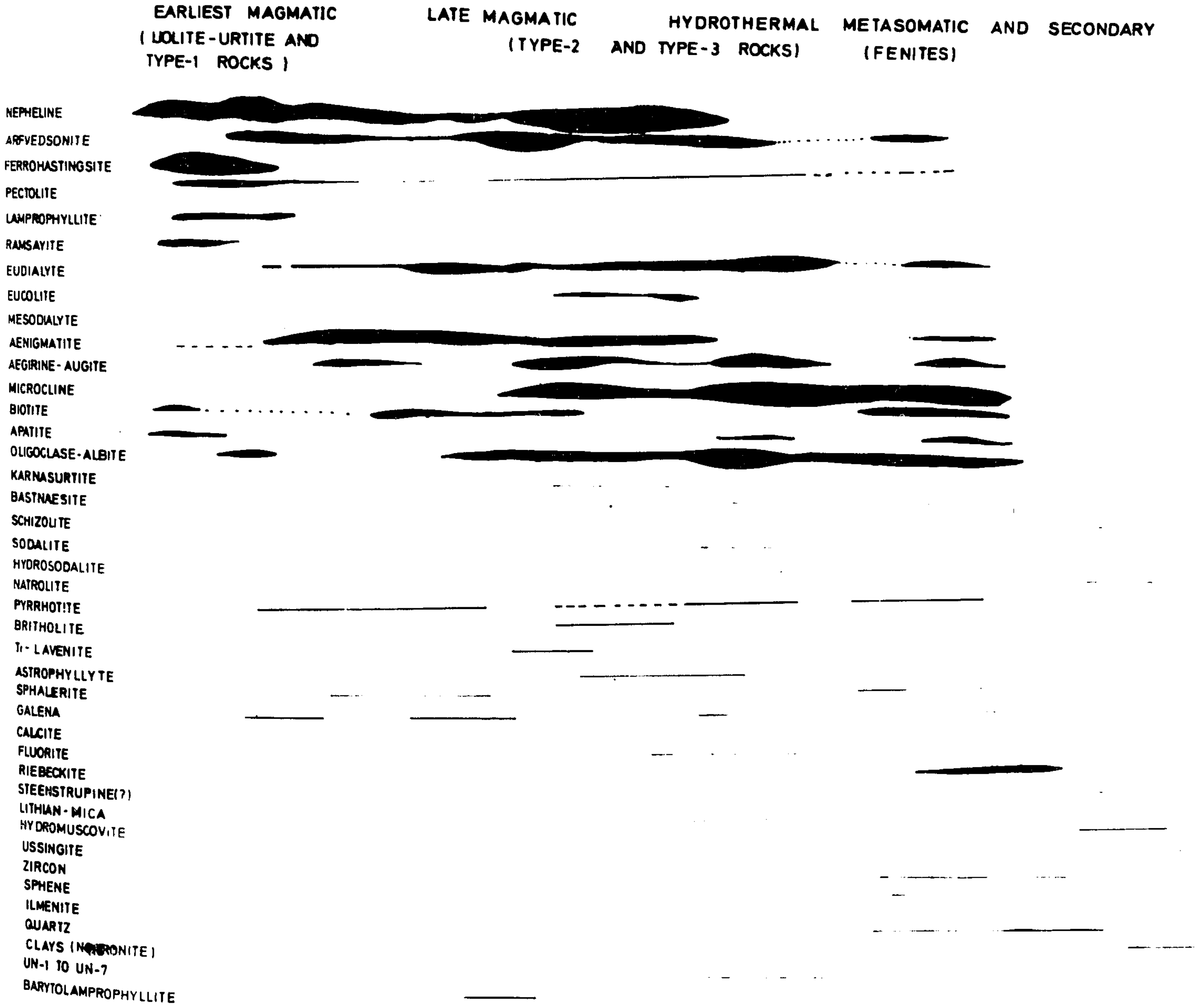
The paragenesis of eudialyte in nature and its synthesis indicate that the mineral can form only in peralkaline environments. The synthesis of aenigmatite and its natural occurrence demonstrate that it can develop only from peralkaline solution under low oxygen fugacity (Ernst 1962, Carmichael 1962, Abbott 1967). Therefore, any theory for the petrogenesis of agpaitic rocks must be consistent with the above factors. However, their influence can only be studied in terms of the mineral associations.

2. Mineral associations in the Joan Lake agpaitic complex

Local variations in the variety of minerals are common in the Joan Lake agpaitic complex (Table 6). The paragenetic mineral sequence

FIG. 17.

GENERALISED MINERAL PARAGENESIS IN THE JOAN LAKE AGPAITIC COMPLEX



MINERALS IDENTIFIED BY X-RAY DIFFRACTION AND OPTICAL MEANS.

THICKNESS OF THE BANDS INDICATES THE SIMPLIFIED RELATIVE MODAL CONTENT OF THE MINERALS.

Fig.18 is in pocket at the end of the thesis.

(petrographically observed) is very complicated (Fig. 17) and the spatial distribution of mineral assemblages does not show any regular variations. The occurrence of xenoliths of sedimentary and volcanic rocks within the pluton suggests an intrusive relationship (Fig. 18).

Assuming that the composition of the original alkalic magma could be expressed in terms of the mineral constituents of crystallized ijolite-urtite, the lujavritic rocks can be crystallized from such a melt at slightly higher oxygen fugacity than that of the primary magma. Under the high oxygen pressure, arfvedsonite will become unstable and give rise to aegirine. Both arfvedsonite and aegirine could precipitate together. Nepheline would have been converted into feldspar when the melt came into contact with silica-rich country rocks. Under these conditions, the melt would precipitate arfvedsonite, aegirine-augite, K-feldspar and albite. Any addition of zirconium in such a peralkaline melt must crystallize eudialyte according to the following reaction.

$$\underbrace{2SiO_2 + Na_2SiO_3 + 3CaSiO_3 + ZrO_2 + CaF_2}_{\text{Liquid}} \rightarrow \underbrace{Na_2Ca_4ZrSi_6O_{18}F_2}_{\text{Eudialyte}}$$

Thus, the mineralogical assemblages subdivided under Type I (Table 6) may represent the two local variations in crystallization.

As the crystallization of lujavrite continued, the oxygen pressure decreased and the melt behaved like a naturally buffered system. Although it is presently impossible to define the buffering agent, the system can be compared with its experimental analogue described by Ernst (1962) with bulk composition $Na_2O \cdot 5FeO \cdot 8SiO_2$ + excess water and with oxygen fugacity defined by the wustite-iron buffer (Fig. 19). Ernst further noted that the field of quartz + fayalite + acmite + fluid showed variations when different buffering agents were used e.g., the field was larger under magnetite wustite

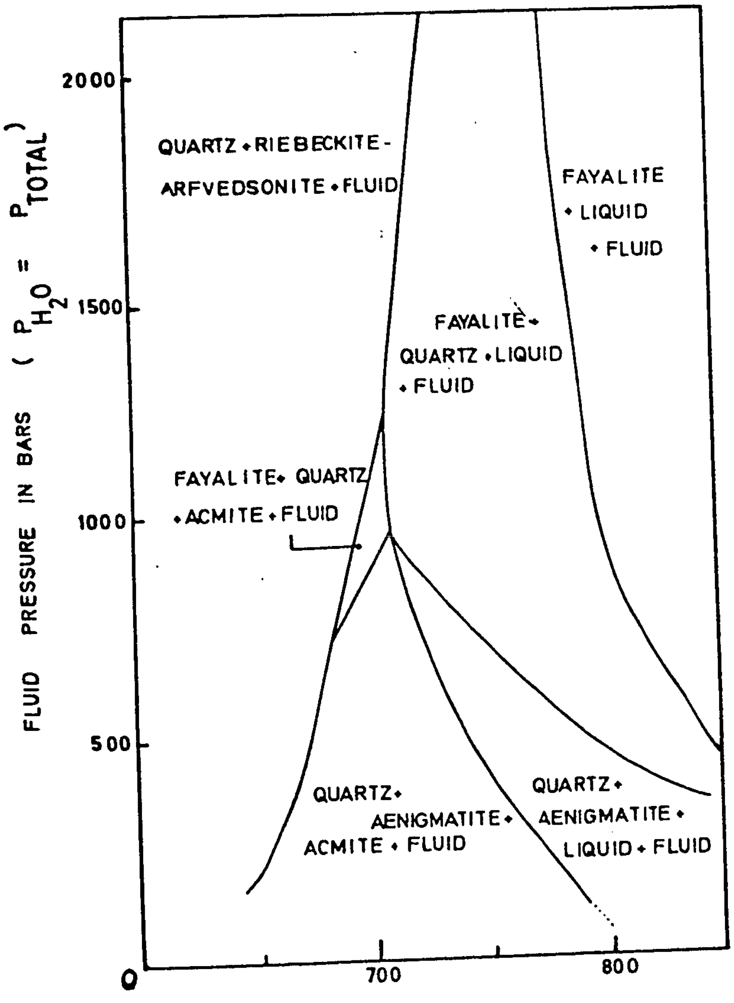


FIG. 19 : P_{fluid} - T DIAGRAM FOR BULK COMPOSITION Na_2O. $5FeO.8SiO_2$ + EXCESS WATER AND WITH OXYGEN FUGACITY DEFINED BY WÜSTITE - IRON BUFFER. (ERNST, 1962 & 1968)

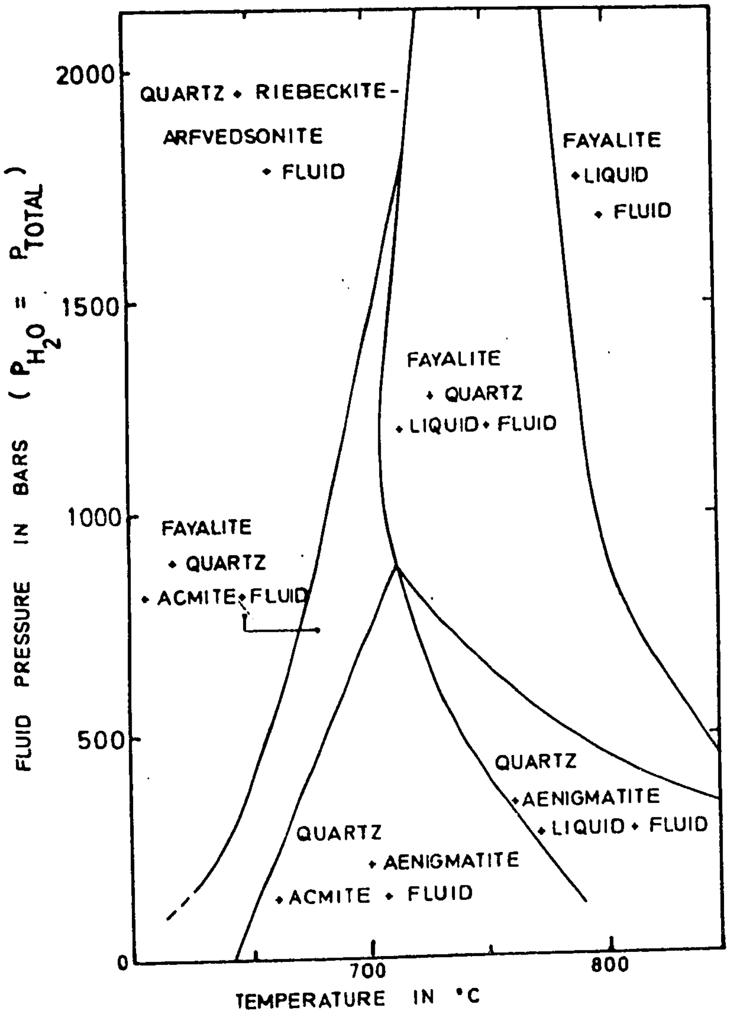


FIG. 20 : P_{fluid} – T DIAGRAM FOR BULK COMPOSITION Na_2O. $5FeO$. $8SiO_2$ + EXCESS WATER AND WITH OXYGEN FUGACITY DEFINED BY MAGNETITE - WÜSTITE BUFFER (ERNST, 1962).

buffers (Fig. 20) than that of wüstite-iron buffer. From such a study it may be postulated that the quartz + fayalite + acmite + fluid field became very restricted or disappeared altogether under severely reducing conditions, thus explaining the absence of this association at Joan Lake. His experimental work also shows that aenigmatite precipitates earlier under a more-reducing buffer. Furthermore, Abbott (1967) suggested that any addition of TiO_2 in a peralkaline buffered melt may result in much earlier precipitation of aenigmatite. It is therefore suggested that, in the Joan Lake area, after the crystallization of lujavrite, aenigmatite could have formed as the fluid pressure fell below a critical value (at least 1000 bars). Under such a condition, arfvedsonite became unstable and aenigmatite plus acmite started forming according to the following reaction:

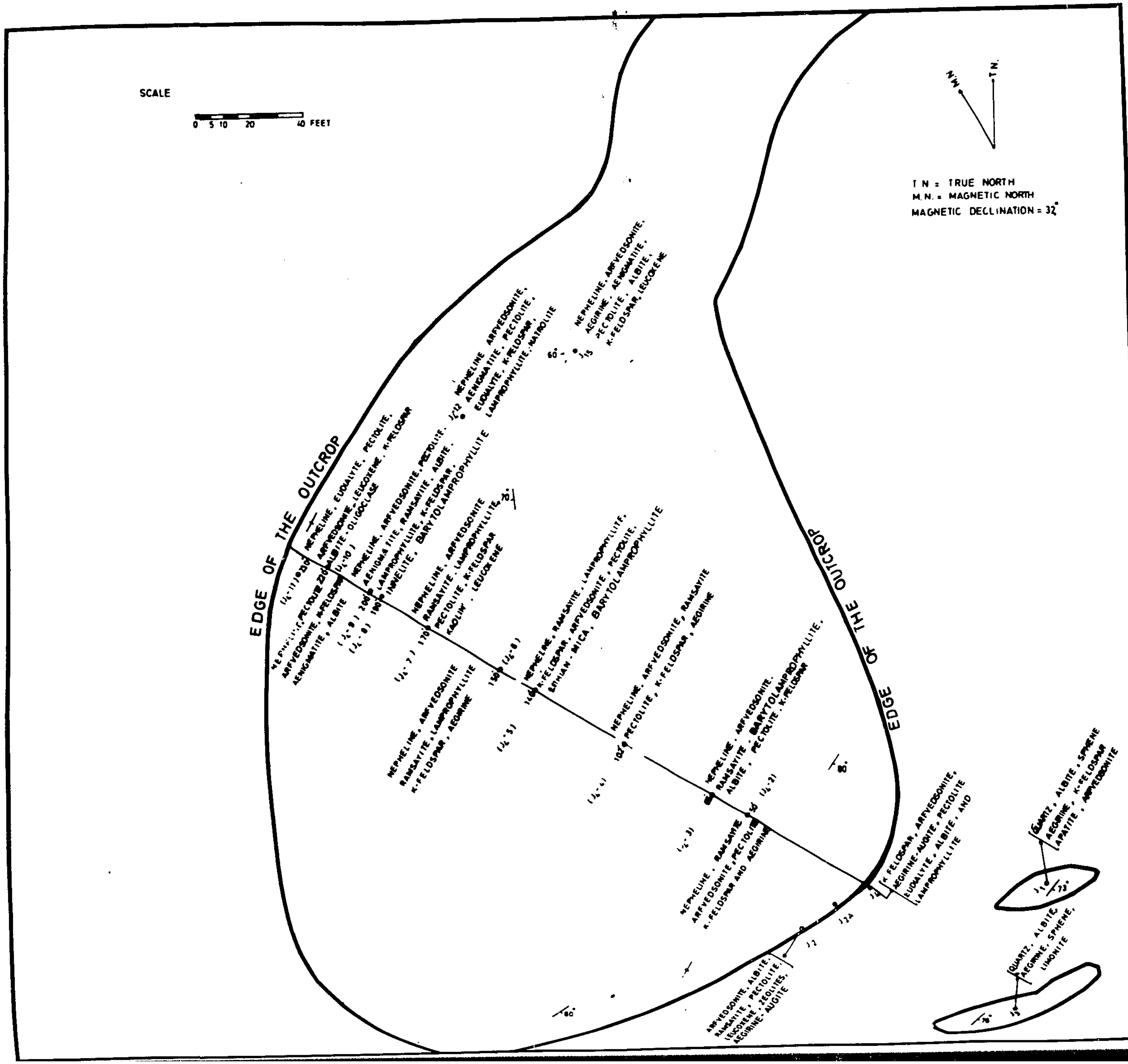
Type I

$$\underbrace{Na_3Fe''_4Fe''' Si_8O_{22}(OH)_2}_{\text{Arfvedsonite}} + \underbrace{Na_2SiO_3 + 6FeO + 2TiO_2 + 5\,SiO_2}_{\text{Liquid}}$$

Type II

$$\longrightarrow \underbrace{Na_4Fe''_{10}Ti_2Si_{12}O_{40}}_{\text{Aenigmatite}} + \underbrace{NaFe''' Si_2O_6}_{\text{Acmite}} + H_2O$$

As the above reaction proceeded, the melt became impoverished in SiO_2 in those regions of the pluton where crystallization of eudialyte and aenigmatite took place. Due to reduced SiO_2, the melt became increasingly peralkaline and **undersaturated.** Thus, the mineral associations observed as Type II crystallized after SiO_2 was reduced, however aenigmatite-bearing associations observed in Type III rocks may have crystallized after the critical SiO_2 limit and partly before such a limit was reached. Therefore, it becomes quite evident that, in the Joan Lake pluton, the mineralogical


SCALE
0 5 10 20 40 FEET
M.N.
T.N.
T.N. = TRUE NORTH
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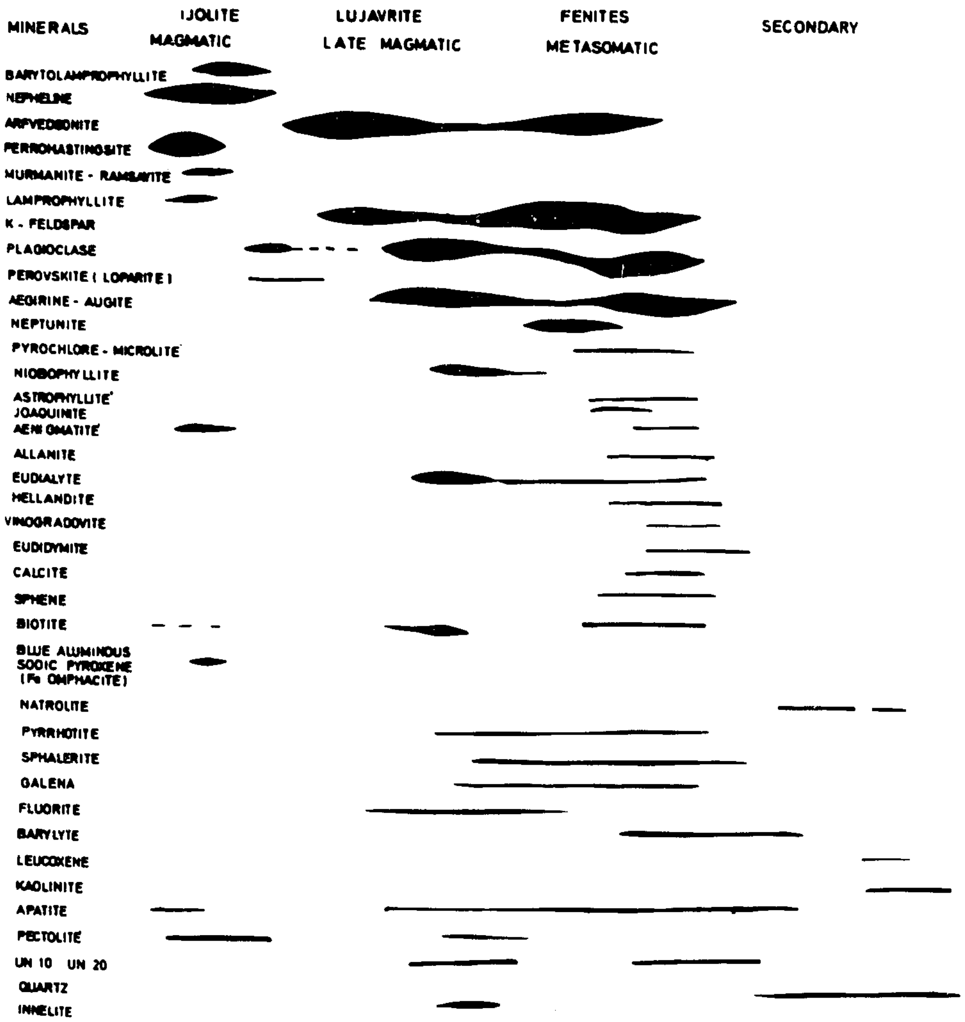
EDGE OF THE OUTCROP
EDGE OF THE OUTCROP
(J6-11) 220
NEPHELINE, EUDIALYTE, PECTOLITE, ARFVEDSONITE, LEUCOXENE, K-FELDSPAR ALBITE-OLIGOCLASE
NEPHELINE, PECTOLITE, ARFVEDSONITE, K-FELDSPAR AENIGMATITE, ALBITE
210 (J6-10)
NEPHELINE, ARFVEDSONITE, PECTOLITE, AENIGMATITE, RAMSAYITE, ALBITE, LAMPROPHYLLITE, K-FELDSPAR, INNELITE, BARYTOLAMPROPHYLLITE
(J6-9) 200
(J6-8) 190
NEPHELINE, ARFVEDSONITE RAMSAYITE, LAMPROPHYLLITE, PECTOLITE, K-FELDSPAR KAOLIN, LEUCOXENE
70°
(J6-7) 170
NEPHELINE, ARFVEDSONITE RAMSAYITE, LAMPROPHYLLITE K-FELDSPAR, AEGIRINE
150 (J6-6)
(J6-5) 140
NEPHELINE, RAMSAYITE, LAMPROPHYLLITE, K-FELDSPAR, ARFVEDSONITE, PECTOLITE, LITHIAN-MICA, BARYTOLAMPROPHYLLITE
(J6-4) 102
NEPHELINE, ARFVEDSONITE, RAMSAYITE PECTOLITE, K-FELDSPAR, AEGIRINE
(J6-3)
NEPHELINE, ARFVEDSONITE, RAMSAYITE, BARYTOLAMPROPHYLLITE, ALBITE, PECTOLITE, K-FELDSPAR
50 (J6-2)
NEPHELINE, RAMSAYITE ARFVEDSONITE, PECTOLITE K-FELDSPAR AND AEGIRINE
8°
J6
K FELDSPAR, ARFVEDSONITE, AEGIRINE-AUGITE, PECTOLITE EUDIALYTE, ALBITE, AND LAMPROPHYLLITE
J24
J2
ARFVEDSONITE, ALBITE, RAMSAYITE, PECTOLITE, LEUCOXENE, ZEOLITES, AEGIRINE-AUGITE
60°
J(12)
NEPHELINE ARFVEDSONITE, AENIGMATITE, PECTOLITE, EUDIALYTE, K-FELDSPAR, LAMPROPHYLLITE, NATROLITE
60°
J15
NEPHELINE, ARFVEDSONITE, AEGIRINE, AENIGMATITE, PECTOLITE, ALBITE, K-FELDSPAR, LEUCOXENE
J1
73°
QUARTZ, ALBITE, SPHENE AEGIRINE, K-FELDSPAR APATITE, ARFVEDSONITE
J3
78°
QUARTZ, ALBITE, AEGIRINE, SPHENE, LIMONITE

FIG. 22.

MINERAL PARAGENESIS IN THE IJOLITE, LUJAVRITE AND FENITES IN THE TEN MILE LAKE AREA, LABRADOR



MINERAL IDENTIFICATIONS CONFIRMED BY X-RAY DIFFRACTION. EXCEPT FOR NATROLITE, LEUCOXENE, BIOTITE AND KAOLINITE

THICKNESS OF BANDS REPRESENTS THE RELATIVE CONTENT OF THE MINERALS.

assemblages are the result of local physico-chemical variations. Furthermore, the mineral associations described under metasomatic rock (Chapter 4) may have been produced by interaction of the ijolite melt with the country rocks.

3. Mineral associations across the ijolite-urtite and lujavrite lens near Ten Mile Lake

At Mann-2, within the Precambrian volcano-sedimentary sequence is a folded lenticular body of fine to medium-grained ijolite-urtite and lujavrite gneiss (Fig. 10). The specimens collected across the lens are plotted together with their principal rock-forming minerals (Fig. 21). The mineral paragenesis, as noted from petrographic study, is summarized in Fig. 22.

Except for a few differences, the principal minerals in alkalic rocks at Mann-2 and ijolite-urtite of the Joan Lake agpaitic complex remain the same but the following features are notable:

1) Eudialyte and aenigmatite crystallize near the margin of the lens but aenigmatite is formed only on the northern side.
2) Mineralogical variations within a small lens are quite obvious.
3) Both eudialyte and aenigmatite can form independently of each other.
4) The amount of alkali-feldspar varies, increasing near the margins and decreasing towards the centre.
5) Fenites around the ijolite-urtite lens are rich in niobium, barium, beryllium, titanium, rare earth and zirconium minerals.

The mineralogical variations in ijolite-urtite, lujavrite lens at Mann-2 can be explained by interaction of the ijolitic melt with the country rocks. Local variations in alkalinity and oxygen fugacity also influenced the mineralogical composition of the rocks.

4. Implications of the mineralogical associations on the evolution of the Joan Lake agpaitic complex

The occurrence of ijolite-urtite and lujavrite, as a folded lenticular body in the Ten Mile Lake area and in the central portion of the Joan Lake pluton, suggests that a melt of ijolite composition existed in the area. Since no free iron or titanium oxides are found within ijolite units (rocks sufficiently rich in iron to crystallize a large amount of arfvedsonite), such a melt probably existed under an oxygen fugacity lower than that required to crystallize magnetite and ilmenite. Thus, it can be postulated that at low oxygen fugacity and high alkalinity, the melt could only precipitate Zr and Ti as complex silicates. The crystallization of arfvedsonite is in accord with the presence of reducing environments (Bailey 1969, Woodard 1957). Ernst's (1962, 1968) experimental study indicated that arfvedsonite and acmite crystallize from a melt at a higher P_{O_2} than required for crystallization of only arfvedsonite. This would imply that Type I (lujavrite), which contains arfvedsonite and aegirine as its main constituents, would have formed under less severely reducing conditions than those of ijolite-urtite, with a much smaller proportion of aegirine.

Appearance of eudialyte along with aenigmatite and arfvedsonite indicates: 1) enrichment of zirconium and titanium; 2) high alkalinity, 3) P_{fluid} below the total pressure (Ernst 1962), and 4) low oxygen fugacity.

Increase in the amount of eudialyte in the peripheral zone of the Joan Lake agpaitic complex indicates two sources of zirconium:

1) ZrO_2 in the melt was fractionated or segregated and transported by some special mechanism.

2) ZrO_2 was drawn from an external source such as granites and quartz diorites.

Regardless of the origin of eudialyte, the field relations and mineralogical associations strongly suggest the following conclusions:

1) Rocks of agpaitic mineralogy form intrusives within the volcano-sedimentary sequence of the Seal Lake Group.
2) Xenoliths of schists, acid volcanics and banded quartzites (Seal Lake Group) are found in the Joan Lake pluton.
3) Fenites in the Ten Mile Lake area and around the Joan Lake pluton are the metasomatic products of the agpaitic activity in the area (Chapter 4).
4) Local mineralogical variations in agpaitic rocks are very common.
5) Both P_{O_2} and peralkalinity are the important factors in producing such mineralogical associations.
6) The transportation of zirconium, titanium and other rare metals towards the peripheral regions of the Joan Lake pluton and precipitation of complex Zr and Ti silicates need some special mechanism.
7) The source of ijolitic melt is uncertain.

CHAPTER 6

PETROCHEMICAL EVOLUTION

1. General introduction

Petrochemical study has led several geologists, for example Eliseev and Fedrov (1953), Gerassimovsky et al. (1966), Bussen and Sakharov (1967), Ferguson (1970a, b), Sobolev (1959) to relate agpaitic rocks with direct crystallization and differentiation of a basaltic magma.

Within the framework of magmatic crystallization and differentiation, the following special mechanisms have been suggested to create agpaitic trends.

a) Extreme differentiation of olivine basalt to form massive anorthosite through a process of plagioclase-flotation. Formation of anorthosite capping over a differentiating diorite melt. Accumulation of volatiles in the space between massive anorthosite and dioritic melt. Formation of agpaitic magma by interaction of volatiles with anorthosite (Bridgewater 1965, 1967, Bridgewater and Harry 1968, Sørensen 1970).

b) The plagioclase effect during crystallization of a residual melt from a differentiated basaltic magma (Bowen 1945, Carmichael and McKenzie 1963, Fersman 1929, Schairer and Yoder 1960, 1964, Edgar and Nolan 1966, Tilley 1958).

c) The separation of an aluminous phase in the early stage of a residual melt under particular P_{H_2O} and P_{O_2} (Bailey and Schairer 1966, Sood and Edgar 1970, Piotrowski and Edgar 1970).

d) Emanation, differentiation, crystallization and assimilation of granitic rocks by a basaltic magma (Vlasov et al. 1966).

