



BULLETIN 287

This document was produced
by scanning the original publication.

Ce document est le produit d'une
numérisation par balayage
de la publication originale.

**A CONTRIBUTION TO THE PETROLOGY
OF THE COLDWELL ALKALINE COMPLEX,
NORTHERN ONTARIO**

K.L. Currie





**GEOLOGICAL SURVEY
BULLETIN 287**

**A CONTRIBUTION TO THE PETROLOGY
OF THE COLDWELL ALKALINE COMPLEX,
NORTHERN ONTARIO**

K.L. Currie

1980

©Minister of Supply and Services Canada 1980

Available in Canada through

authorized bookstore agents
and other bookstores

or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Hull, Québec, Canada K1A 0S9

and from

Geological Survey of Canada
601 Booth Street
Ottawa, Canada K1A 0E8

A deposit copy of this publication is also available
for reference in public libraries across Canada

Cat. No. M42-287E Canada: \$6.00
ISBN — 0-660-10510-1 Other countries: \$7.20

Price subject to change without notice

Critical Reader
D.H. Watkinson

Manuscript received: 1976-05-06
Approved for publication: 1977-02-03

Preface

This report is the result of one of a number of studies of alkaline rocks carried out during the past decade in various parts of Canada. The alkaline rocks are of interest because a surprising variety of metals and industrial minerals are produced from them, including niobium and the rare-earth elements.

The Coldwell alkaline complex lies at the northeast corner of Lake Superior. The wave-washed shores of the lake and the series of spectacular road-cuts along the Trans-Canada Highway well display many of the intricate relationships that characterize the various rock units. The complex comprises three separate but interlocking systems of ring dykes, cone sheets and screens of metasomatized and remobilized country rock emplaced in an Archean volcano-sedimentary assemblage and its surrounding granitoid rocks. The author considers that the wide variety of rock types resulted from differentiation of basaltic magma.

The gabbroic rocks of the complex have been intensively prospected for copper and nickel. They also contain magnetite in varying but large amounts. Some of the magnetite is markedly vanadiferous. An attempt was made to exploit the nepheline syenite as a source of nepheline but because of an unacceptably high iron content in the concentrates, the plan was abandoned.

Ottawa, February 1977

D.J. McLaren,
Director General,
Geological Survey of Canada

CONTENTS

	Page
Abstract/Résumé	vii
CHAPTER 1	
Introduction	1
Location and access	1
Physiography and glacial geology	1
Previous work and scope of present study	1
Acknowledgments	1
CHAPTER 2	
General Geology	2
General statement	2
Description of formations	2
Metamorphosed volcano-sedimentary rocks (units 1-3)	2
Granitoid rocks (unit 4)	6
Diabase and dolerite dykes (unit 5)	6
Coldwell complex (units 6-13)	7
Fenite (unit 6)	7
Ultrafenites and reconstituted rocks (unit 7)	10
Barkevikite syenite (unit 8)	10
Eastern gabbro (unit 9)	13
Augite-amphibole syenite (unit 10)	15
Alkaline gabbro (unit 11)	17
Nepheline syenite (unit 12)	19
Alkaline dykes (unit 13)	23
CHAPTER 3	
Structural Geology	27
Structure of the country rocks	27
Structure of the contact zone of the Coldwell complex	27
Structure of the eastern ring system	28
Structure of the western ring system	28
Structure of the southern ring system	29
Three dimensional form of the Coldwell complex	29
Relation of the Coldwell complex to regional structure	29
CHAPTER 4	
Petrology of the Coldwell complex	30
Differentiation trends in the complex	30
Source and significance of the parent magma	32
Physical chemical conditions of emplacement	34
Trends of metasomatic alteration in the complex	38
Summary and conclusions	39
CHAPTER 5	
Economic Geology	40
References	41
Appendix: Recalculation of Electron Probe Data	43
Tables	
Table 1. Chemical analyses of Archean volcano-sedimentary rocks	4
2. Modal and chemical analyses of granitic rocks	6
3. Chemical analyses of minerals from fenites	8
4. Chemical analyses of fenites	9
5. Chemical analyses of minerals from ultra-fenites	11
6. Chemical analyses of ultra-fenites	11
7. Chemical analyses of minerals from barkevikite syenite	12
8. Chemical analyses of barkevikite syenite	13
9. Chemical analyses of minerals from eastern gabbro	14

	Page
Table 10. Chemical analyses of eastern gabbro and related rocks	15
11. Chemical analyses of minerals from augite-amphibole syenite	16
12. Chemical analyses of augite-amphibole syenite	17
13. Chemical analyses of minerals from alkaline gabbro	18
14. Chemical analyses of alkaline gabbro	19
15. Chemical analyses of minerals from nepheline syenite	21
16. Chemical analyses of nepheline syenite	22
17. Chemical analyses of minerals from alkaline dykes	23
18. Chemical analyses of alkaline dykes	26
19. Calculated composition of magma parental to the gabbroic rocks of the Coldwell complex	31
20. Calculated fractionation from eastern gabbro to augite- amphibole syenite	32
21. Calculated fractionation to nepheline syenite	33
22. Calculated fractionation from mafic dykes to salic dykes	34
23. Compositions of coexisting minerals from units of the Coldwell complex	36

Illustrations

Figure 1. Pic Island, from Premier Mountain	1
2. Fragmental felsic volcanic rock. Highway 17 at Highway 627	5
3. Rheomorphic breccia of felsic volcanics	5
4. Metasomatized amphibolite fragments in fenite	7
5. Magnetic map of the Coldwell complex	in pocket
6. Inch-scale layering in gabbro	15
7. Oriented, assimilated inclusions in nepheline syenite	20
8. Graded layering in nepheline syenite	24
9. Sinuous lamprophyre dyke in nepheline syenite	24
10. Inclusion of nepheline syenite in lamprophyre	25
11. Apparent intrusion of nepheline syenite into lamprophyre	25
12. Projection of structural elements of the eastern gabbro and augite-amphibole syenite	in pocket
13. Schematic representation of the emplacement of the Coldwell complex	in pocket
14. Projection of structural elements of the nepheline syenite	in pocket
15. Schematic three dimensional configuration of the Coldwell complex	in pocket
16. Pressure-temperature conditions during emplacement of the Coldwell complex	in pocket
17. Geological map of the Coldwell alkaline complex	in pocket

A CONTRIBUTION TO THE PETROLOGY OF THE COLDWELL ALKALINE COMPLEX, NORTHERN ONTARIO

Abstract

The Coldwell alkaline complex, a subcircular body about 25 km in diameter, of which more than one third is covered by Lake Superior, comprises three separate but interlocking systems of ring dykes, cone sheets, and intercalated screens of metasomatized and remobilized country rocks, emplaced into an Archean volcano-sedimentary assemblage ("greenstone belt") and its surrounding granitoid rocks.

The oldest, most easterly, ring system comprises an outer crescentic gabbro body cut by syenite cone sheets. Both rock types display well developed layering and mineral alignment, interpreted to have formed in magmatic currents. The alkaline rocks have strongly assimilated and partly melted large amounts of country rocks, giving rise to extensive rheomorphic zones, some of which contain substantial amounts of sulphides.

The western ring system includes one or more outer rings of strongly alkaline gabbro, now partially broken up and assimilated by cone sheets of syenite and nepheline syenite and intercalated with screens of intensely metasomatized and reconstituted country rocks. In some cases it becomes impossible to distinguish between such reconstituted rocks and normal alkaline igneous rocks. Parts of the roof of the western complex are preserved. An artieritic assemblage developed where the alkaline rocks penetrated the volcano-sedimentary assemblage, giving rise to an areally extensive, but shallow, flap of hybrid alkaline rocks. The igneous rocks of the western system all show sporadic graded layering with essentially vertical dips. This layering presumably developed as a result of magmatic currents depositing successive layers of material on the walls of the intrusion.

The youngest, southern, ring system, partially exposed on Pic and Allouez islands, exhibits only vertically layered nepheline syenites and metasomatized screens of country rocks at the present level of exposure. All older units are cut by a characteristically bimodal dyke swarm of biotite lamprophyres and analcite syenites. Rare composite dykes occur, and some lamprophyres contain analcite-rich syenitic ocelli.

Structural analysis of the cone sheets suggests that the igneous rocks were emplaced from a cupola of magma which migrated laterally with time, as well as shrinking and retreating to greater depths. The magmatic source probably shrank from a radius of 12 km to one of 5 km during emplacement of the complex, and migrated downward from a depth of 7 km below the present surface to a depth greater than 10 km. The confinement of gabbroic rocks to ring dykes, and the occurrence of syenite principally as cone sheets, suggests a vertically zoned magma chamber, with more felsic compositions toward the top.

Petrochemical considerations suggest that all of the major igneous rock compositions could be reached by differentiation of an originally basaltic parent. The distinctly bimodal character of the rocks and the small scale evidence of liquid immiscibility, suggest that other processes may have played a role. The age of the complex, 1050 m.y., is identical to that of widespread basaltic igneous activity in the Lake Superior basin. Emplacement of the complex was probably related to tensional deformation during this igneous episode.

Mineral assemblage data suggest emplacement of the gabbroic rocks at temperatures near 900°C and pressures of about one kilobar. Igneous syenites were emplaced at slightly lower temperatures, and formation of metasomatic rocks continued to temperatures near 500°C. Oxygen fugacity was externally buffered, possibly by uptake of water by the intrusion. Large amounts of water were released during crystallization. The resulting metasomatism produced highly oxidized syenites similar to some of the igneous rocks.

Résumé

Le complexe alcalin de Coldwell, qui est un corps annulaire d'environ 25 km de diamètre, dont plus du tiers est occupé par le lac Supérieur, comprend trois réseaux distincts mais imbriqués, de ring dykes, cone sheets et intercalations de roche encaissante métasomatisée et remobilisée, introduits dans un assemblage volcano-sédimentaire archéen ("zone de roches vertes") et les roches granitoides environnantes.

Le système annulaire le plus ancien et situé le plus à l'est comprend un corps gabbroïque externe, en forme de croissant, recoupé par des cones sheets syénitiques. Ces deux types de roches sont caractérisées par une stratification et un alignement de leurs minéraux bien visibles, ce qui semble indiquer qu'elles se sont formées en présence de courants magmatiques. Les roches alcalines ont fortement assimilé et partiellement liquéfié d'importants volumes de roche encaissante, donnant naissance à des zones rhéomorphiques étendues, dont certaines contiennent des quantités substantielles de sulfures.

Le système annulaire situé à l'ouest contient un ou plusieurs anneaux extérieurs de gabbro fortement alcalin, qui ont été partiellement fragmentés et assimilés par des cone sheets de syénite et de syénite néphélinique et alternent avec des zones planes de roche encaissante fortement métasomatisée et reconstituée. Dans certains cas, il devient impossible d'établir une distinction entre les roches reconstituées et les roches ignées alcalines normales. Certaines parties du toit du complexe ouest sont préservées. Un assemblage artéritique s'est formé là où les roches alcalines ont traversé l'assemblage volcano-sédimentaire, et ainsi donné naissance à une tranche étendue, mais peu profonde, de roche alcaline hybride. Les roches ignées du système ouest présentent toutes sporadiquement une stratification rythmique, caractérisée par un pendage généralement vertical. Cette stratification rythmique est probablement due à l'action de courants magmatiques, qui ont déposé des couches successives de matériau le long des parois de l'intrusion.

Du système annulaire sud, le plus jeune, qui affleure partiellement sur les îles Pic et Allouez, n'apparaissent que des syénites néphéliniques à stratification verticale, et des zones planes métasomatisées de roche encaissante, au niveau actuel d'affleurement. Les unités les plus anciennes sont toutes recoupées par un faisceau typiquement bimodal, de dykes composées de lamprophyres à biotite et de syénites à analcite. Les dykes composites sont rares, et certains lamprophyres contiennent des structures circulaires composées de syénite riche en analcite.

L'analyse structurale des cone sheets suggère que la mise en place des roches ignées s'est faite à partir d'un dôme de magma qui a migré latéralement pendant un certain temps avant de se contracter et de s'enfoncer de nouveau. La source de magma a probablement vu son rayon rétrécir de 12 km à 5 km pendant la mise en place du complexe, et a reculé d'une profondeur initiale de 7 km au-dessous de la surface actuelle à une profondeur supérieure à 10 km. Les roches gabbroïques se limitent aux ring dykes, et la syénite apparaît principalement sous forme de cone sheets, ce qui suggère l'existence d'une chambre magmatique à zonalité verticale, dont la composition devient plus felsique à mesure que la profondeur diminue.

Un examen pétrochimique indique que la composition des principales roches ignées résulte peut-être de la différenciation d'un magma parental initialement basaltique. Le caractère nettement bimodal des roches, et certains indices, à une échelle limitée, d'une immiscibilité à l'état liquide suggèrent aussi que d'autres processus ont sans doute joué un rôle. L'âge du complexe, 1050 m.a., correspond exactement à celui d'une activité basaltique généralisée dans le bassin du lac Supérieur. La mise en place du complexe est probablement associée à des déformations produites par des tensions pendant cette période d'activité.

Les données fournies par l'étude des assemblages de minéraux indiquent que la mise en place des roches gabbroïques s'est faite à des températures proches de 900 °C et à des pressions d'environ 1 kilobar. Les syénites ont été mises en place à des températures légèrement plus basses, et la formation des roches métasomatiques s'est poursuivie jusqu'à des températures approchant 500 °C. La fugacité d'oxygène a subi un effet de tamponnage sur le pourtour des intrusions, peut-être par adsorption d'eau pendant le processus de mise en place. D'importantes quantités d'eau ont été libérées pendant la cristallisation. Le métasomatisme a produit des syénites fortement oxydées, semblables à certaines des roches ignées.

A CONTRIBUTION TO THE PETROLOGY OF THE COLDWELL ALKALINE COMPLEX, NORTHERN ONTARIO

CHAPTER 1

INTRODUCTION

The largest alkaline complex in North America lies on the northeast shore of Lake Superior between Pic and Little Pic rivers forming a roughly circular body about 25 km in diameter. Although known for more than a century, no comprehensive study exists, perhaps because of the size and complexity of the body. Many aspects of its petrology and structure were unsolved by earlier workers, in particular the apparent association of hypersthene- and nepheline-bearing rocks, and the relation of sulphide mineralization to the alkaline rocks. These associations raise more general problems containing the origin and differentiation of gabbro-syenite complexes. In this study these problems are examined.

Location and access

The Trans-Canada Highway (Ontario Highway 17) and the trans-continental line of Canadian Pacific Railway cross the complex in a series of large rock cuts close to the shore of Lake Superior. A number of magnificent wave-washed exposures accessible by boat, are present along the mainland shore and on various islands. The town of Marathon and the almost deserted fishing hamlet of Coldwell lie on the lakeshore, from which they are joined to the highway by short access roads.

Although access to the southern parts of the complex is easy, the more northern parts can be reached only with difficulty. The Killala Lake road along the east side of the Little Pic River is possible by auto for several miles, and these are various other roads, notably to Seely and Bamooos mountains, and along Pic River. However most of the northern parts of the complex can be reached only by aircraft or by lengthy journeys by foot across rugged, timbered terrane.

Physiography and glacial geology

The Coldwell region contains some spectacular scenery due to the abrupt rise of steep, wooded hills from the shores of Lake Superior (Fig. 1). The highest hills are close to the lake and in some cases rise nearly 350 m above the mean lake level of 201 m. Typically the hills have precipitous southern faces, gently rounded tops and flat northern slopes. The

highest hills form a roughly north-south trending chain running from Thompson Channel to the Little Pic River. Deep, steep-sided, north-trending valleys, notably those of Pic and Little Pic rivers, transect the high rugged hills of the complex. Locally, northeast trending valleys (Bamooos Lake) and northwest trending valleys (Willie and Boyer lakes) form prominent lineaments.

Glacial striae indicate a south-southeast direction of latest glacial advance and the prominent south-trending valleys may have been enlarged by glacial scouring. Dissected clay plains occupy the broader valley floors, and varved clays follow the Pic River for more than 80 km (Farrand, 1960). The mouths of Pic and Little Pic rivers cross pitted outwash plains merging toward the lake into fresh beach gravels. Although fresh and undissected, the beach gravels of Lake Superior display at least six old beaches at Marathon, extending to 35 m above the present lake level. The highest beach lies at considerably higher elevation near Marathon than at sites farther to the west (Walker, 1956) implying that some of the topographic elevation of this region may be of very recent origin.

Previous work and scope of present study

Sir William Logan (Logan et al., 1863, p. 647) reported nepheline syenites in the Coldwell region during the pioneering days of Canadian geology, and Kerr (1910) published an excellent study of the alkaline rocks with references to the several preceeding investigations. Systematic mapping by the Ontario Department of Mines covers the entire area. The western and eastern extremities were mapped by Walker (1967) and Milne (1967) respectively, while Puskas (1967) examined the large central region. The present investigation therefore required no further systematic mapping. However, during 62 days of fieldwork in 1969, 1970 and 1973, all known nepheline-bearing rocks were remapped together with the complex zone extending from Coubran Lake to Red Sucker Cove. Representative areas of other rock types readily accessible from roads and shoreline were also examined. These observations have been used to revise the map of Puskas (1967).

Laboratory work included quantitative microscopic examination of 138 thin sections, electron microprobe analysis of genetically significant minerals, 36 new whole rock chemical analyses, and two K-Ar age determinations.

Acknowledgments

I am indebted to the staff of Neys Provincial Park for courtesies extended during my examination of that region. Dr. John Ferguson, now of the Bureau of Mineral Resources, Canberra, Australia, assisted in the field work of 1969, and offered invaluable observations and insights. Mr. John Stirling performed much of the routine petrographic examination. I am particularly indebted to École Polytechnique, Montreal, who supported the project during my tenure as research associate, and to Dr. Ramon Coy-Yll who provided electron microprobe analyses. Drs. D.H. Watkinson and R.H. Mitchell read the manuscript at various stages, and suggested improvements.

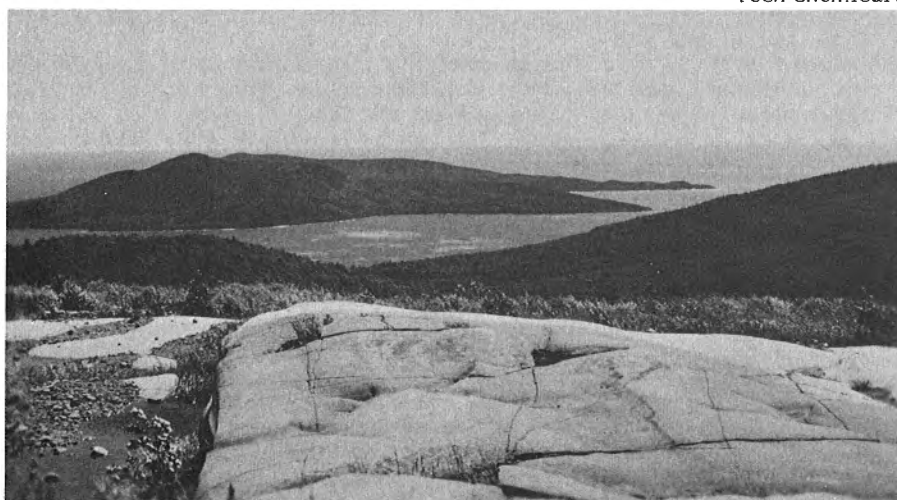


Figure 1. Pic Island from Premier Mountain. (GSC Photo 203034-J)

CHAPTER 2

GENERAL GEOLOGY

General statement

The Coldwell alkaline complex, a roughly circular mass some 25 km in diameter, truncates an east-west trending Archean 'greenstone' belt. The detailed stratigraphy within the volcano-sedimentary belt has not been worked out, but in general the central parts are rich in salic volcanic rocks and clastic sedimentary rocks, while the marginal parts contain mafic volcanic rocks and their metamorphosed equivalents. The metamorphic grade rises from greenschist in the central parts to amphibolite grade close to the surrounding granitoid rocks, and to pyroxene hornfels grade close to some units of the Coldwell complex. The Coldwell complex, which truncates both the greenstone belt and the younger granitoid rocks, comprises three intersecting systems of ring dykes and cone sheets. The ring dykes are composed of mildly to strongly alkaline gabbros, while the slightly younger cone sheets are composed of syenite and nepheline syenite. The included screens of country rocks have been variously metasomatized and reconstituted, in many cases to such an extent that the distinction between igneous and metasomatic rocks is lost. All older rocks are cut by a bimodal suite of strongly alkaline dykes.