TABLE 7

Chemical composition of alkalic rocks from the Joan Lake pluton

Name	Ijolite	Type I (Lujavrite)				Type II		Type III			
R. No.	202*	230*	254*	276*	276A**	44*	743*	215*	272*	274*	274A**
Oxides											
SiO_2	46.85(1)	49.45(1)	52.12(1)	58.12(1)	57.5(1)	48.80(1)	49.27(1)	46.12(1)	46.38(1)	46.88(1)	47.00(1)
TiO_2	0.85(6)	0.29(6)	0.13(6)	0.18(6)	1.08(5)	0.82(6)	0.96(6)	1.08(6)	1.47(6)	1.08(6)	1.18(5)
Al_2O_3	14.26(5)	12.99(5)	12.20(5)	13.98(5)	14.4(5)	13.37(5)	12.13(5)	10.33(5)	10.54(5)	9.92(5)	9.85(5)
Fe_2O_3	4.38	9.86	8.75	7.20	7.8	6.7	6.72	6.75	6.10	3.15	3.1
FeO	14.97	5.38	4.59	3.54	3.49	8.78	8.43	10.91	12.54	17.98	18.08
CaO	4.26(5)	2.77(5)	1.28(5)	1.06(5)	1.10(5)	1.92(5)	1.50(5)	3.31(5)	2.96(5)	3.05(5)	2.55(5)
MgO	0.52(5)	0.10(5)	0.26(5)	0.36(5)	0.26(5)	1.86(5)	1.24(5)	2.15(5)	0.90(5)	0.62(5)	0.72(5)
MnO	0.30(5)	0.51(5)	0.70(5)	0.18(5)	0.09(5)	0.28(5)	0.24(5)	0.40(5)	0.34(5)	0.76(5)	0.66(5)
H_2O^-	n.d.	n.d.	n.d.	n.d.	0.02	n.d.	n.d.	n.d.	n.d.	n.d.	0.02
H_2O^+	n.d.	n.d.	n.d.	n.d.	0.43(2)	n.d.	n.d.	n.d.	n.d.	n.d.	2.15(2)
ZrO_2	n.d.	0.2(7)	0.2(7)	0.2(7)	0.32(3)	0.70(7)	2.2(7)	0.8(7)	2.20(7)	1.2(7)	1.3(3)
Na_2O	9.35(5)	10.53(5)	9.59(5)	9.35(5)	9.27(4)	9.53(5)	9.09(5)	10.12(5)	9.68(5)	9.88(5)	10.00(4)
K_2O	3.39(5)	3.85(5)	4.79(5)	5.62(5)	5.22(4)	4.64(5)	5.47(5)	5.41(5)	5.78(5)	4.32(5)	4.06(4)
Total	99.13	95.93	94.61	99.79	100.98	97.40	97.25	97.38	98.89	98.84	100.67
Agpaitic Index Na_2O+K_2O/Al_2O_3	0.80	1.10	1.17	1.07	1.01	1.13	1.20	1.47	1.45	1.33	1.34
Oxidation Ratio $Fe_2O_3/FeO+Fe_2O_3$ X 100	22.63	69.24	65.59	67.03	69.21	43.42	44.35	38.22	32.72	14.90	14.70

(1) By filtration.
(2) Penfield Method.
(3) By X-ray emission spectography.
(4) By flame photometry.
(5) By atomic absorption.
(6) By colorometric (Spectrophotometric) method.
(7) By modal composition; n.d. = not determined; FeO and Fe_2O_3 were determined by combining 1 and 5.
* Specimens analyzed by S.K. Singh, University of Ottawa, Ottawa, Canada.
** Specimens 274A and 276A (same as 274 and 276) analyzed by Dr. N. Suhr, Mineral Constituents Laboratory, Pennsylvania State University, Pennsylvania, U.S.A.

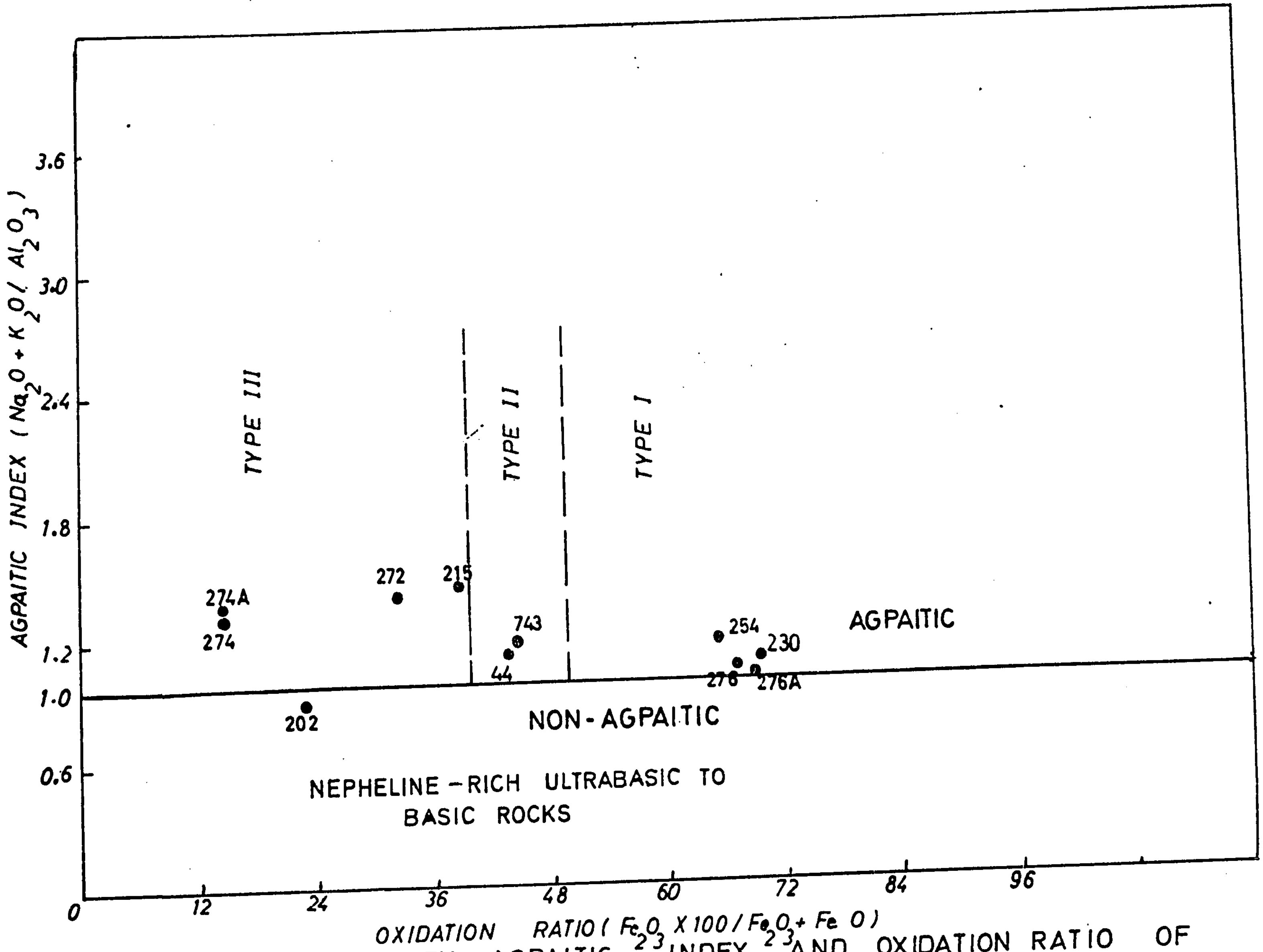


FIG. 23:RELATION BETWEEN AGPAITIC INDEX AND OXIDATION RATIO OF THE JOAN LAKE ALKALIC ROCKS.

e) Overhead stoping of a basaltic magma and its modification to agpaitic melt through assimilation (Ussing 1911).

f) Mixing of an augite syenite magma (a differentiate of basaltic magma) with a granitic magma and differentiation (Ferguson 1964, 1970a).

Several authors (Kuno 1969, Yoder and Tilley 1962, Bailey 1964, 1970, Bailey and Schairer 1962, 1966, Kushiro 1968, Green 1969) have suggested partial melting of lower crustal and upper mantle rocks under the continental shields, especially near rift systems, as a possible mechanism for the generation of alkalic melts. However, Minakov _et al._, (1971) proposed agpaitic rocks as differentiates from an independant ijolitic magma.

Alternatively, the processes of fenitization and rheomorphism have also been suggested (Backlund 1932, von Eckermann 1942, Wegmann 1938, Borodin 1958, Koark 1960, and Heinrich 1966) to produce agpaitic syenites from rocks of suitable composition.

2. Chemical petrology of the Joan Lake agpaitic complex

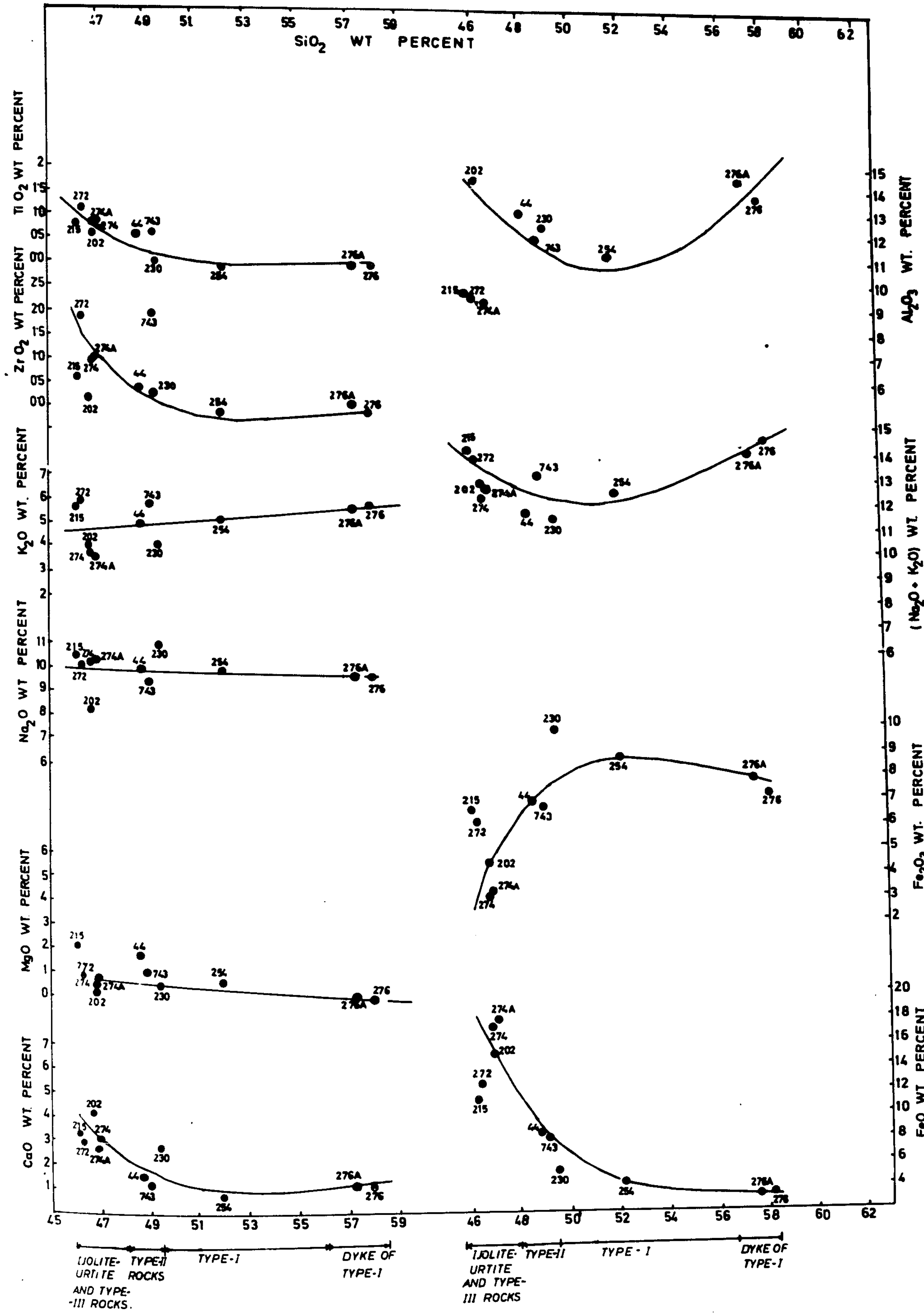
Procedures of selection, preparation and chemical analyses of rock samples are outlined in Appendix II, but the results are listed in Table 7. Based on oxidation ratio, 100 x $Fe_2O_3/FeO + Fe_2O_3$, and agpaitic index, $Na_2O + K_2O/Al_2O_3$, the agpaitic rocks of the Joan Lake area can be subdivided (Fig. 23) as follows:

a) Rocks with oxidation ratio above 50 and agpaitic index less than 1.2 and normally closer to 1.00 e.g., Type I rocks.

b) Rocks with oxidation ratio between 40-50 and agpaitic index ranging between 1.00 and 1.20 e.g., Type II rocks.

c) Rocks with oxidation ratio between 10-40% and agpaitic index greater than 1.2 e.g., Type III rocks.

FIG24: VARIATION DIAGRAMS FOR SOME ROCKS FROM THE JOAN LAKE AGPAITIC COMPLEX, LABRADOR.



The non-agpaitic ijolite shows an oxidation ratio closer to Type III rocks but its agpaitic index is near Type I rock. From these variations and spatial distribution of ijolite and agpaitic rocks in the Joan Lake area the following observations are apparent:

1) By slight increase in the alkalinity and sudden increase in the oxygen content to oxidize Fe^{2+}, the Type I rocks can be crystallized from an ijolitic melt.
2) Increase in agpaitic index (alkalinity) with decrease in oxygen activity would facilitate crystallization of rocks of Type III.
3) Increase in alkalinity without changing oxygen pressures might facilitate crystallization of rocks of Type III or perhaps Type II.

Before the above observations are considered significant, it would be appropriate to appraise the mutual relationship of these rocks more rigourously.

In the variation diagrams of Fig. 24, the following trends can be observed with increase in SiO_2 content.

a) FeO decreases from ijolite (202) to Type III (215, 272, 274, 274A) through Type II (44, 743) and Type I (254, 276, 267A). Fe_2O_3 increases from ijolite to Type I (254) and then decreases gradually to Type I (276).
b) $(Na_2O + K_2O)$ and Al_2O_3 show trends similar to each other but $Na_2O + K_2O/Al_2O_3$ is greater than unity except in ijolite (202).
c) CaO and MgO decrease from ijolite to Type III to Type II to Type I.
d) Na_2O is always greater than K_2O. Na_2O decreases very little from ijolite to Type I. However, K_2O increases markedly from ijolite to Type I.
e) ZrO_2 decreases from Type II through Type III to Type I; however ZrO_2 is less than 0.05% in ijolite.
f) TiO_2 decreases very gradually from ijolite and Type III to Type I.

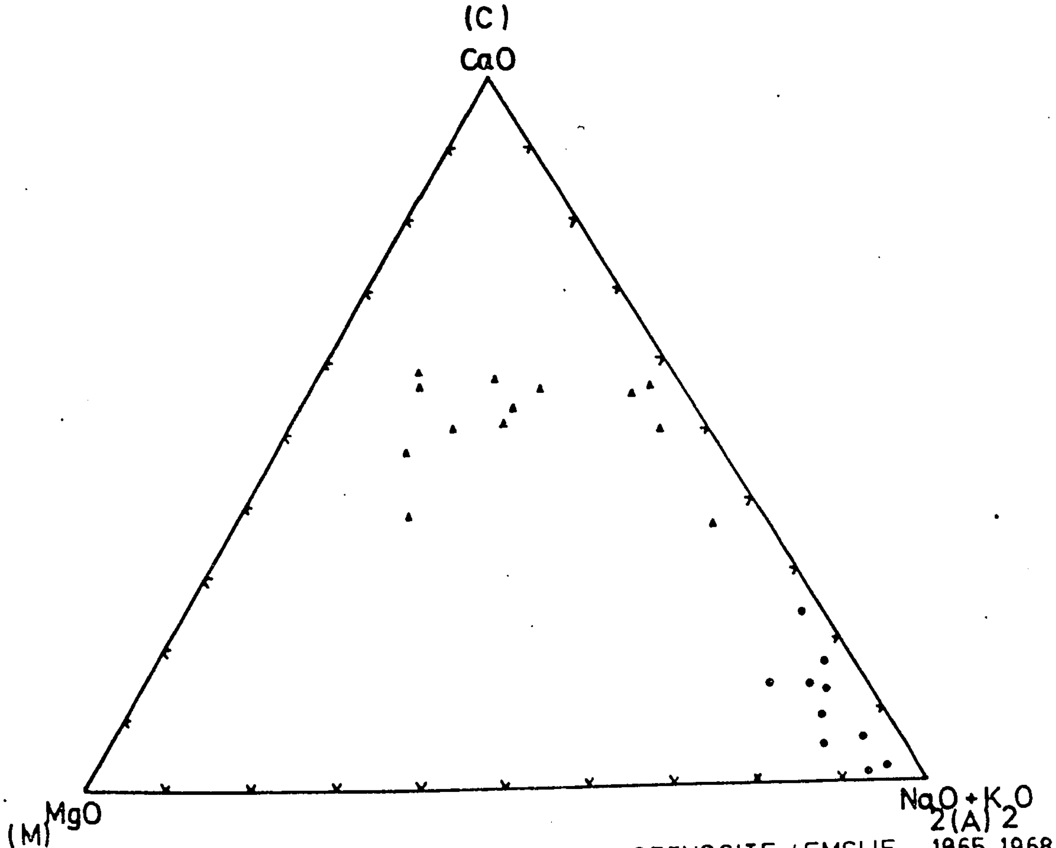


FIG.25:SAMPLES FROM THE MICHIKAMAU ANORTHOSITE (EMSLIE 1965,1968) ▲ AND, THE JOAN LAKE AGPAITIC COMPLEX,●, PLOTTED IN A C M DIAGRAM.

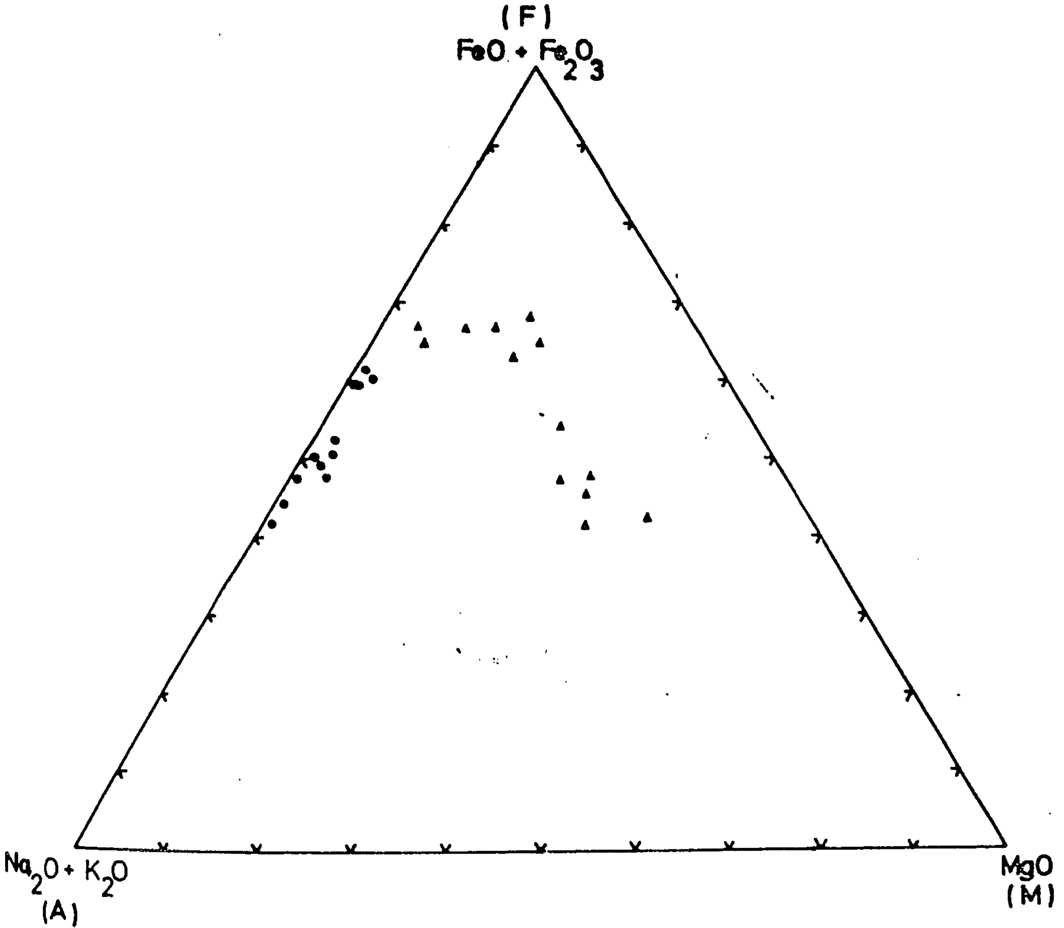
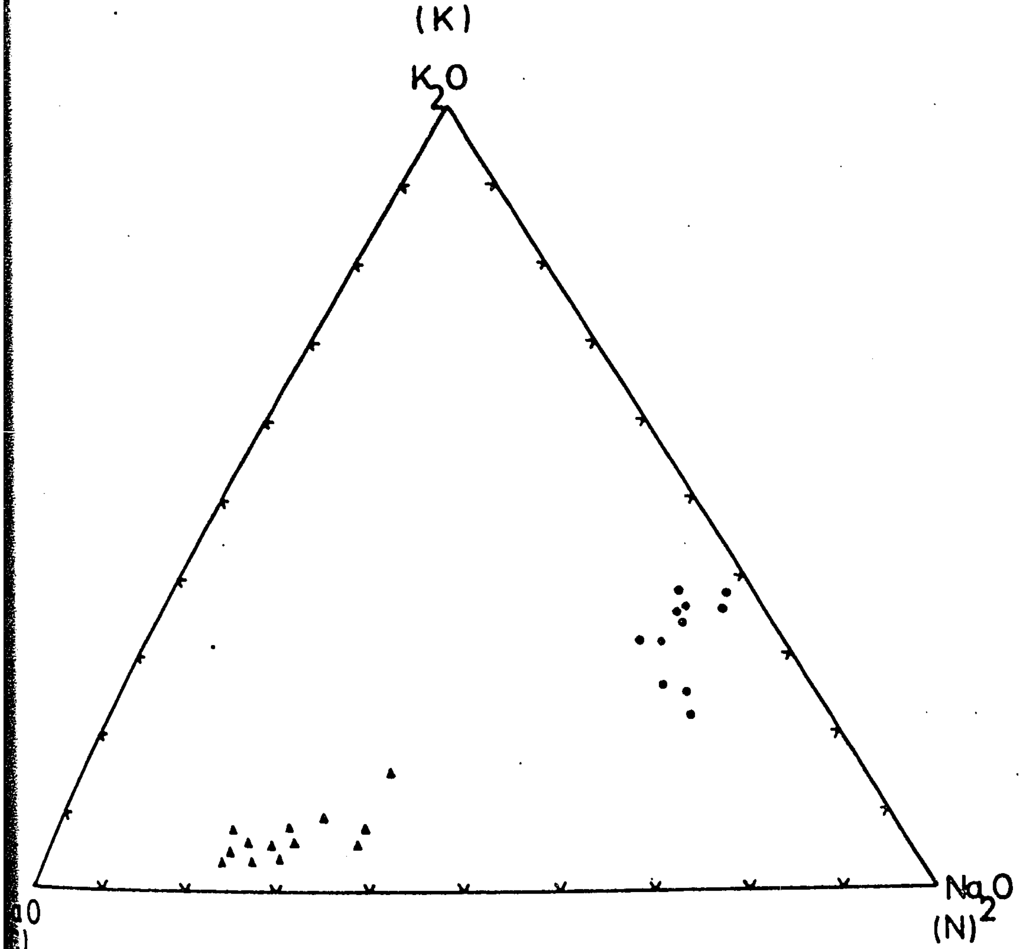


FIG.26: SAMPLES FROM MICHIKAMAU ANORTHOSITE (EMSLIE, 1965, 1968), ▲, AND THE JOAN LAKE AGPAITIC COMPLEX, ●, PLOTTED IN THE A.F.M. DIAGRAM.



G.27:SAMPLES FROM THE MICHIKAMAU ANORTHOSITE (EMSLIE. 1965, 1968) ▲ AND THE JOAN LAKE AGPAITIC COMPLEX ● PLOTTED IN THE CaO - Na_2O - K_2O DIAGRAM.

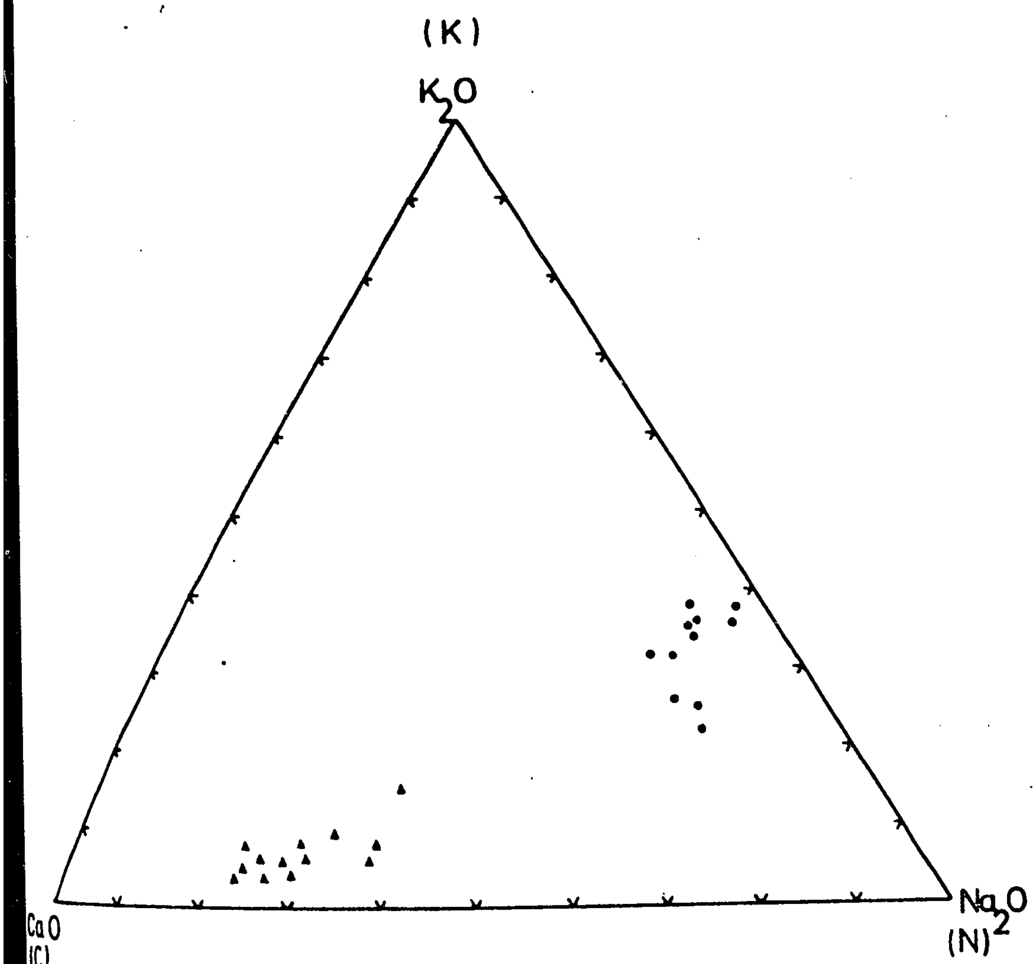


FIG. 27: SAMPLES FROM THE MICHIKAMAU ANORTHOSITE (EMSLIE. 1965, 1968) ▲ AND THE JOAN LAKE AGPAITIC COMPLEX ● PLOTTED IN THE $CaO-Na_2O-K_2O$ DIAGRAM.

Assuming a paragenetic sequence ijolite → Type III → Type II → Type I, the above data are in accord with the normal variations during differentiation from an ijolite melt. Such a process of gradual chemical evolution is also inherent in overall increase of K_2O towards Type I rocks, but ZrO_2 does not fit in the above scheme. In addition, the trends shown by the agpaitic index also contradict the normal differentiation schemes. Combining oxidation ratios and the relationship of different metal oxides with SiO_2, it is suggested that addition of SiO_2 and zirconium with increase in oxygen pressure would lead to crystallization of Type I rock from the ijolitic melt and gradual fall in oxygen pressures may precipitate the minerals of rock Types II and III. In the above scheme, the origin of ijolitic melt and the cause of fluctuations in oxygen pressures remain unexplained.

In view of the possibility suggested by Bridgewater (1967) that agpaitic magma was originally related to anorthosite, Emslie's (1965, 1968) chemical data for the Michikamau anorthosite intrusion (20 miles WNW of the study area) and the Joan Lake agpaitic complex, are plotted on ACM (Fig. 25), AFM (Fig. 26) and Na_2O - CaO - K_2O (Fig. 27) diagrams.

From the ACM diagram, the gross trend seems to favour enrichment in alkalies ($Na_2O + K_2O$) from anorthosites to the Joan Lake agpaitic rocks.

However, the AFM diagram highly favours the model of differentiation of agpaitic rocks from the Michikamau anorthosite magma provided FeO deficiency could be produced by some special mechanism such as fractionation. The NCK (Na_2O-CaO-K_2O) diagram shows a wide gap between the two rock series which is not clear from ACM and AFM diagrams. This gap could be attributed

TABLE 8

Normative composition (Mol %) of
rocks from the Joan Lake pluton

Name	Ijolite	Type I				Type II		Type III			
R.S.	202	230	254	276	276A	44	743	215	272	274	274A
Normative Minerals											
Albite (ab)	---	---	12.83	25.93	23.43	8.48	10.46	6.45	6.56	7.70	10.48
Orthoclase (or)	15.81	20.68	27.17	31.89	29.58	27.35	32.42	12.75	12.21	19.57	19.23
Nepheline (ne)	29.50	24.60	12.86	7.87	11.70	18.65	5.37	24.59	---	13.43	11.93
Leucite (lc)	2.79	0.91	---	---	---	---	---	24.59	13.16	---	---
Acmite (ac)	11.45	28.50	25.08	18.15	18.43	17.18	16.63	17.97	26.17	7.62	5.21
Diopside (di)	17.00	10.68	4.74	3.87	1.97	6.31	5.48	8.87	7.91	9.90	7.82
Wollastonite (wo)	-	-	-	-	-	-	-	-	-	-	-
Aenigmatite (aen)	9.59	3.25	1.44	1.99	12.13	9.05	10.86	12.13	16.65	12.12	0.13
Eudialyte (eud)	---	1.17	1.17	1.17	1.90	4.18	13.38	4.77	4.77	7.42	7.71
Olivine (ol)	7.22	2.52	4.18	2.46	2.69	7.33	4.36	11.04	8.60	12.64	18.23
Sodium (ns) Metasilicate	1.15	2.62	3.24	3.45	0.61	1.63	0.20	---	---	4.53	---
Total	94.51	94.83	92.71	96.78	96.02	99.74	99.89	99.16	98.66	96.03	97.20

TABLE 9

Modal composition of alkalic rocks from the Joan Lake pluton

(vol. %)

Name	Ijolite	Type I			Type II		Type III		
	202	230	254	276	44	743	215	272	274
Eudialyte	-	1.1	1.1	1.2	4.2	13.4	4.5	4.7	7.4
Nepheline	42.3	21.3	10.1	-	20.5	8.2	20.0	5.6	10.2
Alkali-feldspar	2.2	25.3	30.5	40.2	25.3	25.5	-	25.2	13.6
Plagioclase	-	3.5	14.2	12.1	10.2	12.2	24.0	26.6	13.0
Na-amphiboles	53.0	12.6	13.1	14.2	20.7	28.3	16.8	25.6	32.4
Aenigmatite	-	-	-	-	9.4	8.8	1.5	6.3	16.4
Aegirine-augite	0.5	33.7	30.0	31.3	8.3	2.3	32.5	4.0	6.0
Others	2.0	2.5	1.0	1.0	1.4	1.3	0.7	2.0	1.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

N.B. Specimen 276 belongs to a dyke rock of Type I (lujavrite) outside the Joan Lake agpaitic pluton.

to immiscibility of the two melts or may be interpreted indicating separate origins of the two melts. Since Al_2O_3, SiO_2, TiO_2, ZrO_2 form the most important constituents of agpaitic rocks and they have not been considered in the AFM, ACM and NCK (Na_2O - CaO - K_2O) diagrams, the interpretation based on the diagrams is incomplete. Thus, the mechanism proposed by Bridgewater (1967) based on Watt's (1966) chemical analyses of the Gardar Alkaline Province to generate agpaitic magma, is not suggested by the chemistry of agpaitic rocks from the Joan Lake area. Furthermore, it is both difficult and unnecessary to assign an important role to common volatiles in creating and affecting its differentiation. The Joan Lake agpaitic pluton does not show halogen-rich minerals similar to the Ilimaussaq intrusion.