Description of formations

Metamorphosed volcano-sedimentary rocks (units 1-3) form an east-west trending belt more than 100 km long along the north shore of Lake Superior, extending from the vicinity of Schreiber to east of White Lake. In the vicinity of the Coldwell complex this belt is about 20 km wide.

The volcano-sedimentary assemblage consists of three distinct, though commonly interlayered, units, namely mafic volcanic rocks (unit 1), salic volcanic rocks (unit 2), and sedimentary rocks (unit 3). Although the units are interbedded in some outcrops, in general the sedimentary rocks appear slightly younger, and locally lie unconformably on the volcanic rocks. All of the rocks are somewhat metamorphosed, in some cases to such an extent that the original character of the rock cannot be definitely ascertained.

Recognizable mafic volcanic rocks outcrop west of the Coldwell complex where they are well exposed in Dead Horse Creek, and in an east-west belt near Heron Bay. Amphibolitic schists and gneisses believed to be derived from mafic volcanic rocks occur north and northeast of the complex in narrow belts within the granitoid rocks. Transitions between the two types can be seen in Dead Horse Creek and north of Bamoos Lake.

In Dead Horse Creek repetitive sequences of mafic volcanic rocks, up to 10 m thick, are exposed with massive or pillowed lavas at the base, amygdaloidal lava in the centre, and fragmental, commonly schistose, rocks at the top. Occasional thick, homogeneous layers with ophitic texture probably represent sills in the volcanic pile. The colour and grain size change with increasing grade of metamorphism from pale green or brownish aphanitic rocks to greenish black, coarse grained amphibolite.

In thin section the least altered mafic volcanic rocks are seen to consist of about equal amounts of feldt albite microlites and chloritized actinolitic amphibole, presumably

secondary after pyroxene. Variable amounts of epidote, talc, carbonate, chlorite, quartz (including chert and chalcedony), opaque oxides and sericite may be present. A few of the coarser grained rocks contain scattered remnants of augitic pyroxene. With progressive metamorphism, biotite appears, sericite and chlorite disappear, and amphibole forms feathery prisms in the more competent layers. Reddish garnet is locally abundant in the higher grade rocks. Plagioclase compositions range up to An₄₅ with a distinct maximum near An₃₅.

A sample from Dead Horse Creek, believed to be representative of the mafic volcanics, was chemically analyzed (Table 1, col. 1). The rock is a tholeiitic basalt, similar in every respect to the basalts described by Baragar (1972). The relatively low titanium content and the high silica, chromium and nickel contents clearly distinguish it from the gabbroic rocks of the Coldwell complex (Tables 10, 14).

The mafic volcanic rocks display a variety of internal structures. Pillows are sporadically present, even in rather strongly metamorphosed rocks. The fragmental and tuffaceous members invariably display a schistosity, and in all the more metamorphosed rocks schistosity or gneissosity is ubiquitous, commonly accompanied by strong mineral lineation. Small folds are rarely observed in the mafic volcanic rocks.

The contact relations of the mafic volcanic rocks can be observed in Dead Horse Creek. Mafic and felsic volcanic rocks appear to interfinger, and are intercalated. Sedimentary rocks rest unconformably on the mafic volcanics and numerous small pebbles of mafic volcanics occur in the basal beds of the sedimentary rocks. The mafic volcanics are intruded by all units of the Coldwell complex, with or without formation of intrusive breccias. The complex relations of the basalt with the alkaline rocks form one of the keys to understanding the Coldwell complex and are discussed in detail in a subsequent section.

Progressive metamorphism of this unit has been discussed by Walker (1967, p. 6-9). In general the grade rises from greenschist in the core of the 'greenstone belt' to amphibolite facies near the surrounding granite. North of Middleton a thermal aureole has been imposed on the rocks by the Coldwell complex, leading to production of diopside-bearing hornfels.

Felsic metavolcanic rocks (unit 2) occur mainly on the east side of the Coldwell complex. One belt runs northeast from near Bamoos Lake, the other about east-west just south of Highway 17. Small amounts of felsic metavolcanic rocks also occur just west of the complex, and much larger amounts occur a few kilometres farther west near Jackfish.

Felsic metavolcanic rocks can be easily recognized in outcrop by their white to pale buff colour and fragmental texture (Fig. 2). Subangular to bomb-like fragments 2-30 cm in large dimension repose in a fine grained groundmass, and occasional fragments up to several metres in diameter may be present. The matrix commonly displays a finely contorted lamination that bends around the fragments and is suggestive of flow structure. Felsic metavolcanics along Highway 627 contain thin interbeds of greywacke and argillite. Carbonate alteration is ubiquitous in the form of fine veinlets, irregular patches and individual crystals in the matrix.

Table of Formations

Era	Period	Group	Map unit	Lithology
Cenozoic	Quaternary		14	silt, sand, gravel, varved clays, peat, glacial till and outwash
unconformity				
Precambrian	Neohelikian	Coldwell complex (units 6-13)	13	lamprophyre and analcite trachyte
			--intrusive contact	
			12	nepheline syenite, malignite
			--intrusive contact--	
			11	alkaline gabbro and basalt
			--intrusive contact--	
			10	augite-amphibole-syenite
			--intrusive contact--	
			9	gabbro, layered gabbro (may be older than 6, 7, 8 in part)
			--metasomatic contact--	
			8	barkevikite syenite
			--metasomatic contact--	
			7	metasomatized and remobilized country rocks (ultrafenites)
			--metasomatic contact--	
			6	metasomatized country rocks (fenites)
	intrusive contact			
	Helikian(?)		5	diabase and dolerite dykes
	intrusive contact			
	Helikian and Archean		4	Hornblende-biotite granite, granodiorite, granitic gneiss
	intrusive contact			
	Archean		3	greywacke, slate, and derived gneisses and schists
			2	rhyolite and dacite porphyry – agglomerate and tuff, derived phyllitic schists and gneisses
			1	Massive and pillowed basaltic and andesitic flows and tuffs; derived amphibolitic schists and gneisses

In thin section the rocks can be seen to consist of a fine grained aggregate of quartz, alkali feldspar, while mica and carbonate, with small amounts of chlorite, epidote and actinolite. Recognizable phenocrysts of alkali feldspar and quartz occur in some specimens.

Felsic volcanic rocks show good lamination now commonly converted to schistosity. Complex, small-scale, drag folding is common, but apparently unsystematic.

Salic metavolcanics appear to interfinger with mafic volcanic rocks along Dead Horse Creek and with sedimentary rocks along Highway 627. Where intruded by the Coldwell complex the rocks have been locally altered to hornfels, but

more commonly they have been remobilized into complex rheomorphic flow patterns (Fig. 3). Along the eastern side of the complex a well defined flow banding in the metavolcanic rocks parallels the igneous contact.

No strongly regionally metamorphosed equivalents of the salic volcanics were observed by the author although such rocks have been described by Walker (1967). The quartz-sericite schists, described by Puskas (1967) as equivalent to salic volcanics, display large amounts of normative corundum (Table 1) and more closely approach the composition of metasedimentary rocks.

Metasedimentary rocks (unit 3) form a belt about 2 km wide, intersected by the west side of the intrusion near Middleton. Similar rocks outcrop east of the intrusion along Highway 17, where they are intercalated with salic metavolcanic rocks. The best exposed sedimentary section occurs in Dead Horse Creek. Greenish to steel grey greywackes rest unconformably on mafic volcanics. The greywackes display 3 to 10 cm-thick graded beds, passing from a coarse lower portion, which may contain rounded pebbles of slate, volcanics or chert, up into fine grained slaty tops which are in sharp contact with the overlying bed. Just south of Highway 17 the rocks are cross-bedded. The rocks have a schistose or phyllitic texture with cleavage crossing bedding at a low angle.

In thin section the rocks were seen to consist of rounded quartz and feldspar fragments set in a fine grained matrix of chlorite, talc, actinolite and epidote, with local areas of mosaic quartz and plagioclase, and rare clots of magnetite and sphene.

Chemical analysis of a greywacke from Dead Horse Creek (Table 1) shows a high content of normative corundum, suggesting a high original clay content.

A variety of leucocratic quartz-feldspar-mica gneisses and schists outcrop on the edges of the greenstone belt. These rocks were correlated by Walker (1967) with the sedimentary rocks, and by Puskas (1967) with the salic metavolcanics. Chemical analysis of a typical schist from the vicinity of Three Finger Lake shows its composition to be similar to the greywackes, with the characteristic high Ni and Cr content. I conclude that the gneisses correlate best with the sedimentary rocks, and this correlation has been used on Figure 17 (unit 3a).

Granite intrudes the volcano-sedimentary assemblage east of the map-area along Highway 17, as well as north of the Coldwell complex. Extensive migmatite zones were developed at granite-greenstone contact. The greenstones are amphibolitic and a perceptible rise in metamorphic grade, marked by appearance of amphibole crystals and garnet, can be detected as far as 2 km from the contact. Within the migmatite zone numerous small scale intrusive relations between granite and amphibolite can be observed. The intrusive phase is relatively rich in potash feldspar and rather massive. No contacts between greenstone and the gneissic, linedated granodiorite typical of the area north of the complex were seen.

The intrusion of the volcano-sedimentary assemblage by the Coldwell complex resulted in the formation of marginal hornfels, rheomorphic rocks and extensive metasomatism. Hornfels is best exposed west of the complex along the upper part of Dead Horse Creek, whereas intricately deformed rheomorphic rocks are well exposed on Highway 17 east of the complex.

The hornfels aureole can be recognized from the brownish, baked appearance of the rocks, which take on a colour distinctly darker than normal and become much harder and tougher. Although foliation may be preserved, the rocks

Table 1

Chemical analyses of Archean volcano-sedimentary rocks

	1	2	3	4	5	6
SiO ₂	62.5	58.7	50.0	49.51	49.75	71.3
TiO ₂	0.77	0.67	1.00	0.66	1.08	0.34
Al ₂ O ₃	20.2	19.8	14.6	14.98	14.62	12.5
Fe ₂ O ₃	0.6	1.2	2.2	2.90	2.60	1.3
FeO	5.1	5.4	9.3	7.69	9.04	1.8
MnO	0.06	0.07	0.21	0.18	0.21	0.08
MgO	2.6	3.2	6.6	7.25	6.07	0.3
CaO	2.4	1.7	8.9	11.11	9.08	1.6
Na ₂ O	3.0	2.4	2.8	2.75	2.42	4.5
K ₂ O	1.9	3.0	0.7	1.13	0.34	3.0
H ₂ O	2.1	3.6	3.0	1.62	3.32	3.0
CO ₂	0.0	0.0	0.20	0.0	0.76	0.13
P ₂ O ₅	0.17	0.16	0.46	0.33	0.20	0.11
Sample description and location						
1. Deformed quartz-sericite schist, Highway 17 at Three Finger Lake. Trace elements Cr 0.020, Ni 0.011. Molecular norm has 9.25% corundum (70036)*.						
2. Fine grained greenish greywacke, Dead Horse Creek. Trace elements Cr 0.025, Ni 0.015. Molecular norm has 9.90% corundum (70062)*.						
3. Fine grained greenish basalt, Dead Horse Creek. Trace elements Cr 0.054, Ni 0.043 (70186)*.						
4. "Gabbro" from inclusion just east of Little Pic River (Herdman 1974, p. 31, analysis 77, analyst J. Muysen).						
5. Average Archean basalt of the Canadian Shield, (Baragar, 1972, Table 1, p. 132, average of columns 1-4).						
6. Agglomeratic rhyolite, intersection of Highways 17 and 627. (70197)*						
Analyses in columns 1, 2, 3 and 6 by Rapid Methods Group, Geological Survey of Canada.						
* Sample number; location plotted on Figure 17.						

break conchoidally. No sharp contacts with igneous rocks are exposed. The hornfels becomes slightly coarser grained nearer the igneous rocks, and nebulous syenitic schlieren and patches appear, together with rheomorphic veining. Such rocks are essentially migmatitic. Chlorite and actinolite in mafic volcanics are converted to subhedral prisms of blue-green amphibole and diopsidic augite appears in the migmatitic zones. Plagioclase is less altered and more euhedral in the hornfels but not significantly different in composition. In salic rocks biotite occurs in the hornfels and hypersthene in the migmatite. Potassic feldspar forms sieve-like poikiloblasts and quartz displays strong optical orientation. The nature of the intrusive alkaline rocks makes little difference to the type of hornfels. East of the complex, country rocks are in contact with gabbro, but the hornfels is similar to that west of the complex where syenite is the apparent intrusive rock.

Rheomorphic contact rocks are exposed on Highway 17 at the eastern contact of the complex. These rocks now trend parallel to the contact, with moderate to steep dips. Innumerable small folds of diverse attitude are present. The whole rock gives the impression of having been plastic (Fig. 3). Some inclusions seem to visibly assimilated. The mineralogy of these rocks resembles the migmatitic parts of the hornfels aureole. No clear-cut dykes of igneous rocks were found in the rheomorphic aureole and during intrusion of the Coldwell complex it probably acted as a highly viscous liquid rather than as a brittle solid.

The age of formation of the volcano-sedimentary assemblage is not definitely known. It appears correlative with other Archean greenstone belts in northern Ontario. A K-Ar age on biotite from probably correlative rocks at Manitouwadge, 75 km to the northeast, gave 2465 m.y. (Wanless, 1969).

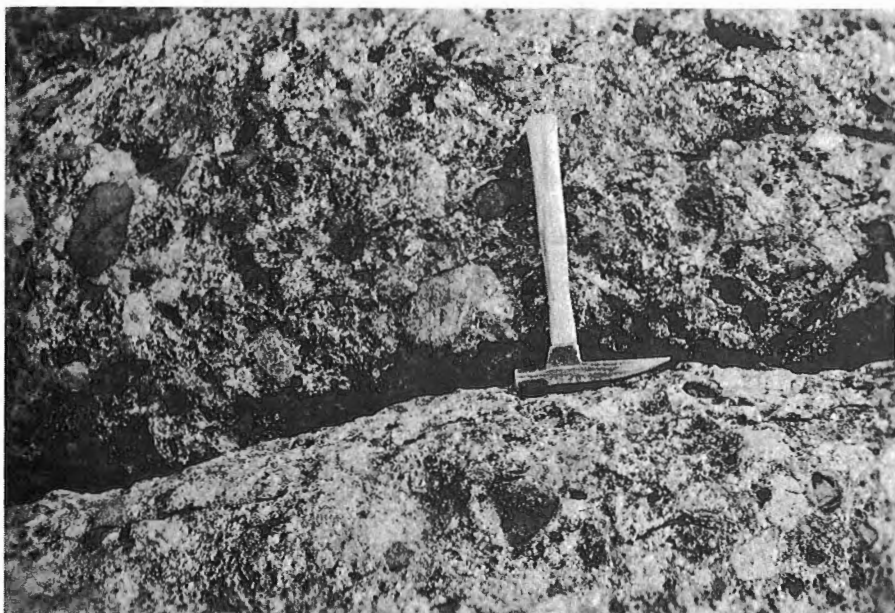
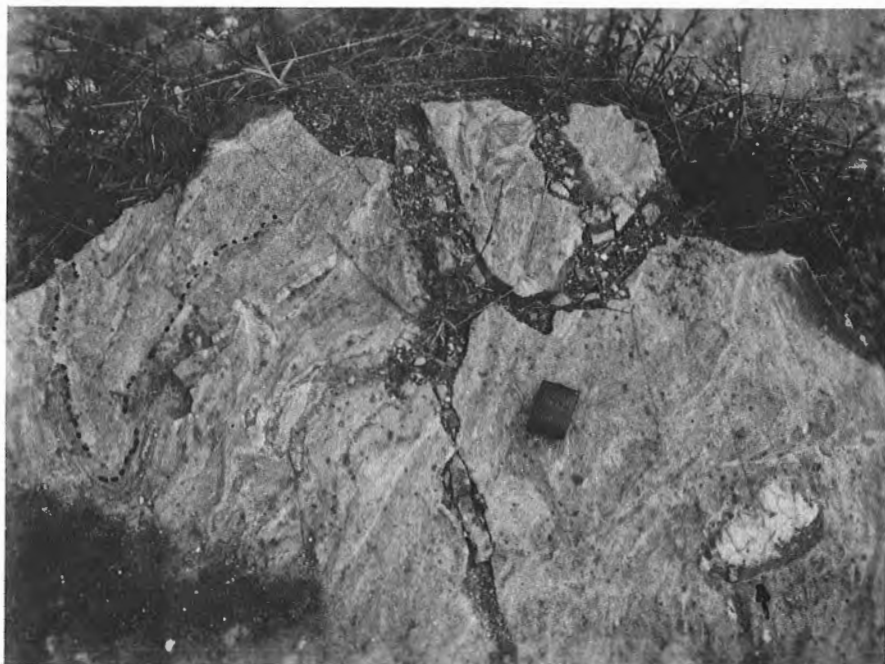


Figure 2.

Fragmental (agglomeratic?) felsic volcanic. Highway 17 at Highway 627. Fragments are amphibolite (dark) and banded rhyolitic rocks. (GSC Photo 203034-I).

Figure 3.

Rheomorphic breccia of felsic volcanics. Note large block with reaction rim in lower right, complexly folded, banded rhyolite at left. Spotted appearance of rock is due to biotite developed in hornfels zone. (GSC Photo 203034-D).



Granitoid rocks (unit 4) of two contrasting types outcrop in the vicinity of the Coldwell complex. The older granitoid rocks consist of buff to greenish biotite granodiorite gneiss, commonly displaying rodded quartz. These rocks are intruded by, or are gradational to, more potassic and leucocratic hornblende-biotite quartz monzonite. Granitoid gneisses underlie the extreme northwestern corner of the map-area, and a broad but rather ill defined band trends northeast from Martinet and Boyer lakes. Massive monzonitic rocks form three well defined bodies, one just intersecting the east edge of the map, the second forming a large rounded mass touching Little Pic River, and the third, a small squarish intrusion outcropping just west of Willie Lake. None of the granite bodies north of the complex is easily accessible, but both types of granite can be examined east of the map area along Highway 17.

The petrographic similarity of all specimens examined suggests that the two types of rocks do not vary greatly. The gneissic granite forms buff or greenish, coarse grained rocks with ubiquitous lineation due to rodding of quartz. More mafic and syenitic phases occur near the margins where the rock passes into migmatite or *lit-par-lit* gneiss. Amphibolitic blocks or schlieren occur throughout the mass. In thin section the rock is seen to consist mainly of quartz and andesine (An_{25}) with lesser amounts of yellowish biotite and accessory green amphibole and microcline. Spinel and garnet are occasionally present. The rocks exhibit a complicated strain texture, with mosaic structure, mortar, and shredding and regrowth of minerals testifying to complex and severe deformation.

The more massive granitic rocks consist of roughly equal amounts of andesine (An_{27}), microcline and quartz, with euhedral yellow brown biotite and a pale green amphibole. Long, slender zircon prisms occur, as well as spinel and an occasional garnet. The rock looks homogeneous and nearly massive, with a pale creamy pink shade. Marginal migmatitic zones are very narrow or absent.

Chemical analysis shows a clear-cut difference between the two types of granitic rocks (Table 2). The massive rocks are typical potassic granite, whereas the gneissic types are granodiorite with an appreciable content of Ni, Cr and Co.

Despite the differences, no clear contact relations between the two could be found. On a small scale the massive granite is seen to intrude and alter the gneissic granite. On map scale however, the contact is gradational, and the two types are complexly intermingled. The gneissic granites have not been radiometrically dated, but such rocks have traditionally been considered syndeformational (McGlynn 1970), and several similar bodies on the north shore of Lake Superior gave ages in the range 2400-2600 m.y. Walker (1967) interpreted the massive granite to be late kinematic, and therefore of similar age. Puskas (1967) believed the mass along the Little Pic River to postdate the Coldwell complex. Chaudhuri et al. (1971) obtained a mineral isochron Rb/Sr age of 1265 ± 20 m.y. for this body, compatible with the age of 1225 m.y. obtained by Fairburn (1959) for the augite syenite of the Coldwell complex. If this date is accepted, all of the enormous granitic mass extending tens of kilometres to the northwest would have to be of the same age, since the Little Pic protrusion can be traced without break into this body. The granite along the Little Pic River has been metasomatized, producing a patchy-coloured reddish rock with a stained net of microfractures. Plagioclase is sericitized, quartz is corroded, alkali feldspar displays large amounts of replacement perthite, and minute prisms of alkali amphibole are developed. These phenomena clearly indicate fenitization by the adjacent Coldwell complex, and hence at least a slightly older age for the granite. The data can be reconciled by assuming large scale metasomatism and

remobilization of the Little Pic River granite by the Coldwell complex. The observed isochron age could then be explained by re-setting of the Sr-Rb clock during emplacement of the Coldwell complex, although the low initial ratio of 0.7015 observed by Chaudhuri et al. (1971) remains rather anomalous on this hypothesis.

Diabase and dolerite dykes (unit 5) ranging from a few centimetres to over 100 m in width cut all older rocks of the area. Commonly the dykes consist entirely of medium grained, massive, equigranular diabase, which may display fine grained to aphanitic margins. Some large dykes contain central pegmatitic cores with crystals up to 10 cm across. Some dykes are porphyritic with plagioclase phenocrysts. In thin sections the dykes are seen to consist of roughly equal amounts of labradorite and an augitic pyroxene with pigeonite lamellae. Granophyric intergrowths of quartz and albite fill interstices. Some dykes contain opaque clots up to a

Table 2
Modal and chemical analyses of granitic rocks

	1	2
SiO ₂	62.4	72.3
TiO ₂	0.61	0.41
Al ₂ O ₃	17.1	13.2
Fe ₂ O ₃	1.6	1.0
FeO	2.4	2.4
MnO	0.06	0.05
MgO	2.1	0.7
CaO	3.8	1.7
Na ₂ O	5.2	2.3
K ₂ O	2.2	5.2
H ₂ O	0.8	0.7
CO ₂	0.0	0.0
P ₂ O ₅	0.26	0.03

Sample description and location

1. Medium grained greenish grey granodiorite, Highway 17 6 km east of Pic River. Specimen consists of quartz 20.4, plagioclase (An_{25}) 26.2, biotite 11.3, amphibole 5.9, spinel 0.1, opaque 0.8, and albite perthite 35.3. Trace elements Sr 0.14, Ba 0.11, Co 0.0035, Cr 0.0014, Ni 0.0027, Zr 0.027, La 0.0073. (70188)*.
2. Pink porphyritic granite, 1 km northwest of Little Pic River crossing on Killala Lake Road. Specimen consists of quartz 26.3, albite 6.1, microcline 39.8, microcline microperthite 10.5, biotite 5.6, amphibole 9.7, spinel 0.3, opaque 1.2. Trace elements Sr 0.0021, Ba 0.0010, Zr 0.031, Nb 0.006, La 0.0062. (70199)*.

Analyses by Rapid Methods Group, Geological Survey of Canada.

* Sample number; location plotted on Figure 17.

centimetre across which consist of pyrite, pyrrhotite, magnetite and ilmenite. Varying amounts of sericite and epidote occur as alteration products.

Within the volcanic rocks the dykes tend to lie either parallel or perpendicular to the foliation, but in the granitic rocks they follow joint sets, trending either northwest or north-northeast. The rocks in contact with the dykes show little megascopic change, although in some cases they are strongly epidotized.

The age of the dykes is unknown, and probably diverse. The compilation of Wanless (1969) suggests that several swarms may be represented, but the presence of preserved granophyric intergrowths strongly implies Proterozoic or younger ages, rather than Archean or Archean ages. The character of the dykes is compatible with other manifestation of Keewawan basaltic igneous activity, and many of the dykes may be roughly comparable in age with the Coldwell complex. Walker (1967) reported that a diabase dyke cuts the Coldwell complex east of Middleton, but no dykes have been found in the main part of the complex.

The Coldwell complex (units 6-13) consists of four major divisions;

- (1) a marginal phase of metasomatized and reconstituted rocks (units 6-8),
- (2) an older, feebly alkaline phase of gabbro and augite-amphibole syenite, (units 9-10)
- (3) a nepheline-bearing series ranging from gabbro to nepheline syenite, (units 11-12)
- (4) a complex but essentially bimodal suite of alkaline dykes, (unit 13)

A distinctive group of rocks, collectively termed the marginal phase, occurs where the alkaline complex invades granitic rocks along Little Pic River and south of Coubran Lake. The degree of alteration and reconstitution within these rocks ranges from mild to complete. Abrupt and rapidly gradational contacts are found on all scales from hand specimen up to mappable units, so that erection of rock units must necessarily be somewhat arbitrary. Rocks that display pronounced metasomatism and disruption, but in which much

of the original texture is preserved can be termed fenites and ascribed to alkaline metasomatism along cracks and joints, with some lesser soaking of the body of the rocks (Currie and Ferguson, 1971). In addition to recognizable fenites, the margins of the Coldwell complex display large volumes of igneous-looking rocks which display many gradational areas of country rock composition and texture, and exhibit features clearly due to metasomatism (unit 7). These rocks are interpreted to be equivalent to the ultra-fenites of von Eckermann (1948), that is rocks so extensively reconstituted that their original form cannot be determined. A confusing series of rocks, intermediate between augite-amphibole syenite (unit 10) and the fenites, appears to have passed through an igneous phase, although textures and compositions vary markedly from the main intrusion. I interpret these rocks (unit 8) as metasomatized and remobilized basement rocks, that is rheomorphic fenites in the sense of von Eckermann (1948).

Fenites (unit 6) can be examined in road cuts along Highway 17 just east of Neys Provincial Park. As is typical of this complex, this occurrence forms a rather small enclave in the surrounding rheomorphic fenites. Similar enclaves occur in railway and highway cuts east of Red Sucker Cove. Fine, irregular, hematite-filled fractures riddle the rock, giving it a chaotic, disaggregated appearance, and a brick-red or purple colour. Such rocks contain jagged, open cavities up to a centimetre wide. In strongly fenitized rocks breccia veinlets up to a centimetre across fill the fractures. In such rocks crystals of secondary feldspar can be seen in remnants of the original rock. The most advanced stage of reconstitution may be either a gritty, reddish rock with accicular 'phenocrysts' developed from the breccia, or a medium grained porphyritic trachytoid syenite developed by recrystallization of the host rock. All variants can be found within a single outcrop, and several variants may be exposed within a few centimetres. The reddish, fine grained rocks locally cut the rest with sharp, dyke-like walls, but if these 'dykes' or apophyses are traced along strike they grade imperceptibly into breccia nests, or into ordinary fenite. Such 'pseudo-dykes' characterize fenite zones (Ferguson and Currie, 1972; Currie, 1971).

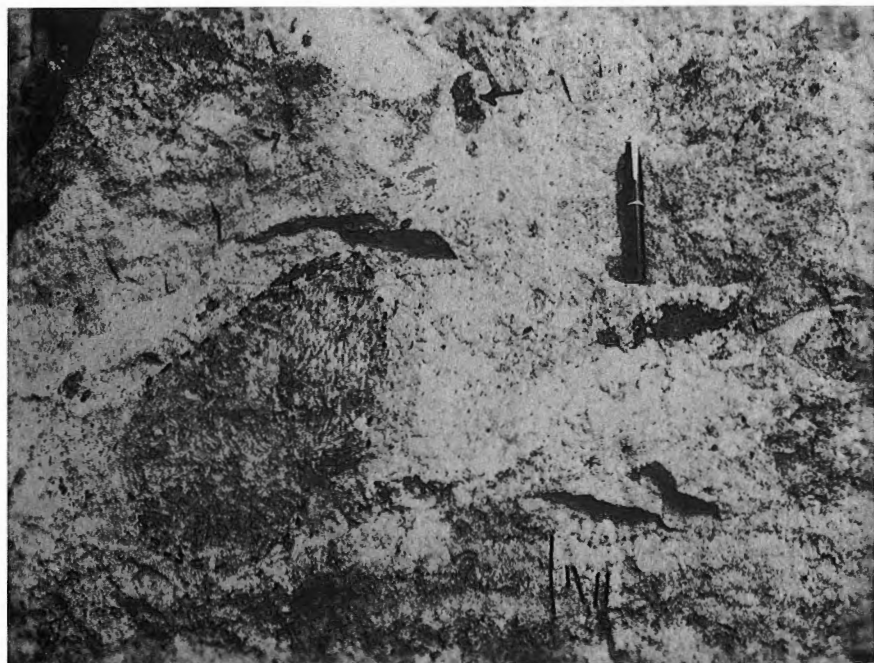


Figure 4.

Metasomatized amphibolite fragments in fenite. Fragments have developed abundant potash feldspar laths and are quite nebulous. The rock has a weak fabric parallel to pen. (GSC Photo 203034-E).

At Neys Provincial Park recognizable, but highly assimilated, amphibolitic schlieren occur in the salic rocks (Fig. 4), and the highway crosses a large inclusion of greenstone. Along the highway north of Red Sucker Cove an old dyke, presumably originally a diabase of unit 5, occurs in the fenitized rocks. The dyke now exhibits an irregular sinuous course, and contains large amounts of brown amphibole and biotite. Various assimilated mafic fragments occur in the syenites between Red Sucker Cove and the highway. With these minor exceptions, all observed fenitized rocks appear to stem from granitoid parents, although the alkaline complex lies mainly within a greenstone belt. The virtual absence of mafic fenites from the central part of the complex appears to require a structural explanation.

In thin section, the fenites are seen to consist mainly of dusty perthitic feldspar ranging from fine rod perthite to coarse patch perthite, even within the same grain. Grains vary in size and exhibit complexly sutured boundaries. Large feldspar grains contain small areas of clear feldspar with peculiar wavy extinction but no perthitic structure. This material has a relatively small optic angle (60-70° compared to 80-90° in the perthite), presumably indicating remnants of an originally less ordered feldspar phase. Corroded granules or mosaic patches of quartz, easily detected by its water-clear character, occur sparsely within or around the perthite. Albite occurs only as haloes around these granules. The quartz-albite aggregates display a complex radiating pattern of small cracks. Some fenites contain only chlorite as a mafic silicate. Chlorite occurs intergrown with rounded magnetite granules in a reticulate network pseudomorphous after amphibole. In more altered but still recognizably granitic rocks, fine grained aggregates of weakly pleochroic amphibole occur (X=yellowish, Y=pale green, Z=pale green, -2V=73, $\angle \alpha = 73^\circ$). These properties suggest hastingsitic amphibole, but chemical analysis gives a barkevikitic composition (Table 3). The rocks east of Little Pic River contain an arfvedsonitic amphibole in sheaves of small crystals (Table 3). Biotite does not occur in strongly fenitized rocks. Ilmenite, apatite, zircon and calcite occur in trace or accessory amounts.

Some chemical analyses of fenites are given in Table 4. Suites of specimens were analyzed from the Neys Park locality, from Little Pic River, and from mafic schlieren. Two contrasting processes seem to be involved. The path of fenitization shown by columns 4-6 of Table 4 compares well with that described for granitoid rocks by Currie and Ferguson (1971), involving loss of SiO₂ gain of alkalis and rare-earths, and oxidation of iron. Analyses 8-11 can be interpreted to result from metasomatism of basalt, with little change in silica content, marked decrease in iron, magnesium, and calcium, and great increase in alkalis. Currie and Ferguson (1972) showed that these apparently diverse paths of metasomatism are consistent with the circulation of the same alkaline brines through rocks of differing compositions. Both courses tend to converge toward a rather mafic, just saturated, syenite, with which the brines are presumably in equilibrium. Analysis 7 of Table 4 represents a rather homogeneous syenitic rock found in moderate amount in fenitized areas. This material is interpreted by the writer to result from partial melting of fenitized rocks during metasomatism, an interpretation that is further discussed in the final chapter.

Analyses 1-3 of Table 4 exhibit a trend of metasomatism which cannot be reconciled with normal fenitization. These rocks exhibit increase in silica with increasing metasomatism, modally expressed by the appearance of myriads of minute quartz crystals on fracture planes, and large increases in K:Na ratio. The process therefore resembles granitization (Marmo, 1971, p. 184ff.). In some instances this type of metasomatism appears to be

Table 3
Chemical analyses of minerals from fenites

	1	2	3	4	5	6	7	8
SiO ₂	50.8	50.7	45.0	38.7	63.7	60.9	63.1	64.2
TiO ₂	1.1	0.8	0.8	3.5	0.0	0.1	0.0	0.0
Al ₂ O ₃	0.5	0.9	4.5	10.6	19.7	23.6	22.9	19.1
FeO*	36.7	35.7	33.2	26.9	0.2	0.2	0.5	0.4
MgO	0.0	0.1	1.8	3.86	0.0	0.0	0.0	0.0
CaO	0.1	0.4	8.1	12.09	0.4	4.7	3.8	0.3
Na ₂ O	9.2	7.5	4.5	2.45	4.2	8.4	8.8	2.8
K ₂ O	0.7	1.5	1.1	1.04	10.2	1.5	0.6	12.6
*Total iron reported as FeO								
Si	7.96	8.00	7.18	6.13	2.93	2.74	2.81	2.96
Al ^{iv}	0.04	0.00	0.82	1.87	1.07	1.26	1.19	1.04
Al ^{vi}	0.06	0.16	0.03	0.11	0.00	0.00	0.00	0.00
Fe ³	0.78	0.94	0.21	0.00	0.01	0.01	0.01	0.01
Ti	0.12	0.10	0.10	0.41	0.00	0.00	0.00	0.00
Fe ²	4.04	3.78	4.22	3.51	0.00	0.00	0.00	0.00
Mg	0.00	0.03	0.44	0.91	0.00	0.00	0.00	0.00
Ca	0.02	0.07	1.39	2.05	0.03	0.23	0.19	0.02
Na	2.79	2.28	1.39	0.75	0.31	0.69	0.76	0.25
K	0.15	0.29	0.22	0.21	0.69	0.08	0.03	0.73
1.	Arfvedsonite, reddened granite 1 km east of Hwy. 17 bridge over Little Pic River. (70141)*.							
2.	Arfvedsonite, brecciated granite, Little Pic River at Killala Lake Road. (70187)*.							
3.	Barkevikite or kataphorite, fenite breccia on Hwy. 17 at Neys Park. (70122)*.							
4.	Kaersutite, fenitized basalt on Hwy. 17, 0.5 km west of Neys Park. (70201)*.							
5,6.	Coexisting alkali feldspar (5) and plagioclase from metasomatized rocks at Little Pic River Bridge, Hwy. 17. (specimen 70121 of Table 4).							
7,8.	Coexisting alkali feldspar (8) and plagioclase (7) from purple fenite breccia near Neys Park (specimen 70122c of Table 4).							
Electron probe analyses by R. Coy-Yll, École Polytechnique.								
* Sample number; location plotted on Figure 17.								

Table 4
Chemical analyses of fenites

	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	63.3	6.3	69.4	72.3	67.7	59.4	61.96	50.1	48.6	49.7	49.6
TiO ₂	0.61	0.38	0.30	0.31	0.44	0.16	0.74	1.01	1.19	1.54	0.86
Al ₂ O ₃	17.3	15.4	15.2	13.9	15.1	19.1	16.54	14.6	15.3	15.1	17.0
Fe ₂ O ₃	1.6	1.6	2.7	1.9	1.8	2.4	3.18	2.2	3.9	3.2	1.3
FeO	2.4	3.6	0.8	1.5	1.7	3.0	3.02	9.3	6.8	7.5	4.5
MnO	0.06	0.15	0.06	0.09	0.06	0.17	0.11	0.21	0.22	0.16	0.11
MgO	2.1	0.2	0.3	0.6	0.5	0.8	0.42	6.6	5.8	5.7	3.9
CaO	3.8	1.8	0.9	1.3	1.5	1.2	1.78	8.9	10.6	6.9	7.6
Na ₂ O	5.2	4.8	5.8	3.0	4.6	5.7	5.84	2.8	3.5	4.3	6.4
K ₂ O	2.2	5.4	4.8	4.9	5.0	5.8	4.97	0.7	1.3	2.9	2.6
H ₂ O	0.8	0.7	0.8	0.8	0.7	1.5	1.08	3.0	1.6	2.0	2.2
CO ₂	0.00	0.04	0.00	0.0	0.3	0.1	0.18	0.21	0.09	0.20	1.90
P ₂ O ₅	0.26	0.05	0.02	0.12	0.10	0.04	0.18	0.46	1.12	0.43	0.31

Sample descriptions and locations

1. Mildly fenitized granodiorite fragment, Little Pic River bridge on Hwy. 17. Trace elements Sr 0.14, Ba 0.11, Zr 0.03, La 0.007. (70189)*.
2. Quartz syenite, interpreted as moderately fenitized granodiorite (same locality as 1). Trace elements Sr 0.07, Ba 0.12 (70141)*.
3. Purple syenitic breccia (same locality as 1 and 2). Trace elements Sr 0.023, Ba 0.006, Zr 0.037, Nb 0.14, La 0.039, Ce 0.055, Nd 0.020. Columns 1-3 represent a sequence of increasing metasomatism. (70122)*.
4. Fractured, mildly fenitized granite, Neys Park. Trace elements Sr 0.006, Ba 0.001, Zr 0.042, Y 0.009, Nb 0.005. (70122a)*.
5. Fractured granitic fenite (middle zone of Currie and Ferguson 1971). Trace elements Sr 0.005, Ba 0.002, Zr 0.056, Ce 0.050, Y 0.029, Nb 0.030, La 0.020. Same locality as 4. (70122b).
6. Innerzone fenite (purple breccia), same locality as 4 and 5. Trace elements Sr 0.0049, Ba 0.0014, Zr 0.042, Ce 0.064, Y 0.034, Nb 0.020 (Analyses 4, 5, and 6 represent a fenitization sequence, from mildly to strongly fenitized rocks.)
7. Average of two quartz syenites, Neys Park area (Herdman 1974, p. 31). These rocks are interpreted here as anatectically melted fenite.
8. Archean basalt, Dead Horse Creek. Trace elements Sr 0.056, Ba 0.021, Cr 0.070, Ni 0.11, Zr 0.033, Nb 0.005, Y 0.0044. (70186)*.
9. Basalt inclusion in syenite, northwest of Neys Park. (Herdman 1974, p. 31).
10. Strongly metasomatized basaltic schlier in fenite, Guse Point. Trace elements Sr 0.056, Ba 0.10, Cr 0.006, Ni 0.0031, Zr 0.029, Nb 0.016, La 0.013, Y 0.0030. (70167)*.
11. Strongly assimilated amphibolite fragment, Red Sucker Cove. Trace elements Sr 0.052, Ba 0.10, Cr 0.013, Ni 0.0085, Zr 0.036, Nb 0.029, La 0.015, Y 0.004. (69150a)*.