Considering the above features, it can be concluded that agpaitic rocks are neither related to anorthosite through a special mechanism of differentiation nor are they the product of interaction of volatiles and anorthosites in the Joan Lake area.

Since the rocks reported from Michikamau anorthosite and the Joan Lake area do not show normative wollastonite (Table 8), the "plagioclase effect" as originally suggested by Bowen (1945) is not the operative mechanism for producing peralkaline trends from a basaltic magma. None of the alkali feldspars reported from the differentiates of the Michikamau anorthosite have been shown to be high in Fe^{3+} (Emslie 1968). Therefore, the "orthoclase effect" suggested by Bailey and Schairer (1964) is also ruled out as a possible mechanism to produce peralkaline trends in the basaltic magma.

In short, neither the normal processes of differentiation, nor the special mechanisms suggested to create peralkaline trends from a basaltic magma, appear to be operative to create the Joan Lake agpaitic intrusives.

Sood and Edgar (1970) suggest that crystallization of nepheline, feldspar and diopside-augite from an already undersaturated melt, under high P_{O_2} may give rise to agpaitic trends during differentiation. This mechanism implies that primary crystallization of nepheline and feldspar would impoverish the melt in alumina and the separation of calcic-pyroxene would create a necessary deficiency in CaO and MgO in the earlier stages. The crystallization of nepheline and feldspar would not only deplete the melt in Al_2O_3 but also in Na_2O and K_2O (depending upon the type and amount of feldspar). Furthermore, separation of diopside-augite and feldspar (silicic minerals) would result in a silica-deficient rather than alumina-poor melt. The Joan Lake agpaitic rocks, the agpaitic rocks from Ilimaussaq (Ferguson 1964) and those of Kola Peninsula (Gerassimovsky 1966) neither show an early differentiate of a mineralogical composition suggested by the above hypothesis nor do they show silica deficiency compared with the common nepheline syenites. On the other hand, all agpaitic rocks show higher SiO_2 values than those observed in most nepheline rocks (Piotrowski and Edgar 1970 and Sood and Edgar 1970). Therefore, the theory of Sood and Edgar (1970) is inapplicable for the genesis of agpaitic rocks.

Several petrologists (Ferguson 1964, 1967, 1970a, Sørensen 1969), have discussed petrogenesis of agpaitic rocks in terms of C.I.P.W. norms. The norms thus calculated do not tally the modes of agpaitic rocks. Since both eudialyte and aenigmatite form the essential constituents of the Joan Lake agpaitic rocks and they are common in the igneous paragenesis, it is advisable to include them in normative calculations. In the present

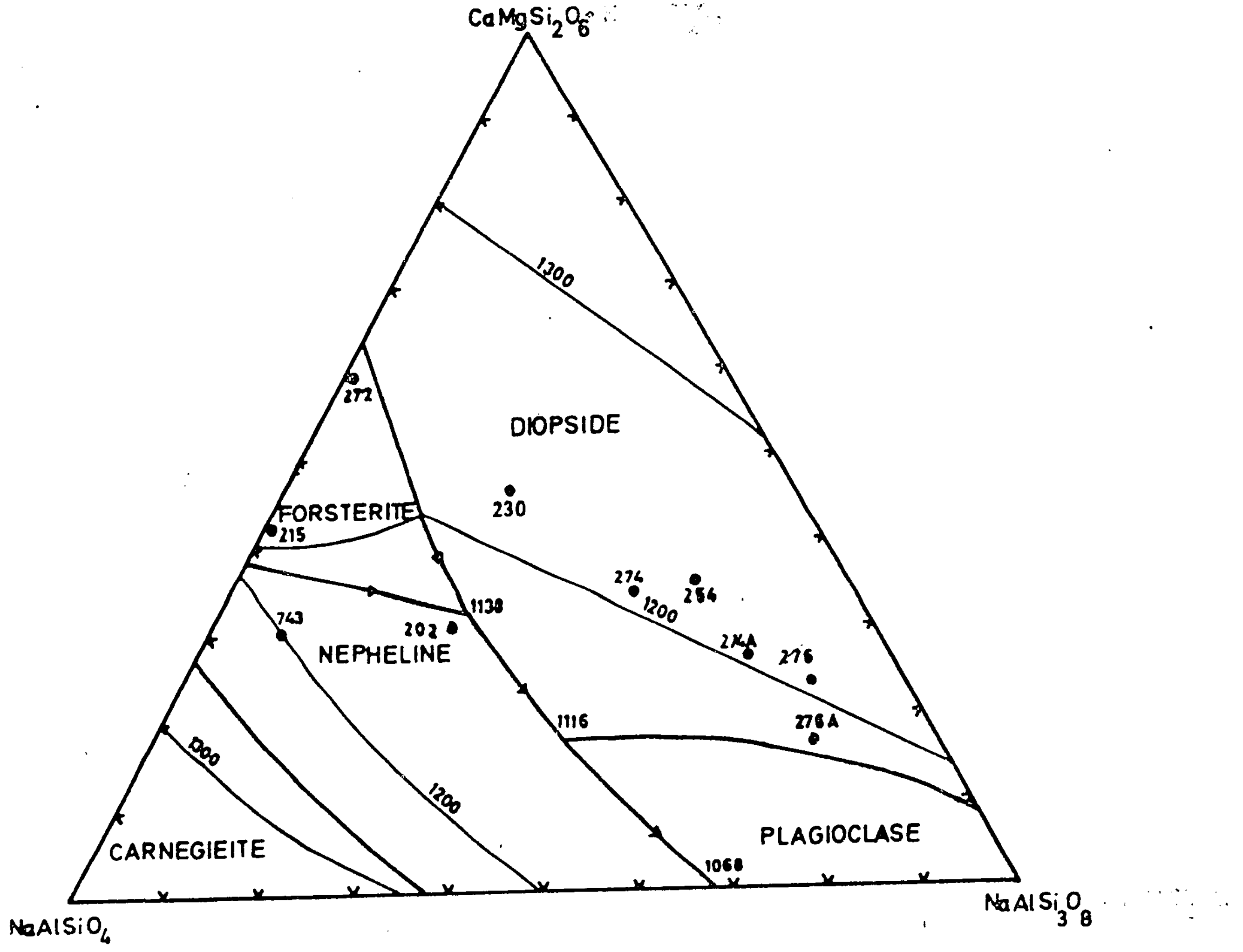


FIG.28 : SAMPLES FROM THE JOAN LAKE AGPAITIC COMPLEX PLOTTED IN THE SYSTEM DIOPSIDE–NEPHELINE–ALBITE AT 1 ATMOSPHERE.

study, norms have been calculated by introducing eudialyte and aenigmatite for the agpaitic rocks(Table 8). The modified scheme of norm calculations is given in Appendix I.

In view of the lack of experimental data on a system involving eudialyte -nepheline-aegirine-diopside-aenigmatite-arfvedsonite-orthoclase-albite, all attempts made to explain the petrogenesis of agpaitic rocks are necessarily qualitative. The study based on nepheline-quartz-kalsilite(ne-qtz-ks) system alone cannot give the complete history of differentiation of agpaitic melt.

In order to compare liquidus temperatures of the agpaitic rocks from the Joan Lake area with those of available synthetic systems of similar composition, all the agpaitic and non-agpaitic rocks from Joan Lake can be plotted in the modified nepheline-diopside-albite diagram(Fig.28, after Piotrowski and Edgar 1970). In this scheme, the diopside represents normative di+ac, nepheline equals ne+ks+lc while feldspar (albite) equals normative ab+or+an.

Thus ijolite(Specimen 202) falls close to the thermal minimum(approximately near 1140°C according to the work of Piotrowski and Edgar 1970), while all the agpaitic rocks plot well outside the thermal valley.

These temperatures may suggest that the ijolite crystallized later than agpaitic rocks which is a contradiction to the proposed scheme of differentiation.

During melting experiments on undersaturated rocks, Sood and Edgar(1970) noted that the agpaitic index is related to the melting intervals (Fig.29). Thus, the agpaitic index of the rocks from the Joan Lake complex can be used to work out the consolidation range of the melt . Ijolite(Specimen 202)

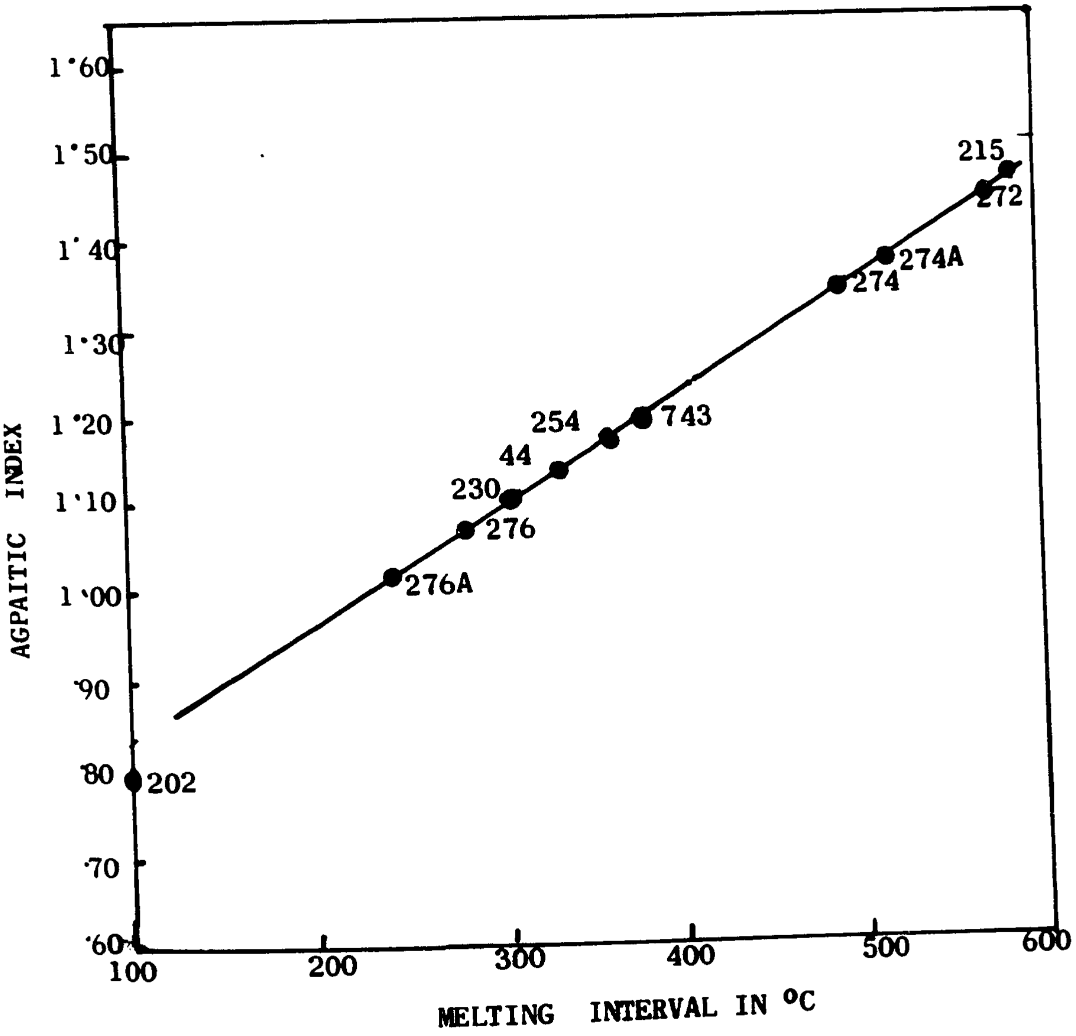


FIG.29:Relationship between melting intervals and agpaitic indices at one atmosphere in air(Sood and Edgar 1970). ●Specimens from the Joan Lake alkalic complex.

with agpaitic index=0·80 gives maximum 100°C melting interval at one atmosphere in air. Similarly, Type I shows 230-350°C, Type II, 325-375°C and Type III 475-575°C, melting intervals(consolidation range) at one atmosphere.

Thus, it can be suggested that ijolite could remain at a molten stage between 1140°C and 1040°C while Type I(lujavrites) would remain molten between 1250-900°C at one atmosphere. On the other hand, rocks included in Type II, could remain in a molten state between 1200-825°C and Type III rocks could have existed as a melt between 1250-625°C at one atmosphere.

From the above information, it can be concluded that ijolite and agpaitic melts could have coexisted. Addition of ZrO_2 might have raised the melting temperatures of the rocks belonging to Type II and Type III. The differences in consolidation range of various magma types have been used to explain apparent schistosity observed in lujavrites(Ferguson 1970c).

Ijolite-urtite rocks may have been derived by partial melting of melilite basalt or peralkaline syenite(Bailey and Schairer 1966) associated with the rift systems(Bailey 1964). Alternatively, the partial melting of peridotite in the mantle has been proposed as a possible mechanism to produce olivine nephelinite(Bultitude and Green 1967, Kushiro 1968) and subsequently ijolite-urtite intrusives.

Irrespective of the mechanism, the existence of the ijolite magma has been well documented(Bailey and Schairer 1966, Minakov <u>et al</u>. 1971). Petrochemistry of the Joan Lake agpaitic complex points to the following features which must be explained before its evolution can be considered:

a) Ijolite-magma existed in the Joan Lake and the Ten Mile Lake areas at low oxygen fugacity.

b) In the Joan Lake area Zr, Nb, R.E., Ti and other rare metals played different roles in different regions.

c) Ijolite-urtite and Type I (lujavrite) could exist as molten rock at the similar physical conditions.

d) Oxygen fugacities and agpaicity differed at various regions within the same pluton.

e) Ijolitic magma cannot be related to Michikamau anorthosite or basalts by process of differentiation or by any special mechanism of crystallization.

f) Oxygen fugacities remained below the stability limits of magnetite and ilmenite during the evolution of the Joan Lake agpaitic complex.

It is difficult to postulate an overall theory of genesis for the Joan Lake agpaitic complex due to the marked change in the role of the individual components at different stages in its evolution.

Its evolution has to be discussed in terms of mineralogical and chemical composition of various units and their spatial and tectonic relations to the rocks in the surrounding areas. Any acceptable hypothesis of magmatic melt must entail the study of the following significant features which might contribute to the complexity of the mineralogical and chemical evolution of the Joan Lake agpaitic complex:

a) the chemical composition of the parental magma,

b) assimilation of the country rocks and the effects of metasomatism,

c) the emanation processes and their role in segregation,

d) crystallization and differentiation,

e) changes in oxygen fugacity at different stages and its effect on the mineralogy,

f) alkalinity and its role in transportation of rare metal-complexes, and

g) metamorphism postdating the agpaitic intrusives.

CHAPTER 7

THE EVOLUTION OF THE JOAN LAKE AGPAITIC COMPLEX

The Joan Lake agpaitic complex is situated at the junction of the Grenville and Nain Provinces of the Canadian Shield. It is emplaced into a Precambrian volcano-sedimentary sequence on three sides and abuts against metamorphosed diorites and gabbros to the southeast. The volcano-sedimentary sequence has been metasomatized to fenites while diorites and gabbros have been thermally metamorphosed only.

The Joan Lake agpaitic complex can be divided into zones based on the mineralogical and textural criteria. It consists of ijolite-urtite and lujavrite in the core while rocks of Type II and Type III form the peripherical zones. Mineralogical and textural variations in the composition of the rocks are very common. The agpaitic complex can be subdivided into low and high P_{O_2} zones based on the appearance of aenigmatite. Both eudialyte and aenigmatite are concentrated in the peripheral region. The mineralogical and petrochemical studies lead to the following unsolved problems in the petrogenetic evolution of the complex:

a) the nature and the origin of the melt from which the agpaitic pluton evolved,

b) the controls in selective concentration of elements (e.g., Ti, Zr, Nb, R.E.) in the peripheral zones and the mechanism of their transport. The origin of complex chemico-mineralogical features,

c) the dual behaviour (contact metamorphic and metasomatic) of the rocks on either side of the pluton.

Before the above problems are solved, it would be appropriate to review the geophysical information available pertaining to the study area.

1. Geophysical interpretation of the study area

The area has been covered by magnetic, gravity and radiometric surveys. Geomagnetic data lead to the conclusion that the Red Wine Mountain anorthosite rests in a trough with a steeply dipping edge, 10 kilometers deep (Tanner 1969). Basin analysis of the rocks mapped from the area does not give a fit for a model of a large sedimentary trough and therefore, strongly suggests the presence of rift between Red Wine Mountains and Naskaupi River (Tanner 1969). A low gravity channel extends along the length of the Grenville front in the study area. Gravity surveys combined with the seismic experimental work suggest that the Grenville front is a major fault structure penetrating well into the upper mantle (Mereu and Jobidon 1971).

Airborne radiometric surveys (Sutton 1967) indicate zones of high radioactivity above the Joan Lake agpaitic pluton and throughout the fenite zone in the Ten Mile Lake area. The intensity of radioactivity falls steeply outside the alkalic rocks.

Thus any petrogenetic model proposed must consider the following two major features:

a) The Joan Lake and the Red Wine River agpaitic complexes along with their fenitic rocks lie near the Grenville front, a major fault structure probably penetrating into the mantle.

b) The radiometric anomalies are restricted either to the agpaitic rocks or the surrounding fenites.

2. Petrogenetic evolution of the Joan Lake agpaitic complex

a) The nature and the origin of the magma

Field studies combined with the mineralogical and petrochemical investigations indicate that an ijolitic melt existed in the Joan Lake and Ten Mile Lake areas.

Mineralogical associations point to the low oxygen fugacity during the evolution of the entire complex. The presence of anhydrous eudialyte (see Part 3) and aenigmatite indicates a low content of water in the melt. Since the Joan Lake area lies in the weak zone and has a direct access to the mantle, the processes of partial melting as suggested by several authors (Bultitude and Green 1967, Kushiro 1968) might have played a role in generation of a peralkaline magma.

Dawson's discovery (Dawson and Frisch 1971) of eudialyte-nepheline syenite blocks in the agpaitic phonolites at Oldoinyo Lengai (Gregory rift valley), Tanzania, lends further support to the hypotheses that agpaitic rocks can be connected with rift systems and are possibly related genetically to such rock types as phonolites. To generate such a melt at the transition of lower crust and upper mantle, an enormous amount of heat is required. The tectonic pressures generated during arching of the floor of a rift system (Bailey 1964) and the concentration of radioactive elements (Beloussov 1962, 1971) have been suggested as possible sources for the required heat. The thermodynamic basis of de-gassing of the mantle, heat focussing, partial melting and magma generation in weak zones of the earth have been discussed by several authors (Bailey 1970, Velinskiy 1971, Bass 1970).

The initial ijolitic magma beneath the Joan Lake area, rich in radioactive elements and other rare metals, might have been produced by combinations of the above processes.

b) Element concentration and mineral paragenesis

Redistribution of elements in the different parts of the agpaitic massifs (Vlasov _et al_. 1966) has been ascribed to the special role played by emanation factors. The emanation factors include the following processes (Vlasov 1956):

1. all the processes involved in concentration of sodium, potassium and other light elements by volatiles including chlorine, fluorine and hydrogen,
2. special mechanisms involved in transportation of Ti, Zr and other rare elements as metal complexes. Decomposition of such complexes and deposition of rare metals,
3. all processes of dispersion of certain metals from crystallizing melts involving a vapour phase.

Vlasov _et al_. (1966) describe the role of the above factors as follows:

> "Any intrusion formed under the tectonic disturbances (pressure reduction) will act as a distillation column in which the vertical distribution of the elements and their compounds will depend on their volatility i.e., vapour and gas pressure. Thus, if a single magmatic hearth is differentiated into a complex of separate magmas, the alkalic magmas will occupy the upper part of the distillation column, since their compounds are the most volatile."

In the Joan Lake area, the eudialyte and aenigmatite rocks do not show an evidence of enrichment in halogens, however, fluorite has been observed at places as a minor phase. It has been suggested that zirconium and titanium cannot be transported in solutions of sodium and potassium hydroxides or carbonates (Kuznetsov 1971) but concentration of alkalies and other elements might have been affected by the common volatiles to a small degree.

In addition to the lack of common volatiles, the petrochemical investigations of the Joan Lake pluton indicate a higher initial solidification temperature for the rocks forming the peripheral zones (Chapter 6). In the absence of halogens, it has been suggested that transfer of the rare elements can be accomplished by the formation of partially dissociated titanates, zirconates and hafnates (Gerassimvosky 1967, 1968). Such a mechanism of transfer would lead to their broad dissipation and removal for considerable distances from the source, because of the weak hydrolysis of their carrier compounds in strongly alkaline solutions (Kuznetsov 1971). Moreover, the peripheral rocks of the Joan Lake agpaitic complex show that their mineralogical evolution took place under quite low oxygen pressures and anhydrous mineral phases were crystallized due to the lack of water in the melt. The lack of hydrated minerals and the presence of aenigmatite would suggest that any hypothesis involving such oxygen-rich compounds as titanates and zirconates and their transfer by alkaline solutions was not operative at Joan Lake.

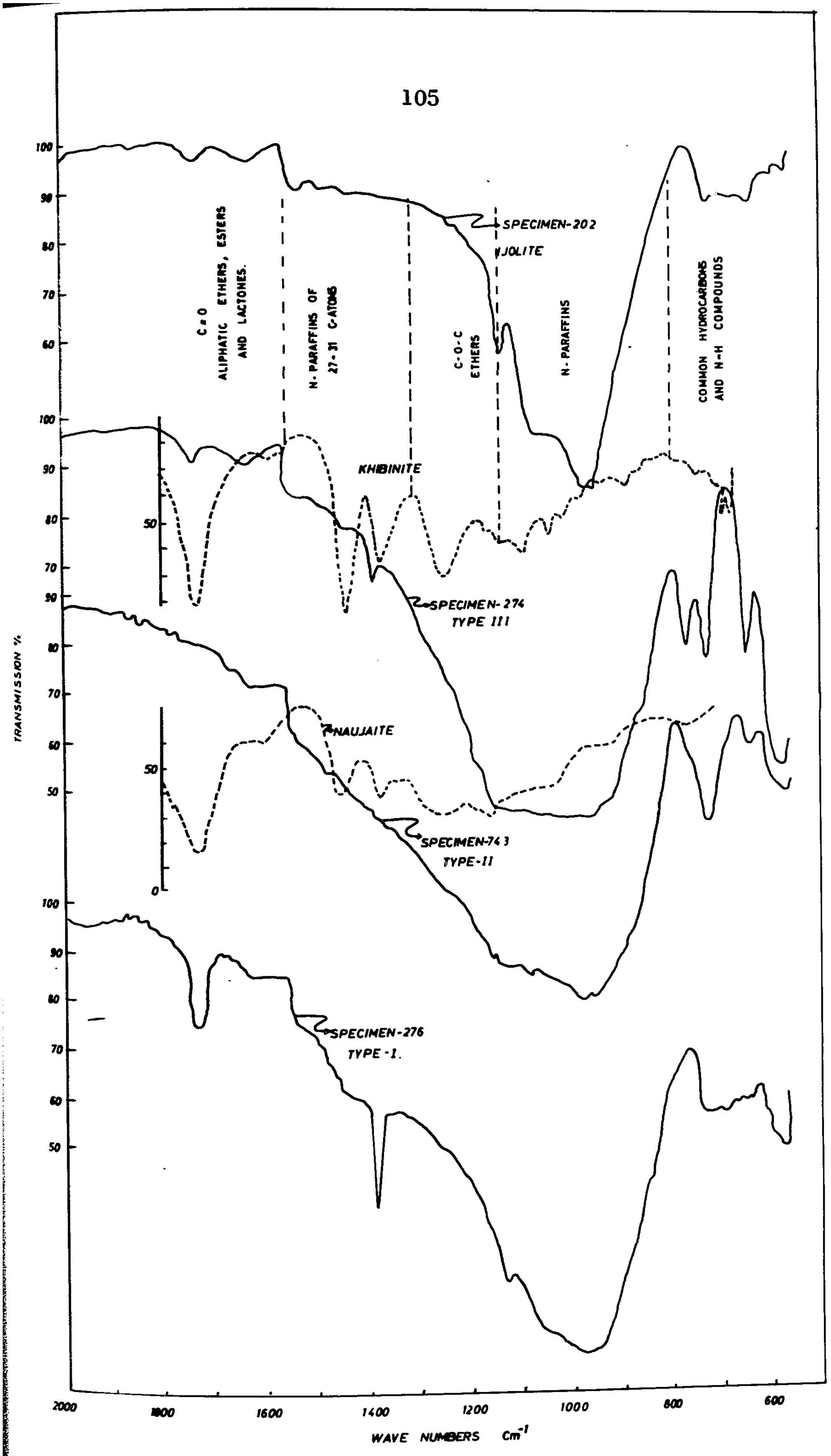


FIG. 30 : ABSORPTION SPECTRA OF CHLOROFORM EXTRACT OF BITUMEN FROM KHIBINITE AND NAUJAITE (PETERSILIE & SØRENSEN 1970) COMPARED WITH THOSE OF THE ALKALIC ROCKS FROM THE JOAN LAKE AGPAITIC COMPLEX.

The infrared analyses of eudialyte (Part 3) and agpaitic rocks (Fig. 30) from the Joan Lake area show absorption peaks characteristic of hydrocarbons e.g., CH_4, C_2H_6 and other paraffins, esters and lactones. Similar hydrocarbons and several other compounds including NH_3 and nitrogen have been reported from the agpaitic rocks of Ilimaussaq (Petersilie and Sørensen 1970) and Kola Peninsula (Petersilie et al. 1965). Some of the agpaitic rocks contain 30-60 cm^3/Kg of these gases. Further δC^{13}* (-0.53 to -1.26) of agpaitic rocks is similar to that of diamonds (-0.24 to -0.80) and carbonatites (-0.50 to -0.90) but is quite different from that of methane of biochemical origin (-6.9 to -8.4) or natural gas (-2.1 to -2.9). Hotun (1970) observed that eudialyte formed in large amounts when CH_4 buffer was used with NH_4Cl in a solution of eudialyte components.

The above observations suggest the following ways by which the emanation factors combined to influence the chemical and mineralogical evolution of the Joan Lake agpaitic pluton.

1. Interaction of hydrocarbons and other gases with zirconium, titanium and rare earths to form volatile complexes (see Songina 1970 and Feld and Cowe 1965). Some of these complexes may form as a result of endothermic reactions and exist as vapour phase reaction products.
2. Transfer of such complexes towards the margins and apical portions of the pluton. Decomposition of such complexes may evolve heat (Schäfer 1964). This process of decomposition of gases may facilitate their synthesis to bitumens in the presence of nepheline (acting as catalyst) as suggested by Bashikrov et al. (1956). As the

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$$*\delta C^{13} = \frac{(C^{13}/C^{12})_{sample} - (C^{13}/C^{12})_{standard}}{(C^{13}/C^{12})_{standard}}$$; International standard P.D.B. (C^{13}/C^{12}=0.889)

decomposition of these complexes may evolve heat, the melt in such regions might be at a higher temperature than the rest of the pluton. However, decomposition of some volatile compounds and deposition of rare metals might also be facilitated by higher temperatures (see Schäfer 1964, for systems with reversible transport directions).

3. Increase in partial pressures of carrier gases due to decomposition of complexes (vapour reaction products) and development of reducing conditions.
4. Crystallization of various complex silicates under reducing conditions.

In addition to the emanation factors, crystallization played a minor role in differentiation of various mineral associations of the Joan Lake pluton. It has been already noted (Chapters 4 and 5) that the distribution of minerals follows specific rules. The preponderance of sodium over potassium in the magma and the deficiency of silicon led, in the first place, to the crystallization of nepheline which during slow cooling possibly grew locally as a continuous layer.

The differentiation of the pluton into clearly defined layers of ijolite-urtite and lujavrite must have begun at this time. The lujavrite rocks may have formed by the interaction of the ijolite and urtite rocks with the melt below it, which was impoverished in sodium and alumina by earlier separation of nepheline. At a certain stage, the concentration of nepheline components in the layer beneath the urtite was greatly reduced and could not be adjusted by diffusion. Thus, a magma layer, in which K-feldspar and aegirine components(iron, potassium and silicon) were in a supersaturated state, formed between the lower boundary of the continuous nepheline layer and the magma layer that was still rich in nepheline components. The nepheline formed in this way crystallized along with microcline and aegirine (Chapter 5).

The portion of the magma, enriched in rare elements by gas transfer reactions, was very low in its water component, therefore, anhydrous minerals like aenigmatite crystallized from it at the expense of arfvedsonite (rock Types II and III). Furthermore, aenigmatite was joined by eudialyte in this zone because of favourable alkalinity and availability of zirconium.

c) Dual behaviour of the rocks on either side of the Joan Lake pluton

The alkalic magma of the Joan Lake agpaitic pluton was injected into rocks of two types of sharply contrasting chemical composition and the processes of assimilation are therefore revealed in dual fashion. At the steeply dipping lateral contacts where it borders on the diorites and gabbroic rocks, assimilation was not effective owing probably to the following reasons:

1. the alkalic magma in those regions was not rich in volatiles like chlorine, fluorine and water,
2. the diorite and gabbroic rocks belong to higher reaction series and therefore could not be assimilated by alkalic magma,
3. the temperature of the alkalic magma was insufficient to dissolve diorite but its temperature was sufficient to cause thermal metamorphism,
4. the diorites were impermeable as compared to sedimentary rocks.

In the central part, the schists and volcanic rocks have been enriched in feldspar, aegirine and riebeckite. On the three sides, the alkalic magma of the Joan Lake complex came in contact with acid volcanic or sedimentary rocks and recrystallized large amounts of feldspar. The distribution of alkalic rocks suggests that the direction of injection of the Joan Lake alkalic magma was from south to north. Some of the fluids at the apical portion of that magma transformed the country rocks into bodies with nebulous outline and developed aenigmatite and eudialyte in quartz-rich rocks.

The alkalic magma was emplaced into the Seal Lake rocks and at least some fenites developed before the intrusion of the Joan Lake pluton. Those fenites which formed before were mylonitized by intrusion. The history of deformation within the pluton and outside was complicated by several events which might have taken place before, during and after the intrusion of alkalic magma in such a tectonically active zone.

PART 3

MINERALOGY OF THE JOAN LAKE AGPAITIC COMPLEX

CHAPTER 8

DESCRIPTION OF MINERALS

Forty-seven mineral species and several varieties have been identified by X-ray diffraction and/or optical means.The chemical analyses of some of these minerals were made by atomic absorption,spectrophotometer and electron microprobe.For some minerals, Mössbauer resonance, electronic spin resonance, infrared and visible range absorption studies were carried out. Only the results of the above studies are recorded here. In addition, 26 minerals could not be identified. Their five most intense X-ray diffraction lines are recorded.

Several mineral species e.g. nepheline,aenigmatite, perovskite(loparite), karnasurtite, ramsayite, vinogradovite, lamprophyllite, barytolamprophyllite, nontronite, britholite, ussingite , sodalite (and hydrosodalite), natrolite, lithium-mica, steenstrupine(?),ferroan-titanian-omphacite(blue pyroxene), titanian -lavenite, astrophyllite, allanite, hellandite and innelite have been recorded for the first time from Central Labrador. Some minerals have been given group names because of insufficient data e.g. lithium-mica instead of lepidolite(1M) or polylithionite while several varieties of other minerals are described e.g. mesodialyte and eucolite. In the present description the chemical formulae are taken from Fleischer(1971) with some slight modifications.

It should be emphasized that there are a number of other minerals with grain size too small to permit detailed work.

1. Aegirine and Aegirine-Augite

Aegirine-augite ($2V_x=64^o - 88^o$) grains are common in agpaitic and fenitic rocks. They are observed as,

1) tiny needles and microlites in fenites,
2) large poikilitic anhedra enclosing nepheline, microcline, albite and arfvedsonite in Type I rock,
3) large irregularly zoned subhedra in some lujavritic gneisses (Type I, not amongst the analyses tabulated in table 10). In such cases, cores are $Ac_{56}Di_{44}$ and rims are $Ac_{68}Di_{32}$ (X-ray diffraction and optical study, assuming only acmite and diopside components and applying the curves of Edgar 1964 and Winchell 1951),
4) alteration product of arfvedsonite anhedra in Type II and Type III.

Below are given some of the partial analyses of aegirine separates from the various rocks.

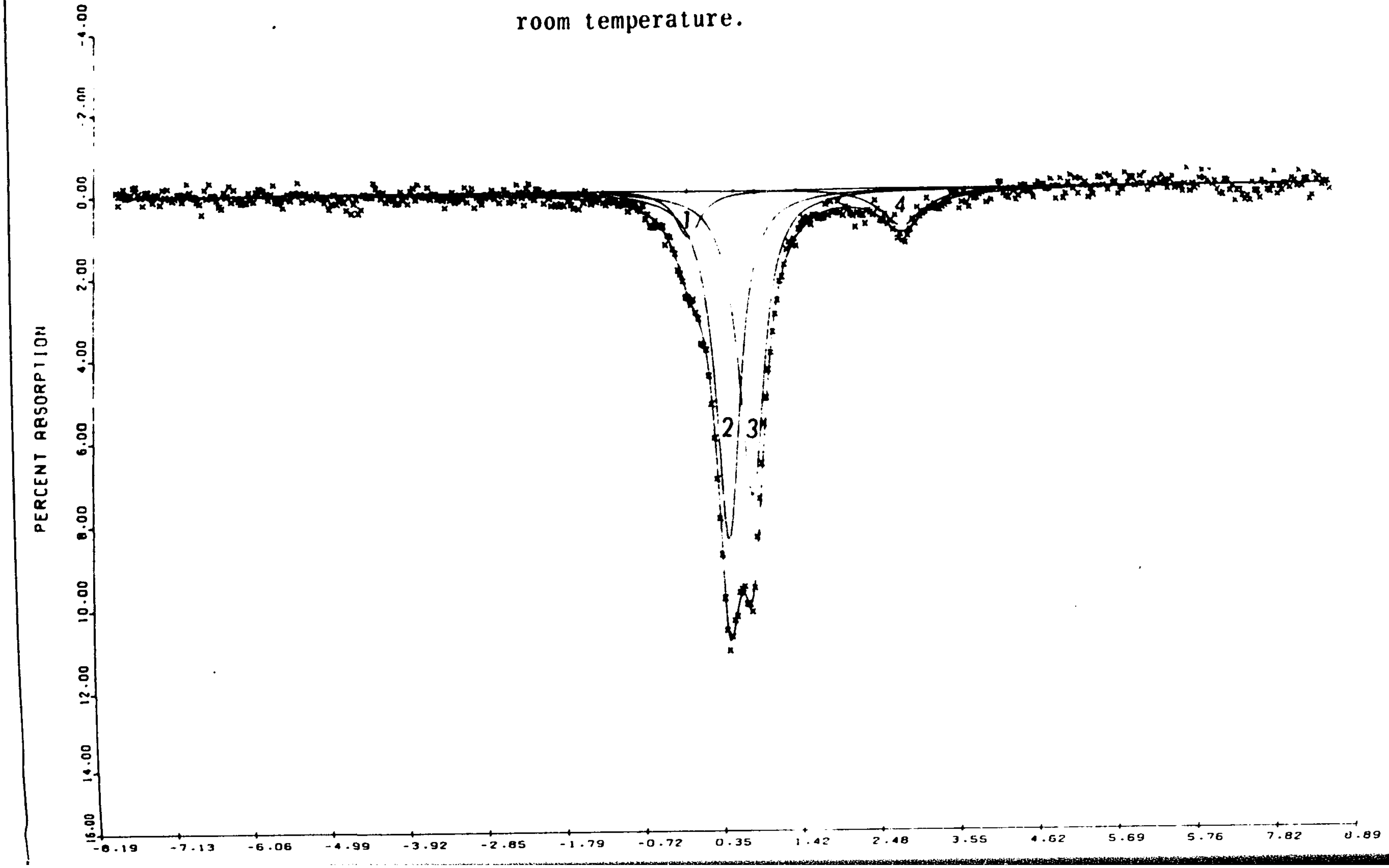
TABLE 10

Partial chemical analyses of aegirine and aegirine-augite

	Type II		Type III		Fenites		
Oxides	743	44	215	274	287	1*	II*
TiO_2	2.36	2.24	3.70	3.65	3.00	2.70	0.83
Al_2O_3	4.75	5.22	4.72	5.21	7.10	2.52	1.13
Fe_2O_3	5.04	6.40	4.72	4.72	5.04	18.53	32.45
FeO	15.02	14.40	13.50	13.67	11.16	7.56	0.79
MnO	0.02	0.02	0.005	0.02	0.02	1.01	0.25
MgO	0.38	0.38	0.74	0.38	0.42	0.31	0.08
CaO	1.53	1.54	3.20	2.54	2.41	3.46	0.43
Na_2O	11.53	12.11	11.68	12.11	11.83	10.34	12.68
K_2O	0.24	0.20	0.17	0.26	0.28	0.35	0.00
Total	40.81	42.51	42.435	42.52	41.26	46.78	48.64

*analyses from Nickel and Mark (1965)

Fig. 31 : Mössbauer resonance of aegirine-augite (Specimen 274) taken at room temperature.



All the grains seen in the agpaitic rocks are optically biaxial negative and pleochroism varies from Z = greenish yellow to straw yellow, Y = yellowish green, X = grass green to dark green. Absorption: $Y > X \gg Z$, extinction: $X \wedge C = 4^{0} - 20^{0}$, $2V_{X} = 64^{0} - 88^{0}$, refractive indices, $\alpha = 1.745 - 1.752$, $\beta = 1.754 - 1.758$, $\gamma = 1.795 - 1.798$. X-ray diffraction data are identical to those in Nickel and Mark (1965).

Mössbauer spectra (Fig. 31) show that two sites are occupied by iron in the structure of aegirine-augite (Specimen 274). The Fe^{2+} M(2) site occupied by Fe^{2+} gives $\Delta eq. = 2.878 \pm .001$ and $\delta = 1.296 \pm .001$ (peaks 1 and 4) while the Fe^{3+} M (1) site (peaks 2 and 3) filled by Fe^{3+} gives $\Delta eq. = 0.321 \pm .001$ and $\delta = 0.525 \pm .001$ (table 11). From the areas under the respective peaks, the Fe^{3+}: Fe^{2+} ratio is determined to be 5: 1.

TABLE 11

Mössbauer parameters of aegirine-augite

Average mean Square Residual = 591.625 Chi Squared = 549

(Specimen - 274)

Site	Chemical Shift (δ) mm/sec.	Quadrupole Splitting (Δeq) mm/sec.	Width at ½ peak height (Γ) mm/sec.		Area A (A) Counts Channel x10-5		Intensity (I) mm/sec.	
Fe^{2+} in M (2)	$1.296 \pm .001$	$2.89 \pm .001$	Γ_1	Γ_4	A_1	A_4	I_1	I_4
			0.63	1.00	0.80	1.11	0.407	0.338
Fe^{3} in M (1)	δ_{23}	Δ_{23}	Γ_2	Γ_3	A_2	A_3	I_2	I_3
	0.526 ± 001	$0.321 \pm .001$	0.58	0.61	5.73	5.26	3.12	2.73

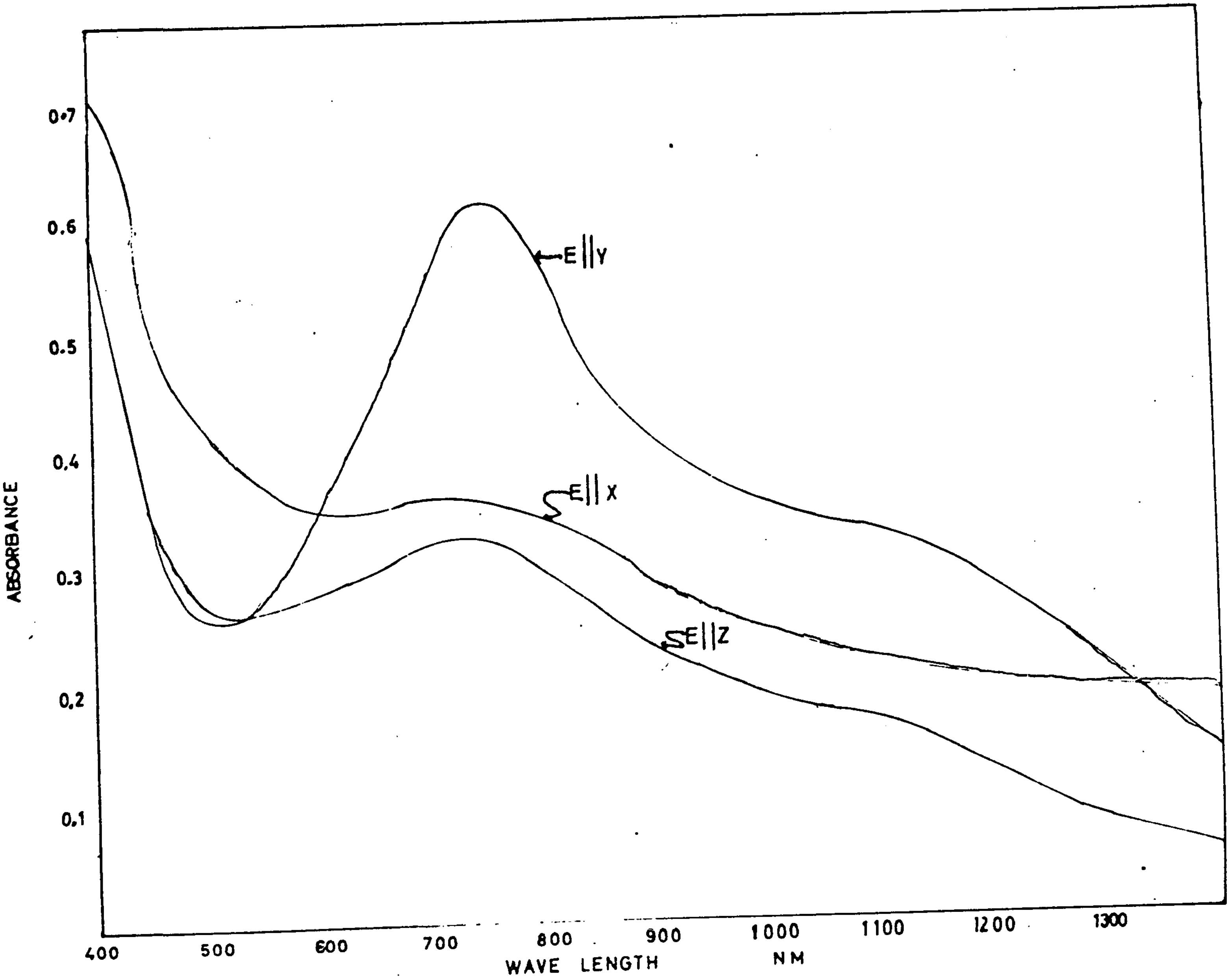


FIGURE 32 : OPTICAL SPECTRA OF AEGIRINE-AUGITE (SPECIMEN 274)

The optical absorption spectra of aegirine-augite (Fig. 32) includes a shoulder at 1100nm which may be due to forbidden d - d transition and maximum observed around 750nm may be attributed to $Fe^{2+} \rightarrow Fe^{3+}$ charge transfer. A peak beyond the short wavelength registration of the instrument (<400nm) could be due to $O^{2-} \rightarrow Fe^{3+}$ charge transfer.

2. Aenigmatite

$Na_4Fe_{10}Ti_2Si_{12}O_{40}$

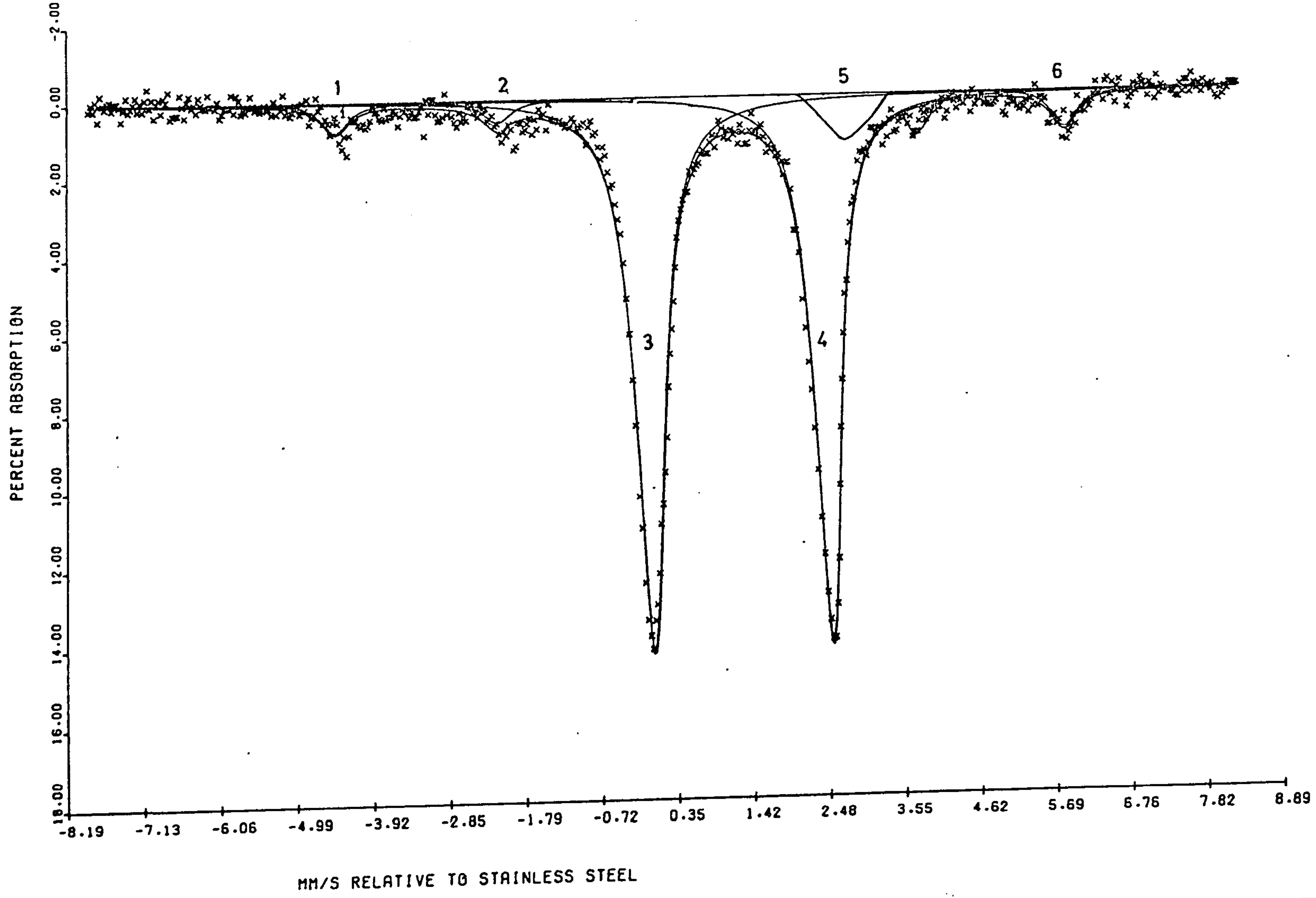
Aenigmatite occurs in rocks of Type II, Type III and some fenites. In the rocks belonging to Type II, subhedra of aenigmatite are seen within arfvedsonite poikilites. In Type III rocks, aenigmatite is subhedral but in fenites it is intergrown with aegirine-augite. In a few fenites, it coexists with ilmenite and ramsayite. Rarely ramsayite forms a core to aenigmatite. In the ijolitic sill of the Ten-Mile Lake area (Mann - 2), aenigmatite coexists with ramsayite, lamprophyllite and arfvedsonite. The optical properties of aenigmatite are summarized below.

TABLE 12

Optical properties of aenigmatite (Specimen 274)

Refractive Index:	$\alpha = 1.81 \pm 0.01$;	$\beta = 1.83 \pm 0.01$
	$\gamma = 1.88 \pm 0.01$	
Pleochroism:	X = wine red	Y = reddish brown
	Z = dark red	
Absorption:	$Z > Y > X$	
Optic Angle:	$2\ V_Z = 32^{\circ} - 34^{\circ}$	
Elongation:	Positive on 010	
Orientation:	Optic plane is nearly parallel to 010	
Dispersion:	$r \gg v$	
Extinction:	$Z \wedge c$ on 010 = $42^{\circ} - 43^{\circ}$	

FIG. 33 : MÖSSBAUER RESONANCE OF AENIGMATITE



Three chemical analyses of the aenigmatite grains from different rock types gave the following results.

TABLE 13

Chemical composition of Aenigmatite

Oxides	SG-112-GG*	Type III 274**	Type II 743**
SiO_2	41.5	39.9	40.4
TiO_2	8.9	11.8	11.4
Al_2O_3	--	1.2	1.2
Fe_2O_3	--	6.2	6.5
FeO	39.6	30.0	30.6
MnO	1.6	2.4	2.4
MgO	tr.	--	--
CaO	--	0.4	0.4
K_2O	--	0.1	0.2
Na_2O	7.4	6.8	5.7
Total	99.0	98.8	98.8

* Aenigmatite from the Red Wine pluton analysed by A.G. Plant, Geol. Surv. by electron microprobe (all iron as FeO).

** Analyst S.K. Singh.

The Mössbauer spectra of aenigmatite resemble those of $Fe_2SiO_4 + Fe_3O_4$ slags described by Carson and Tremblay (1971).

FIGURE 34 : OPTICAL ABSORPTION SPECTRA OF AENIGMATITE.

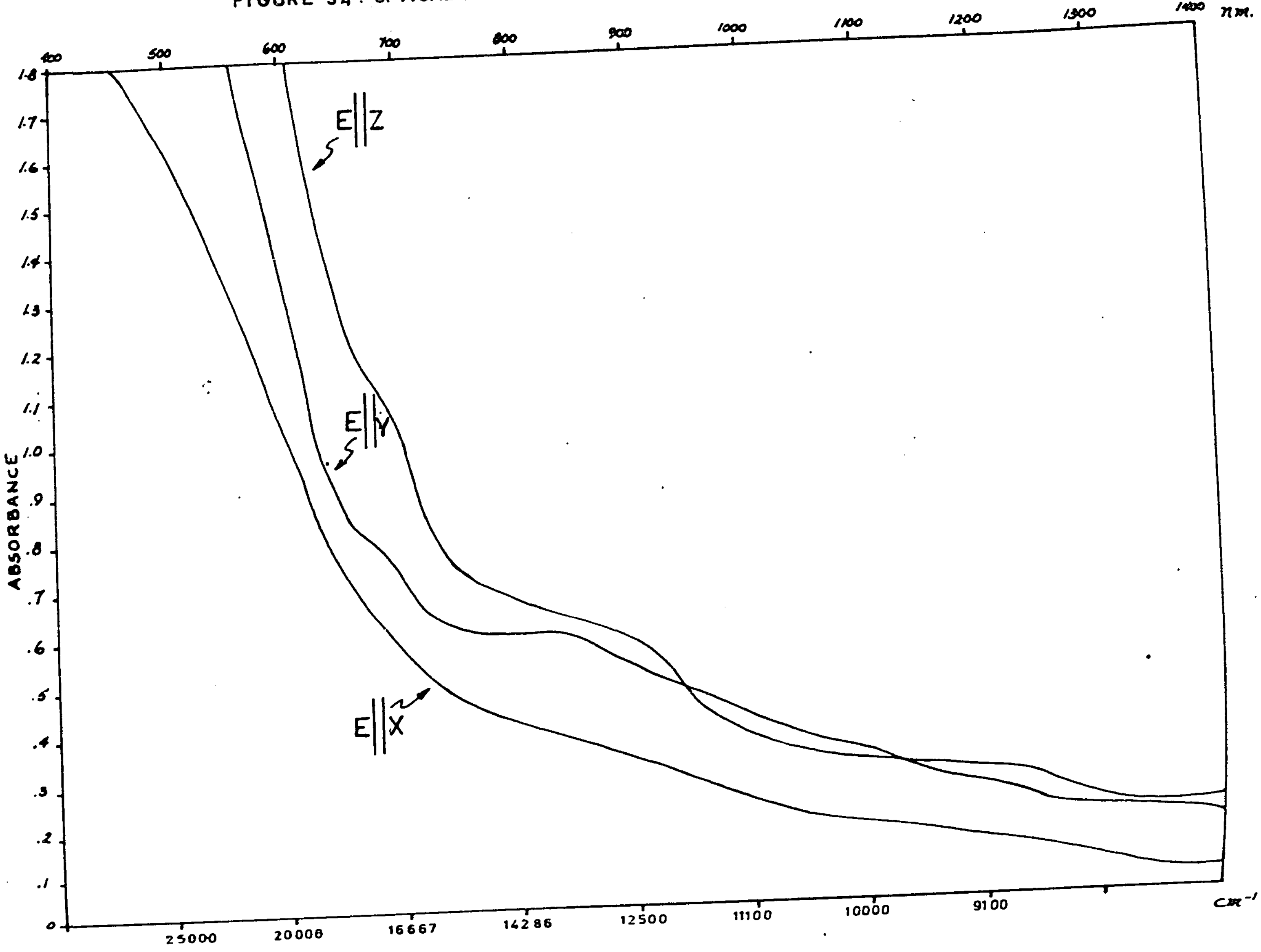


TABLE 14

Mössbauer parameters of aenigmatite

(Specimen 274)

Average Mean Square residual = 687.951

Chi Squared = 550

Possible Site	Chemical Shift mm/sec	Q.S. mm/sec	Width at ½ peak height mm/sec	Intensity mm/sec	Counts channel x10^{-5}
Fe^{2+} in M - site			Γ_3 Γ_4	I_3 I_4	A_3 A_4
	1.283 ± .001	2.51	0.73 .66	3.44 3.39	7.87 7.04
Fe^{2+} and Fe^{3+} in a paramagnetic unit.	δ	Δ	Γ_1 Γ_2 Γ_6	I_1 I_2 I_6	A_1 A_2 A_6
	---	0.15	0.70 0.70 0.68	0.19 0.14 0.23	0.41 0.30 0.50
$Fe^{3}/Fe^{+2}+Fe^{+3}=.125$					

The Mössbauer spectra of aenigmatite (Table 14) indicate that Fe^{2+} enters the M-site which resembles the M(2) site of aegirine and M(3) site of arfvedsonite. Furthermore, the hyperfine interaction gives three peaks which may be attributed to the presence of a $Fe''Fe'''Fe'''O_4$ (Fe_3O_4) or $Fe^{2+}Ti_2O_4$structural unit. If Fe^{2+} and Fe^{3+} in such a unit were randomly distributed, the hyperfine splitting should give 3:2:1:1:2:3 intensity ratios. It can be concluded that Fe^{2+} and Fe^{3+} atoms are non-randomly distributed in a spinel-type unit or the Fe^{2+}, Fe^{3+} octahedra in such a case are asymmetrical, or the low signal to noise makes determination difficult.

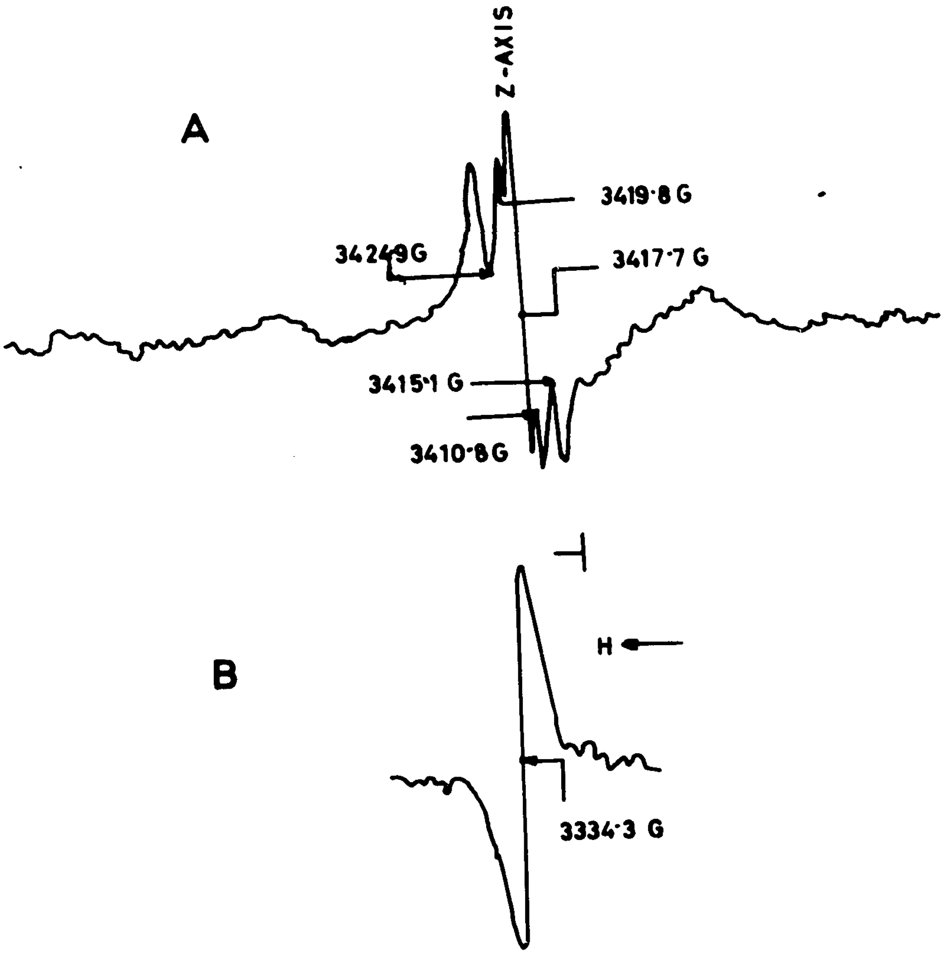


FIGURE 35:
A : MAXIMUM RESOLUTION OF E.S.R. LINES WITH MAGNETIC FIELD PARALLEL TO Z-AXIS OF FLUORAPATITE.

B: ISOTROPIC CHARACTER OF E.S.R. LINES PERPENDICULAR TO Z-AXIS OF FLUORAPATITE.

Fig. 35 : E. S. R. spectra of fluorapatite.

Optical absorption spectra (Fig. 34) of aenigmatite lead to the following tentative interpretation:

1. The weak features in the 8,000-10,000 cm^{-1} range are probably due to six coordinate Fe^{2+}.
2. The weak shoulder between 12,000-17,000 cm^{-1} could be attributed to $6A_{1g} \rightarrow 4T_{1g}$ and $6A_{1g} \rightarrow 4T_{2g}$ spin forbidden transitions of six coordinate Fe^{3+}.
3. The absorption edge around 17,000 cm^{-1} may be attributed to $2T_{2g} \rightarrow 2E_g$ (D) transition of Ti^{3+}; however the contribution of $O^{2-} \rightarrow Fe^{3+}$ charge transfer would also enhance the absorption in the region between 17,000-18,000 cm^{-1}.

X-ray diffraction of aenigmatite from the Joan Lake agpaitic pluton gives 8.12 Å, 3.14 Å, 2.702 Å, 2.93 Å, 2.552 Å and 2.352 Å as spacings of the strongest lines in order of their intensities.

3. Allanite

$(Ce,Ca,Y)_2(Al,Fe)_3Si_3O_{12}(OH)$

Allanite is confined to fenites. In a few grains, it is highly pleochroic (X = yellow orange, Y = red orange, Z = dark red) with small optic angle. Due to intense absorption, the sign and distinction of the slow and fast rays are uncertain. In another rock, reddish grains of allanite are surrounded by a colourless mineral ($2V_x = 80°$, $X \wedge 001 = 44° - 48°$) probably belonging to epidote group. X-ray diffraction of allanite gave 2.91 Å, 2.89 Å, 2.67 Å, as the strongest line-spacings in order of their intensities.

4. Apatite

$Ca_5(PO_4)_3(F,OH,Cl)_3$

Several varieties of apatite had been reported from fenites (Nickel 1963) of the Ten Mile Lake area but present investigation revealed fluorapatite forming an important accessory in all rocks of the Joan Lake agpaitic intrusion. The X-ray diffraction pattern of this apatite is comparable with the synthetic fluorapatite.

Electron spin resonance (Fig. 35A, B) of the fluorapatite gave 5 asymmetrical E.S.R. lines, when the magnetic field is applied parallel to the Z-axis (= c axis), but the mineral gives no resolution with $H \perp Z$. From experimental analyses we get $g_{\perp} = 2.050 \pm .002$ and $g_{\parallel} - 2.00 \pm 0.002$ and measurements of absorption lines give data summarized in tables 15 and 16.