Analyses by Rapid Methods Group, Geological Survey of Canada

* Sample number; location plotted on Figure 17.

overprinted by later fenitization. These observations can be explained by assuming that the metasomatizing fluids derived not from the alkaline complex, but from the country rocks. If they were initially drawn inward toward a water undersaturated complex and there heated and equilibrated with granitoid rocks, the metasomatism caused by the return of these fluids would agree with the experimental data of Burnham (1967). This model is considered in more detail in the final chapter of this report. An implication of such a model is that metasomatism of this type could only be expected outside the alkaline complex proper. This appears to be the case for the Coldwell complex.

The fenites display extraordinarily complex internal structure dominated by shattering and brecciation. Streaky gneissosity is locally present, either inherited from a precursor or developed by mobilization during fenitization. No pattern can be discerned in the fracturing, which seems to trend in every conceivable direction and to anastomose with bewildering complexity. Fenites tend to be associated with syenitic, particularly nepheline syenitic, rocks rather than mafic rocks. Although veins of syenite or nepheline syenite can locally be found in the fenites, sharp contacts between fenites and syenitic rocks cannot be found on a large scale. Numerous clear-cut intrusive contacts can be observed between fenites and mafic rocks, for example around Coubran Lake and at the head of Red Sucker Cove. The fenitic zone north of Red Sucker Cove is riddled with dykes of alkaline gabbro, which can be correlated with unit 11. Since the mafic rocks are intruded and brecciated by nepheline syenite, the fenites must represent an early event in the formation of the Coldwell complex. No fenites unequivocally associated with the eastern part of the complex have been recognized, and fenitization may possibly be later than emplacement of these rocks.

A mildly fenitized rock from Little Pic River near the Killala Lake road was submitted for age determination by the K-Ar method on biotite. The resultant age, 1015 ± 36 m.y. ($K=6.87\%$, 97% ^{40}Ar , G.S.C. K-Ar date 1885), essentially coincides with the age of a gabbro from Three Finger Lake (1005 ± 36 m.y.; $K=7.00\%$, 98% ^{40}Ar , G.S.C. K-Ar date 1884). Presumably both dates represent cooling ages. If the Rb/Sr isochron ages of 1265 m.y. obtained by Chaudhuri et al. (1971) on the Little Pic River granite, and 1225 m.y. obtained by Fairbairn (1959) on the augite syenite represent formation ages, then the thermal histories of the intrusive rocks and the fenites have been essentially congruent.

Ultrafenites and reconstituted rocks (unit 7) resemble fenites but have a darker, more igneous appearance. They outcrop in an irregular belt from Coubran Lake to Craddock Cove and on the islands to the south. A strip of similar rocks outcrops on Coldwell Peninsula and enclaves of similar rocks are rather common within the rheomorphic syenites of unit 8 of the western part of the complex. In outcrop these rocks vary from brownish grey, coarse syenodiorite to red, fine grained trachyte and porphyritic syenite. Neither boundaries against other units, nor internal contacts can be clearly defined because of innumerable gradations toward the more fractured and oxidized fenitic rocks on the one hand, and the syenitic rocks of units 8 and 10 on the other. The rocks commonly look composite, or hybrid. Colours have a reddish tinge, but vary greatly even within a single specimen. In rocks gradational to fenites the colours are bright, but patchy, and colour streaks are present along fractures. Olive to brownish shades are common, but the rocks look hybrid even when the grain size is regular and no macroscopic compositional banding is evident. Reddish microsyenitic patches or vein-like masses occur, characterized by aligned potassic feldspar microlites and minute pyroxene needles. Although these syenitic patches may show complex interfingering relationships with the darker matrix, clear cut intrusive relationships

were not observed. A narrow gradational zone always separates the dark and red portions and there appears to be complete gradation from the microsyenite to brick red gritty trachyte. The latter is commonly shattered with the formation of irregular open cavities, occasionally lined with small granitic fragments. The darker matrix of the rocks passes from black to reddish tinge in the more hybrid rocks, to a rich brownish black in more homogeneous material. The grain size of the dark material is always coarser than that of the light bands, and the dark homogeneous rocks contain large feldspar crystals. In some places such rocks cannot be reliably distinguished from the brown syenites of unit 10. Reconstituted basic rocks were not recognized within this unit, but abundant mafic fragments occur within it along Highway 17 north of Red Sucker Cove. Most of these fragments contain large porphyroblasts of potassic feldspar and are relatively coarse grained. Their provenance cannot be certainly identified. They may come from mafic units of the alkaline complex or from the greenstones of unit 1. Fine grained fragments consisting principally of chlorite, very altered plagioclase and secondary carbonate occur in much smaller numbers. They are presumed to derive from the Archean volcanic rocks.

When seen in thin section the ultrafenites exhibit considerable textural and mineralogical diversity. Quartz occurs but rarely, and when present forms rounded and corroded granules. Many of the rocks exhibit an unusual mosaic seriate texture with interstices filled with golden chloritic films. Others have more granoblastic textures with patches of feldspar rosettes. Rosettes and trachytic patches of clear feldspar do not form the major feldspar in any section. Older, cloudy, commonly mosaic feldspar, similar to that in the fenites, occurs in all sections, either as rounded patches or as a mosaic matrix in which new feldspar develops. The most common type of feldspar is patchily extinguishing material with anomalous bluish extinction, presumably due to development of submicroscopic perthite. Plagioclase occurs only as small irregular grains that commonly display chess-board twinning. Microlites of more calcic plagioclase, about An_{25} , occasionally occur in the midst of potassic feldspar rosettes. Some rocks include as the mafic mineral, only a golden, almost nonpleochroic chlorite that probably replaces pyroxene. Most sections contain relics of an augitic pyroxene (Table 5) which is almost colourless and has positive 2V near 70° . This pyroxene may be fringed by a deep green but nonpleochroic pyroxene similar to some of the faintly alkaline pyroxenes of the alkaline igneous rocks of the Coldwell complex. A few rocks contain considerable amounts of a very dark brown, almost opaque amphibole. Microprobe analysis shows this mineral to be very rich in iron; it is probably best referred to as ferro-hastingsite. Biotite was seen in two specimens, but the outlines were cusped and corroded, and the mineral is probably relict. Hematite is ubiquitous as fine dust, either interstitial or within older feldspars. Pyrite is common in the redder rocks. Clear euhedral apatite is a common accessory.

The chemical compositions of the ultrafenites (Table 6) lie between those of the igneous syenites and those of the fenites. They vary from slightly quartz-normative (70080, 69001) to slightly nepheline-normative (70153). They tend to be higher in sodium and rare-earth contents than the fenites and lower in silica and alumina. They closely approach the composition of the igneous syenites (unit 10), although lower in iron and calcium. There appears to be complete gradation from metasomatized rocks through ultrafenites to truly igneous varieties.

Barkevikite syenite (unit 8) outcrops as massive, coarse grained, intensely red rocks. Such rocks occur along Highway 17 northwest of Coldwell, and in smaller amount between Hare and Knob lakes, as well as in less homogeneous

Table 5
Chemical analyses of minerals from ultrafenites

	1	2	3	4	5	6	7
SiO ₂	35.3	51.6	63.4	64.6	36.8	50.2	42.0
TiO ₂	5.8	0.0	0.0	0.0	5.2	0.3	1.8
Al ₂ O ₃	13.3	2.7	22.9	19.4	13.7	2.3	7.3
FeO*	25.9	14.4	0.09	0.04	22.4	14.9	29.3
MgO	8.2	8.1	0.0	0.0	10.3	10.0	2.8
CaO	0.0	21.2	4.2	0.4	0.0	20.8	11.4
Na ₂ O	0.2	0.6	8.9	3.7	0.2	0.6	2.4
K ₂ O	9.4	0.0	0.5	11.0	9.7	0.0	1.1
*Total iron reported as FeO							
Si	2.70	1.96	2.80	2.96	2.76	1.95	6.64
Al ^{iv}	1.22	0.04	1.19	1.04	1.21	0.05	1.36
Al ^{vi}	0.00	0.08	0.00	0.00	0.00	0.06	0.01
Fe ³	0.00	0.00	0.02	0.01	0.00	0.02	0.52
Ti	0.33	0.00	0.00	0.00	0.29	0.01	0.22
Fe ²	1.66	0.46	0.00	0.00	1.40	0.45	3.33
Mg	0.94	0.46	0.00	0.01	1.16	0.46	0.68
Ca	0.00	0.95	0.21	0.02	0.00	0.95	1.94
Na	0.03	0.05	0.78	0.34	0.03	0.05	0.74
K	0.92	0.00	0.02	0.65	0.93	0.00	0.23

1. Biotite, reddish brown monzonite, Coubran Lake (specimen 70153, Table 6).
2. Pyroxene, same rock as 1 (average of 3).
3. Plagioclase, same rock as 1 (average of 6).
4. Alkali feldspar, same rock as 1 (average of 4).
5. Biotite, reddish brown trachytoid syenite, Knob Lake (specimen 69001 of Table 6).
6. Pyroxene, same rock as 5 (average of 2).
7. Amphibole (ferrohastingsite), same rock as 5 (average of 2).

Analyses 1, 2, 5, 6 by G.A. Lachance, Geological Survey of Canada, analyses 3, 4, and 7 by R. Coy-Yll, École Polytechnique.

masses on Pic, McDonald and Foster islands. The rock can be recognized by its coarse grained character, intense reddish or purplish colour, and acicular mafics. Irregular colour streaking is common and the rock locally shades into brown tones indistinguishable from syenite of unit 10. East of Middleton and around Hare Lake crude layering of units 8 and 10 is present. Typically the rocks consist of tabular feldspar crystals up to 7 mm in length forming a reticulate network with greenish black interstitial mafics. Sheaves and rosettes of feldspar crystals may be present.

Innumerable gradations occur between red syenite, brown syenite and hybrid rocks. South of Coubran Lake assignment of outcrops to a particular unit becomes almost arbitrary. West of Little Pic River the distinction between units 7, 8 and 10 disappears in an area of syenitic rocks of very diverse colour and texture. Gradations occur in colour and texture. Purplish patches, characteristic of reconstituted

Table 6
Chemical analyses of ultrafenites

	1	2	3
SiO ₂	59.3	57.0	60.3
TiO ₂	1.16	0.68	0.34
Al ₂ O ₃	16.5	15.9	18.2
Fe ₂ O ₃	7.3	4.9	1.6
FeO	1.6	5.0	3.7
MnO	0.19	0.25	0.18
MgO	0.2	0.3	0.3
CaO	1.9	2.9	1.3
Na ₂ O	7.9	5.4	6.7
K ₂ O	1.2	4.9	4.9
H ₂ O	1.0	1.0	0.7
CO ₂	0.7	1.3	0.9
P ₂ O ₅	99.2	99.7	99.1

Sample descriptions and locations

1. Heterogeneous grey-green syenite, Hwy. 17, 3 km west of Knob Lake. Total includes Sr 0.013, Ba 0.028, Ni 0.0027, Zr 0.077, Nb 0.029, La 0.026, Nd 0.021, Tb 0.0082, Y 0.0082. (70080)*
2. Dark red-brown trachytoid syenite, 2 km west of Knob Lake on highway. Total includes Sr 0.014, Ba 0.11, Ni 0.0023, Zr 0.070, Nb 0.021, La 0.026, Nd 0.025, Yb 0.00063, Y 0.0057. (69001)*
3. Brown syenite with red schliers, Coubran Lake. Total includes Sr 0.0057, Ba 0.065, Ni 0.0044, Zr 0.12, Nb 0.025, La 0.031, Nd 0.020, Yb 0.0035. (70153)*.

Analyses by Rapid Methods Group, Geological Survey of Canada

* Sample number; location plotted on Figure 17.

Table 7
Chemical analyses of minerals from barkevikite syenite

	1	2	3	4	5	6	7	8	9
SiO ₂	35.1	48.3	39.2	63.2	64.9	34.5	29.9	48.1	38.5
TiO ₂	5.8	1.2	3.3	0.0	0.0	5.5	0.0	0.8	2.4
Al ₂ O ₃	12.0	1.1	9.1	22.9	19.4	12.7	0.0	1.0	8.7
FeO*	35.8	23.4	29.9	0.1	0.1	36.6	65.9	22.4	33.3
MgO	1.4	4.5	2.5	0.1	0.0	1.3	1.8	6.0	1.2
CaO	0.1	21.5	11.0	4.2	0.2	0.0	0.2	21.2	10.9
Na ₂ O	0.2	0.4	3.5	8.9	3.7	0.3	0.0	0.7	2.8
K ₂ O	8.8	0.0	1.6	0.4	11.1	8.6	0.0	0.0	1.5
*Total iron reported as FeO									
Si	2.79	1.98	6.06	2.79	2.98	2.74	1.00	1.95	6.22
Al ^{iv}	1.12	0.02	1.72	1.20	1.02	1.19	0.00	0.05	1.66
Al ^{vi}	0.00	0.03	0.00	0.00	0.00	0.00	0.04	0.00	0.00
Fe ³	0.00	0.02	0.00	0.01	0.01	0.00	0.00	0.10	0.35
Ti	0.35	0.04	0.40	0.00	0.00	0.33	0.00	0.03	0.29
Fe ²	2.38	0.88	4.00	0.00	0.00	2.43	1.90	0.80	4.15
Mg	0.19	0.09	0.60	0.01	0.01	0.16	0.09	0.13	0.31
Ca	0.01	0.94	1.88	0.22	0.01	0.00	0.01	0.92	1.89
Na	0.03	0.04	1.08	0.77	0.34	0.05	0.00	0.05	0.88
K	0.89	0.00	0.33	0.01	0.65	0.87	0.00	0.00	0.31
1. Biotite, coarse red syenite, Hwy. 17 near Coldwell. (Table 8, 70051) 2. Pyroxene (same rock as 1) (average of 3). 3. Barkevikitic amphibole (same rock as 1). 4. Plagioclase (same rock as 1). 5. Alkali feldspar (same rock as 1). 6. Biotite, coarse white syenite, Carden Cove. (Table 8, 70027). 7. Olivine (same rock as 6) (average of 2). 8. Pyroxene (same rock as 6) (average of 2). 9. Barkevikitic amphibole (same rock as 6). Electron probe analyses by G.A. Lachance, Geological Survey of Canada.									

rocks, occur in many red syenites, commonly associated with breccia veinlets or patches. Feldspar lamination, typical of the igneous syenites, has not been found in red syenites. The red barkevikite syenite is therefore a mappable unit, although its genetic significance may be dubious.

In thin section the barkevikite syenites are seen to consist mainly of coarse grained, xenomorphic, seriate feldspar. Large grains approach tabular shape, but with very irregular, sutured edges. Such grains commonly exhibit relict Carlsbad twinning with a very sinuous twin plane. Most of the feldspar forms coarse patch perthite in which many of the plagioclase patches exhibit fine regular albite twinning. The plagioclase in these areas approaches pure albite. Some rocks contain independent small prisms of plagioclase around the margin of the perthite in which the composition approaches An₂₅. Although most feldspar is coarsely perthitic, some sections contain areas of non-perthitic feldspar with peculiar bluish, patchy extinction, presumably due to submicroscopic perthite. Most, but not all, sections contain a small amount of quartz as lobate granules or "worms" in the feldspar.

Characteristically this unit contains barkevikitic amphibole as a mafic mineral (Table 7); this occurs in rosettes or interpenetrating sheaves. The pleochroism varies considerably, but the colours are lighter, and have a more greenish tinge than the amphiboles of unit 10. Large amphibole crystals commonly have a pale green or bluish rim of quite different optical properties which approach those of richterite (presumably ferorichterite since the iron content of the amphiboles is extremely high). Amphibole sheaves commonly enclose small euhedral prisms of feldspar. Pyroxene occurs in all specimens and is more abundant than amphibole in some. The habit varies from large corroded prisms, partially replaced by amphibole, to masses of small granules shredding and replacing larger grains. The pyroxene is nearly colourless but faint green tinges appear along cracks and cleavages. Electron probe analyses (Table 7) indicate a remarkable range in composition from faintly sodic hedenbergite in large grains to essentially pure acmite in the granules. Fayalitic olivine occur as clumps of rounded to subhedral grains, now largely replaced by bowlingite or rimmed by clumps of opaque granules. Biotite forms small radiating clusters in the amphibole. Chlorite occur interstitially. Feldspars are locally zeolitized. Magnetite with exsolved ilmenite occurs in specimen 70027, but 70051 contains no biotite, no oxides, and small amounts of an opaque brownish mineral, possibly aenigmatite.

Table 8
Chemical analyses of barkevikite syenite

	1	2
SiO ₂	57.4	58.4
TiO ₂	1.03	0.85
Al ₂ O ₃	16.3	15.0
Fe ₂ O ₃	1.7	2.7
FeO	8.1	7.7
MnO	0.25	0.27
MgO	0.7	0.2
CaO	3.6	3.1
Na ₂ O	4.7	5.3
K ₂ O	5.3	5.0
H ₂ O	1.0	1.2
CO ₂	0.0	0.0
P ₂ O ₅	0.28	0.13
Total	100.36	99.85

Sample descriptions and locations

1. Coarse grained white syenite, Carden Cove. Analysis includes Sr 0.026, Ba 0.33, Zr 0.029, Y 0.025, Nb 0.012, La 0.011, Sc 0.0017. (70027)*
2. Coarse grained red syenite, Hwy 17, 2 km northeast of Coldwell. Analysis includes Sr 0.007, Ba 0.040, Zr 0.050, Y 0.059, Nd 0.028, Nb 0.020, La 0.021, Yb 0.00064. (70126)*.

Analyses by Rapid Methods Group, Geological Survey of Canada

* Sample number; location plotted on Figure 17.

The chemical composition of the extreme variants of the unit (Table 8) are similar, and approach silica saturation. However the algaic index of analysis 2 exceeds unity, possibly due to alkaline metasomatism. Despite the intensely red colour of the rocks, the ferric/ferrous ratio is not particularly high. A relatively low oxygen fugacity is suggested by presence of the oxygen buffering assemblage quartz-fayalite-magnetite. The hematitic alteration of the rocks is therefore secondary.

Barkevikite syenite shows little internal structure and the rocks are essentially massive with local discoloration and brecciation. The lack of feldspar lamination suggests significant differences from the augite syenite and nepheline syenite (units 10 and 12). Barkevikite syenite exhibits few well defined contact relations. Less reconstituted rocks of units 6 and 7 appear in it as nebulous relicts. On the highway east of Neys Provincial Park the contact of the fenitized complex is marked by rather fine grained variants of the barkevikite syenite; these form an interfingering assemblage of dykes, migmatites, and metasomatized and reconstituted rocks. Although contacts are locally sharp and cross-cutting, the overall impression is of hybridization. A few hundred metres northwest of Coldwell an apparently complete

gradation to augite-amphibole syenite is exposed. A similar gradation occurs at the west end of Seeley Lake. Contacts with nepheline syenite are marked by pegmatitic and hybridized zones in both rocks. Field relations strongly suggest the barkevikite syenite differs from the more massive and homogeneous igneous syenites. The presence of hybrid and brecciated zones within it suggest links to the fenitic rocks that the barkevikite syenite represents the ultimate stage of metasomatism of granitoid country rocks. However the hypothesis that it represents the ultimate stage of magmatic differentiation of igneous syenite can not be excluded. Ambiguous relations between altered country rocks and igneous rocks typify many alkaline complexes.

The eastern gabbro (unit 9) outcrops in a crescentic mass around the eastern side of the intrusion. A somewhat similar, but amphibole-rich, mafic rock forms a ring dyke within the western part of the complex (unit 11). The eastern gabbro can be examined in road cuts on Highway 17 near Three Finger Lake and on mining prospects to the north. The gabbro displays a characteristic magnetic signature (Fig. 5) marked by a prominent magnetic low due to reverse magnetization of the rocks. The termination of this signature shows that the unit has no hidden extensions beyond the known outcrop. The fragments of gabbro in the western part of the complex show magnetic highs, suggesting that they are not parts of the same gabbroic body, as was assumed by Puskas (1967).

In hand specimen the gabbro ranges from fine grained, brownish black rock through coarser, massive varieties to variously layered and laminated types. The rock is strikingly heterogeneous in outcrop. Varieties are intermixed with one another, and in large outcrops coarse to pegmatitic veins and schlieren of white syenitic material are almost always present. Inclusions of metavolcanic rocks are a characteristic feature of the gabbro. In addition to the large mappable inclusions, many thousands of small inclusions riddle the gabbro, ranging down to microscopic size. In some cases for example east of Bamoo Lake the distinction between gabbro and digested country rocks more or less disappears.

Although it is convenient to divide the gabbro into fine grained 'contact' type, massive type, and layered type, these distinctions are not mappable, because of the complex and gradational interrelations between them, even on hand specimen scale.

In thin section the gabbro is seen to consist mainly of labradoritic plagioclase and clinopyroxene, with subsidiary and variable amounts of olivine, biotite, magnetite, ilmenomagnetite, sulphides and apatite. Amphibole occurs in gabbro associated with syenite, and orthopyroxene, alkali feldspar, and even quartz occur in some schlieren-like pods, probably contaminated by inclusions of country rocks. The grain size varies rather abruptly, but pegmatitic varieties occur only in complex hybrids, commonly found near inclusions.

Plagioclase generally occurs in subhedral, tabular, well-twinned grains showing moderately strong zoning from about An₅₅ to An₄₀. Lum (1973) in a detailed petrographic study reported a maximum variation from An₆₀ to An₃₅. Strong orientation of plagioclase is present almost everywhere, although a few specimens show more or less random orientation, yielding an ophitic texture. The most common orientation is a parallelism of the c axes, with the other axes roughly randomly arranged. Less commonly all three axes may be distinctly oriented. Pyroxene ranges from pale yellow nonpleochroic varieties near the diopside-hedenbergite join (Table 9) to rather strongly pleochroic titanium-rich varieties (2V=55°, a=b=pale green, c=reddish green). Although some grains are subhedral, most are strongly corroded, or reduced to wormy masses of granules. An intensely poikilitic, feebly pleochroic, brown amphibole, in some cases almost isotropic,

locally overgrows these masses. Olivine commonly occurs in subhedral grains up to 2 mm across, surrounded by a halo of opaque granules. The amount of olivine is variable, ranging up to 20 per cent, but olivine does not occur in amphibole-bearing rocks. Lum (1973) reported that olivine compositions range from Fo₄₃ to Fo₆₇ with a strong maximum near Fo₅₃. Some parts of the gabbro contain distinctive interstitial clots of magnetite, ilmeno-magnetite, sulphides, and apatite ranging up to a centimetre across. Biotite commonly overgrows the oxide phases. Watkinson et al. (1973) reported pyrrhotite and chalcopyrite to be the most abundant sulphides, with smaller amounts of cobalt-rich pentlandite, cubanite, pyrite, bornite, arsenopyrite and mackinawite. Many sulphide concentrations occur on the boundaries of, or very close to, xenoliths of volcanic rocks.

Puskas (1967) and Watkinson et al. (1973) regard the hypersthene occasionally found in the gabbro as a primary mineral. Lum (1973) did not find orthopyroxene in the massive gabbro or the layered gabbro, the two phases most likely to exhibit uncontaminated mineralogy. I found hypersthene in only two specimens, one from the west end of Three-Finger Lake, and the other from southeast of Bamoo's Lake. In both cases the mineral appeared to be the result of contamination, since it was associated with poikilitic alkali feldspar, and in one case with trace amounts of quartz. Both localities are particularly rich in inclusions of volcanic rocks from the greenstone belt. Chemical analyses of the gabbro (Table 10) suggest a mildly, but distinctly, alkaline character incompatible with the primary crystallization of hypersthene except at extremely high pressures (greater than 10 kilobars). No other evidence of such pressures has been found, and the petrographic character of the mineral is not consistent with relict high pressure origin. In my opinion, the available evidence suggests that the hypersthene originated by contamination, either as xenocrysts from hypersthene-bearing tholeiitic gabbro in the greenstone belt, or from assimilation of quartz-bearing rocks by the alkaline gabbro.

Since the gabbro appears to be hybridized and contaminated in many outcrops, selection of material for chemical analysis presents difficulties. A fine grained, brownish black apophysis which protrudes from the edge of the gabbro into metasedimentary rocks north of Three-Finger Lake was selected. This material appears homogeneous and free of inclusions. D.H. Watkinson kindly supplied four other analyses of fine grained inclusions, presumably cognate, which are very similar to this analysis. Four of the five analyses contain normative nepheline, although in small amount, hence hypersthene would not crystallize from them under crustal conditions. The analyses are similar to the average alkaline andesite of Nockolds (1954), although the potassium content is higher, and the magnesia and lime contents slightly lower than Nockold's values.

Lum (1973) found that olivine and pyroxene showed modest iron enrichment with increasing bulk-rock Fe/Mg, but the trend was not strong. Analyses of biotite and kaersutite during the present study suggested relatively constant compositions. Lum (1973) found that plagioclase composition remained fairly constant over most of the 260-m vertical section studied by him, but fell abruptly from an average value of An₅₅ to about An₃₅ near the top of the section. Olivine showed a maximum forsterite content near the middle of the section, falling roughly symmetrically in both directions. Neither petrographic nor chemical analyses suggest gradation from the gabbro to any other unit.

The gabbro exhibits widespread but erratically distributed layering. Rhythmic layering, with or without grading, is best displayed on the highway near Three Finger Lake. Inch-scale layering occurs locally at the same outcrop,

together with features resembling channel-scours or slumps (Fig. 6). Dark layers are commonly finer grained, in some cases consisting exclusively of oxides, sulphides and apatite. Such bodies occasionally transect the layering. A study of the layering attitudes along Highway 17 showed that they defined an asymmetric anticlinal form, with shallow inward dips toward Peninsula Bay on the west side, and steep dips in the opposite direction on the east side (Puskas, 1970). This configuration indicates that the gabbro is exposed along the top of a cupola. The shape of the magnetic signature suggests that this must be the crest of an almost vertically dipping body.

Table 9
Chemical analyses of minerals from the eastern gabbro

	1	2	3	4	5
SiO ₂	35.3	51.6	38.7	43.4	0.3
TiO ₂	0.0	1.3	2.8	2.2	26.8
Al ₂ O ₃	0.1	3.6	15.4	11.2	2.3
FeO*	38.0	6.7	13.7	10.6	65.2
MgO	25.8	12.4	17.5	15.5	1.9
CaO	0.1	23.5	0.0	12.3	0.6
Na ₂ O	0.0	0.8	0.6	3.1	0.0
K ₂ O	0.0	0.0	9.6	1.6	0.0
*Total iron reported as FeO					
Si	1.00	1.89	2.78	6.24	0.01
Al ^{iv}	0.00	0.11	1.22	1.76	0.00
Al ^{vi}	0.003	0.03	0.08	0.14	0.10
Fe ³	0.00	0.00	0.00	0.20	0.23
Ti	0.00	0.04	0.15	0.24	0.74
Fe ²	0.90	0.21	0.82	1.08	1.79
Mg	1.09	0.69	1.89	3.33	0.10
Ca	0.003	0.94	0.00	1.90	0.02
Na	0.00	0.06	0.08	0.86	0.00
K	0.00	0.00	0.89	0.29	0.00
1. Olivine, fine grained brown gabbro dyke, Three Finger Lake (specimen 70066, Table 10).					
2. Pyroxene, same rock as 1.					
3. Biotite, same rock as 1.					
4. Amphibole, same rock as 1.					
5. Magnetite, same rock as 1.					
Electron probe analyses by R. Coy-Yll, École Polytechnique.					

Table 10
Chemical analyses of eastern gabbro

	1	2	3	4
SiO ₂	48.91	48.79	43.10 — 52.14	47.63
TiO ₂	2.04	1.87	1.33 — 2.04	2.84
Al ₂ O ₃	14.47	14.44	13.34 — 14.87	14.57
Fe ₂ O ₃	4.43	3.70	3.27 — 4.43	3.97
FeO	9.25	9.70	9.06 — 11.26	7.83
MnO	0.22	0.24	0.20 — 0.29	0.18
MgO	4.48	4.72	2.70 — 8.38	7.25
CaO	7.81	8.51	7.81 — 11.60	9.48
Na ₂ O	3.92	3.39	2.13 — 3.92	3.75
K ₂ O	2.28	2.07	0.83 — 2.28	1.20
H ₂ O	0.61	0.82	0.61 — 1.35	0.78
CO ₂	0.00	0.35	0.00 — 0.93	-
P ₂ O ₅	1.02	1.03	1.00 — 1.09	0.52

Specimen description and location

1. Fine grained brownish gabbro. North side of Three Finger Lake. (70066) Analysis includes Sr 0.051, Ba 0.14, Cr 0.0028, Ni 0.0045, Zr 0.033, Nb 0.016, La 0.012, Y 0.0044. Analysis by Rapid Methods Group, Geological Survey of Canada.
2. Average of five analyses of fine-grained gabbroic rocks (70066 plus four analyses supplied by D.H. Watkinson).
3. Maximum range in the five analyses of column 2.
4. Average alkali andesite (Nockolds, 1954).

Widespread rheomorphism and anatexis occur along the contact between the gabbro and the older greenstone belt. These observations suggest that formation of hypersthene-bearing rocks by contamination and assimilation may have been a widespread phenomenon. The contact of the gabbro with the granitoid country rocks north of Boyer Lake was not examined.

The gabbro is consistently intruded by various syenitic rocks. Although these syenitic rocks presumably correlate with unit 10, they are commonly white or pale pink, rather than brownish or reddish. Numerous hybrids between gabbro and syenite were seen, but no instances of gradation from one to another. Gabbro and syenite appear to be separate intrusions at the present level of exposure, with the syenite younger than the gabbro.

Direct relationships between the gabbro and other units of the alkaline complex have not been observed. Gabbroid dykes, perhaps correlative with the eastern gabbro, occur in fenitic rocks south of Coubran Lake. These dykes are somewhat recrystallized and display porphyroblasts of potash feldspar. They therefore predate the end of metasomatism.

Puskas (1970) correlated the eastern gabbro with certain small bodies of gabbro west of the complex near Middleton, and claimed the gabbro passed gradationally into syenitic rocks. The latter claim is clearly disproved by mapping and drilling results. At least part of the western gabbro belongs to alkaline gabbros of unit 11. Some may be metasomatized older gabbro from the greenstone belt (Walker, 1967). None shows the distinctive magnetic signature of the eastern gabbro.

Augite-amphibole syenite (unit 10) Perhaps the best known rock of the Coldwell complex is a homogeneous, coarse grained, olive-brown syenite or monzonite, termed 'laurvikite' by Puskas (1967). Such rocks outcrop in a large crescentic area in the eastern part of the complex, and are transected by numerous highway and railway cuts. Similar rocks appear north of Coldwell and west of the Killala Lake road, but in these regions many of the outcrops are strongly altered.

In outcrop, fresh augite-amphibole syenite is a massive, homogeneous brownish-green rock. The rocks tend to be cut into large square blocks by clean, planar joints. Although the rock is generally massive, close inspection commonly reveals a distinct alignment of feldspars, best detected by reflection of light from crystal faces. Crude

Figure 6.

Inch-scale layering in gabbro, Three Finger Lake area. Some layers show distinct grading suggesting right-side up. Three groups of cyclical layers can be seen from bottom to top. The significance of these cycles is unknown. (GSC Photo 203034-A).



layering, marked by slight colour changes, occurs in some specimens. The lineation direction of the feldspar lies within the layer planes when the latter are present. Finer grained, porphyritic syenite outcrops along the western edge of the mass, from Coubran Lake south to Seeley Mountain. A dyke of similar material cuts metasomatized country rocks on Coldwell Peninsula. Some other subtle variations in texture and colour occur, and the unit may be a composite of several sub-units. No clear evidence of sub-units was recognized during the present study.

In thin section most specimens of the rock are seen to be dominated by alkali feldspar. Although feldspars appear

ehedral in hand specimen, in thin section they show complex sutured boundaries and interstitial mosaic zones. Fine braid perthite occurs on grain margins, and may extend over the whole volume. Commonly the centre of the grain extinguishes in patchy, irregular fashion without visible perthite development. In other grains the central core is albite with well developed twinning. Independent grains of oligoclase occur in some specimens as small tabular grains interstitial to alkali feldspar. All the feldspar has a faint yellowish cast, and a slightly dusty appearance, but visible alteration is rare.

Mafic minerals may be olivine, olivine+pyroxene, or pyroxene+amphibole, but the latter assemblage is by far the most common. Rocks interpreted to lie near the base of the unit contain large amounts of rounded, subhedral olivine, up to 40 per cent in some cases, and clearly represent cumulates. In the rock richest in olivine (42 per cent) the mineral forms a reticulate network with interstitial (adcumulus) pyroxene and alkali feldspar. Electron probe analysis shows the olivine to be markedly richer in iron than the olivine of the gabbro (Table 11). Pyroxene occurs as blocky, colourless grains with greenish margins. The 2V ranges from 50-69° but the extinction angle is strikingly low (8-14°). Electron probe analysis does not suggest strikingly high Ti content (Table 11), and the reason for the anomalous optical property is unknown. In iron-rich rocks the pyroxene is commonly rimmed by and intergrown with a brownish amphibole. In the most leucocratic rocks the amphibole is lighter in colour and has a pale green tinge. The amphibole was termed kaersutite by Puskas (1967) but analysis (Table 11) suggests a hastingsite-type amphibole. Some rocks contain small amounts of biotite, pleochroic from chestnut to pale green. Biotite replaces sphene and magnetite, the two most common accessories. Fluorite occurs in trace amounts, particularly in iron-rich rocks, and zircon is present in the more mafic-rich rocks. Calcite was observed in one specimen. There are traces of interstitial quartz in rocks of very high Fe/Fe+Mg ratios.

Chemical analyses (Table 12) show the syenitic rocks to be a well defined group, characterized by subequal weight percentages of Na₂O and K₂O, high to extreme Fe/Fe+Mg ratios, and high Na+K/Al ratios (ranging up to 0.93). The latter properties suggest that they could give rise to peralkaline residuals in some cases. Norms of the analyses show neither normative quartz nor normative nepheline, and show normative orthopyroxene in only one case.

The syenite displays well developed internal structure defined by feldspar lamination, which plunges toward the northern part of Peninsula Bay at a fairly constant 30 degrees. Rare layering confirms this attitude. The plunge steepens slightly to as much

Table 11

Chemical analyses of minerals from augite-amphibole syenite

	1	2	3	4	5	6	7	8	9	10
SiO ₂	40.3	50.6	34.5	40.9	49.2	60.1	64.7	60.2	64.3	30.6
TiO ₂	1.9	1.2	0.1	1.7	1.2	0.0	0.0	0.0	0.0	0.0
Al ₂ O ₃	11.6	1.6	0.6	11.7	2.3	24.8	20.1	24.6	19.9	0.1
FeO*	21.3	14.4	42.2	20.8	14.9	0.3	0.2	0.6	0.3	65.3
MgO	7.3	8.9	21.1	8.8	8.5	0.0	0.0	0.0	0.0	1.7
CaO	12.6	21.5	0.4	11.1	21.5	6.6	0.4	6.5	0.3	0.2
Na ₂ O	2.1	1.6	0.0	2.8	1.5	7.5	4.3	7.4	4.4	0.0
K ₂ O	1.7	0.0	0.0	1.9	0.0	0.3	10.2	0.6	10.2	0.0
*Total iron reported as FeO										
Si	6.13	1.93	1.00	6.17	1.89	2.67	2.94	2.68	2.96	1.02
Al ^{iv}	1.87	0.07	0.00	1.83	0.10	1.32	1.05	1.32	1.04	0.00
Al ^{vi}	0.20	0.01	0.02	0.25	0.00	0.00	0.00	0.00	0.00	0.04
Fe ³	0.43	0.12	0.00	0.63	0.16	0.01	0.01	0.00	0.01	0.00
Ti	0.22	0.03	0.02	0.19	0.04	0.00	0.00	0.00	0.00	0.00
Fe ²	2.29	0.34	1.03	1.99	0.32	0.00	0.00	0.01	0.00	1.92
Mg	1.60	0.51	0.91	1.93	0.50	0.00	0.00	0.00	0.00	0.08
Ca	2.05	0.88	0.01	1.79	0.88	0.33	0.02	0.32	0.01	0.01
Na	0.83	0.12	0.00	0.61	0.12	0.65	0.38	0.64	0.39	0.00
K	0.33	0.00	0.00	0.37	0.00	0.02	0.60	0.04	0.60	0.00

1. Amphibole, brown melasyenite, Hwy. 17, 1 km east of Marathon (70026, Table 12).
2. Pyroxene, same rock as 1.
3. Olivine, same rock as 1.
4. Amphibole, brown syenite, 1 km north of Coldwell (69152a).
5. Pyroxene, same rock as 4.
6. Plagioclase, same rock as 4.
7. Alkali feldspar, same rock as 4.
8. Plagioclase, brown syenite, Hare Lake. (70047).
9. Alkali feldspar, same rock as 8.
10. Olivine same rock as 8.

Electron probe analyses by R. Coy-Yll, École Polytechnique.

as 50 degrees as the centre of the complex is approached. Along the highway several finer grained and porphyritic zones can be detected, suggesting that internal contacts may exist. I was unable to define such a contact exactly, because the zones could not be traced away from the highway.

Contacts of the augite-amphibole syenite are exposed only with other units of the alkaline complex. The syenites clearly cut the eastern gabbro (unit 9), forming complex agmatites with it. In these contact zones, schlieren and rootless masses of syenite occur. The gabbro contains large amounts of coarse biotite and alkali feldspar. These relations led Puskas (1967) to assume a gradational relationship. Field evidence clearly shows an intrusive relationship, and chemical analyses suggest little relation between the compositions. Alkaline gabbro intrudes augite-amphibole syenite around Port Munroe and at the Little Pic River bridge. In both cases complex agmatites accompanied by reddening and metasomatism obscure the contact. Similar relations, involving blocks of syenite too small to map, appear on Coldwell

Table 12

Chemical analyses of augite-amphibole syenite

	1	2	3	4
SiO ₂	57.17	38.01	59.50	60.61
TiO ₂	0.96	1.94	0.85	0.41
Al ₂ O ₃	15.24	5.11	15.41	18.59
Fe ₂ O ₃	2.66	13.10	2.71	1.76
FeO	7.23	29.49	7.56	2.93
MnO	0.26	1.44	0.27	0.21
MgO	0.36	2.02	0.16	0.44
CaO	3.33	4.41	2.99	2.02
Na ₂ O	5.13	1.29	5.24	5.78
K ₂ O	5.22	1.31	4.95	6.21
H ₂ O	1.02	1.20	0.66	0.89
CO ₂	0.19	0.00	0.00	0.17
P ₂ O ₅	0.14	0.38	0.13	0.06

Sample descriptions and locations

1. Coarse grained, massive brown syenite, 0.7 km east of Marathon access road on Highway 17. Trace elements Sr 0.01, Ba 0.11, Zr 0.024, Nb 0.012, Y 0.0031, La 0.0099, Sc 0.00099. (70012).
2. Medium grained, massive dense brownish black melasyenite, 1.0 km east of Marathon on Highway 17. Trace elements Sr 0.029, Ba 0.0088, Zr 0.012, Y 0.0022, Co, 0.0025, La 0.0089, Sc 0.0023. (70026).
3. Massive brown syenite from road cut in Highway 17 at Hare Lake. Sr 0.007, Ba 0.04, Zr 0.05, Y 0.0059, Nd 0.028, Nb 0.020, La 0.021, Sc 0.00083, Yb 0.00064. (70047).
4. Massive pale brown, coarse grained syenite, 1 km north of Coldwell. Trace elements Sr 0.025, Ba 0.15, Zr 0.037, Nb 0.0065, La 0.0090, Sc 0.0067. (69152a).