TABLE 15

Position of E.S.R. lines at $H \parallel Z$ axis of apatite

Sample 206 (Type II)

Line	Position	Line Separations
1	3410.8G	→ 4.3G
2	3415.1G	→ 2.6G
3	3417.7G	→ 2.1G
4	3419.8G	→ 5.1G
5	3424.9G	

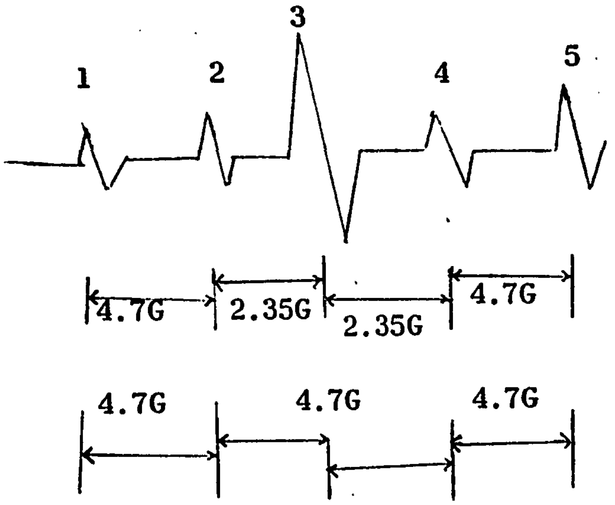
When H is parallel to the Z-axis, we find the E.S.R. lines are inequidistant but an average weighting produced the following results:

TABLE 16

Mean positions of E.S.R. lines of apatite

Lines	Line Separations	Centre of gravity	Lines	Line Separations
1 - 3	6.9	14.1/2 = 7.05	1 - 2	4.7 ± .05
		or 7.0 ± .05G	2 - 3	2.3 ± .05
3 - 5			3 - 4	2.3 ± .05
			4 - 5	4.7 ± .05
2 - 3	4.7	2.35 or		
		2.3 ± .05		

From the above data we get a spectrum which is, in fact, an average of the actual spectrum and is shown below:



(Not to the scale)

Therefore, the asymmetric E.S.R. pattern observed in the apatite from the Joan Lake area can be compared with the three line spectra due to O^{-2} residing in F-site described by Segall et.al. (1962) and those due to Mn^{2+} because both the species have $g_{\parallel} = 2.001 \pm .001$. Alternatively, the spectra can also be interpreted as superimposition of two spectra: those of Cl - occupying F-site and those due to ½-spin fluorine.

5. Arfvedsonite

$Na_3Fe''_4Fe'''Si_8O_{22}(OH,F,Cl)_2$

Arfvedsonite ($2V_x = 86^\circ$ $\alpha = 1.644$, $X\wedge c = 44^\circ$, X = deep green, Y = brown, Z = greenish brown; Specimen 274) is a common mineral in all rocks in the agpaitic complex. It occurs as 1) anhedra altering to aegirine-augite in lujavrite, 2) poikilitic subhedral grains in Type II and Type III rocks, 3) anhedra mantled by blue pyroxenes (omphacite) in ijolite-urtite of the Ten Mile Lake area and 4) subhedra altering to aegirine at the margin, in Type II and III rocks.

The chemical composition of arfvedsonite grains varies from place to place and also within a single hand specimen (Table 17).

Optical properties of ferrohastingsite resemble partly those of arfvedsonite (Table 18).

TABLE 17

Chemical composition of Sodic Amphibole (Arfvedsonite) from the Joan Lake Agpaitic complex

	Type II	Type III		Type 1 (lujavrite)			*Ijolite from Ten Mile Lake			
Oxides	▲44	▲274	▲215	▲230	▲254	▲206	1	2	3	4
SiO_2	47.40	50.97	46.85	48.50	49.65	47.50	48.94	49.18	49.85	48.84
TiO_2	3.60	1.10	1.19	1.10	1.21	2.21	1.31	1.47	0.54	1.19
Al_2O_3	1.65	1.64	1.89	1.08	1.19	1.31	3.60	3.67	2.37	3.67
Fe_2O_3	8.33	9.12	8.40	17.53	15.16	1.00	--	--	--	--
FeO	24.34	20.60	24.35	14.31	20.57	31.65	26.87	26.81	25.54	26.78
MnO	0.66	2.27	0.63	0.66	0.82	0.67	0.64	0.70	0.73	0.68
MgO	0.65	0.92	0.87	1.31	0.46	0.83	4.58	4.41	6.19	4.50
CaO	3.20	1.32	5.02	5.43	0.63	2.78	2.92	3.01	5.35	3.08
Na_2O	7.46	6.85	7.35	7.87	6.10	7.88	6.54	6.74	5.40	6.48
K_2O	2.55	3.61	2.80	1.48	1.26	3.90	3.66	3.52	3.92	3.81
Total	99.84	98.40	99.35	99.27	97.05	99.72	99.06	99.51	99.89	99.03
$\frac{100 \times Mg}{Fe+Mn+Mg}$	3.4	5.0	4.4	2.2	2.4	4.3	22.9	22.1	29.6	22.6

* Electron-microprobe analyses provided by Dr. J. Gittins, University of Toronto.

1, 2 Separate Grains
3 Core } Zoned arfvedsonite
4 Rim }

▲ Analyst S.K. Singh, University of Ottawa

FIG 36: MÖSSBAUER RESONANCE OF ARFVEDSONITE (SPECIMEN 274)
TAKEN AT ROOM TEMPERATURE.

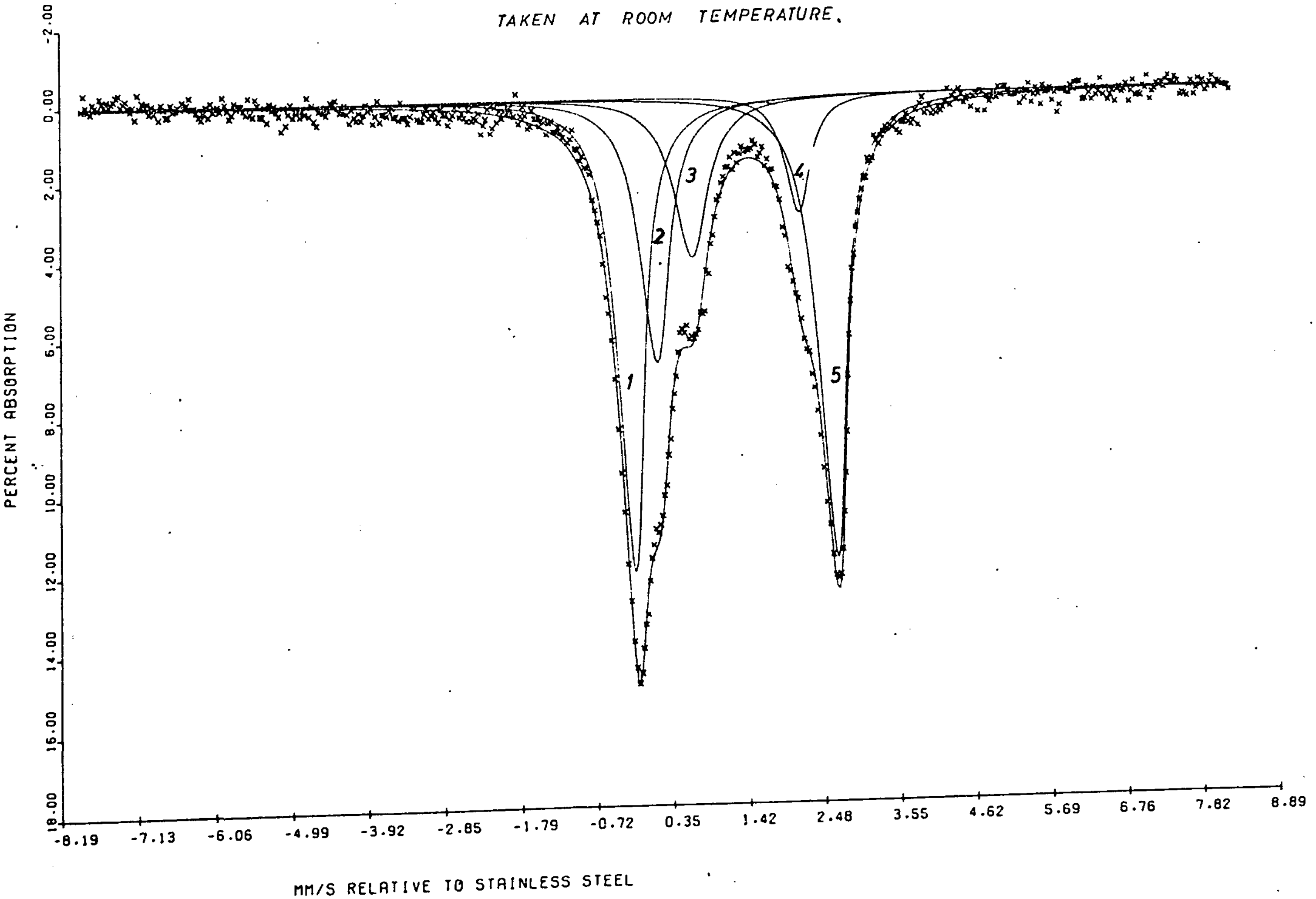


TABLE 18

Optical properties of ferrohastingsite from ijolite of the Joan Lake area (Specimen 202)

Pleochroism: X = Pale green, Y = Brownish green Z = Smoky blue

Absorption: $Z > Y \geq X$ Dispersion: v>r, notably inclined.

Orientation: Length slow, Y = b

Extinction: $Z \wedge c = 34^{\circ} - 37^{\circ}$

Optic Angle: $2V_x = 10^{\circ}$ R I.: $\alpha = 1.664$ $\beta = 1.682$ $\gamma = 1.698$

The Mössbauer spectra of arfvedsonite (taken at room temperature, Fig. 36) give the following parameters:

TABLE 19

Mössbauer parameters of arfvedsonite

Arf. Average Mean Square Residual = 639.856 Chi Squared = 549

Site	Chemical Shift mm/sec	Quadrupole Splitting mm/sec	Width at ½ Peak height mm/sec		Area Counts Channel $\times 10^{-5}$		Intensity mm/sec	
Fe^{2+} in M(1)	δ 15	Δ 15	Γ_1	Γ_5	A_1	A_5	I_1	I_5
	1.283	2.86± .003	0.65	0.69	0.72	0.74	3.50	3.43
Fe^{2+} in M(3) M(2)	δ 34 Chemical Shift	Δ_{34}	Γ_3	Γ_4	A_3	A_4	I_3	I_4
	1.517	1.531 ±.005	0.87	0.63	0.32	0.18	1.19	0.884
Fe^{3+} in M(2) M(3)	δ_2	Δ_2	Γ_2		A_2		I_2	
	0.364	0.00	0.75		0.197		0.469	

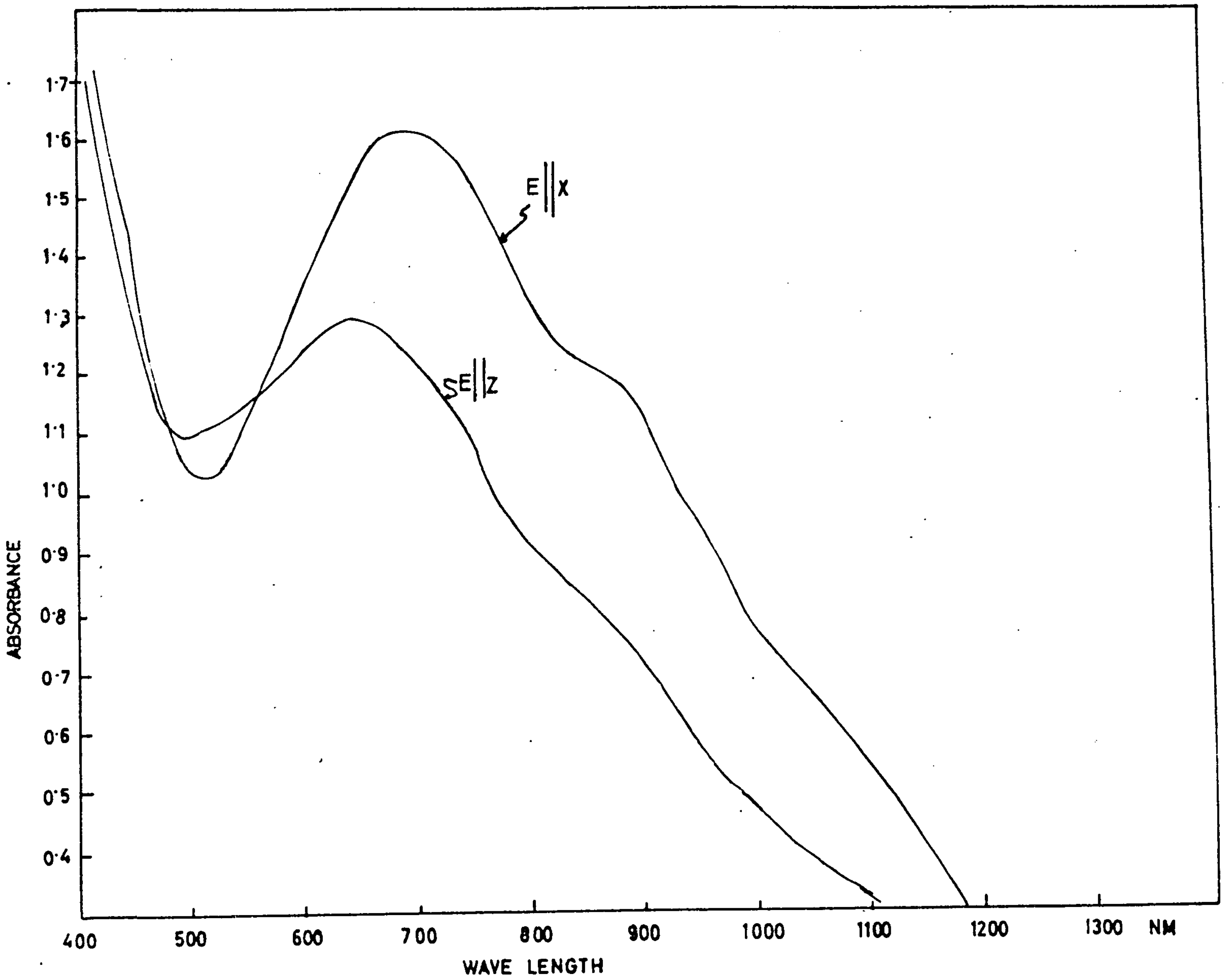


FIGURE 37 : OPTICAL SPECTRA OF ARFVEDSONITE (SPECIMEN-274).

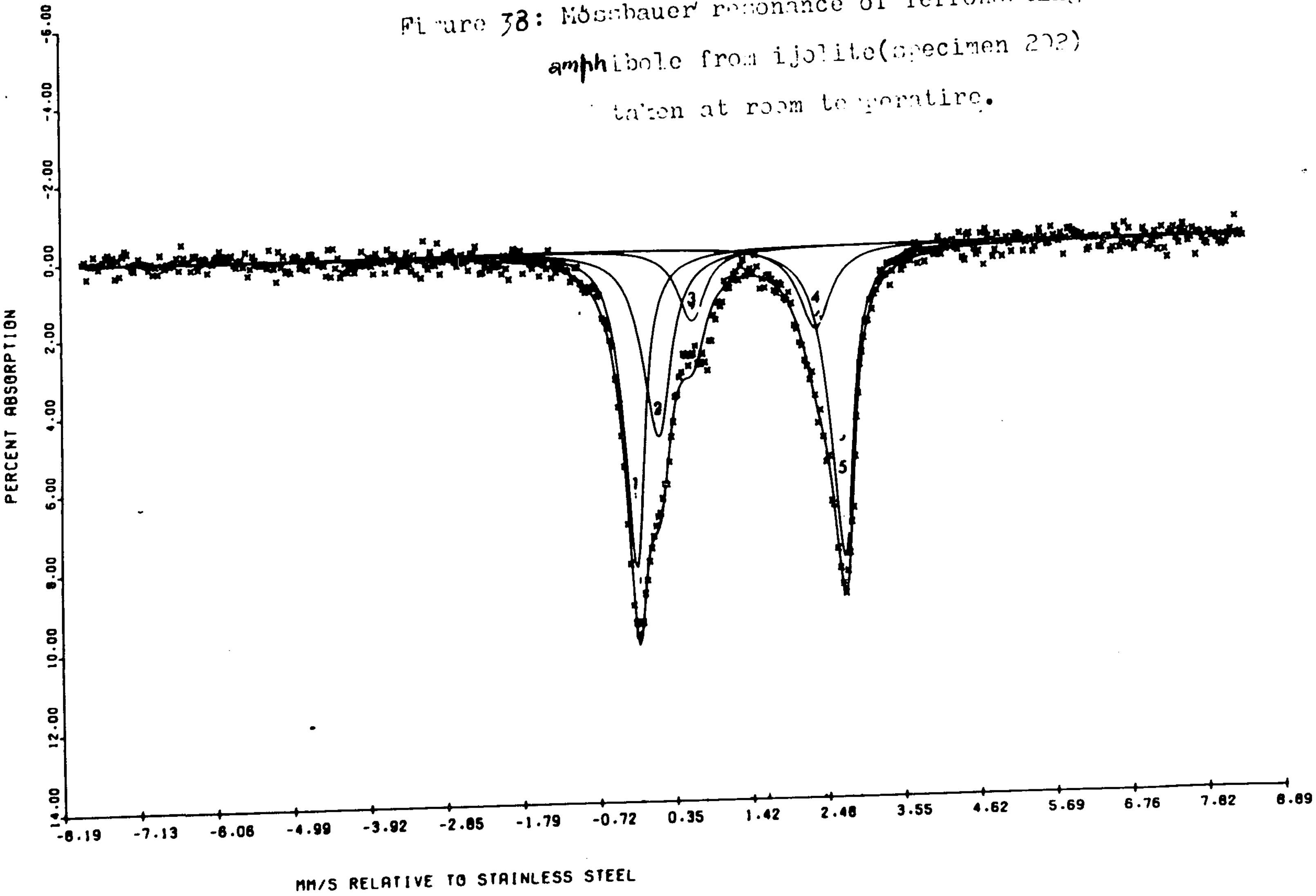


Figure 38: Mössbauer resonance of ferrohastingsitic amphibole from ijolite(specimen 202) taken at room temperature.

The Mössbauer parameters (Table 19) of arfvedsonite indicate that Fe^{2+} occupies the M(1) and M(3) sites in a ratio 3:1, while Fe^{3+} is accommodated in the M(2) and M(3) sites. The differences in Γ-values and intensities can be attributed to smearing of the hyperfine interaction by randomly distributed impurities in the structure of arfvedsonite from Type III. Infrared absorption shows a peak at 3652 cm^{-1} suggesting that OH is attached with Fe^{3+} in the M(3) site.

The optical absorption spectra (Fig. 37) show a shoulder around 850 nm in E $\|$ X attributed to a forbidden d - d transition in octahedrally coordinated Fe^{2+}. The absorption shown at 700 nm could be explained due to $Fe^{2+} \rightarrow Fe^{3+}$ charge transfer while the sharp absorption edge could be ascribed to $O^{2-} \rightarrow Fe^{3+}$, perhaps enhanced by the transition $Ti^{3+} \rightarrow Ti^{4+}$.

Mössbauer spectra (Fig. 38) taken for a ferrohastingsite gave the following parameters (table 20).

TABLE 20

Mössbauer parameters of ferrohastingsite from ijolite (202).

Average Mean Square Residual = 537.30 Chi Squared = 548

Site	Chemical Shift mm/sec.	Quadrupole Splitting mm/sec.	Width at ½ peak height mm/sec.		Area Counts Channel $x10^{-5}$		Intensity mm/sec.	
Fe^{2+} in M(1)	δ 15	Δ 15	Γ_1	Γ_5	A_1	A_5	I_1	I_5
	1.296 ± .001	2.915± .001	0.52	0.59	3.125	6.580	1.90	1.86
Fe^{2+} in M(3)	δ 34	Δ 34	Γ_3	Γ_4	A_3	A_4	I_3	I_4
	1.541 ± .001	1.731± .001	0.90	0.80	0.96	1.26	0.44	0.50
Fe^{3+} in M(2),M(3)	0.33 ± 0.000	0.000	Γ_2		A_2		I_2	
			0.71		2.55		1.13	

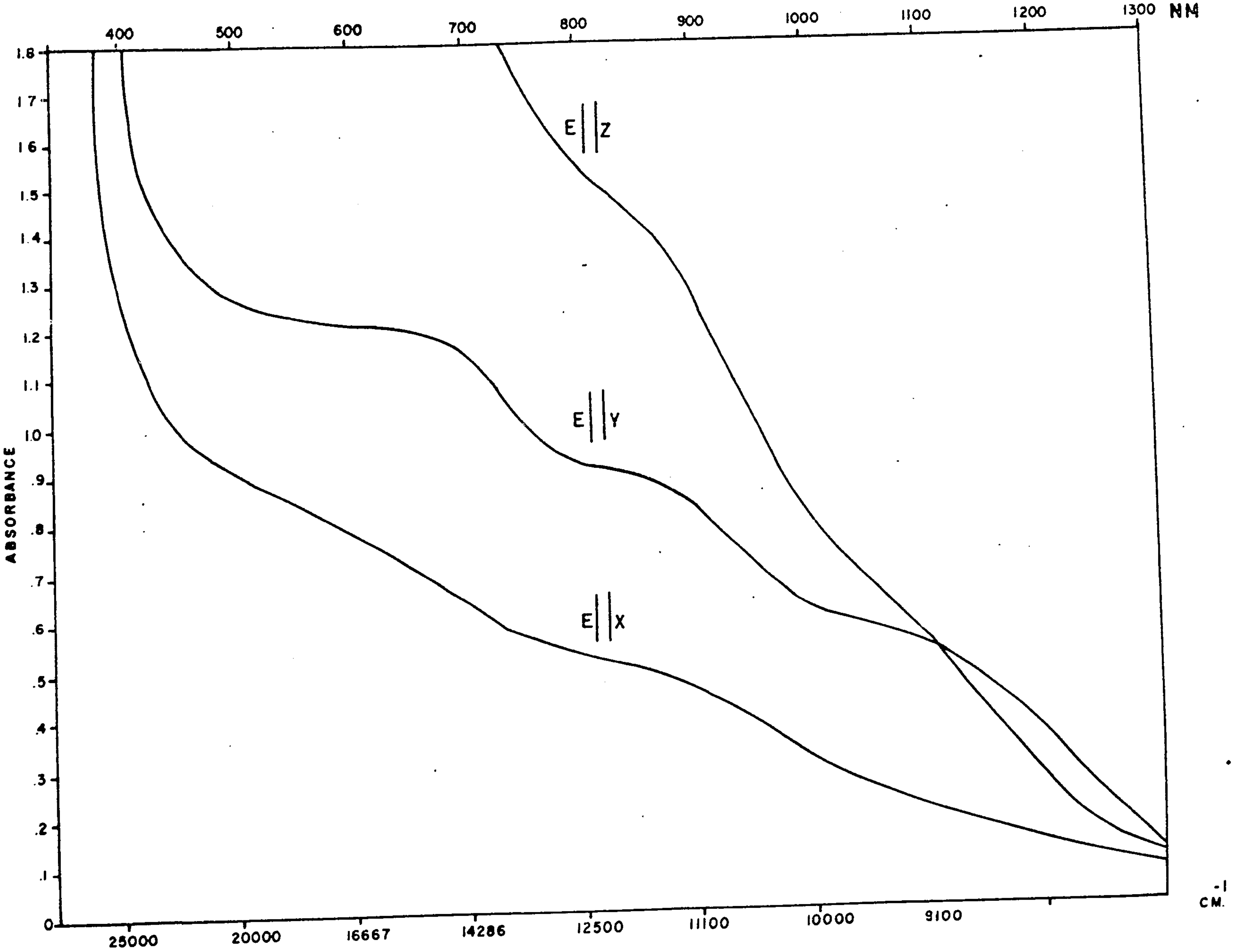


FIGURE 39 : OPTICAL ABSORPTION SPECTRA OF FERROHASTINGSITE(SPECIMEN-202) FROM IJOLITE.

In ferrohastingsitic amphiboles, like in arfvedsonite, the Fe^{2+} can be alloted to the M(1) and M(3) sites but Fe^{2+} in the M(3) site gives greater Δ-values than those observed in arfvedsonite. Fe^{3+} is again confined to the M(2) site. Infrared analysis gives an absorption peak at 3654 cm^{-1} which can be alloted to Fe^{3+} linked with OH in the M(3) site. The area proportion of different peaks gives Fe^{2+} in M(1): M(3) = 3:1 and Fe^{2+} in M(1) plus M(3): Fe^{3+} in M(2) equal to 4:1 (approximately). This ratio may indicate that 3 atomic postitions are similar to M(1) while one position is similar to each of M(2) and M(3) sites. From the above discussion it appears that Fe^{3+} is located in the M(3) site in minor amount. Since Fe^{2+} - OH does not give peaks in infrared spectra, arfvedsonite may be very poor in hydroxyl.

The differences between arfvedsonite and ferrohastingsitic amphibole become clear in their electronic absorptions spectra (Fig. 39). In general, in ferrohastingsite, it can be stated that Fe^{2+} on both M_1 and M_2 sites produce two d-d bands each and these bands overlap extensively to give a diffuse absorption envelope in XY-section around 9000-12000 cm^{-1}.

ZY-section with $E \parallel Z$ absorption is more intense than $E \parallel b = E \parallel Y$ with respect to the $Fe^{2+} \longrightarrow Fe^{3+}$ charge transfer because the projection of M_1 - M_2 vector is greater parallel to Z than that of b or Y.

6. Astrophyllite

$(K,Na)_3 (Fe,Mn)_7Ti_2 Si_8 O_{24} (O,OH)_7$

The mineral occurs in small bronze to golden yellow flakes intergrown with aenigmatite in fenites (frontispiece). This mineral can be easily identified by its pleochroism; the strongest absorption is observed perpendicular to the plane of vibration of the polarizer provided length of the grains lies parallel to the preferred direction of the polarizer. X-ray diffraction compares well with that of astrophyllite from El Paso, Colorado, U.S.A. (Nickel et al., 1964). Optically, it gives $2V_z = 72^o$ $\alpha = 1.683$ $\beta = 1.706$ $\gamma = 1.744$; X = reddish yellow (bronze) Y = orange yellow and Z = lemon yellow.

7. Barylite

$BaBe_2Si_2O_7$

Barylite is common in Mann - 1 area to the north of Lititia Lake in fenites and has not been found in the Joan Lake agpaitic pluton. X-ray diffraction analyses of the mineral gives the same pattern as recorded by Heinrich and Deane (1962); however barylite commonly alters to an unidentifiable brownish mineral (Un-12). No new chemical analysis was attempted as the material could not be separated. Chemical analysis given by Heinrich and Deane (1962) was later modified by Nickel and Charette (1962). Optically, the mineral gives $2V_z = 65^o - 68^o$ $\alpha = 1.684$ $\beta = 1.692$ $\gamma = 1.716$.

8. Barytolamprophyllite

$(Na,K)_6\ (Ba,Ca,Sr)_3(Ti,Fe)_7\ Si_8\ O_{32}(O,OH,F,Cl)_4$

Small subhedra of barytolamprophyllite are seen in the alkalic rocks of the Ten Mile Lake area. Optically the mineral resembles lamprophyllite but is non-pleochroic to only weakly pleochroic. A few subhedra show polysynthetic twinning and $2V_z = 40^o$. Since the grains are very small, no refractive index measurements were carried out. X-ray diffraction gave 2.85 Å, 2.19Å, 1.51Å, 3.51Å, 3.81Å as spacings of the strongest lines. The chemical analysis of barytolamprophyllite from Ten Mile Lake compares well with that from the Kola Peninsula (Table 21).

TABLE 21

Chemical composition of barytolamprophyllite

	*Barytolamprophyllite from the Ten Mile Lake area	**Barytolamprophyllite from Kola Peninsula, U.S.S.R.
SiO_2	27.82	28.53
Al_2O_3	4.61	1.12
TiO_2	27.70	26.60
FeO	2.70	2.72
Fe_2O_3	--	2.63
MnO	0.51	1.75
MgO	0.35	1.00
CaO	0.80	1.70
K_2O	1.58	3.10
Na_2O	10.86	9.52
BaO	22.00	17.24
F	1.32	1.60
Cl	0.19	0.51
Total	99.44	98.02

* Electron microprobe analysis supplied by Dr. J. Gittins University of Toronto (iron as FeO).
** Peng and Chang (1965).

9. <u>Bastnaesite</u>

$(Ce,Y,La)(CO_3)F$

A pale brown to dark brown mineral develops as long prismatic grains within Type II (743). Optically, it is uniaxially positive with $\omega = 1.722$ $\epsilon = 1.824$.

In thin section, it is generally pale brown, weakly pleochroic but has altered cores. The X-ray diffraction patterns of bastnaesite from the Joan Lake area gives 2.86Å, 3.54Å, 2.05Å, 4.86Å, 1.88Å as spacings of the strongest lines.

10. Biotite

Biotite is common to fenitic rocks and schists around the Joan Lake pluton but phlogopite is found as an accessory mineral in ijolite and lujavritic rocks. The following optical properties are determined on phlogopite from ijolite.

$2V_x = 15^{\circ}$ $\gamma = 1.664$

X = yellowish brown

Y = Z = dark brown

Normally, the biotite flakes are unaltered with a few inclusions of apatite.

11. Blue Pyroxene

(Fe-Ti-Omphacite)

Blue pyroxene mantles arfvedsonite anhedra in ijolite to the south of Ten Mile Lake. Chemical analyses of such grains are recorded in Table 22.