Analyses by Rapid Methods Group, Geological Survey of Canada

Peninsula. Nepheline syenite appears to cut augite-amphibole syenite north of Coldwell, but no clear intrusive contact was discovered. The augite-amphibole syenite appears to have been brecciated and included in the nepheline syenite, but the intensity of metasomatism and assimilation is such that the genesis of particular fragments cannot be reliably recognized. Augite-amphibole syenite clearly veins and brecciates fenites (unit 6) east of Little Pic River, but both rocks have been severely brecciated and altered. The net result of alteration, metasomatism and assimilation in all these cases is the development of an intensely red syenite essentially identical to barkevikite syenite of unit 8.

The augite-amphibole syenite was included among the rock units sampled by Chaudhuri et al. (1971) in obtaining a Rb/Sr isochron age of 1052 ± 15 m.y. for the Coldwell complex, with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7040.

Alkaline gabbro (unit 11) A group of rocks of generally melanocratic appearance and peculiar lumpy texture outcrop in a sinuous band along the western and southern sides of Coldwell Peninsula. In various places they exhibit panidiomorphic mafic minerals of several generations (lamprophyric texture). In other places they resemble the eastern gabbro. Melasyenitic, and even basaltic, varieties occur locally. Despite the heterogeneity, the unit is readily mappable, and exhibits a characteristic strong positive magnetic anomaly (Fig. 5) which forms an almost complete ring in the western part of the complex. This unit is the alkaline gabbro.

Typically these rocks are coarse grained and dark coloured, often with greenish tints. On outcrop surface the rock exhibits a characteristic lumpy pitted appearance, and may show chalky blue 'nepheline weathering'. Salic minerals occur in blotchy poikilitic masses. Finer grained rocks are more homogeneous, and may have a brownish cast. Dyke rocks of this type are abundant east of Red Sucker Cove, where both varieties of gabbro (units 9 and 11) occur. Some parts of the unit contain large (to 5 cm) crystals of amphibole and pyroxene, and approach feldspar-free alkaline ultramafics, but where salic blotches are abundant, such rocks seem to show complete gradation to nepheline syenite.

In thin section, the textures vary as much as they do in hand specimen. In general, however, the textures appear to be igneous, not hybrid or metasomatic. The most gabbroic rocks consist essentially of labradoritic plagioclase, diopsidic pyroxene and olivine. Plagioclase occurs in large, ragged, tabular grains with good, but patchy, albite twinning. The pyroxene (Table 13) approaches diopside, but exhibits a distinct greenish tinge in thin section. Olivine is almost always present in the form of rounded, subhedral grains surrounded by a shell of talcose alteration. Large poikilitic, brown, hastingsitic amphiboles (Table 13) may include the olivine. Magnetite, often with fine ilmenite lamellae, is always present, but rarely forms more than 2 per cent of the volume. Most of the rocks contain sufficient potassic feldspar that they cannot strictly be termed gabbro. In the most gabbroic rocks, potash feldspar forms thick shells on plagioclase lathes. The shells display the bluish undulating extinction typical of cryptoperthite. In more feldspar-rich rocks, potassic feldspar forms large amoeboid grains with patches of braid perthite. Large grains commonly display relict Carlsbad twinning. Biotite occurs only in feldspar-rich rocks in the form of dull brown, barely pleochroic interstitial grains. Fresh nepheline is not common, even in the most feldspathic rocks, but brownish mats of muscovite and analcite, probably secondary after nepheline, are common. In some cases these form squarish areas, probably relict after phenocrysts, but in other cases the mats are included in feldspar, which may itself replace nepheline. Northeast of Prisoners Cove the rocks appear to contain primary analcite and/or thompsonite rather than nepheline.

Table 13
Chemical analyses of minerals from alkaline gabbro

	1	2	3	4	5	6	7	8	9	10
SiO ₂	35.3	49.7	43.4	41.4	54.8	35.8	51.3	38.7	41.6	54.0
TiO ₂	0.0	2.2	2.2	0.0	0.0	0.0	1.1	2.8	0.0	0.0
Al ₂ O ₃	0.1	4.6	10.9	35.0	28.4	0.1	3.2	15.4	34.9	29.3
FeO*	36.6	6.8	10.7	0.3	0.9	36.8	7.4	13.7	0.4	0.1
MgO	26.7	12.5	15.4	0.0	0.0	26.2	12.7	17.5	0.0	0.0
CaO	0.6	23.2	12.3	1.1	11.2	0.1	23.4	0.0	1.2	11.4
Na ₂ O	0.0	1.1	3.1	17.2	4.9	0.0	1.0	0.7	17.1	4.8
K ₂ O	0.0	0.0	1.6	4.9	0.4	0.0	0.0	9.6	4.8	0.3
*Total iron reported as FeO										
Si	0.99	1.84	6.28	0.99	2.46	1.01	1.90	2.78	1.00	2.44
Al ^{iv}	0.003	0.16	1.72	1.00	1.51	0.00	0.10	1.22	0.99	1.56
Al ^{vi}	0.00	0.04	0.14	0.00	0.00	0.003	0.04	0.08	0.00	0.00
Fe ³	0.00	0.08	0.11	0.01	0.10	0.00	0.07	0.00	0.01	0.01
Ti	0.00	0.06	0.24	0.00	0.00	0.00	0.03	0.15	0.00	0.00
Fe ²	0.87	0.13	1.19	0.00	0.00	0.89	0.16	0.82	0.00	0.00
Mg	1.13	0.69	3.32	0.00	0.00	1.10	0.70	1.87	0.00	0.00
Ca	0.02	0.92	1.91	0.03	0.58	0.003	0.93	0.00	0.03	0.58
Na	0.00	0.08	0.87	0.80	0.42	0.00	0.07	0.10	0.80	0.42
K	0.00	0.00	0.30	0.16	0.005	0.00	0.00	0.88	0.16	0.01
<u>Sample descriptions and locations</u>										
1. Olivine, gabbro dyke in railway cut at Port Munroe. (70009, Table 14).										
2. Pyroxene, same rock as 1.										
3. Amphibole, same rock as 1.										
4. Nepheline, same rock as 1.										
5. Plagioclase, same rock as 1.										
6. Olivine, lamprophyric gabbro, Hwy. 17 at Red Sucker Cove. (691506, Table 14).										
7. Pyroxene, same rock as 6.										
8. Biotite, same rock as 6.										
9. Nepheline, same rock as 6.										
10. Plagioclase, same rock as 6.										
Electron probe analyses by G.R. Lachance, Geological Survey of Canada.										

In general the texture becomes more granular, xenomorphic and disordered with increasing salic content. This progression suggests the action of metasomatic or metamorphic processes on the alkaline mafic rocks. However the chemical analyses (Table 14) form a well defined group, distinguished from most other mafic alkaline rocks by low titanium content. The analyses contain large amounts of normative nepheline and orthoclase.

Unlike most other units of the alkaline complex, the alkaline gabbro shows no perceptible internal structure. In the region north of Port Munro the gabbro appears in the form of dykes, but these appear to show no preferred orientation.

The contacts of the alkaline gabbro with other units of the complex cannot be well determined. Alkaline gabbro fringes nepheline syenite on Coldwell Peninsula, but the exact relations are unclear. A myriad of mafic inclusions can be seen in the nepheline syenite, but their textures suggest that they come from the greenstone (unit 1) rather than from the alkaline gabbro. Some phases of the nepheline syenite are

Table 14
Chemical analyses of alkaline gabbro

	1	2	3
SiO ₂	47.1	45.8	49.3
TiO ₂	0.40	0.67	0.68
Al ₂ O ₃	12.7	13.8	14.3
Fe ₂ O ₃	1.9	1.7	1.4
FeO	6.7	8.3	7.3
MnO	0.16	0.19	0.17
MgO	10.8	9.9	9.2
CaO	13.6	9.1	7.8
Na ₂ O	2.5	3.0	3.4
K ₂ O	1.2	3.1	3.0
H ₂ O	1.4	2.1	1.2
CO ₂	0.00	0.00	0.10
P ₂ O ₅	98.52	98.69	98.61

Specimen locations and descriptions

1. Fine grained homogeneous brownish black dyke from railway cut at Port Munro. Total includes Sr 0.035, Ba 0.034, Cr 0.08, Ni 0.003, Co 0.0014, Zr 0.013, Nb 0.011, La 0.0070, Sc 0.0046. (70009).
2. Lamprophyric greenish black gabbro, Hwy. 17 northwest of Red Sucker Cove. Total includes Sr 0.047, Ba 0.091, Cr 0.13, Ni 0.026, Co 0.0042, Zr 0.027, Nb 0.014, La 0.014, Y 0.0034, Sc 0.0026. (60150b).
3. Coarse grained, blotchy, black mela-syenite, Prisoners Cove. Total includes Sr 0.041, Ba 0.099, Cr 0.10, Ni 0.027, Co 0.0038, Zr 0.03, Nb 0.017, La 0.013, Y 0.0030, Sc 0.0023. (70171).

relatively mafic, and seem to grade toward the alkaline gabbro. Alkaline mafic dykes clearly cut all metasomatized rocks (units 6, 7, 8) north of Peninsula Bay. Unlike older units, these dykes show no signs of metasomatism. Near Middleton, the alkaline gabbro contains patches and schlieren of gabbroic and basaltic material of non-alkaline appearance, and the whole complex seems to grade into the surrounding greenstones of unit 1. This part of the gabbro also displays a distinct east-west foliation parallel to that in the greenstones. This region can be interpreted as a patch of intensely metasomatized basaltic and gabbroic rocks derived from the greenstone belt. Possibly the small basaltic inclusions near the Killala Lake road may be similar.

The relations between more leucocratic and melanocratic alkaline rocks, whereby the former vein and brecciate the latter so that melanocratic rocks are rarely in direct contact with the country rocks, resembles the augite-amphibole syenite-eastern gabbro contact in the eastern part of the complex.

The unusual textures observed in the alkaline gabbro may be due, at least in part, to alteration and metasomatism, but petrographic observations do not demonstrate this relationship. Except for hematite dust in the feldspar, and alteration of nepheline and olivine which obviously postdates crystallization, the rocks are essentially unaltered, and their textures resemble those of undoubtedly igneous rocks.

Puskas (1967) considered the alkaline gabbro correlative with the eastern gabbro. I consider this correlation unlikely due to the marked petrographic and chemical differences. The eastern gabbro exhibits igneous texture, high titanium content and low potassium content, whereas the alkaline gabbro has an unusual texture, low titanium content and high potassium content. The magnetic signatures of the two units contrast sharply. In fact the two units differ markedly, despite local areas of similar material.

Nepheline syenite (unit 12) Diverse varieties of nepheline syenite outcrop in two major arcs, one running across the foot of Coldwell Peninsula from Red Sucker Cove, and the other lying north of Coldwell. Sizeable areas of nepheline syenite outcrop on Pic and Allouez islands, and dykes and schlieren of nepheline syenite are found in various places in the margins of the complex, particularly in the fenitized rocks north of Red Sucker Cove, and in the western margin of the complex, west of Little Pic River.

At least four distinct types of nepheline syenite occur. The most common variety is pale grey or creamy, with acicular, euhedral mafics and reddish orange spots ('hydronepheline'). This rock forms the central part of the major masses, and in the form of pegmatic schlieren accounts for much of the marginal nepheline syenite. Darker grey rocks without 'hydronepheline' always display two generations of mafics, large corroded euhedra and smaller aligned needles, the latter giving the rock a foliation. Such rocks occur in hybrid zones and along contacts with alkaline gabbro. Trachytic, red nepheline syenite dykes occur northwest of Red Sucker Cove and on the hydro right-of-way north of Coldwell. The Pic Island nepheline syenite is typically a coarse grained leucocratic rock with 'flower-like' clumps of mafics and little 'hydronepheline'.

All varieties are full of diverse inclusions. Metasomatized and assimilated mafic rocks form the most obvious and spectacular inclusions, but close examination reveals a host of diverse small inclusions (Fig. 7). A wide variety of breccia types are exposed along the hydro right-of-way north of Red Sucker Cove. The inclusions range from a few centimetres across to hundreds of metres in length. The blocks appear more or less syenitic due to porphyroblastic feldspar and assimilation. No distinct contacts can be seen between the nepheline syenite and other rocks because the



Figure 7. Oriented, assimilated inclusions in nepheline syenite. (GSC Photo 203034-B).

junctions with other units are invariably obscured by complex zones of alteration, metasomatism and gradation.

In hand specimen many of the nepheline syenites display elongate acicular amphiboles, which may be curved, and commonly taper from the middle toward both ends. In pegmatitic varieties, such amphiboles may be several centimetres long. Brick red spots, characteristic of the leucocratic varieties, show well developed crystal faces in some specimens, but in others form irregular blotches, or rather diffuse areas. Giant zircons, up to a centimetre long, occur in two pegmatitic schlieren west of the Little Pic River. Many syenites show pronounced trachytoid foliation or lineation. Much of the unit is composed of heterogeneous material.

In thin section the rocks are seen to consist mainly of perthitic alkali feldspar, nepheline and its alteration products, and greenish brown hastingsitic amphibole. Small amounts of biotite, clinopyroxene and fayalitic olivine occur in a few specimens. Alkali feldspar is the dominant phase in all nepheline syenites and plagioclase occurs only as patches within the perthites. Fine patch perthite, locally grading to braid perthite, characterizes the rocks. The matrix of the perthite exhibits a pale, cloudy brown shade, while the patches and braids are water-clear. Similar clear material forms mantles around many of the feldspar grains, and broad mantles commonly show albite twinning. Electron probe analyses (Table 15) show that the mantles are virtually pure albite coexisting with a moderately potassium-rich phase. Many of the large feldspar grains are in good optical

alignment. Boundaries between such grains are either sutured, or show mosaic recrystallized patches. In some rock this mosaic feldspar comprises the bulk of the feldspar. In such specimens chess-board twinning is common. All the apparently massive rocks were seen in thin sections to possess mosaic structure, commonly to the exclusion of other structures. Interlocking feldspar euhedra, suggestive of primary igneous texture, were found only in some of the finer grained phases of the pegmatites.

Nepheline originally occurred as masses interstitial to feldspar, commonly displaying a subhedral square outline. Most nepheline has been converted to a pale yellow mat of oriented muscovite, natrolite, thompsonite and analcite (the orange "hydronepheline" of hand specimens). Although these four minerals commonly grow together in a mat stained reddish by iron oxides, other examples exhibit mono- or bimineralic replacement of nepheline. Radiating sprays of natrolite and thompsonite replace nepheline in more basic rocks. Monomineralic aggregates of thompsonite occur in the most mafic rocks, but it is not clear that these replace nepheline. Monomineralic analcite occurs in the most leucocratic rocks. Coleman (1900) noted the presence of apparently primary analcite in dyke rocks from the Heron Bay region, just southeast of the complex. Possibly some of the zeolites observed in the nepheline syenite may be primary. All observed examples are stained with iron oxides. If this staining resulted from the process which stained the matrix feldspar, then the zeolites were formed before the clear albite component of the perthites. Hence if the perthite is considered primary, the zeolites should also be considered primary.

An iron-rich amphibole occurs in all the nepheline syenites. The mineral forms subhedral prisms in hand specimen, but in thin section the prisms exhibit lacy boundaries, with many separate granules of amphibole. This texture suggests partial replacement by the surrounding salic minerals. The amphibole displays rather weak pleochroism (x=pale brown, y=yellowish brown, z=greenish brown or greenish). Electron probe analyses (Table 15) reveal a sodic amphibole with moderate Fe/Fe+Mg ratio, resembling the amphibole found in the alkaline gabbro (unit 11). Amphibole shows a simple twinning parallel to (100) in the most igneous appearing rocks, but twinning is absent in rocks which appear to have been recrystallized.

Pyroxene was found in about two thirds of the sections examined, commonly in the form of granules, or small clots of granules, associated with amphibole. In a few rocks the mineral occurs as fine acicular prisms, or tabular grains. Pyroxene exhibits a strong green colour but little or no pleochroism, a typical scheme being x=brownish, y=brownish green, z=green. The pyroxenes have rather large $2V$ (+75-80) and $zAc(70-75^\circ)$. Probe analysis (Table 15) shows that they are weakly sodic pyroxenes falling close to the diopside-hedenbergite join.

Biotite commonly occurs in small amounts fringing opaque granules, or occasionally pyroxene. The pleochroism is very strong, from straw yellow to almost opaque. A few rocks contain large poikilitic biotite flakes, but biotite is never the major mafic mineral in the syenite. Olivine was noted only near Red Sucker Cove, where it is surrounded by reddish brown bowlingite, and partly replaced by carboante and chlorite. The mineral may be xenocrystic from the nearby alkaline gabbro (unit 11).

Accessory minerals found in the nepheline syenite include hematite, magnetite, sphene, zircon, apatite, fluorite, and epidote. Fine hematite dust imparts the typical reddish colour to 'hydronepheline' and some of the reddish dyke rocks. Magnetite forms the older and principal opaque mineral, commonly occurring as rounded, homogeneous

Table 15
Chemical analyses of minerals from nepheline syenite

	1	2	3	4	5	6	7	8	9	10	11	12
SiO ₂	50.9	42.1	42.6	64.3	49.7	44.3	42.6	65.2	57.0	37.5	50.1	42.8
TiO ₂	1.1	2.7	0.0	0.0	2.3	2.9	0.0	0.0	0.0	3.9	1.4	3.1
Al ₂ O ₃	2.3	9.3	35.1	19.3	3.6	10.9	35.0	20.0	27.0	13.7	3.2	10.2
FeO*	9.5	15.1	0.5	0.05	7.3	9.5	0.4	0.4	0.5	21.1	8.1	13.7
MgO	11.9	13.0	0.0	0.0	13.5	16.6	0.0	0.0	0.0	12.8	13.0	12.4
CaO	23.3	11.7	1.1	0.5	22.9	12.1	1.3	0.5	8.5	0.0	23.3	12.1
Na ₂ O	0.9	2.4	17.0	3.0	1.0	2.5	17.9	3.2	6.5	0.2	0.8	3.3
K ₂ O	0.0	1.8	5.4	12.9	0.0	1.6	4.8	13.2	0.3	10.6	0.0	1.4
*Total iron reported as FeO												
Si	1.92	6.29	1.01	2.95	1.86	6.26	1.21	2.86	2.56	2.77	1.89	6.39
Al ^{iv}	0.08	1.63	0.98	1.05	0.14	1.74	0.98	1.00	1.43	1.20	0.11	1.61
Al ^{vi}	0.02	0.00	0.00	0.00	0.02	0.08	0.00	0.00	0.00	0.00	0.03	0.18
Fe ³	0.07	0.42	0.01	0.01	0.07	0.39	0.01	0.02	0.02	0.00	0.06	0.03
Ti	0.03	0.30	0.00	0.00	0.06	0.31	0.00	0.00	0.00	0.22	0.04	0.35
Fe ²	0.23	1.46	0.00	0.00	0.16	0.73	0.00	0.00	0.00	1.31	0.16	1.68
Mg	0.66	2.90	0.00	0.00	0.75	3.50	0.00	0.00	0.00	1.41	0.72	2.76
Ca	0.93	1.87	0.05	0.02	0.92	1.83	0.03	0.03	0.41	0.00	0.93	1.94
Na	0.07	0.69	0.78	0.25	0.07	0.69	0.82	0.26	0.57	0.03	0.06	0.95
K	0.00	0.34	0.17	0.73	0.00	0.28	0.15	0.71	0.02	0.99	0.00	0.27
<u>Sample descriptions and location</u>												
Columns 1-4; Hydronepheline leuco-syenite, road cut near Coldwell (specimen 69154a, Table 16). Columns are: 1-pyroxene, 2-amphibole; 3-nepheline, 4-alkali feldspar.												
Columns 5-9; Melanocratic nepheline syenite, Red Sucker Cove at C.P.R. crossing (specimen 70088, Table 16). Columns are: 5-pyroxene; 6-amphibole; 7-nepheline; 8-alkali feldspar; 9-plagioclase.												
Columns 10-12; Pegmatitic, mesocratic nepheline syenite, 4.5 km northeast of Coldwell in road cut, (specimen 70150c, Table 16). Columns are: 10-biotite; 11-pyroxene; 12-amphibole.												
Electron probe analyses by G.R. Lachance, Geological Survey of Canada.												

granules. Spene occurs erratically as single granules or chains of granules up to one centimetre in length. Spene in leucocratic rocks is markedly paler in colour than the cloudy, brownish material of the melanocratic varieties. Zircon, found throughout the nepheline syenites, occurs in spectacular fashion in nepheline pegmatites west of Little Pic River, where crystals up to 4 cm long can be found. The giant zircons commonly have a reddish coating, and are intensely

Table 16
Chemical analyses of nepheline syenite

	1	2	3	4	5	6	7
SiO ₂	50.0	49.9	49.8	56.8	53.4	57.2	55.8
TiO ₂	0.55	0.64	0.56	0.39	0.29	0.35	0.47
Al ₂ O ₃	15.5	15.5	16.7	18.1	22.3	18.0	19.8
Fe ₂ O ₃	0.8	3.1	1.6	5.0	1.2	1.2	3.9
FeO	6.7	6.4	5.3	3.4	3.6	4.5	2.8
MnO	0.15	0.16	0.11	0.25	0.13	0.21	0.19
MgO	8.3	7.3	6.9	0.4	0.6	0.4	0.2
CaO	7.4	6.9	7.6	2.4	2.0	2.9	3.5
Na ₂ O	4.3	4.3	5.1	5.8	8.8	5.4	6.6
K ₂ O	3.2	2.9	2.6	5.7	6.5	7.8	3.7
H ₂ O	1.0	2.0	2.2	1.0	0.6	1.3	0.8
CO ₂	0.1	0.2	0.9	0.4	0.0	0.3	1.9
P ₂ O ₅	0.46	0.43	0.31	0.07	0.12	0.11	0.24

Descriptions and locations of samples

1. Coarse grained mesocratic nepheline syenite, Red Sucker Cove; Analysis includes Sr 0.043, Ba 0.089, Cr 0.099, Ni 0.030, Co 0.0029, Zr 0.030, Nb 0.020, La 0.014. (70088).
2. Mesocratic nepheline syenite, Coldwell Peninsula. Analysis includes Sr 0.054, Ba 0.10, Cr 0.060, Ni 0.020, Co 0.0038, Zr 0.029, Nb 0.016, La 0.013. (69154a).
3. Heterogeneous mesocratic syenite, 1.5 km northeast of Coldwell. Analysis includes Sr 0.032, Ba 0.10, Cr 0.013, Ni 0.0085, Co 0.038, Zr 0.036, Nb 0.029, La 0.0073, Y 0.0038. (69156).
4. Hydronepheline leucosyenite, Hwy. 17, west of Little Pic River. Analysis includes Sr 0.041, Ba 0.13, Zr 0.027, Nb 0.017, La 0.0088. (70133).
5. Red trachytoid syenite, 3 km north of Coldwell. Analysis includes Sr 0.017, Ba 0.011, Zr 0.11, Ce 0.056, La 0.040, Nd 0.031, Yb 0.001; Nb 0.057, Y 0.0088, Ni 0.0045. (69150c).
6. Pearl grey leucosyenite, 2 km northeast of Coldwell. Analysis includes Sr 0.057, Ba 0.065, Ni 0.0044, Zr 0.12, Nb 0.025, La 0.031. (70076).
7. Homogeneous leucosyenite, Red Sucker Cove. Analysis includes Sr 0.044, Ba 0.057, Zr 0.10, Nb 0.036, La 0.033, Ni 0.0040. (70089).

Analyses by Rapid Methods Group, Geological Survey of Canada.

shattered internally. Disseminated, accessory fluorite can be found in many specimens. Northeast of Coldwell, purplish seams of fluorite constitute 2-4 per cent of the rock. Epidote occurs as seams of small brownish granules in two specimens from the southern part of Coldwell Peninsula. No visible reaction relations were observed between epidote and any of the other minerals, and epidote is considered tentatively to be a primary constituent of the rock, perhaps resulting from assimilation during magmatic processes.

Chemical analyses of the nepheline syenites (Table 16) show that the rocks contain rather more silica and less alumina than typical nepheline syenites. All analyses display more than 5 per cent normative nepheline, despite probable alteration and post-magmatic processes in many of the rocks. The most marked feature of the analyses is the sharp distinction between mesocratic syenites and leucocratic syenites. This distinction could not be satisfactorily mapped in the field due to the innumerable and rapid gradations from one to the other. However chemical analyses of mesocratic syenite show a closer relationship to alkaline gabbro (unit 11) than to leucocratic syenite. Despite the close spatial and mineralogical links, it appears that the nepheline syenite unit contains at least two distinctly different phases. The leucocratic syenites exhibit the extreme Fe/Fe+Mg ratios, and concentrations of incompatible elements (for example Zr) typical of late magmatic differentiates.

The nepheline syenite locally exhibits excellent layering (Fig. 8), particularly on Pic and Allouez islands (Leszczyszyn, 1959), at Prisoners Cove, and around Coldwell. Graded layering, slump structures and scours are all well developed, even though the layering dips at steep angles, ranging from 60° at Prisoners Cove to vertical on Pic Island. The layering in the band of syenite across Coldwell Peninsula suggests a centre of intrusion somewhere north of Coldwell. The island occurrences point to a separate centre of intrusion in Windy Bay. Trachytoid lineation of feldspar is common north of Highway 17. Although less regular than the layering, the lineation points toward a focus north of Coldwell. The plunge of lineation averages about 50°, noticeably less than the dips of the layering.

Contact relations of the nepheline syenite with other units of the alkaline complex are obscured by intense metasomatism and brecciation, and contacts occur in zones of heterogeneous agmatitic material. Nepheline syenite is not clearly seen in contact with country rocks, although west of Little Pic River lenticles of nepheline-bearing rocks occur within a few metres of recognizable greenstones. Dykes of nepheline syenite cut units 7 and 11 of the complex on Guse Point and the headlands to the north. The contacts of these dykes are sharp and planar, and the dykes contain numerous metasomatized fragments of wall rocks. Nepheline syenite contains recognizable fragments of alkaline gabbro on Pic Island. Lamprophyric and analcite syenite dykes cut the nepheline syenite, but such dykes are blobby and sinuous (Fig. 9) suggesting that the host was soft at the time of intrusion.

Nepheline syenites display a broad range of alteration and metasomatism, ranging from fresh rocks of igneous appearance to completely recrystallized rocks containing no nepheline, and probably no primary feldspar. The development of recrystallization and metasomatism seems to be related to emplacement of the alkaline complex itself, rather than some separate and later event. It can therefore be ascribed to autometasomatism. The net result of this process has been the transformation of the nepheline syenite into a heterogeneous mass of rocks, such that correlation between different parts of the body is very difficult. Some large bodies of nepheline syenite clearly form mappably continuous units, but there seems to be no way of clearly deciding whether the three major masses of nepheline syenite are

correlative in age and mode of emplacement, or whether they represent separate pulses of magma emplaced at diverse times in diverse circumstances. Neither field nor petrographic nor geophysical evidence is suitable to remove this ambiguity.

Alkaline dyke rocks (unit 13) The dyke suite associated with the Coldwell complex comprises both melanocratic lamprophyres and porphyritic orange trachytes. Most dykes occur in the altered and reconstituted rocks of units 6, 7, and 8, but dykes are found in all units of the alkaline complex and in unaltered country rocks around the complex. Dykes can be best studied along the shore of Lake Superior from Middleton to Guse Point, in road cuts from Coldwell to Knob Lake, and in railway cuts east of Heron Bay.

The mafic dykes are black to greenish black, fine grained rocks with small phenocrysts of pyroxene and amphibole. They commonly exhibit a sinuous ground plain,

although planar dykes occur in some country rocks remote from the complex. Bifurcations and off-sets (Currie and Ferguson, 1970) occur commonly. Dykes range in width from 10 to 100 cm.

At least four types of mafic dykes can be recognized; lamprophyre dykes with carbonate ocelli, lamprophyre dykes with feldspathic ocelli, lamprophyre dykes without ocelli, and mafic non-lamprophyric dykes. The last two types were not examined in any detail during this study. Walker (1967) noted that some of the latter dykes cut lamprophyres. They may be significantly younger than the complex and not directly related to it. R.H. Mitchell (pers. comm., 1976) has found high-pressure mineralogy in some of the non-ocellar lamprophyres.

The ocellar lamprophyres consist of a massive matrix, with faintly to strongly aligned phenocrysts, ocelli and vesicles. In a few rocks the alignment produces a strong

Table 17
Chemical analyses of minerals from alkaline dykes

	1	2	3	4	5	6	7	8	9	10
SiO ₂	50.9	48.0	40.1	41.6	50.7	33.25	39.92	40.38	50.9	36.1
TiO ₂	1.4	2.6	1.4	0.0	0.0	0.0	1.46	1.39	0.1	5.5
Al ₂ O ₃	3.7	5.4	14.5	33.6	31.8	0.3	14.67	14.29	2.5	13.5
FeO*	5.5	11.2	13.9	0.5	0.3	48.9	13.95	13.89	14.6	24.2
MgO	13.6	9.4	10.8	0.0	0.0	16.9	10.76	10.79	9.9	8.7
CaO	24.0	21.8	12.0	0.8	13.4	0.6	12.02	11.91	21.0	0.0
Na ₂ O	0.7	1.6	2.5	16.8	3.9	0.0	2.62	2.46	0.6	0.2
K ₂ O	0.0	0.0	1.5	6.1	0.2	0.0	1.00	1.05	0.0	9.5
*Total iron reported as FeO										
Si	1.88	1.81	6.05	1.01	2.26	1.00	5.91	6.08	1.94	2.75
Al ^{iv}	0.12	0.19	1.95	0.00	0.00	0.00	2.09	1.92	0.06	1.22
Al ^{vi}	0.04	0.05	0.62	0.98	1.67	0.01	0.55	0.62	0.05	0.00
Fe ³	0.05	0.12	0.20	0.01	0.01	0.00	0.31	0.21	0.04	0.00
Ti	0.04	0.075	0.16	0.00	0.00	0.00	0.17	0.16	0.003	0.32
Fe ²	0.12	0.23	1.55	0.00	0.00	1.23	1.47	1.54	0.42	1.54
Mg	0.75	0.53	2.43	0.00	0.00	0.76	2.45	2.42	0.56	0.99
Ca	0.95	0.88	1.93	0.02	0.64	0.02	1.97	1.92	0.86	0.00
Na	0.05	0.12	0.74	0.79	0.34	0.00	0.775	0.72	0.04	0.03
K	0.00	0.00	0.29	0.19	0.01	0.00	0.19	0.20	0.00	0.93

Sample descriptions and locations

Columns 1-6. Greenish fine grained dyke, Red Sucker Cove. 1-core of pyroxene phenocryst; 2-rim of same phenocryst; 3-amphibole; 4-nepheline; 5-plagioclase; 6-olivine. (69152d).

Columns 7-8. Core and rim of amphibole from lamprophyre (Herdman (1974, p. 41, analyses 16A, 16C).

Columns 9-10. Aphanitic red trachyte dyke, Red Sucker Cove. 9-pyroxene; 10-biotite. (69152e).

Electron probe analyses by G.R. Lachance, Geological Survey of Canada, except as noted.

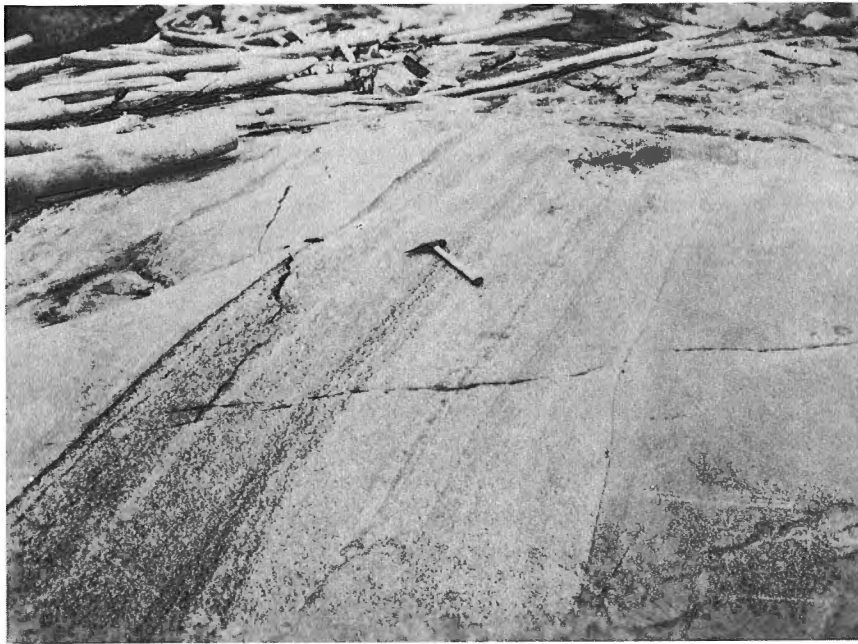


Figure 8.

Graded layering in nepheline syenite, Prisoners Cove. The hammer handle points in the direction of younging. The layering dips about 70° in the same direction. Note the wavy top of the sequence of layers at right of photo. (GSC Photo 203034-F).

foliation, amounting to layering. Such rocks commonly exhibit variations in grain size of the matrix and numerous internal contacts.

Strong alteration has affected virtually all the ocellar lamprophyres and chlorite and talc now form up to 40 per cent of the rock. The matrix in all cases consists of labradoritic plagioclase, a diopsidic pyroxene, and brown paragenetic amphibole. Altered aligned plagioclase lathes, giving a strong trachytoid foliation, have optic properties suggestive of An_{55-65} , but some sections contain small amounts of granular, unaltered albite, presumably a secondary mineral. Some dykes contain radiating intergrowths of plagioclase and alkali feldspar, but the amount of alkali feldspar is small.

Pyroxenes range from colourless to faintly pleochroic in buff and green. At least two generations of pyroxenes can be detected, the older forming cores of phenocrysts, and the younger forming rims of phenocrysts and small grains in the matrix. Phenocryst cores appear cloudy and full of vermicular opaque material. Electron probe analysis (Table 17) shows that the cores are magnesian titanite, whereas the rims are richer in iron and sodium. The optic properties show a rather startling variation from steel blue extinction colours in the core to normal second-order interference colours in the rim.

Amphibole occurs in rather minor amounts as subhedral granules. The margins of the amphibole commonly enclose tiny inclusions of feldspar. The pleochroic scheme resembles that of the nepheline syenite amphiboles, displaying brownish green colours with rich green in the z direction. Electron probe analyses by Herdman (1974) quoted in Table 17, show that the amphibole lies between pargasite and hastingsite, and is distinctly more magnesian than that in the nepheline syenite. Amphibole also occurs within the feldspathic ocelli in the form of acicular prisms, some of which grow across ocelli boundaries, suggesting that ocellus and matrix grew in equilibrium (Ferguson and Currie, 1971). The optic properties of ocellus amphibole are identical to that of matrix amphibole.

Biotite occurs in minor amount as small disseminated euhedra showing strong golden brown colour but weak pleochroism. Calcite occurs as polygonal masses in carbonate



Figure 9. Sinuous lamprophyre dyke in nepheline syenite, Prisoners Cove. Note layering of syenite on right of photo, and fine irregularities of contact at lower left, suggesting both rocks must have been soft. (GSC Photo 203034-K).



Figure 10.

Inclusion of nepheline syenite in lamprophyre. Highway cut north of Coldwell. (GSC Photo 203034).

ocelli, and in trace amounts in the matrix of dykes containing carbonate ocelli. Staining showed that no dolomite is present. The ubiquitous chlorite commonly forms radiating sheaves. It may form a border between matrix and ocelli. Talc, commonly intergrown with chlorite, may completely replace pyroxene.

Carbonate ocelli consist mainly of calcite, but may contain amphibole, scapolite (containing 76 per cent meionite component according to Herdman (1974)), and plagioclase in the oligoclase to andesine range. Feldspathic ocelli consist partly of plagioclase and alkali feldspar, but with variable and commonly large amounts of thompsonite and analcite. Some ocelli are essentially filled with radiating sheaves of brown-stained thompsonite.

Chemically, the lamprophyres are ultrabasic, rather weakly alkaline rocks containing about 1 per cent of nepheline in the norm (Table 18). They show many analogies to the eastern gabbro, but contain much higher volatile contents. Chemically and petrographically they belong to the group of camptonite lamprophyres characteristically associated with gabbro-syenite complexes.

Salic dykes display a markedly porphyritic texture. They can be divided into two groups depending on the phenocrysts. Analcite trachyte dykes, termed "heronite" by Coleman (1900), contain rounded to subhedral orange or red analcite phenocrysts up to one centimetre across. In most rocks, the texture of the matrix is weakly trachytoid or felted, as in tinguaites, but some exhibit a granular, fine grained matrix. Glomeroporphyritic trachyte is similar, but instead of analcite, this type of dyke contains rounded to tabular plates of orange feldspar, commonly clumped together in groups up to one centimetre across.



Figure 11. *Apparent intrusion of nepheline syenite into lamprophyre. Hammer point indicates face where syenite appears to intrude and include lamprophyre. (GSC Photo 203034-C).*

Table 18
Chemical analyses of alkaline dykes

	1	2	3	4	5	6	7
SiO ₂	42.6	42.3	43.3	43.3	52.73	48.07	52.03
TiO ₂	1.86	1.48	1.62	1.90	0.00	0.00	0.00
Al ₂ O ₃	12.6	14.5	15.4	16.1	20.05	18.36	20.58
Fe ₂ O ₃	3.0	4.4	3.6	2.9	3.43	3.95	3.40
FeO	8.5	5.3	9.0	6.0	0.99	3.39	1.98
MnO	0.27	0.18	0.16	0.21	0.00	0.55	0.13
MgO	10.5	6.2	5.9	2.1	0.17	0.32	0.27
CaO	10.2	8.9	6.9	9.8	3.35	3.76	2.46
Na ₂ O	2.2	4.8	4.5	3.8	7.94	8.72	8.63
K ₂ O	1.5	0.6	1.1	3.3	4.77	4.71	5.46
H ₂ O	3.8	5.0	4.3	2.9	5.54	5.10	5.30
CO ₂	0.8	4.3	1.6	5.7	0.93	2.65	0.26
P ₂ O ₅	0.95	1.07	0.76	1.30	0.01	0.14	0.07

Sample descriptions and locations

1. Fine grained greenish lamprophyre, 1 km northwest of Coldwell. Analysis includes Sr 0.11, Ba 0.10, Cr 0.076, Zr 0.026, Ni 0.026, Nb 0.013, Co 0.0047, La 0.012, Sc 0.0024. (69152d).
2. Black, zoned ocellar lamprophyre, Hwy. 17. Premier Mountain, Coldwell Peninsula. Analysis includes Sr 0.23, Ba 0.27, Cr 0.031, Zr 0.025, Ni 0.0098, Y 0.0025, Nb 0.016, Co 0.0030, La 0.018. (69154b).
3. Fine grained black dyke, shore of Prisoners Cove. Analysis includes Sr 0.082, Ba 0.030, Cr 0.0023, Zr 0.021, Ni 0.0080, Nb 0.010, La 0.009, Sc 0.0020. (70006).
4. Ocellar lamprophyre, lake shore near Middleton. Analysis includes Sr 0.094, Ba 0.17, Zr 0.027, Y 0.0023, Nb 0.013, Co 0.0023, La 0.013, Sc 0.0013. (70007).
- 5-7. Analyses of analcite trachyte dykes ("heronite") from the vicinity of Heron Bay (Coleman, 1900, p. 189).