TABLE 22

Chemical analyses of Fe, Ti-Omphacite*

	1	2	3	4
SiO_2	53.52	53.59	53.26	53.48
TiO_2	2.02	2.47	1.64	3.09
Al_2O_3	8.69	9.68	8.93	8.70
FeO	14.71	14.57	14.69	14.60
MnO	0.53	0.55	0.58	0.53
MgO	1.72	1.47	1.74	1.81
CaO	11.03	10.18	11.04	9.17
Na_2O	8.26	8.68	8.12	9.12
K_2O	0.07	0.05	0.06	0.05
Total	100.55	101.24	100.06	100.54

3 Core }
4 Rim } single grain; 1, 2 separate grains.

1 $(Ca_{.441}Na_{.602})$ 1.043 $(Mg,Fe,Ti,Al)_{1.011}$ $Si_{1.999}O_6$; Al_{IV} nil

2 $(Ca_{.403}Na_{.625})$ 1.028 $(Mg,Fe,Ti,Al)_{1.022}$ $Si_{2.000}O_6$; Al_{IV} 0.018

3 $(Ca_{.444}Na_{.594})$ 1.038 $(Mg,Fe,Ti,Al)_{1.018}$ $Si_{1.999}O_6$; Al_{IV} nil

4 $(Ca_{.366}Na_{.661})$ 1.027 $(Mg,Fe,Ti,Al)_{1.033}$ $Si_{2.000}O_6$; Al_{IV} 0.008

* Electron Microprobe analyses provided by Dr. J. Gittins, University of Toronto

Optically, the blue pyroxenes are biaxial with $2V_x = 86^\circ$-88°, orientation Y = b, and γ' falls near to 1.76, other R.I.s are difficult to determine. Marked pleochroism X = greenish blue Y = deep blue Z = blue. Absorption = $Z < X \ll Y$, extinction $(Z \wedge C)$ varies from 32°-45° with rather large fluctuations in zoned grains.

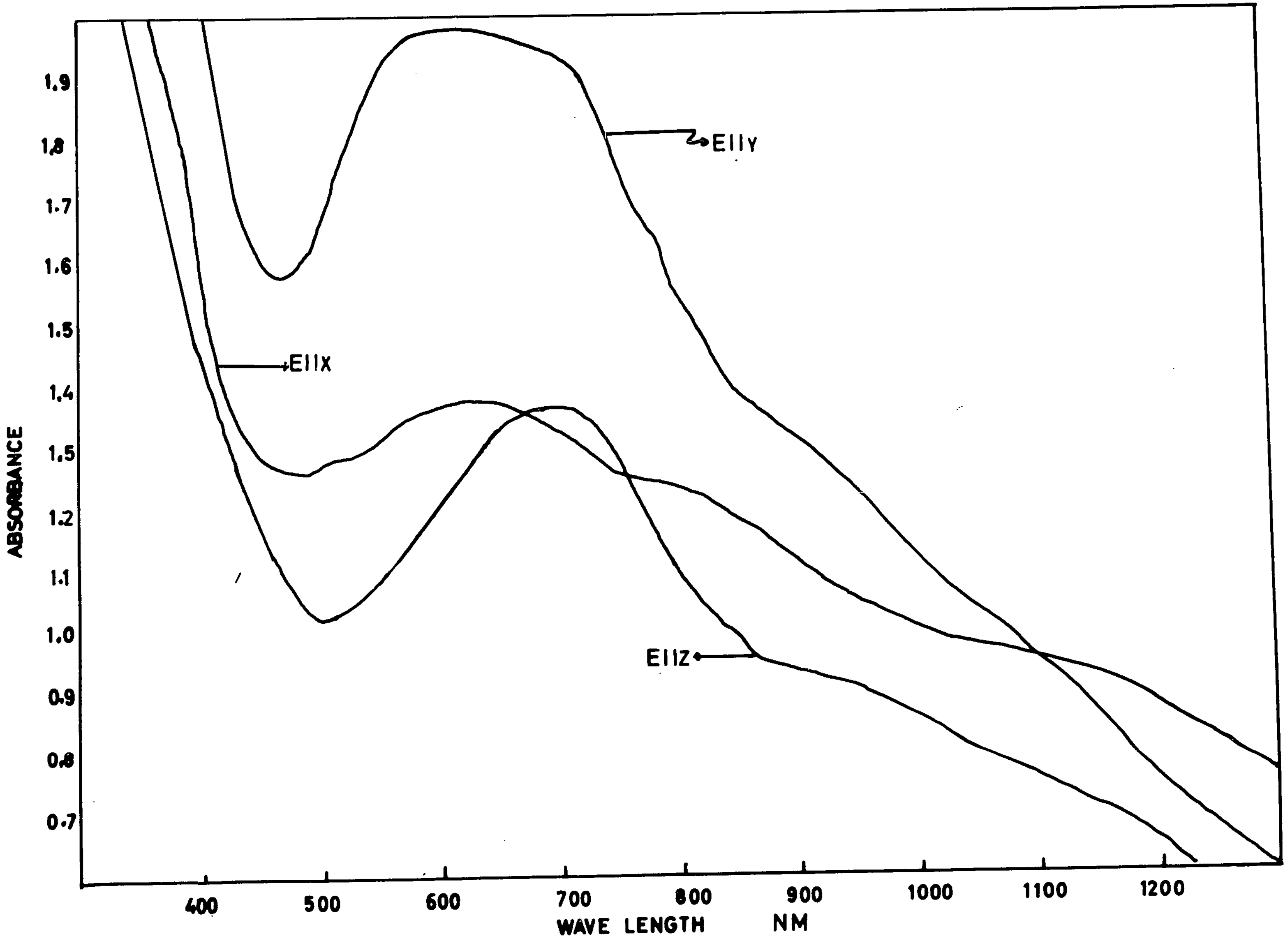


FIGURE 40 : ABSORPTION SPECTRA OF FERROAN-TITANIAN OMPHACITE

The features observed in optical absorption spectra (Fig. 40) can be tentatively explained as follows:

1) The weak shoulder observed between 800 and 900 nm E||X and E||Y can be attributed to a spin forbidden d - d transition of octahedral Fe^{2+}.

2) The sharp absorption edge near 400 nm may be assigned to $Fe^{2+} \rightarrow Ti^{4+}$ or enhanced by $O^{2-} \rightarrow Fe^{3+}$ charge transfer.

3) The absorption band observed in E|| Z around 700 nm may be assigned to $Fe^{2+} \rightarrow Fe^{3+}$ charge transfer.

4) The absorption band (weak) observed in E||X around 820 - 830 nm may be assigned to d - d transition of Fe^{2+}.

5) The absorption band (weak) observed in E||X around 600 nm may be assigned to $Fe^{2+} \rightarrow Fe^{3+}$ charge transfer.

6) The broad absorption envelope observed in E||Y could be presumed to contain three unresolved peaks around 700 nm, 650 nm and 575 nm which may be due to $Fe^{2+} \rightarrow Fe^{3+}$, $O^{2-} \rightarrow Fe^{3+}$ and $O^{2-} \rightarrow Ti^{3+}$ charge transfers.

12. Britholite

$(Ca,Ce)_5\ (SiO_4,PO_4)_3(OH,F)$

Tiny grains of britholite (X-ray identification) occur in fenites and schists near the Joan Lake agpaitic complex. Optically, the mineral can be identified by its high refractive index $\omega = 1.772$ and alteration in the centre of most of the grains. Some grains show $2V_x = 5^o$. The britholite from agpaitic rocks gives an X-ray pattern resembling "lessingite". Such grains give larger cell size than normal britholite, probably due to rather high content of Al and Si (or both). The X-ray diffraction gives 2.89Å, 2.86Å, 2.79Å, 3.16Å, and 3.54Å as X-ray spacings of the most intense lines.

13. Calcite

$CaCO_3$

Commonly occurs in the trachytic volcanics and schists, by X-ray photographs of tiny, colourless grains from lujavrite also gave lines similar to calcite. These anhedra are of insufficient size to measure physical properties.

14. Clay minerals

Amongst the clay minerals nontronite forms green earthy masses. It is common in Mann - 1 fenitic gneisses in association with aegirine. X-ray diffraction gave 4.45Å, 3.54Å, 1.52Å, 1.48Å, and 1.52Å as spacings of the strongest lines.

15. Eudialyte-eucolite

$Na_2Ca_4Zr\ Si_6O_{18}(F,Cl)_2$

Eudialyte (pinkish to cherry red) occurs as anhedral to subhedral grains in all agpaitic rocks and fenitic gneisses of the Ten Mile Lake area. In addition, some veins and lenses of eudialytite (60 - 80%

TABLE 23

*Chemical Composition of eudialyte from the Joan Lake agpaitic pluton (Specimen 215)

SiO_2	51.28
TiO_2	0.06
Al_2O_3	0.58
Fe_2O_3	0.25
MgO	0.01
FeO	5.23
MnO	0.51
CaO	8.64
Na_2O	13.46
K_2O	0.46
P_2O_5	0.01
Y_2O_3	0.88
Yb_2O_3	0.07
La_2O_3	0.18
Ce_2O_3	0.35
Total	81.97

*Chemical analysis provided by E. Hotun, Carleton University, Ottawa, Ontario.

eudialyte-containing rocks) are also seen in Type III rocks. Eucolite (uniaxially negative) and mesodialyte (isotropic) are rare and can be observed in Type III and Type II rocks. Rarely mesodialyte is seen in fenites. In some rocks from the Red Wine pluton, eudialyte alters to a brownish, isotropic mineral but X-ray diffraction did not yield any pattern (Un-25). Generally, eudialyte grains alter to fluorite, steenstrupine(?), cerite (hydrocerite ?, Un-26), pectolite, white mica and an unidentifiable yellow fibrous mineral.

Eudialyte crystals vary in size from microscopic dimensions to 0.5 X 0.3 X 0.3 cm, those in the eudialytites being larger than those of the lujavrites.

In peripheral zones, eudialyte forms rounded or hexagonal segregations which vary from 4-5 mm to 10 x 15 x 15 cm in diameter. In pegmatoid zones, fined-grained monomineralic segregations, some 3-4 meters long and 1 m. wide, are common.

Optically, eudialyte is uniaxial positive, with $\omega = 1.604$ $\epsilon = 1.616$ (Specimen 274) but refractive indices vary from one rock to another. Eudialyte from the Joan Lake area was analysed by Hotun (Table 23). X-ray diffraction patterns of eudialyte from the Joan Lake area give 7.15Å, 2.98Å, 2.87Å, 4.34Å, and 3.57Å as spacings of the strongest lines in order of their intensities. Some grains of eudialyte are biaxial positive ($2V_z = 15\text{-}25^{\circ}$).

Infrared spectra of eudialyte showed prominant peaks in the region between 1500 - 500 cm^{-1} and the results are tabulated in table 24.

TABLE 24

Infrared data of eudialyte from the Joan Lake area

Absorption peaks	I	II	III	IV	V	VI	VII
Sample No.							
215	1120cm^{-1} (Weak)	$1000\ \text{cm}^{-1}$ (Broad)	$910\ \text{cm}^{-1}$ (Weak)	735cm^{-1} (Sharp)	680cm^{-1} (Sharp)	650cm^{-1} (Fair)	500cm^{-1} (Sharp)
743	1140cm^{-1} (Weak)	$1000\ \text{cm}^{-1}$ (Broad)	$920\ \text{cm}^{-1}$ (Weak)	735cm^{-1} (Sharp)	680cm^{-1} (Sharp)	650cm^{-1} (Fair)	500cm^{-1} (Sharp)

Microscopically, both the samples showed patchy zoning and this zoning could possibly be caused by hydrocarbons i.e., the grayish areas with local concentrations of the hydrocarbons or ammonium compounds indicated by infrared analyses.

16. Eudidymite

$NaBe\ Si_3O_7\ (OH)$

Eudidymite, discovered by Dujardin (1961) at Mann -1 has been identified from fenites at Mann -2 by X-ray diffraction. The refractive index measurements gave $\alpha = 1.546$ $\gamma = 1.552$ with $2V_z = 24°$. These values compare well with those recorded by Nickel (1963) and therefore, no further analysis of the mineral was undertaken.

17. Fluorite

CaF_2

The mineral is observed in fenites, schist xenoliths (Specimen 207) within the Joan Lake agpaitic complex and in quartz fluorite-ussingite veins. In addition, some eudialyte grains alter to fluorite. In Type II agpaitic rocks, fluorite occurs as independent subhedra.

18. Galena

PbS

Galena is commonly associated with sphalerite in quartz-microcline veins at Mann -2 and also lujavrite. Rarely, small grains of galena are seen within the Type III agpaitic rocks at Joan Lake.

19. Hellandite

$Ca_3(Y,Ce)_4B_4Si_6O_{27}.3H_2O$

This mineral occurs as tiny yellowish prismatic grains in fenites to the north of Joan Lake (Specimen 319) and has been identified by X-ray diffraction which gave 2.63Å, 2.82Å, 4.69Å, 3.46Å, and 3.20Å as spacings of the strongest lines in order of their intensities. Grains are anhedral to elongate with very low birefringence. They are length fast with parallel or nearly parallel extinction. The other optical properties of the mineral could not be determined due to its grain size.

20. Hydromuscovite

The mineral occurs as sheaf-like aggregates within large nepheline grains in Type II and lujavritic rocks. X-ray diffraction gave a very weak pattern resembling hydromuscovite from Lovozero massif, U.S.S.R. (M. Bonardi, personal communication).

21. Ilmenite

$FeTiO_3$

Large grains of ilmenite, magnetite and hematite are common in gabbroic and dioritic rocks and a few fenites such as specimen 235, show co-existing aenigmatite, ilmenite and ramsayite.

22. Innelite

$Na_2(Ba,K)_4(Ca,Mg,Fe)Ti_3Si_4O_{18}(OH,F)_{1.5}(SO_4)$

In ijolite (J_{4-8}) rock of the Ten Mile Lake area innelite occurs as tiny rectangular to squared grains, ($2V_z = 35^\circ$, weakly pleochroic). Some grains also show zoning. Other optical properties are difficult to record due to the size of the grains. An X-ray diffraction pattern gave 3.93Å, 1.97Å, 2.98Å, 3.05Å, 6.39Å, 1.75Å, 5.40Å as the strongest line-spacings.

23. Joaquinite

$Ba_2NaCe_2Fe(Ti,Nb)_2Si_8O_{26}(OH,F)_2$

Squared to prismatic grains (elongated parallel to c) of joaquinite are intergrown with aegirine-augite and lamprophyllite in the fenitic rocks (Specimen 240) of the Joan Lake agpaitic complex. X-ray diffraction analyses* give the following data.

Orthorhombic: tentatively assigned to Cc2m.

$a = 10.52$Å
$b = 9.68$Å
$c = 22.30$A
$\alpha = \beta = \gamma = 90^\circ$

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* Precession and Weissenberg photographs taken by M. Bonardi at the Geological Survey of Canada.

According to Laird and Albee (1972), Joaquinite belongs to two modifications: monoclinic and orthorhombic..

The optical properties of the mineral are given as follows:

Colour: Pale brown, weakly pleochroic

R.I. $\alpha = 1.754 \pm .001$ $\beta = 1.764 \pm .001$

$\gamma = 1.814 \pm .001$

Optical Orientation: Z = c (Defined by 110 cleavage traces)

Optical Angle: $2V_Z = 36^\circ$

X-ray diffraction patterns give 2.78Å, 5.58Å, 2.95Å, 4.43Å, and 3.28Å, as spacings of the strongest lines, in order of their intensities.

The chemical composition of the mineral shows marked variations. Some grains are zoned. The qualitative spectrographic analyses at Geological Survey of Canada (W.H. Champ) showed the presence of Ba, Ti, Fe^{2+}, Na, K, Ce, Y, Si, Mn, Mg, Sr, Pb but electron microprobe* gave the following semi-quantitative results for the joaquinite grain.

SiO_2	28%
BaO	25%
TiO_2	14%
FeO	4%
Na_2O	2.5%
RE_2O_3	25%
	98.5%

* Analysis by A.G. Plant, Geological Survey of Canada (Total iron as FeO).

24. Karnasurtite

$(Ce,La,Th))(Ti,Nb)(Al,Fe)(Si,P)_2\ O_7(OH)_4\ 3H_2O$

The mineral occurs as yellowish prismatic grains in Type II (S-206) and resembles apatite. Optically it is uniaxial negative with $\epsilon = 1.606$, $\omega = 1.624$. It was identified by X-ray diffraction and compared well with karnasurtite from Lovozero U.S.S.R. (Vlasov et al., 1966). It gave 4.68Å, 2.87Å, 3.11Å, 3.29Å and 3.50Å as the spacings of the strongest lines. No prior heating was necessary to obtain a good X-ray diffraction pattern.

25. Lamprophyllite

$Na_2(Sr,Ba)_2Ti_3(SiO_4)_4(O,OH)_2$

Lamprophyllite is present in ijolite associated with ramsayite, aenigmatite and arfvedsonite. Rarely, these grains form stellate clusters in lujavrites. Optically, the lamprophyllite plates show X = pale yellow (brilliant), Y = straw yellow, Z = bronze yellow. $\alpha = 1.746$ $\beta = 1.752$, $\gamma = 1.776$ with $2V_z = 30^\circ - 32^\circ$ and lamellar twinning on (100). An X-ray diffraction pattern gives 3.46Å, 3.29Å, 2.80Å, 2.69Å, 2.62Å, 2.15Å and 1.99Å as spacings of the strongest lines.

26. Li-Mica

The colourless flakes form micaceous segregations. Optically, the mineral is biaxial negative with $2V_x = 20^\circ$-25°. True values of refractive indices could not be determined as the grains were very small. An X-ray diffraction pattern resembles lepidolite (1M) and polylithionite from Lovozero massif (Vlasov et al., 1966). Spacings of the most intense lines are 3.64Å, 3.29Å, 2.80Å, 2.69Å, 2.62Å, 2.15Å, 1.99Å. The mineral is common in agpaitic rocks and is presently described as Li-mica due to lack of chemical analysis.

27. Microcline (K-feldspar)

$KAlSi_3O_8$

Microcline in agpaitic rocks lacks the normal cross-hatched twinning. Instead a chess board type of penetration twin is common. Laths of microcline are flattened parallel to (010) and may have been elongated parallel to the a - axis.

In grains with both cleavages developed, the relationship between crystallographic axes and the axes of the indicatrix were determined on the universal stage with the following results. $X \wedge a = 20^\circ$ $Z \wedge b = 19^\circ$, $Y \wedge c = 18^\circ$. The angles between the crystallographic axes were found to be: $\alpha = 91^\circ$ $\beta = 114^\circ$ and $\gamma = 89^\circ$. The readings on the universal stage are probably correct within $\pm 2^\circ$.

However, optical measurements ($Z \wedge b$) clearly indicate the high triclinicity of the microcline. The angles between the twin axis (B) of the albite twins and the axes of the indicatrix were found to be $B \wedge X = 74^\circ$ $B \wedge Y = 80^\circ$ and $B \wedge Z = 17^\circ$. The optical angle ($2V_x$) varies from $75^\circ - 86^\circ \pm 2^\circ$.

28. Natrolite

$Na_2Al_2Si_3O_{10} \cdot 2H_2O$

Natrolite occurs as fibres in ijolite, urtite, Type I and Type II rocks of the agpaitic intrusion. Due to small grain size, no X-ray diffraction and optical work could be carried out except measurement of $2V_z$ on the U-stage which gave the values ranging from $52^\circ - 60^\circ$ with optic plane parallel to 010 and orientation $Z = c$.

29. Nepheline

$Na\ Al\ SiO_4$

Nepheline occurs 1) as subhedra in ijolite coexisting with ferrohastingsite, arfvedsonite, pectolite, ramsayite and lamprophyllite, 2) as anhedral to subhedral grains in association with eudialyte, aenigmatite, aegirine-augite and arfvedsonite in Type II and III of the agpaitic complex, 3) intergrown with microcline in lujavrites (Type I).

In Type III, nepheline grains near their margins rarely alter to sodalite while in Type II rocks, hydromuscovite develops as an alteration product. Natrolite is a common alteration product within ijolitic rocks. Both X-ray (method of Smith and Sahama 1956) and optical analyses (Curves in Winchell.1951) confirmed by the chemical analyses of two nepheline grains gave K_2O = 5.85% (Type III - 274) and 6.5% (ijolite, 202).

30. Neptunite

$(Na,K)_2(Fe,Mn)\ Ti\ Si_4\ O_{12}$

Neptunite was discovered and described by Heinrich and Quon (1963) from fenites of Mann - 1 area. Both optical and X-ray diffraction results of neptunite resemble the description given by the previous authors, and therefore no further work was done on this mineral. However, grains of neptunite were also recorded from the Mann - 2 area.

31. Niobophyllite

$(K,Na)_3(Fe,Mn)_6\ (Nb,Ti)_2\ Si_8(O,OH,F,Cl)_{31}$

Flakes of niobophyllite in fenites resemble astrophyllite in appearance but in detail they are optically distinctive with $2V_x = 60^\circ - 65^\circ$, $X \wedge b = 13^\circ - 15^\circ$, negative elongation and higher refractive indices. Furthermore, the X-ray diffraction pattern tallies very well with the description of Nickel *et al*., (1964).

32. Pectolite

$NaCa_2Si_3O_8(OH)$

Pectolite is commonly found in ijolite and all agpaitic rocks in the Joan Lake area. Generally, the subhedral grains show two sets of perfect cleavages. The optic plane and Z are nearly normal to (010) with $Z \wedge b = 14^\circ$ and $X \wedge c = 18^\circ$ and $2V_z = 38^\circ - 42^\circ$. An X-ray diffraction pattern gives 2.98Å, 3.08Å, 3.24Å, 2.16Å and 1.70Å as the spacings of the strongest lines.

33. Perovskite (loparite)

$CaTiO_3 -(Ce,Na,Ca)_2 (Ti,Nb)_2 O_6$,

Dark brown cubic to well twinned grains (inter-penetrant fluorite twin) are common in the schistose ijolite from the Ten Mile Lake area. The X-ray diffraction patterns compare well with loparite recorded from Lovozero Massif, U.S.S.R. and give 2.76Å, 1.87Å, 1.20Å, and 1.02Å as spacings of the strongest lines.

34. Plagioclase

Most common amongst plagioclases are the thin laths of albite with albite, Carlsbad and complex albite-Carlsbad twins. In some grains, three twin lamellae can be seen. Compositionally, the albite grains (4-axis U-stage measurements) vary from $An_6 - An_8$. The determination of optical angle with the U - stage give values from $2V_z = 72^\circ - 80^\circ$. Oligoclase ($An_{14-18}$) has also been observed in some fenites.

35. Pyrochlore - Microlite

$(Na,Ca)_2(Nb,Ta)_2 O_6(O,OH,F)$

Pyrochlore - Microlite occurs as yellow to pale brown, tiny isotropic grains with high refractive index in fenites (Mann-1). They give an X-ray diffraction pattern comparable to microlite with 1.58Å, 1.84Å, 3.00Å, 2.16Å and 3.14Å (A.S.T.M. No. 3-1139) as spacings of the strongest lines.

36. Pyrrhotite

$Fe_{1-x}S$

A few grains of pyrrhotite were observed in lujavritic Type I and Type III rocks from the Joan Lake area. Locally, in Type III rocks, large grains are seen. X-ray determination gave results comparable with hexagonal pyrrhotite.

37. Ramsayite

$Na_2Ti_2Si_2O_9$

Ramsayite is a common mineral in ijolite of both the Joan Lake and Ten Mile Lake areas. It occurs as tiny (.01 - .05 mm) to quite large (1 - 4 mm) grains and sometimes sheafs. Generally, it coexists with lamprophyllite but rarely with aenigmatite. The grains of ramsayite show high order of interference colours and $2V_x = 30^o - 35^o$. X-ray diffraction data of the ramsayite from the Joan Lake area are comparable with those of A.S.T.M. card 18-1261. The Joan Lake ramsayite gives 3.68Å, 3.32Å, 3.02Å, 2.75Å and 2.45Å as spacings of the strongest lines.

38. Schizolite

Manganoan-Pectolite

The mineral occurs as a pale brown alteration product of eudialyte and has been identified by X-ray diffraction (2.88Å, 3.02Å, 3.21Å, 2.40Å, 2.53Å, 2.65Å as spacings of the strongest lines). It is commonly found in Type II and Type III rocks of the Joan Lake agpaitic complex and has been reported from the fenitic rocks of the Ten Mile Lake area (Nickel 1963). Optical properties are indeterminate due to high degree of alteration.

39. Sodalite

$Na_4Al_3(SiO_4)_3Cl$

Tiny grains of sodalite are seen in ijolite and pegmatoid Type III of the agpaitic rocks. The mineral shows negative relief and is isotropic. X-ray determination could not be carried out due to the size of the grains.

A few grains of the variety hydrosodalite (?)(brownish masses: R.I. = 1.497) are seen in ijolite from the Joan Lake pluton (202) and loparite bearing ijolite of the Ten Mile Lake area. They are commonly associated with natrolite and other zeolites (unidentified).

40. Sphalerite

$(Zn,Fe)S$

Lujavrite, Type III rocks, and fenites contain sphalerite. The sphalerite grains in lujavrite are pale yellow in thin section while those in Type III rocks are red. An X-ray diffraction analysis gives a = 5.43Å for a variety from fenites and a = 5.38Å for the sphalerite from Type III. Some pale brown sphalerite grains are also seen in fenitic gneisses at Mann - 1.

41. Steenstrupine (?)

$(Ce,La,Na,Mn)_6(Si,P)_6O_{18}(OH)$

A pale brown to yellow alteration of eudialyte gave (unheated) an X-ray diffraction pattern comparable with that of ignited steenstrupine from Kola Peninsula (Vlasov et al. 1966) with 2.86Å, 3.03Å, 1.85Å, 1.94Å as spacings of the strongest lines. Since the X-ray pattern contained a few lines not quoted by Vlasov et al., (1966) and because grains were not amenable to optical studies, the identification of steenstrupine is tentative.

42. Titanian Lavenite

$(Na,Ca)_3(Ti,Zr)(Si_2O_7)(O,OH,F)_2$

The mineral is intergrown in very minor amount with aegirine-augite in lujavrite. An X-ray diffraction gave 2.89Å, 3.22Å, 2.82Å, 3.99Å, 1.75Å as spacings of the strongest lines.

43. Titanite

$CaTiSi\ O_5$

Several types of titanite (sphene) have been observed in the fenites. Detailed optical analysis of the various types shows the optical angle ($2V_z$) ranging from 25 - 35°, with markedly pleochroic to non-pleochroic varieties. X-ray diffraction patterns of these types are similar, suggesting that the optical differences can be traced to minor variations in chemical composition.

44. Ussingite

$Na_2Al\ Si_3O_8(OH)$

The mineral occurs as very tiny flakes in a quartz-fluorite vein. An X-ray diffraction pattern of a mixture of fluorite and ussingite gave 2.95Å, 2.69Å and 6.35Å as spacings which identified the mineral. Since it occurs as very tiny grains, no further study could be made.

45. Vinogradovite

$(Na,Ca,K)_4Ti_4Al\ Si_6O_{23}\ 2H_2\ O$

Yellow to pale brown granules common to Type II and Type III rocks gave an X-ray diffraction pattern with 3.19Å, 3.03Å, 2.89Å, 2.60Å, 2.01Å, 1.84Å and 1.57Å as spacings of the strongest lines. Rarely, the mineral is seen in fenites of the Ten Mile Lake area.

46. White Mica

Small flakes develop as an alteration product of eudialyte. Due to grain-size difficulties, no optical measurements were made but X-ray diffraction gave 3.24Å, 2.87Å, 2.54Å, 2.08Å and 1.72Å as spacings of the strongest lines. Since the X-ray pattern from which the above readings were taken was not good, these micaceous flakes are described simply as white mica.

47. Zircon

$ZrSiO_4$

Zircon is commonly found as tiny prismatic to squared grains in fenites. The mineral is not seen within agpaitic rocks. X-ray diffraction gave 3.32Å, 4.46Å, 2.53Å, 1.72Å and 2.08Å as spacings of the strongest lines.

Unidentified Minerals

Spacings of the five most intense X-ray diffraction lines of minerals which cannot, at present, be identified are given in table 25.

TABLE 25

Diffraction data giving spacings of the 5 most intense (dÅ)lines of unidentified minerals*

(Listing in order of intensities)

Un - 1	2.98	2.92	2.18	1.78	7.15
Un - 2	3.22	3.80	2.95	1.81	1.58
Un - 3	2.86	3.16	2.26	2.47	1.97
Un - 4	3.34	1.38	1.82	1.55	1.67
Un - 5	1.93	1.69	1.21	3.40	--
Un - 6	1.96	1.67	1.22	2.88	--
	1.94	1.69	1.22	2.88	--
Un - 7	2.87	3.29	2.48	1.87	--
Un - 8	3.17	2.71	1.44	2.33	1.67
	3.18	2.72	1.49	2.39	1.68
Un - 9	3.26	2.88	1.81	1.60	--
Un - 10	2.47	3.00	2.85	1.49	--
Un - 11	2.71	3.17	2.82	3.29	--
Un - 12	3.29	1.81	1.38	1.59	2.92
Un - 13	2.92	2.50	1.77	1.50	2.60
Un - 14	2.53	1.55	1.32	2.86	3.27
Un - 15	3.22	1.84	2.89	2.17	2.56
Un - 16	2.97	3.20	2.21	2.10	1.43
Un - 17	3.09	3.29	4.74	2.87	2.61
Un - 18	2.72	2.57	1.47	2.92	3.15
Un - 19	2.98	3.25	3.39	1.98	2.78
Un - 20	2.99	4.42	4.70	2.93	2.79
Un - 21	2.75	4.14	3.35	3.05	3.74
Un - 22	3.20	1.80	1.43	1.58	1.46
Un - 23	2.86	3.27	2.48	1.75	1.50
Un - 24	2.84	2.98	1.77	7.05	1.37
Un - 25	Does not yield X-ray diffraction pattern when unheated but on heating gives 2.94Å, 1.80Å, 2.55Å, 2.34Å and 1.17Å as spacings of the most intense lines.				
Un - 26	Gives 3.22Å, 5.44Å, 3.41Å, 2.89Å, 2.75Å as spacings of the most intense lines.				

* All specimens are from the Joan Lake complex except Un-25 and Un-26 which are from the Red Wine Mountain complex.

PART 4

CONCLUSION OF THE STUDY

CHAPTER 9

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

1. Conclusions

The present study leads to the following conclusions:

1) Rocks formerly described as Lititia Lake Formation, comprise the Joan Lake agpaitic pluton, ijolite, urtite, lujavrite dykes, fenites (products of alkali metasomatism) and acidic volcanics interbedded with argillites.

2) The rocks definitely bear evidence for having been regionally metamorphosed before the alkalic activity. The cataclastic metamorphism continued even after the development of fenites. The event, which resulted in the development of mylonitic zones, is at least partly later than the development of fenites but possibly contemporaneous with a late stage of the agpaitic activity. Fenites were formed both before and probably after the main alkalic intrusion, however vapours emanating from the Joan Lake intrusion might have played some role in their development. Therefore, the alkalic metasomatism cannot be precisely dated.

3) The diorites and gabbros near the Joan Lake area have been intruded by agpaitic pluton. They bear an imprint of thermal metamorphism, though they might have been regionally metamorphosed before the alkalic activity.

4) The Joan Lake agpaitic complex (1000-1400 m. y. old) is composed of a zoned pluton with ijolite-urtite at the core, Type I (lujavrite), Type II (khibinite or kakortokite), Type III (similar to rischörrite) and

Type IV (eudialytite) rocks at the margins. The pluton contains supracrustal (volcanic and sedimentary) xenoliths and is surrounded by metasomatic gneisses and nebulous igneous-looking fenites on three sides while on the southeastern side it borders on thermally metamorphosed diorites.

4) Petrochemical and mineralogical investigations suggest that the ijolite magma, derived by partial melting of melilite-basalt or peridotite in the upper mantle, could be the source of agpaitic rocks of the Joan Lake area. The alkalic magma was produced by partial melting developed under low oxygen fugacity.
5) The mineralogical evolution of ijolite-urtite took place under reducing environments at the earliest stage while increase in oxygen by crystallizing earlier mineralogical phases triggered processes to convert original ijolite-urtite to Type I rock (Fig. 5D). The marginal stages of the Joan Lake pluton developed at lower oxygen fugacity than that of lujavrite.
6) Transportation of Ti, Zr and other rare elements towards the margin is attributed to emanation factors; however crystallization and assimilation also played minor roles in the evolution of the pluton.
7) Forty-seven minerals have been recorded while twenty-six have been left unidentified due to their small grain size and inability to match X-ray patterns with the known standards.

2. Suggestions for future work

The present study suggests the following projects in central Labrador and in experimental petrology:

1) A complete and careful structural re-interpretation of the area including Seal Lake trough rocks.
2) Geological mapping based on complete and careful petrographical and mineralogical examination of the rocks from the Red Wine River Valley and Red Wine Mountains.
3) Experimental investigation of a system containing Na_2O-CaO-Al_2O_3-FeO-ZrO_2-TiO_2-SiO_2-H_2O under controlled oxygen pressures.
4) Experimental investigations on transfer of Zr, Ti, R.E. and other rare metals in different media e.g., in organic, fluoridic, chloridic and ammonium complexes, in alkaline solutions at temperatures ranging from 400 to 1000°C.
5) The variations in hydrocarbon content from the core (ijolite-urtite) to the margin of the Joan Lake complex.

APPENDIX I

Calculations of Norms for the Joan Lake Agpaitic Rocks

The method of calculations of norms for the rocks of the Joan Lake area is based on Kelsey's (1965) scheme for quartz free syenitic rocks. Eudialyte and aenigmatite being essential constituents, have also been included (Table 26). The general rules are outlined as follows:

1. Calculate the molecular proportions by dividing the weight percentages by appropriate formula weights.
2. Add MnO to FeO.
3. Set ZrO_2 = eu. Subtract an amount equal to 2 eu from Na_2O and eu from both FeO and CaO. Put 6 eu equal to Y.
4. Put aen = $TiO_2/2$. Subtract an amount equal to 9 aen , 2 aen , aen /2 from FeO, Na_2O and Fe_2O_3 respectively. Set 12 aen to Y.
5. If $Al_2O_3 > K_2O$, set or' = K_2O and subtract an amount equal to or' from Al_2O_3. Add an amount equal to 6 or' to Y.

   If $Al_2O_3 < K_2O$, set or' = Al_2O_3 and subtract an amount equal to or' from K_2O. There is no further Al_2O_3 available to form another normative mineral. Set K_2O = Ks. Add an amount equal to (6 or' + Ks) to Y.

TABLE 26

Molecular formulae of the normative minerals

Normative Minerals	Molecular Formula
1) Eudialyte (eu)	$2Na_2O. FeO.CaO. ZrO_2.6 SiO_2$
2) Aenigmatite (aen)	$2Na_2O.9FeO.Fe_2O_3.2TiO_2.12SiO_2$
3) Orthoclase (or')	$K_2O. Al_2O_3. 6 SiO_2$
4) Albite (ab')	$Na_2O.Al_2O_3. 6 SiO_2$
5) Acmite (ac)	$Na_2O. Fe_2O_3. 4 SiO_2$
6) Sodium Metasilicate (ns)	$Na_2O. SiO_2$
7) Diopside (di')	$CaO.(Mg Fe) O. 2SiO_2$
8) Wollastonite (wo')	$CaO. SiO_2$
9) Hypersthene (hy')	$(Mg Fe) O. SiO_2$
10) Olivine (ol)	$2 (Mg,Fe) O. SiO_2$
11) Nepheline (ne')	$Na_2O. Al_2O_3. 2 SiO_2$
12) Leucite (lc')	$K_2O. Al_2O_3. 4 SiO_2$
13) Calcium Disilicate (cs)	$CaO. 2 SiO_2$
14) **Kaliophilite** (kp')	$K_2O. Al_2O_3. SiO_2$

Note: Minerals with prime (') are provisional, while without prime standard normative. If provisional silicic minerals are not recalculated into subsilicic counterparts, they are considered as standard normative minerals.

6. If $Al_2O_3 >$ Na_2O, set ab' = Na_2O. Subtract an amount equal to ab' from Al_2O_3. Add 6 ab' to Y. There is no further Na_2O available to form any other mineral. If $Al_2O_3 <$ Na_2O, set ab' = Al_2O_3. Subtract an amount equal to ab' from Na_2O. There is no further Al_2O_3 available to form any other mineral. Add 6 ab' to Y.

7. If $Al_2O_3 >$ CaO, set an ' = CaO. Subtract an amount equal to an' from Al_2O_3. There is no further CaO available to form any mineral. Add an amount equal to 2 an' to Y. Usually these rocks are deficient in Al_2O_3, therefore no corundum is formed.

   If $Al_2O_3 <$ CaO, set an' = Al_2O_3. Subtract an amount equal to an ' from CaO. There is no further Al_2O_3 available to form any mineral. Add 2 an' to Y.

8. If $Fe_2O_3 >$ Na_2O, set ac = Na_2O. Subtract an amount equal to ac from Fe_2O_3. Add 4 ac to Y. If $Fe_2O_3 <$ Na_2O, set ac = Fe_2O_3. Subtract an amount equal to ac from Na_2O and set ns = Na_2O. There is no further Na_2O and Fe_2O_3 available to form any other mineral. Add an amount equal to 4 ac + ns to Y.

9. Add MgO to FeO to form (Mg, Fe) O. Calculate the ratio MgO/ (FeO+MgO) and FeO/ (FeO + MgO) and use these relative proportions to form diopside, hypersthene and olivine.

10. If CaO $>$ (MgFe) O, set di' = (MgFe) O. Subtract an amount equal to di' from CaO. Set wo' = CaO. Add an amount equal (2 di' + wo') to Y. If CaO $<$ (MgFe) O, set di' = CaO. Subtract an amount equal to di' from (MgFe) O. Set hy' = (MgFe) O. Add an amount equal to (2 di' + hy') to Y. This gives the SiO_2 required for all the normative minerals so far formed. In peralkaline rocks Y $>$ SiO_2 (always). Therefore proceed as follows:

11. Set D = y - SiO_2 where D is the deficiency in SiO_2. If D $>$ hy'/2, set ol = D and hy = hy' - 2D. The silica deficiency is now zero. If D $<$ hy'/2, set ol = hy'/2 and hy = 0. Put D_1 = D - hy½.

12. If $D_1 >$ 4 ab', set ne = ab' and ab = 0. Put $D_2 = D_1 - 4$ ab'. If $D_1 <$ 4 ab', set ne = D¼. Put ab = ab' - 4ne The silica deficiency is now zero.

13. If $D_2 >$ 2 or', set lc = $D_2/2$ Put or = or' - $D_2/2$ If $D_2 <$ 2 or', set lc = 2 or'. Put or = 0 and $D_3 = D_2 - 2$ or'. The silica deficiency is now zero.

14. If $D_3 >$ wo'/2, set cs = D_3 and wo = wo' - $2D_3$. The silica deficiency is now zero.
If $D_3 <$ wo'/2, set cs = wo'/2 and wo = 0. Put $D_4 = D_3$-wo'/2.

15. If $D_4 >$ di', add an amount equal to $D_4/2$ to the amounts of cs and ol already in the norm. If cs is not present, add an amount equal to $D_4/2$ to ol. Set di = di' - $D_4/2$ The silica deficiency is now equal to zero.
If $D_4 <$ di', set $D_5 = D_4$ - di'. Add an amount equal to di/2 to each ol or cs or di to any one which is present in the norm.

16. Set Kp = $D_5/2$ and lc = lc' - $D_5/2$ The silica deficiency is now zero.

APPENDIX II

Determinative Methods

Preparation of samples

Rock samples of medium grain size (2x2x1½ in) ranging in weight from 5 lbs - 10 lbs were crushed in a small jaw crusher to pea size (4-6mm), coned and quartered. One half of the above sample was crushed to -50/+80 mesh size and washed with water. Coning and quartering was repeated. One half was used for mineral separation while the other half was crushed to -200 mesh. The magnetic impurities were separated. Five grams of the sample were subjected to grinding in an automatic ball mill using plastic balls and the sample was reduced to a finer grain size. Two grams were ground to a finer grain size using small agate mortar and pestle. After grinding, the sample was kept for 2 hrs. in an oven at 110°F and subjected to chemical treatment.

The separation of eudialyte, nepheline, arfvedsonite, aegirine-augite and aenigmatite was accomplished with Frantz isodynamic separater and heavy liquids. To ensure complete separation, a powder of -200/+250 mesh was used during heavy liquid centrifuging. Each sample was washed, cleaned and X-rayed before chemical analyses were carried out. In some cases, the impurities were hand-picked under the binocular microscope. The above powders were ground in an agate mortar and passed through 300 mesh. The powders were thoroughly cleaned and dried. The dry powders were used for chemical analysis, infrared absorption, Mössbauer resonance, X-ray diffraction, electron spin resonance and optical analysis.

Chemical Analyses

After 10 minutes of cooling in a desiccator, 0.1 gm. was weighed in a platinum crucible and humidified by adding a few drops of distilled water. About 5 drops of perchloric acid and 5 ml. of 40% hydrofluoric acid were added and the crucible was left in the fuming board overnight.

The next day the solution thus obtained was subjected to complete evaporation at 80°F below a Monla infrared Lamp. During the above process continual stirring was carried out by platinum wire to ensure complete dissolution of the rock. After complete evaporation, five drops of perchloric acid and 5 ml. of 40% hydrofluoric acid were added to dissolve the residue which was further evaporated under a Monla Lamp, repeating the same procedure. After the second complete evaporation a few drops of perchloric acid and 10cc. of water were added to the crucible. The crucible was heated at 60°F until the residue was completely dissolved. The volume was made up to 100 ml. by adding distilled water. The solutions obtained in this way were analyzed for Na, K, Ca, Al, Fe, Mg and Mn, using an atomic absorption spectrophotometer while Ti and Fe^{3+} contents were determined on a Dk-2 spectrophotometer, as described by Bennet and Hawley (1965). The Fe^{2+} content obtained by gravimetric method gave the Fe^{3+} by difference of the total iron determined on the AA-4 spectrophotometer.

Both the methods appear to give results within 3% precision. All determinations were made in quadriplicate; the reference solutions were prepared from Fisher's standards and two U.S.G.S. rock standards (AGV-1. and BCR-1) were also taken into solution and included as test samples for checking the consistency and precision of the analyses. The aliquots of the solutions were subdivided and standardization was repeated after every 10 readings. The normal procedures for avoiding the inter-elemental effects were followed to avoid interference. The SiO_2 content of the rocks was determined by gravimetric methods while ZrO_2 was calculated from modal percentage of eudialyte. Some minerals were analyzed by the electron microprobe. To check the accuracy of the analyses, two duplicates were independently analysed by Dr. N. Suhr, Pennsylvania State University, by "rapid methods".

Infrared analyses

A well ground powder was kept 2 hours in an oven at 80^{0}F (under vacuum) and cooled in a desiccator for 15 minutes. The powder was then diluted by adding potassium bromide in a 50:1 ratio. A one-inch diameter pellet was made under 10,000 p.s.i. pressure. Infrared spectra were recorded at room temperature with a Perkin- Elmer spectrophotometer -421.

Mössbauer resonance

To avoid absorption effects, dried samples were crushed to -400/+ 500 mesh size as a prepared cake of 1 - 2 mm. thickness and 2.54 cm diameter and then sealed in cellotape. The cake of each mineral was fixed in a slot of a brass plate to fit in the Mössbauer apparatus. The apparatus, fitted with an electronic recording system, was run for 3 hours at room temperature and the data, thus collected, were used to get Lorentzian peaks by using a computer program available at Mines Branch, Department of Energy, Mines and Resources, Ottawa.

X-ray Diffraction

X-ray diffraction powder photographs and charts using a Debye-Scherrer (57.3mm dia.) camera and a diffractometer were made to estimate the approximate composition of nepheline and aegirine-augite. Two hundred and fifty mineral grains were extracted from the rock sections for X-ray powder diffraction identification.

Electron Spin Resonance

An E.S.R. spectrometer was made available by the Physics Department, University of Ottawa to study apatite grains. The frequency used was 9.5 GH_Z. At first the spectra were obtained with an orientation of 10^{o} interval from c-axis, keeping magnetic field direction constant. The spectra were taken with $H \parallel Z$ and $H \perp Z$. The g factor was calculated from the following formula:

$$g = h\nu/\beta H.$$

where $h = 6.6256 \times 10^{-27}$ erg. sec^{-1} (Planck constant)

ν = precession frequency sec^{-1}

g = landé factor

$\beta = 0.92732 \times 10^{-2}$ erg. $gauss^{-1}$ (Bohr constant)

H = applied magnetic field, gauss.

The detailed interpretation of the spectra was attempted from quantum mechanics viewpoint.

Besides the above methods used for chemical and physical analyses of minerals, a Cary-14 spectrophotometer was used to get optical absorption spectra from the finely polished thin sections.

REFERENCES

Abbott, M.J., 1967: Aenigmatite from the groundmass of a peralkaline trachyte. Amer. Mineral.,52, 1895-1901.

Adamson, O.J., 1944: The petrology of the Norra Kärr district. An occurrence of alkaline rocks in Southern Sweden. Geol. Foren. Stockholm,For., 66, 113-255.

Agard, J., 1960: Les carbonatites et les roches à silicates et carbonates associés du massif de roches alcalines du Tamazert (Haut Atlas de Midelt, Maroc) et les problèmes de leur genèse. 21st Int. Geol. Congr., 13, 293-303.

Arsandoux, H., 1906: L'étude des roches alkalines de l'est Africain, Paris.

Backlund, H.G., 1932: On the mode of intrusion of deep-seated alkaline bodies. Bull. Geol. Inst. Univ. Upsala, 24, 1-24.

Bailey, D.K., 1960: Carbonatites in the Rufunsa valley, Fiera District, North Rhodesia. North.Rhodesia, Geol. Surv. Bull., 5.

_____, 1964: Crustal warping - A possible tectonic control of alkaline magmatism. Jour. Geophys. Res., 69, 1103-1111.

_____, 1969: The stability of acmite in the presence of H_2O. Amer. Jour. Sci., (Schairer volume) 267-A, 1-16.

_____, 1970: Volatile flux, heat focussing and the generation of magmas, in Mechanism of Igneous Intrusion, edited by G. Newall and N. Rast, Gallery Press, Liverpool, England, 177-186.

_____, and Schairer, J.F., 1962: Peralkaline residual liquids; some petrogenetic considerations. Carnegie Inst. Washington, Yearbook 61, 95-96.

_____, and Schairer, J.F., 1964: Feldspar-liquid equilibria in peralkaline liquids,- the orthoclase effect. Amer. Jour. Sci., 262, 1198-1206.

_____, and Schairer, J.F., 1966: The system $Na_2O-Al_2O_3-Fe_2O_3-SiO_2$ at 1 atmosphere and petrogenesis of alkaline rocks. J. Petrology, 7, 114-170.

Baragar, W.R.A., 1968: Report of activities. Geol. Surv. Canada Paper, 69-1, part 1, 142-147.

Barth, T.F.W., 1927: Die pegmatitgänge der kaledonischen intrusivgesteine in Seiland Gebiete. Skr. Norske Vid. Oslo, 1 Mat. Nat. K-1, 1927, 8, 1-123.

Bashikrov, A.N., Loktev, S.M. and Kamzolkin, V.V., 1956: On the catalytic activity of some silicate minerals in the synthesis of hydrocarbons from carbon oxides and hydrogen. Chem. and Tech. Topliva, No. 3, 38-42.

Bass, M.N., 1970: North American feldspathoidal rocks in space and time (A discussion). Bull. Geol. Soc. America, 81, 3493-3500.

Beavan, A.P., 1958: The Labrador Uranium Area. Proc. Geol. Assoc. Canada, 10, 137-145.

Beloussov, V.V., 1962: Fundamental problems of Geotectonics. Publ. 2e, Gosgeoltekhizdat.

————————, 1971: On possible forms of relationship between magmatism and tectogenesis. J . Geol. Soc., 127, 57-68.

Bennet H. and Hawley, W.G., 1965: Methods of silicate analysis. Academic Press IMCA, London.

Bordet, P., Freulon, J.M. and Lefranc, J.P., 1955: Phonolite à eudialyte de Jebel Fessan. Bull. Soc. fr. Min., 76, 425-431.

Borodin, L.S., 1958: The chemistry of aegirinization and nephelinization of pyroxene in the formation of metasomatic nepheline-pyroxene rocks. Geochemistry, 5, 637-640.

_____, and Nazarenko, I.I., 1957: Eudialyte from alkalic rocks of Cape Ture and the chemical nature of eudialyte. Dokl. Akad. Nauk. SSSR, 112, 318-321. (Zbl. Min. Geol., I, 168-169.)

Bouchart, J. and Denaeyer, M.E., 1925: Sur les caractères lithologiques des laves de l'Ahaggar, Sahara central. Compt. Rend. Acad. Sci., (Paris), 181, 1073-1074.

Bowen, N.L., 1937: A note on aenigmatite. Amer. Mineral., 22, 139-140.

_____, 1945: Phase equilibria bearing on the origin and differentiation of alkaline rocks. Amer. Jour. Sci., 243A (Daly volume), 75-89.

Breithaupt, A., 1865-66: Mineralogische studien. Berg und Huttenm., 24, 1-397.

Bridgewater, A., 1965: Isotopic age determinations from South Greenland and their geological setting. Medd. Grønland, 179, 4, 1-56.

_____, 1967: Feldspathic inclusions in the Gardar igneous rocks of South Greenland and their relevance to the formation of major anorthosites in the Canadian Shield. Can. Jour. Earth Sci., 4, 995-1014.

Bridgewater, A. and Harry, W.T., 1968: Anorthosite xenoliths and plagioclase megacrysts in Pre-Cambrian intrusions of South Greenland. Medd. Grønland, 185, 2, 1-243.

Brögger, W.C., 1890: Die Mineralien der Syenitpegmatitgange des Sudnorwegischen Augit und Nephelinsyenit. Zeits. Krist., 16, 1-663.

Brummer, J.J., 1956: Preliminary report on the radioactive prospects in the Ten Mile Lake area of Frobisher Seal Lake Concession. Unpublished manuscript. Kennco Exploration Ltd., (Canada).

_____, 1957: Frobisher Seal Lake Concession, Labrador, Newfoundland. Vol. 1. Report on operation for 1956. Vol. 11. Core logs of holes drilled during 1956. Unpublished manuscript. Kennco Exploration Ltd., (Canada).

_____, and Mann, E.L., 1961: Geology of the Seal Lake area, Labrador. Bull. Geol. Soc. America, 72, 1361-1382.

Bultitude, R.J. and Green, D.H., 1967: Experimental study at high pressures of the origin of olivine nephelinite and olivine melilite-nephelinite magmas. Earth and Planet. Sci. Let., 3, 325-327.

Bussen, I.V. and Sakharov, A.S., 1967: Geology of the Lovozero Tundra. Izd. Nauka, Moscow.

Carmichael, I.S.E., 1962: Pantelleritic liquids and their phenocrysts. Min. Mag., 33, 86-113.

_____, and McKenzie, W.S., 1963: Feldspar-liquid equilibria in pantellerites: An experimental study. Amer. Jour. Sci., 261, 382-396.

Carson, D.W. and Tremblay, R.J., 1971: Mössbauer spectroscopy as applied to the determination of the Fe^{2+}/Fe^{3+} ratio in iron-silicate slags. Mines Branch, Internal Report Ms-71-16.

Christie, A.M., Roscoe, S.M. and Fahrig, W.F., 1953: Preliminary Map, Central Labrador Coast. Geol. Surv. Canada, paper 53-14.

Clabaugh, S.E., 1949: Eudialyte and eucolite from southern New Mexico. Bull. Geol. Soc. America, 60, 1879-80.

Cumming, G.L., Wilson, J.T., Farquhar, R.M. and Russell, R.D., 1955: Some dates and subdivisions of the Canadian Shield. Proc. Geol. Assoc. Canada, 7, 2, p. 27-79.

Davies, W.H.A., 1840-43: A quote from "Native Copper discoveries in the Seal Lake Area, Labrador" by E.L. Evans. Proc. Geol. Assoc. Canada, 5, 111-116.

Dawson, J.B., 1971: A preliminary note on eucolite from Oldoinyo Lengai, Tanzania. Min. Mag., 38, 385.

_____, and Frisch, T., 1971: Eucolite from Oldoinyo Lengai, Tanzania. Lithos, 4, 3, 297-303.

De Andre, M., 1954: Contribution à l'étude des roches alcalines d'Angola. 19me Internat. Geol. Congr. Algiers (1952), 20, 241-252.

Denaeyer, M.E., 1923: Les rochers dl'Ahrar de Iforass et de l'Ahaggar. Compt. Rend. Acad. Sci., (Paris). 176, 1161.

Dujardin, R.A., 1961: Ten Mile Lake drilling report 1961, Unpublished manuscript, Rio Tinto, Canada.

Dusmatov, B.D., Popova, N.A. and Kabanova, L.K., 1967: The first discovery of reedmergnerite in the U.S.S.R. Akad. Nauk Tadzhikskoi S.S.R., Doklady, 10, 51-53.

von Eckermann, H., 1942: E.H. Preliminaert medelande om nya forskningsron inom Alno alkalina Omrade. Geol. For. i. Stockholm, 64, 399-455.

Edgar, A.D., 1964: Phase equilibrium relation in the system diopside-nepheline-albite-H_2O at 1000 kg/cm^2 water vapour pressure. Amer. Mineral., 49, 573-585.

_____, and Nolan, J., 1966: Phase relations in the system albite-nepheline-acmite-dioside-H_2O and its importance in the genesis of alkaline undersaturated rocks. Indian Min., Special I.M.A.Vol., 176-181.

Efimov, A.F., Dusmatov, V.D., Alkhazov, V. Yu., Pudovkina, Z.G. and Kazakova, M.E., 1970: Tadzhikite, a new borosilicate of the rare earths of the hellandite group. Doklady Akad. Nauk., S.S.S.R., 195, 1190-1193.

Eliseev, N.A. and Fedrov, E.E., 1953: The Lovozero pluton and its deposits. Trudy Labor. Precambrian Geol., Leningrad, 19, 1-38.

_____, Ogimsky, I.S. and Volodin, E.N., 1939: Geological map of Khibina Tundra. Trudy Len. Geol. Up., 19.

Emslie, R.F., 1965: The Michikamau Anorthositic Intrusion, Labrador. Can. Jour. Earth. Sci., 2, 385-399.

_____, 1968: Crystallization and differentiation of the Michikamau Intrusion, in Origin of anorthosite and related rocks edited by Y. Isachsen, New York State Museum and Science, Mem., 18, 163-173.

Ernst, W.G., 1962: Synthesis, stability relations, and occurrence of riebeckite and riebeckite-arfvedsonite solid solutions. *Jour. Geology*, 70, 689-736.

_____, 1968: Amphiboles . *Minerals, Rocks and Inorganic Materials*, Monograph 1.

Evans, E.L. and Dujardin, R.A., 1961: A unique beryllium deposit in the vicinity of Ten Mile Lake, Seal Lake Area, Labrador. *Proc., Geol. Assoc. Canada*, 13, 45-51.

Fahrig, W.F., 1959: Snegamook Lake, Labrador, Newfoundland. *Geol. Surv. Canada*, map 1079A.

Fawley, A.P. and James, T.C., 1955: A pyrochlore (columbium) carbonatite, Southern Tanganyika. *Econ. Geol*., 50, 571-585.

Feld, R. and Cowe, L.P., 1965: *The organic chemistry of titanium*. Butterworth and Co. Ltd., London.

Ferguson, J., 1964: Geology of the Ilimaussaq alkaline intrusion, South Greenland (Description of map and structure). *Medd. Grønland*, 172, 4, 1-82.

_____, 1967: *The alkaline igneous intrusion of Ilimaussaq, South Greenland*. Ph.D. Thesis (unpublished), Univ. of Witwatersrand, Johannesberg, Africa.

_____, 1970a: The differentiation of agpaitic magmas: the Ilimaussaq intrusion, South Greenland. *Can. Mineral*., 10, 335-350.

_____, 1970b: The significance of kakortokite in the evolution of the Ilimaussaq intrusion, South Greenland. *Medd. Grønland*, 190, 1., 1-193.

_____, 1970c: On the schistose structure of some lujavrites, *Bull. Geol. Soc. Denmark*, 20, 67-68.

Fersman, A.E., 1923: Mineral associations of the Khibiny and Lovozero tundras. *Bull. Acad. Sci., Russia*, 6, 17, 65-80 (*Min. Abst*. 2,398).

_____, 1926: Minerals of the Kola Peninsula. *Amer. Mineral*. 11, 289-299.

_____, 1929: *Geochimische migration der elemente Teil*, 1. Abhandt. prakt. Geol. Und. Berquirtschaftslehre, 18, 1-73.

_____, 1937: *Minerals of Khibina and Lovozero Tundras*. Academy of Sciences Press, Moscow (English Edition).

Fick, J.L. and Van Der Heyde, C. 1959: Additional data on the geology of the Mbeya carbonatite. Econ. Geol., 54, 842-872.

Fleischer, M., 1971: Glossary of mineral species. Mineralogical Record, Inc., Bowie, Maryland.

Foerstner, H., 1881: Nota preliminare geologia dell' isola di Pantelleria scondo gli studii fatti negli anni 1874e 1881. Boll. R. Com. Geol. Italia, 12, 523-528.

Galakhov, A.V., 1961: Geological and petrological features of the Khibina alkaline massif and problems for further scientific investigations (Russian), in Questions of geology, mineralogy and petrology of the Khibina Tundra, 6-21.

__________, 1967a: Chemical composition of rocks in the Khibiny alkalic massif. Dokl. Acad. Sci., U.S.S.R., 171, 225-227.

_____, 1967b: Alkalic-ultrabasic igneous activity in the Khibiny tundras (Kola Peninsula). Dokl. Acad. Sci., U.S.S.R., 170, 85-87.

Gerassimovsky, V.I., 1936: On the mineralogy of the South-eastern part of Lujavrut. Trans. Lomonosov Inst. Acad. Sci. U.S.S.R., 7, 5-49, (Min. Abstr., 7, 210).

_____, 1956: Geochemistry and mineralogy of nepheline syenite intrusions. Geochemistry, 5, 494-510.

_____, 1966: Geochemical features of agpaitic nepheline syenites, in A.P. Vingradov, ed. Chemistry of the Earth's crust., 1, 104-118, Daniel Davey Co., New York.

_____, 1967: Chief geochemical characteristics of nepheline syenites of Kola Peninsula. Geokhimiya, 11, 1320-1327. (Geochem. Internat., 4, 1076-1083).

_____, 1968: Geochemistry of agpaitic nepheline syenites. 23rd. Int. Geol. Congr., 6, 259-265.

Gerassimovsky, V.I., Volkov, V.P., Kogarko, L.N., Polyakov, A.I., Saprykina, T.V. and Balashov, Yu. A., 1966: The geochemistry of the Lovozero Massif, Izd. Nauka, Moscow.

Goldschimidt, V.M., 1930: Elemente und Minerale pegmatitischer Gesteine. Nachr. Gesellsch. Wiss. Göttingen. Math. Phys. Kl., 370-378.

Gössner, B., 1925: Die chemische Zusammentzung von Crossit, Arfvedsonite, Aenigmatit, Rhonit und von Babingtot. Zeits., Krist., 61, 538-544.

Gössner, B. and Spielberger, F., 1930: Chemische und rontgenographische untersuchungen an silikaten. Ein Beitrag zur kenntnis der hornblende grouppe. *Zeits., Krist.*, 72, 111-142.

Green, D.H., 1969: The origin of basaltic and nephelinitic magmas in the Earth's mantle. *Tectonophysics*, 7, 409-422.

Halet, R.A., 1946: Geological reconnaissance of the Naskaupi mountains and adjoining central regions. Unpublished manuscript. *Dome Exploration Ltd., Toronto*.

Heinrich, E.W., 1966: *The geology of carbonatites*. Rand McNally, Chicago.

_____, and Moore, D.G., Jr., 1970: Metasomatic potash-feldspar rocks associated with igneous alkalic complexes. *Can. Mineral.*, 10, 2, 571-597.

_____, and Deane, R.W., 1962: An occurrence of barylite near Seal Lake, Labrador. *Amer. Mineral.*, 10, 2, 571-597.

_____, and Quon, S.H., 1963: Neptunite from Seal Lake Labrador, *Can. Mineral.*, 7, 650-654.

Hotun, E., 1970: *Crystallography of eudialyte and eucolite*. M.Sc. thesis, (unpublished), Carleton University, Ottawa.

James, T.C., 1958: Carbonatites and rift valleys in East Africa (abs). *Comm. Tech. Co-op. Africa south of Sahara, joint Meet.*, Leopoldville, 305.

Johannsen, A., 1939: *A descriptive petrography of igneous rocks*. Chicago Press, Chicago, 1, 69-83.

Kaneoka, I., 1972: The effect of hydration of the K/Ar ages of volcanic rocks. *Earth and Planet. Science. Let.*, 14, 216-220.

Karpoff, R., 1953: Trois nouveaux affleurements de syénites à néphéline et eudialyte au Nord-Ouest dl Adrar des Iforas (Sahara Soudanais) *Compt. Rend. Acad. Sci.,(Paris)*, 236, 401-402.

Kelsey, C.H., 1965: Calculation of the C.I.P.W. norm. *Min. Mag.* (Tilley Volume), 276-282.

_____, and McKie, D., 1964: The unit cell of aenigmatite. *Min. Mag.*, 33, 986-1001.

Knight, E.F., 1925: *Oversea Britain; a descriptive record of the geography, the historical, ethnological and political development and economic resources of the empire.*, John Murray, London.

Koark, H.K., 1960: Zum gefugeverhalten des nephelins in zwei vorkommen alkaliner kristaliner schiefer. Bull. Geol. Inst. Upsala, 39, 1-37.

Kogarko, L.N., 1970: Use of the thermodynamic activities of the components of agpaitic nepheline syenites in solving geochemical problems. Geochemistry Internat., 8, 337-348.

Kostyleva, E.E., 1929: Isomorphic Reine Eudialyte - Eucolit aus den Chibina und Lujawrut Tundren. Trav. Mus. Min. Ac. Sci., S.S.S.R., 3, 169-222 (N. Jahrb. 1931, 1, 366).

Kuno, H., 1969: Origin of basaltic magmas and ultramafic rocks. Tectonophysics, 17, 521-523.

Kushiro, I., 1968: Composition of magmas formed by partial melting of the Earth's upper mantle. Jour. Geophys. Res., 73, 619-648.

Kuznetsov, V.I., 1971: Transfers of titanium, zirconium and hafnium in high temperature alkaline solutions. Internat. Geol. Rev., 13, 1795-1797.

Lacroix, A., 1910: Minéralogie de la France, Paris, 4.

_____, 1911: Les syénites néphéliniques de l'Archipel de Los et leurs minéraux. Nouvelles archives du museum, Paris, ser. 5, 3.

_____, 1915: Sur une eucolite cérifère de Madagascar provenant d'un type nouveau de roche granitique à aegirine. Bull. Soc. fr. Min., 38, 278-285.

_____, 1922: Minéralogie de Madagascar. 2, Librairie maritime et coloniale, Paris, France.

Laird, J. and Albee, L.A., 1972: Chemical composition and physical, optical and structural properties of benitoite, neptunite and joaquinite. Amer. Mineral., 57, 85-102.

Landes, K.K., 1931: A paragenetic classification of the Magnet Cove, Arkansas, minerals. Amer. Mineral., 16, 313-326.

Lorenzen, J., 1881: Undersogelse af nogle Mineraler i sodalith-syeniten fra Julianehaab District. Medd. Grønland, 2, 43-48.

Mann, E.L., 1959: The geology of the Seal Lake Area, Central Labrador, Ph.D. Thesis (unpublished), McGill University, Montreal.

Marshall, P., 1936: Geology of Mayor Island, Trans. Roy. Soc. New Zealand, 66, 337-345.

Mereu, R.E. and Jobidon, G., 1971: A seismic investigation of the crust and Moho on a line perpendicular to the Grenville Front. Can. Jour. Earth. Sci., 8, 1553-1583.

Michel-Lévy, M.C., 1961: Reproduction artificielle de quelques minéraux riches en zirconium (zircon, eudialyte, catapléite, elpidite); comparaison avec leurs conditions naturelles de formation. Bull. Soc. fr. Min., 84, 265-269.

Minakov, F.V., Kamenev, Ye and Klinkin, M.M., 1971: Initial composition and evolution of ijolite-urtite magma of the Khibiny alkali massif. Geol. Internat., 8, 738-753.

Moore, J.C.G., 1968: Report of work on the Seal Lake beryllium deposits during 1967. Unpublished manuscript, Rio Tinto, Canada.

Nickel, E.H., 1963: Eudidymite from Seal Lake, Labrador, Newfoundland. Can. Mineral., 7, 643-649.

_____, and Charette, D.J., 1962: Additional data on barylite from Seal Lake, Labrador. Amer. Mineral., 47, 746-768.

_____, and Mark, E., 1965: Arfvedsonite and aegirine-augite from Seal Lake, Labrador. Can. Mineral., 8, 185-197.

_____, and Rowland, J.F. and Charette, D.J., 1964: Niobophyllite-the niobium analogue of astrophyllite, a new mineral from Seal Lake, Labrador. Can. Mineral., 8, 40-52.

Niggli, P., Koenigsberger, J. and Parker, R.L., 1940: Die Mineralien der Schweizeralpen. Wepf., Basel.

Nockolds, S.R., 1950: On the occurrence of neptunite and eudialyte in quartz bearing syenites from Barnavave, Carlingford, Ireland. Min. Mag., 29, 27-33.

Ossan, A., 1896: Beitrage zur Geologie und Petrographie der Apache (Davis) Mts., West Texas. Tsch. Min. Petrog. Mitt., 15, 394-456.

Pecora, W.T., 1942: Nepheline syenite pegmatites, Rocky Boy Stock, Bear Paw Mountains, Montana. Amer. Mineral.,27, 397-424.

Peng, Tze-Chung and Chang, C.H. 1965: New varieties of lamprophyllite, barytolamprophyllite and orthorhombic lamprophyllite, Scient. Sinica, 14, 1927-1940.

Petersilie, I.A., Andreva, E.D. and Svenshnikova, E.V., 1965: The organic substances in the rocks of certain alkalic massifs of Siberia. Izv. Acad. Sci., U.S.S.R., Geol., ser., 6, 26-38.

Petersilie, I.A. and Sørensen, H., 1970: Hydrocarbon and bituminous substances in rocks from the Ilimaussaq alkaline intrusion, South Greenland. Lithos, 3, 69-76.

Piotrowski, J.M. and Edgar, A.D., 1970: Melting relations of undersaturated alkaline rocks from South Greenland compared to those of Africa and Canada. Medd. Grønland, 181, 11, 1-62.

Prior, G.T., 1928: Note on the alkali lavas of Mount Nimrud, Armenia. Min. Mag., 21, 485-488.

Ramsay, W., 1890: Geologische Beobachtungen auf der Halbinsel Kola, Petrographische Beschreibung der Gesteine des Lujavrut, Fennia, 3, No. 7, 1-52.

_____, 1898: Das Nephelinsyenitgeiet auf der Haibinsel Kola II. Fennia, 15, No. 2., 1-27.

_____, and Hackmann, V., 1894: Das Nephelinsyenitgebiet auf der Halbinsel Kola I. Fennia, 11, No. 2., 1-225.

Robinson, W.G. and Cruft, E.F., 1958: Exploration during 1957 in an area adjacent to the Frobisher Concessions in Labrador. Technical File 13KP2 unpublished manuscript, Riocanex, Ltd., (Toronto).

Schäfer, H., 1964: Chemical Transport Reactions, (Translated from German) by Hans Frankfort. Academic Press Inc., New York, 35-114.

Schairer, J.F. and Yoder, H.S., Jr., 1960: The nature of residual liquids from crystallization with data on the system nepheline-diopside-silica. Amer. Jour. Sci., 258-A, (Bradley Volume), 273-283.

_____, and Yoder, H.S., Jr., 1964: Crystal and liquid trends in simplified alkali basalts. Carnegie Inst. Yearbook, 63, 65-73.

Scott, H.S. and Conn, H.K., 1950: Geology of the Goose Bay area, Labrador, Unpublished manuscript, Photographic Survey Corporation, (Toronto).

Segall, B., Ludwig, G., Woodbury, H.H. and Johnson, B.B., 1962: Electron spin resonance of a center in calcium fluorophosphate. Physics Rev., 1, 76-79.

Semenov, E.I., 1969: Mineralogy of Ilimaussaq alkaline massif, Izd. Nauka, Moscow.

Shand, S.J., 1928: The geology of Pilansberg in the Western Transvaal; a study of alkaline rocks and ring intrusives. Trans. Geol. Soc. South Africa, 31, 97-138.

Shewman, R.W., 1967: The geology of the Seal Lake area beryllium property. Unpublished manuscript, Rio Canex Ltd. (Toronto).

Singh, S.K., 1969: Preliminary report on field investigations; Joan Lake eudialyte occurrence, Labrador. Unpublished manuscript, Brinex Ltd., (Montreal).

_____, and Kamineni, D.C., 1971: Mineralogy and texture of cordierite-sillimanite rocks from Labrador. Geol. Mag., 108, 439-444.

Smith, D., 1968: Follow up of radioactive anomalies, Barringer Areas "E" Seal Lake, Labrador. Unpublished manuscript, Brinex Ltd., (Montreal).

Smith, J.V. and Sahama, Th.G., 1956: Determination of the composition of natural nephelines by an X-ray method. Min. Mag., 30, 439-449.

Smith, W.C., 1931: A classification of some rhyolite, trachyte and phonolites from part of Kenya Colony with a note on some associated basaltic rocks. Quart. Jour. Geol. Soc., 87, 212-218.

Sobolev, B.P., 1959: The role of fluorine compounds in the evolution of beryllium and formation of phenacite. Geochemistry, 1. 21-32.

Soellner, J., 1909: Beiträge zur Isenntnis des cossyrits von Pantellaria. Zeits. Krist., 46, 518-562.

Sood, M.K. and Edgar, A.D., 1970: Melting relations of undersaturated alkaline rocks from the Ilimaussaq intrusion and Gronnedal-Ika complex, Greenland, under water vapour and controlled partial oxygen pressures. Medd. Grønland, 181, 12, 1-42.

Songina, O.A., 1970: Rare Metals. (Russian) Translated by J. Schimrock, Israel Program for Scientific translation Ltd., Jerusalem.

Sørensen, H., 1958: The Ilimaussaq batholith, a review and discussion. Medd. Grønland, 162, 3, 1-48.

_____, 1960: On agpaitic rocks. 21st Int. Geol. Congr. Norden., 13, 319-327.

_____, 1962: On the occurrence of steenstrupine in the Ilimaussaq massif, southwest Greenland. Medd. Grønland, 167. No.1, 1-251.

_____, 1969: Rhythmic igneous layering in peralkaline intrusions. Lithos, 2, 261-283.

_____, 1970: Internal structure and geological setting of the three agpaitic intrusions-Khibina, Lovozero of Kola Peninsula and Ilimaussaq, south Greenland. Canadian Mineral., 10, 299-334.

Sørensen, H., Leonardsen, E.S. and Petersen, V.O., 1970: Trona and thermonatrite from the Ilimaussaq alkaline intrusion, South Greenland. Bull. Geol. Soc. Denmark, 20, 1-19.

Spry, A., 1969: Metamorphic Textures. Pergamon Press.

Stevenson, I.M., 1969: Lac Brulé and Winukapau Lake map-areas, Newfoundland and Quebec. Geol. Surv. Canada, paper 67-69.

Stobbe, H. and Murray, E.G., 1956: A new occurrence of eucolite near Waussau, Marathon County, Wisconsin. Amer. Mineral., 41, 932-934.

Stockwell, C.H., McGlynn, J., Emslie, R.F., Sanford, B.V., Norris, A.W., Donaldson, J.A., Fahrig, W.F., and Currie, K.L., 1970: Geology of the Canadian Shield, in "Geology and Economic minerals of Canada." Geol. Surv. Canada, Econ. Geol. Ser. 1, 5th ed., 44-150.

Sutherland, D.S., 1965: Nomenclature of the potassic-feldspathic rocks associated with carbonatites. Bull. Geol. Soc. America, 76, 1409-1412.

_____, 1967: A note on the occurrence of potassium-rich trachytes in the Kaiserstuhl carbonatite complex, West Germany. Min. Mag., 36, 334-341.

Sutton, W.R., 1967: Radioactive scintillation surveys in the Seal Lake area, Labrador. Unpublished report, Brinex Ltd., (Montreal).

Tanner, J.A., 1969: Geophysical interpretation of structural boundaries in the Eastern Canadian Shield. Ph.D. Thesis (unpublished), Durham University, England.

Teale, E.O. and Smith, W.C., 1923: Nepheline bearing lavas and intrusive rocks of the Zambezi River with a note on an outcrop of Karroo lavas in the Buzi valley. Geol. Mag., 60, 226-237.

Tilley, C.E., 1958: Problems of alkali rock genesis. Quart. Jour. Geol. Soc., 113, 323-360.

Tomita, J., 1934: On kaersutite from Dogo, Oki Islands, Japan, and its magmatic alteration and resorption. Journ. Shangai Sci. Inst., Sec., 2, 1, 99-136.

Ussing, N.V., 1911: Geology of the country around Julianehaab, Greenland. Medd. Grønland, 38, 1-376.

Varet, J., 1969: Les phonolites agpaitiques et miaskitiques du Cantal Septentrional (Auvergne, France). Bull. Volcan., 33, 621-656.

Velinskiy, V.V., 1971: Degassing of the upper mantle as the principal factor in genesis of magmas. Internat. Geol. Rev., 13, 595-602.

Venkatesh, V., 1954: Twinning in cordierite. Amer. Mineral., 39, 636-646.

Vlasov, K.A., 1956: The emanation process and crystallization differentiation as principal factors in the formation of a number of rare element deposits. In Problems of Geochemistry and Mineralogy, Akad. Nauk. S.S.S.R., Moscow, pp. 83-93.

_____, Kuzmenko, M.V. and E'skova, E.M., 1966: The Lovozero Alkalic massif. Oliver and Boyd Co., Edinburgh.

Washington, H.S., 1914: The volcanics and rocks of Pantelleria. Jour. Geol., 21, 653-683.

_____, 1917: Chemical analyses of igneous rocks. U.S. Geol. Surv., paper 99.

Watt, W.S., 1966: Chemical analyses from the Gardar igneous province, South Greenland. Rapp. Grønland. Geol. Unders., No., 6., 1-92.

Wegmann, C.E., 1938: Geological investigation in southern Greenland. Vol. 1, on the structural division of south Greenland. Medd. Grønland, 113, 2, 1-148.

Williams, H., Turner, F.J. and Gilbert, C.M., 1954: Petrography. Freeman and sons, San Francisco.

Williams, J.R., 1891: The igneous rocks of Arkansas. Ann. Rept. Geol. Survey. Arkansas, 1890, 2.

Winchell, A.N., 1951: Elements of optical mineralogy, Part II, description of minerals. John Wiley and Sons, Inc., New York.

Woodard, H.H., 1957: Diffusion of chemical elements in some naturally occurring silicate inclusions. Jour. Geol., 65, 61-84.

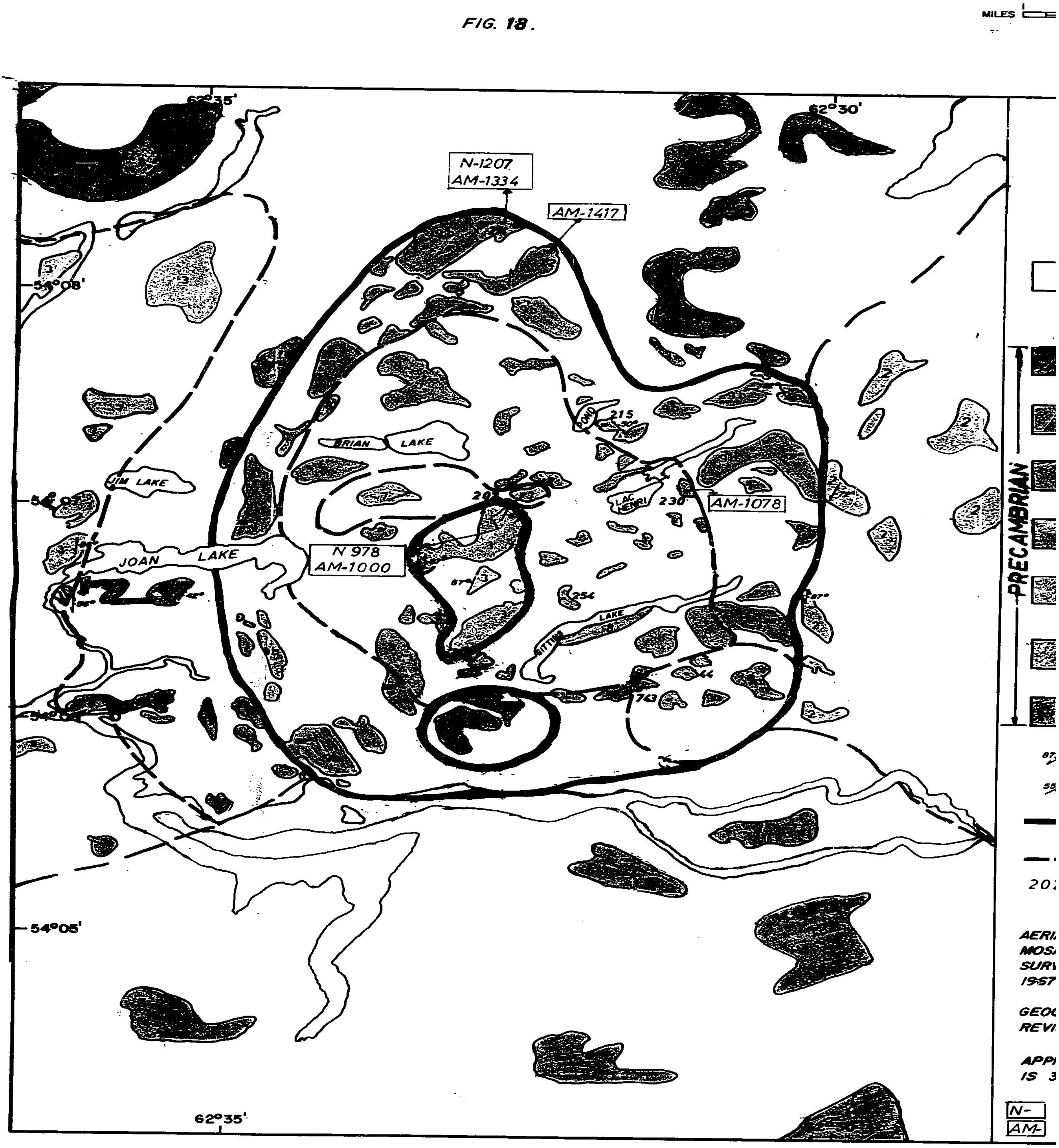
Yagi, K., 1953: Petrochemical studies on the alkali rocks of the Morotu District, Sakhalin. Bull. Geol. Soc. America, 64, 769-810.

Yoder, H.S. and Tilley, C.E., 1962: Origin of basalt magmas: an experimental study of natural and synthetic rock systems. Jour. Petrology., 3, 342-532.

Zies, E.G., 1966: A new analysis of cossyrite from the island of Pantelleria Amer. Mineral., 51, 200-205.

GEOLOGY OF THE JOAN LAKE AREA
CENTRAL LABRADOR

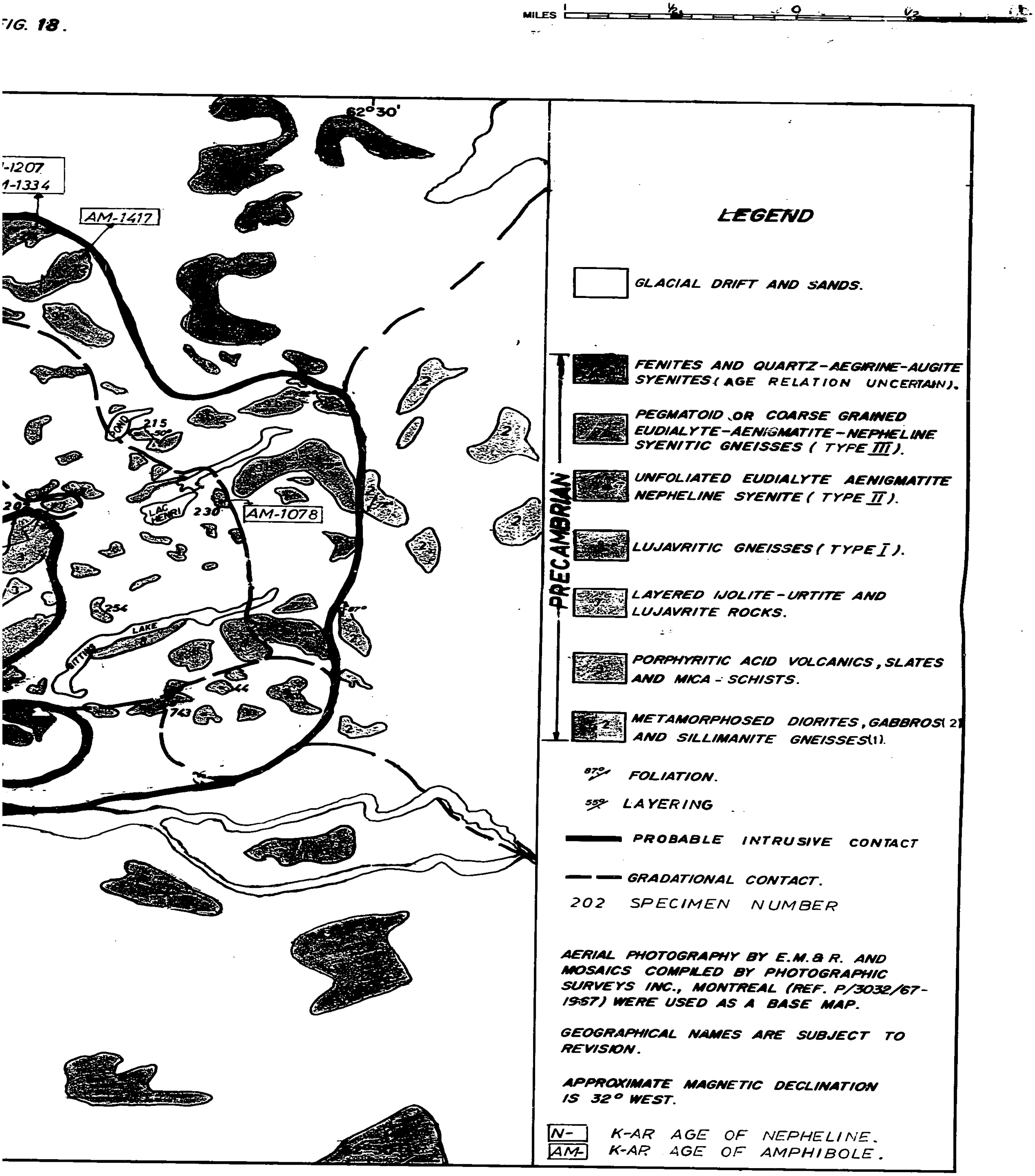
FIG. 18.



GEOLOGY BY S.K. SINGH, 1969, 1

OF THE JOAN LAKE AREA
CENTRAL LABRADOR

IG. 18.



AERIAL PHOTOGRAPHY BY E.M.& R. AND MOSAICS COMPILED BY PHOTOGRAPHIC SURVEYS INC., MONTREAL (REF. P/3032/67-1967) WERE USED AS A BASE MAP.

GEOGRAPHICAL NAMES ARE SUBJECT TO REVISION.

APPROXIMATE MAGNETIC DECLINATION IS 32° WEST.

GEOLOGY BY S.K. SINGH, 1969, 1971

GEOLOGY OF THE JOAN LAKE AND SURROUNDING AREAS

CENTRAL LABRADOR

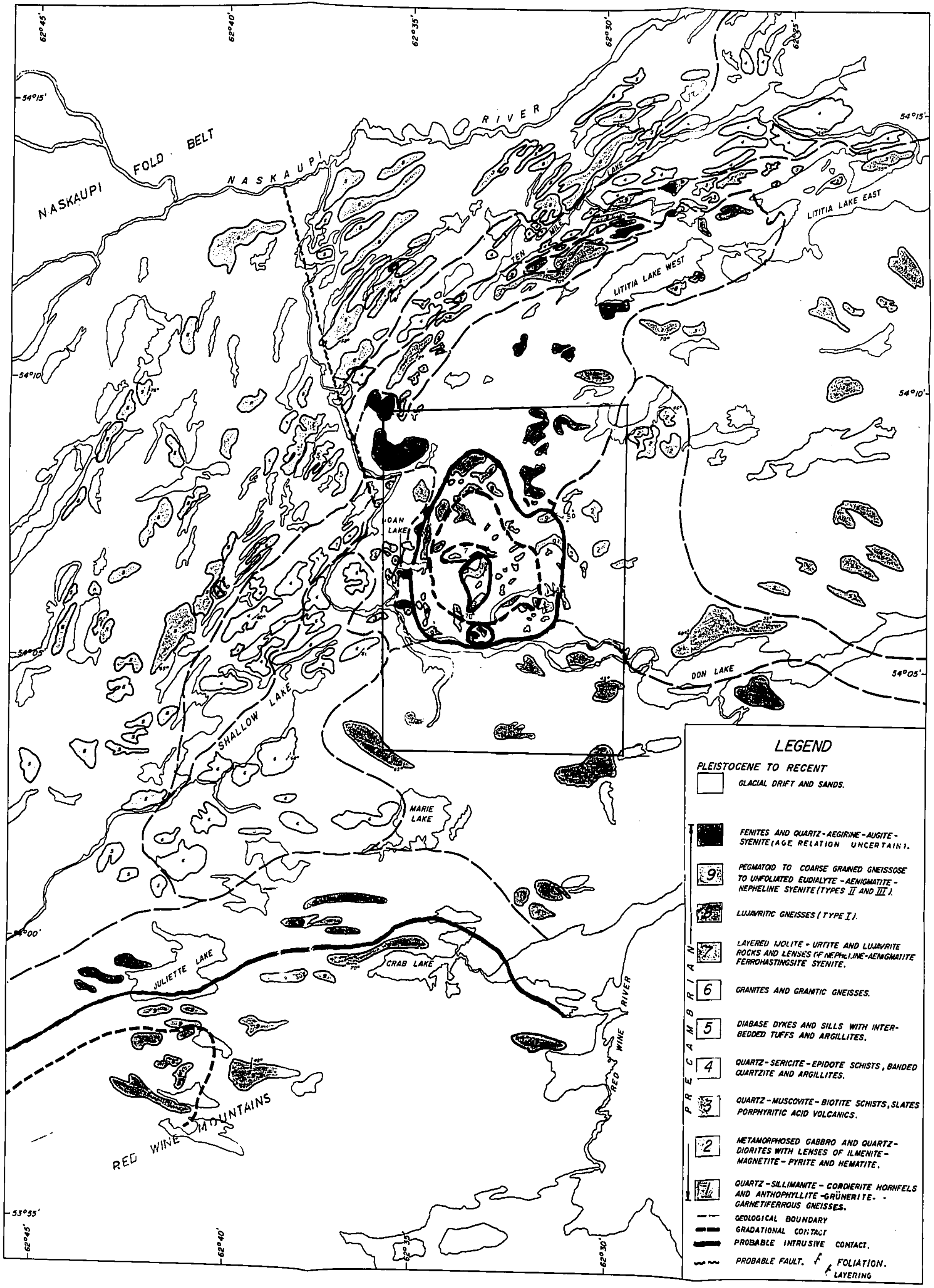
AERIAL PHOTOGRAPHS (1967-1968) CANADA - DEPT. OF ENERGY, MINES AND RESOURCES WERE USED AS BASE MAP.
GEOGRAPHICAL NAMES ARE SUBJECT TO REVISION.

T.N.
MAGNETIC NORTH
33°59'

APPROXIMATE DECLINATION, 1964
FOR CENTRE OF MAP
MEAN ANNUAL CHANGE DECREASING 4.2°

FIG. 10

Scale
MILES 2 1 0 1 2 MILES

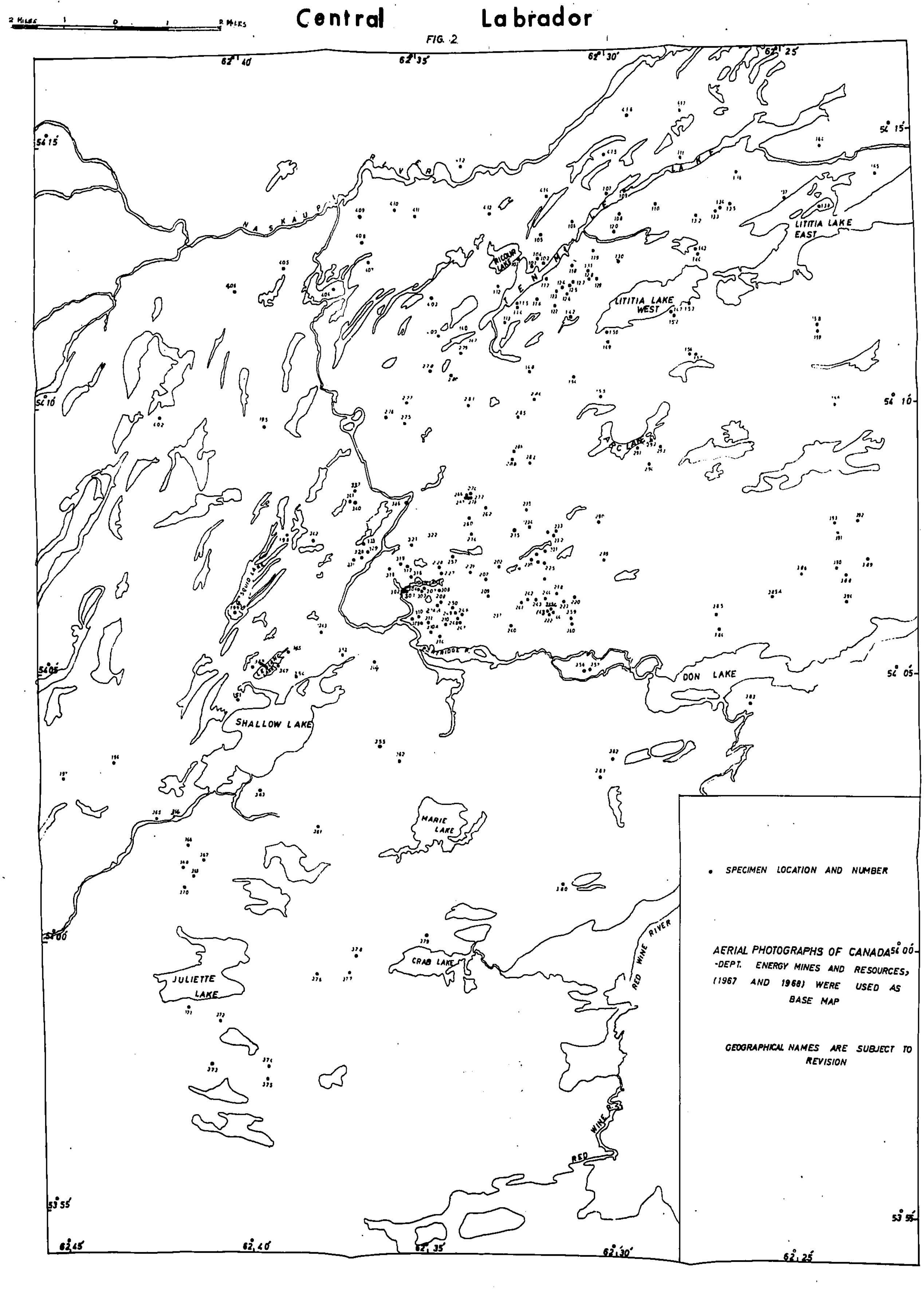


GEOLOGY BY S.K. SINGH, 1969, 1971.

Fig. 10

SPECIMEN LOCATION MAP OF JOAN LAKE AND SURROUNDING AREAS
Central Labrador

FIG. 2



• SPECIMEN LOCATION AND NUMBER

AERIAL PHOTOGRAPHS OF CANADA -DEPT. ENERGY MINES AND RESOURCES, (1967 AND 1968) WERE USED AS BASE MAP

GEOGRAPHICAL NAMES ARE SUBJECT TO REVISION