In thin section the rocks are seen to consist of alkali feldspar, analcite, aegirine, and variable amounts of nepheline, with a little accessory fluorite. The feldspar occurs as euhedral tabular plates, or as rosettes of lathes. The plates show perthitic patches with albite twinning, but the grains commonly have clear edges, and in most cases the albite twinned patches form only a minor percentage of the

volume. Analcite occurs not only as rare hexagonal phenocrysts, but commonly as an interstitial matrix to other constituents in the analcite trachytes. The mineral, although it contains a host of minute feldspar and aegirine inclusions that giving it a cloudy appearance, seems to be fresh and unaltered. Nepheline occurs as small, euhedral cubic phenocrysts, commonly included in analcite. In one specimen, analcite appeared to have partially broken down to an intimate mixture of nepheline and albite. An intensely green pyroxene occurs as small acicular inclusions within feldspar and analcite. Despite the strong colour, electron probe analyses (Table 17) show it to be sodic hedenbergite rather than aegirine. Fluorite, distinguished by faint purple colour and low relief, occurs interstitially in amounts up to 3 per cent.

Chemical analyses by Coleman (1900), quoted in Table 18, show that the salic dykes contain alkali contents similar to those of the nepheline syenites, but that the silica contents of the dykes are lower. Petrographic data do not suggest that the analcite is a secondary mineral. Rather they suggest that after a short initial period of crystallization of pyroxene and nepheline, analcite and feldspar crystallized together in equilibrium during most of the crystallization history of the rock. These relations appear to require crystallization of the salic dykes under physical-chemical conditions stabilizing analcite relative to the chemically equivalent assemblage nepheline+albite.

Both salic and mafic dykes show numerous internal chilled contacts that produce complex layering within the dykes. Presumably this feature results from multiple intrusion (Currie and Ferguson, 1970). Currie and Ferguson (1970) showed that blobby and offset structures in lamprophyres result from high volatile pressures in the magma. The Coldwell lamprophyres show these structures within and near the complex but not at distances of more than a few hundred metres from the contact. This suggests that volatiles were lost by leakage to the surroundings as magma travelled away from the complex. The reddened and altered margins of the dykes become less prominent with distance from the complex, probably because such alteration requires high volatile contents in the magma. At distances of more than one kilometre from the margin of the complex, lamprophyre dykes cannot be reliably distinguished in the field from older (or younger?) regional diabase dykes of unit 5. At these distances the alkaline dykes contain no ocelli, and the porphyritic structure is inconspicuous.

Lamprophyre dykes cut all other members of the Coldwell complex and inclusions of other members can be found within them (Fig. 10), although rarely. The relations of some lamprophyres to alkaline gabbro (unit 11) and nepheline syenite (unit 12) are somewhat ambiguous. The texture of the alkaline gabbro locally approaches lamprophyric. Nepheline syenite forms complex interfingering margins with lamprophyre (Fig. 11), suggesting that the syenite was plastic when the lamprophyre was emplaced. These relations suggest that many of the lamprophyres were emplaced at roughly the same time as the more alkaline parts of the Coldwell complex and that the lamprophyres may be genetically related to these parts.

STRUCTURAL GEOLOGY

The Coldwell complex forms a sub-circular mass of igneous rocks emplaced into a generally east-trending Archean volcano-sedimentary assemblage intruded by younger plutonic rocks. The area affected by emplacement of the Coldwell complex exceeds 1500 km², which was far too large for detailed examination during this essentially petrological study. The following remarks are based mainly on a compilation of the literature, supplemented to a considerable extent by the author's own observations and interpretations.

Geological mapping shows that the complex falls into three distinct parts. The eastern units (units 9 and 10) form an arcuate mass with a centre somewhere in Peninsula Bay. This mass is cut by a younger circular complex with its centre north of Coldwell. The layered syenites of Pic and Allouez islands do not belong to either of these units, and must therefore form part of a separate intrusion. Effects of intrusion can be observed in country rocks both east and west of the Coldwell complex, but since the intrusive rocks differ, the observed effects of intrusion also differ. The structural geology can be conveniently considered under five headings: (1) structure of the country rocks, (2) structure of the contact zone of country rocks and igneous rocks, (3) structure of the eastern ring system, (4) structure of the western ring system, and (5) structure of the southern syenites.

Structure of the country rocks

West of the Coldwell complex, Archean volcanic and sedimentary rocks occur within a complex east-trending synclinorium from 15–20 km wide (Walker, 1967). The various folds within this belt are approximately isoclinal with vertical or very steeply dipping axial planes and low plunges. This regularity is disturbed by the presence of granitoid bosses up to several kilometres in largest dimension, around which the folds deflect. Several narrow, anastomosing networks of volcanic rocks strike northerly into the granitoid terrane for a few kilometres, presumably due to formation of synclinal keels between granitoid domes.

East of the complex, Milne (1967) found two directions of folding, an older northeast trending set of folds, and a younger north-northwest trending set. Both are approximately isoclinal, with moderate to steep axial plunges. Puskas (1967) noted that the trend of folding southeast of the complex approximated north 70° east. The Coldwell complex appears to be emplaced at a marked flexure in the volcano-sedimentary belt. The regional compilation of Ayers et al. (1970) shows that this flexure corresponds to a bifurcation of the belt.

All of the folds show lineations subparallel to fold axes, commonly defined by alignment of amphibole (b-lineation). The intersection of drag folds and foliation locally defines an a-lineation, rarely paralleled by tiny drag folds and crenulation. Lineation within granitoid massifs north and west of the Coldwell complex parallels those in the surrounding rocks, although the folds in the host rocks wrap around the granitoid bosses. These relations, together with the general concordance of the granitoid plutons, suggest syn-deformational emplacement for lineated granites, although some bodies may be younger.

This conclusion is strengthened by the observation that joint planes tend to similar attitudes in metavolcanic and

granitoid rocks (Puskas, 1967; Milne, 1967). The major joint sets strike about 285°, 330° and 020° and dip vertically. Milne concluded from a structural analysis that the rocks northeast of the complex were subjected to a single period of compressive stress, directed about northwest, which produced folding, jointing and lineation.

All older rocks are cut by faults parallel to major joint directions. According to Milne (1967), the largest fault trends north 55° west, and displays a left hand separation with the north side moving down. The compilation of Ayers, et al. (1970) shows faults parallel to the other joint trends, but their offsets are unknown. Mafic dykes predating the Coldwell complex occupy the first two of these joint sets, while the third is commonly occupied by dykes associated with the complex.

Structure of the contact zone of the Coldwell complex

The contact of the Coldwell complex with Archean rocks occupies a complex zone some tens to hundreds of metres wide. No example of a clean-cut, transecting igneous contact between the main part of the igneous complex and the country rocks has been found. On the east side of the complex, the contacts are rheomorphic, whereas to the west they are assimilative.

East of the complex, country rocks strike parallel to the contact as much as one kilometre away from recognizably igneous rocks. Closer to the contact the metavolcanics exhibit complex, disordered small-scale folding suggestive of plastic deformation. In a general way the sense of the folds suggests that the side near the intrusion moved up, although there are many local exceptions. The folds verge toward the contact, except for a narrow zone, a few metres wide, at the immediate contact where the vergence locally reverses. The texture of the rocks is hornfelsic throughout the plastically folded zone. Small porphyroblasts of alkali feldspar appear close to the contact and the 'contact' itself is marked by lenticles and veins of grey-pink, coarse to pegmatitic syenite. West of the contact, gabbroic material appears in increasing amount as schlieren-like masses. No where is there a chilled zone. The marginal phases are pegmatitic. Northeast of the Marathon airfield the hybridized border zone is at least one kilometre wide within which all varieties of 'agmatitic' mixtures of gabbroic, syenitic and metavolcanic rocks occur. Most of these hybrid rocks display foliation parallel to the edge of the complex, with steep westerly dips.

West of the complex gabbro occurs only in minor amounts but contact relations are equally complex. The contact zone consists of an intimate mixture of augite syenite with aplitic and quartz syenitic phases. Metasomatism, assimilation and alteration characterize the rocks over a large area, producing fenites with lenticles and veinlets of trachytic and aplitic material. Using visible reddening as a criterion, this border zone extends west from the Killala Lake road at least 5 km into the country rocks. Many outcrops appear to be relatively massive alkaline igneous rocks, but recognizable screens and inclusions of country rocks abound. Walker (1967) noted the difficulty in distinguishing gabbro of the Coldwell complex from metasomatized older gabbro. The same difficulty arises with the felsic rocks. West of Little Pic River alkaline rocks exhibit east-west foliation, presumably relict from the greenstone belt.

Despite the highly assimilative nature of the contact, a recognizable thermal aureole extends several hundred metres west of the intrusion (Walker, 1967). At the highest grade, chlorite in the greenstones has been converted to bluish amphibole and minor garnet.

Structure of the eastern ring system

The eastern part of the complex consists of a central, rather massive syenite surrounded by an older ring of gabbroic rocks. Both of these units locally display layering and lamination with gentle inward dips. The range in dip of layering observed by the author was 11° to 70° ; both values were observed in a small area near Bamooos Lake. The layering varies rapidly both in character and attitude along and across strike. The same layer, or even the same area of layering, can rarely be traced as far as 100 m. Layers may disappear gradationally into hybrid or pegmatitic material or be truncated abruptly by trough-like structures. Inclusions are invariably surrounded by a massive aureole, commonly hybrid in appearance.

In the gabbroic phase, rhythmic, inch-scale, and cryptic layering have all been described by Puskas (1967). The base of the rhythmic layers commonly consists of sulphides and oxides, almost to the exclusion of silicates. Lum (1973) suggested that these relationships indicated immiscibility. In the syenite, the darker basal parts of the layers contain alkali feldspar of distinctly higher structural state than the overlying lighter layers (Puskas, 1967). Further, the basic layers are essentially anhydrous, while the salic layers contain iddingsite, amphibole and biotite.

A plot of the lineations and foliation within the syenite (Fig. 12) showed that they defined a rather diffuse focus near Craddock Cove of Peninsula Bay at a depth of about 6 km. These relations are compatible with a "lopolith theory" for the intrusion. However Puskas (1967) showed that layering in the gabbro locally defines a dome-like pattern, dipping gently on the west side and steeply on the east. Analysis of geophysical data by Corbett et al. (1967) showed that the eastern margin of the complex must be essentially vertical. The strong magnetic signature of the gabbro (Fig. 5) shows that the gabbro has no hidden extensions beyond the observed outcrop area, although extensions may have been truncated by more alkaline rocks west of Coubran Lake. The eastern gabbro forms an elongate, crescentic, vertical body – a ring dyke. Corbett et al. (1967) showed that this body extends to a depth of about 8 miles (12 km).

The dyke-like form of the gabbro and the apparent funnel-like form of the syenite could result from intrusion of syenite from the upper, central part of a cupola of vertically differentiated magma, with gabbro drawn from deeper, more peripheral levels. Lineation within the syenite could develop due to flowage in a cone sheet type of intrusion (Fig. 13). Layering of the gabbro presumably resulted from circulation of magma up the centre of the dyke and down the walls, as hypothesized by Philpotts (1968) for the Mount Johnson intrusion. Alternately, the intrusion may be a cauldron subsidence like the petrographically similar Oslo cauldron subsidences (Ofteidahl, 1960). Large masses of country rocks would exist beneath the central syenite in either case. The chain of large inclusions roughly following the gabbro-syenite contact may be part of such a mass. The size of the syenite mass suggests that it could hardly be a single magma injection under either mechanism. The mass must presumably be composed of several smaller sub-units, although these have not yet been identified.

Puskas (1967) showed that joint patterns in the syenite and gabbro were essentially identical, consisting of vertical radial joints and horizontal joints. This pattern suggests that the two units cooled essentially as a single mass. Locally the

joints have permitted relative movements between various parts of the igneous mass. The most prominent such faults outline a sector south of Bamooos Lake along which the underlying gabbro has been pushed up through the syenite. The northern bounding fault can be examined in detail along a canyon-like valley. The evidence of movement decreases westward, and the faults converge and disappear. These data suggest a late upward movement of the rim of the Coldwell complex with respect to the centre. Such a movement might have been associated with a late pulse of magma.

Structure of the western ring system

The western part of the Coldwell complex exhibits a series of crescents, or broken rings, of alkaline rocks centred about a point some 4 km north of Coldwell. The outer ring of alkaline gabbro has a very strong and distinctive magnetic signature (Fig. 5) which shows the ring to be essentially continuous over 300° of arc, with a marked break in the region of Thompson Channel. This break may be due to truncation of the gabbro by later nepheline syenite of the Pic Island centre. The magnetic anomaly is continuous beneath the fenitized rocks in the northeastern part of Peninsula Bay, showing that these rocks form part of the roof of the intrusion, as first suggested by Puskas (1967).

Layering within the rocks of the western complex is much rarer than within the eastern complex, but is locally present, particularly in the nepheline syenites. Within the gabbros and the mafic nepheline syenites, the fabric commonly results from orientation of schlieren, or faint compositional banding. Such zones have rather variable trends, but on the average dip steeply away from the complex. This observation agrees with the slight outward displacement of the magnetic anomaly over the gabbro. Considerable parts of the nepheline syenite show excellent graded layering (Fig. 8), and scour and fill structures are not uncommon. The dip of the layering, invariably steep, commonly exceeds 60° , and the scours suggest that the younger rocks lie toward the centre of the mass. At several places on Coldwell Peninsula, layering in the leucocratic syenites appears to truncate that in the melanocratic syenite, suggesting that there is more than one syenite intrusion. The nepheline syenites north of Highway 17 rarely show layering, but trachytoid foliation is common in the finer grained varieties. Plotting of layering and feldspar lineation (Fig. 14) suggests an ill-defined focus at a depth of about 10 km. This could be explained by assuming a cupola of magma rather smaller and at greater depth than that responsible for the eastern ring complex. In this model, the syenitic rings are interpreted as cone sheets, while the more mafic rocks form ring dykes. This model can be made to accord with the calculations of Corbett et al. (1967) who found that the western margin of the complex dips eastward at a moderate angle. According to the model the syenitic rocks of the western margin would then be assumed to be part of a cone sheet, although much of the syenitic rock may be metasomatic. The configuration of the western complex, which lacks a well defined bounding ring dyke, seems unlikely to be due to cauldron subsidence.

Wedge type faulting, similar to that observed south of Bamooos Lake, is exposed along Highway 17 northwest of Red Sucker Cove. A wedge of nepheline syenite has been lifted up through intensely altered rocks (units 6, 7 & 8). The inward termination of this wedge is poorly exposed, but there seems little doubt that the bounding faults die out inward, as they do in the eastern example.

Because of intense metasomatism and assimilation in the western part of the complex, the exact number of ring dykes and cone sheets is unclear. Probably the gabbroic rocks all form part of one intrusion. Two sheets of augite-amphibole syenite seem to be present, one just north of

Coldwell, and a bifurcating sheet east of Little Pic River. There may be as many as four sheets of nepheline syenite including a thin mesocratic sheet outside the gabbro, a melanocratic sheet just inside the gabbro, and two leucocratic sheets. Other rocks seem to form part of the metasomatized rock screens, although certain identification cannot be made in many cases.

Structure of the southern ring system

The beautifully layered syenites of Pic and Allouez islands do not fit into either of the ring systems discussed above. For this reason, and because the magnetic signature of the alkaline gabbro is clearly truncated by Pic Island, the author assumes that these syenites belong to a third ring system. The layering in the syenites is essentially vertical with the younger side toward Ashburton Bay. In the exposures on the islands the layering bends through an arc of about 120°. These data, together with the size of the break in the magnetic anomaly, are compatible with a circular complex about 4 to 5 km in radius with a centre somewhere off Guse Point. On this model the fenitized rocks on Guse Point and part of the alkaline gabbro form a roof to this intrusion.

Three dimensional form of the Coldwell complex

A combination of outcrop and geophysical data for the Coldwell complex permit a reasonable reconstruction of its three dimensional form. Corbett et al. (1967) have shown from gravity data that the complex as a whole must be relatively dense, and that the geophysical data can be explained by assuming a gabbroic intrusion extending to a depth of 12 km. Allowing for the large amount of light syenitic rocks among the exposed parts of the complex, the base of the complex probably lies at somewhat greater depths. On the eastern margin, geophysical data suggest an essentially vertical contact, while on the western margin the contact is deduced to dip inward at moderate angles. Outcrop data and deductions from structural considerations show that the surficial part of the complex consists of roughly 75 per cent syenitic rocks and 25 per cent gabbroic rocks. Reasonable extrapolation suggests that this ratio persists to a depth of several kilometres, probably to the foci deduced from layering and lineation in the syenites. If this depth is assumed to be 10 km, and if it is also assumed that the syenitic rocks show negligible density contrast with the surrounding granitoid rocks, then the upper 10 km of the crust would account for only 20 per cent of the excess mass observed by Corbett et al. (1967). Assuming that the dense rocks below this level are gabbro and that the density contrast is that assumed by Corbett et al. (1967), then gabbro must extend another 40 km downward. Such models cannot be made free of ambiguity, but they show that gabbro, or other dense rocks, must compose over half the Coldwell complex, and that the roots of the complex extend through much of the crust.

Structural data suggest that the complex consists of a series of ring dykes, cone sheets, and possibly subsided blocks (cauldron subsidences). According to the classic work of Anderson (1951) the foci of the syenitic rocks (cone sheets) represent the distance to the top of the cupola of magma responsible for them, while the outer ring dyke roughly gives the diameter of the cupola. The emplacement of the rocks results from intrusion into fractures opened up by tensile stresses at the top of the cupolas, which themselves form protuberances on a larger body of magma. The sequence of ring systems shows that several cupolas developed during emplacement of the Coldwell complex, with the centre of

magmatic activity gradually shifting to the south and west. The variations in composition of the rocks suggest that each cupola showed vertical compositional zoning with syenitic material at the top, and more mafic material below. The deduced three dimensional form of the complex resulting from this model is pictured in Figure 15.

The present erosion surface lies close to the top of the Coldwell complex. The roof is partly preserved in the zone south of Coubran Lake and probably on Guse Point. Some of the fenitized material along Little Pic River may also be part of the roof. None of these roof fragments contain any mafic volcanic rocks of the Archean greenstone belt that outcrops on both sides of the complex. The complex was therefore emplaced below the base of this belt and the granitoid roof has been substantially uplifted from its original position. Such a method of emplacement is compatible with forceful emplacement of magma by injection of cone sheets and ring dykes. The age of 1265 m.y. obtained by Chaudhuri et al. (1971) from rocks on Little Pic River suggests that disruption of the greenstone belt may have preceded emplacement of the Coldwell complex, and that the latter was emplaced along older regional structural and magmatic features.

Relation of the Coldwell complex to regional structure

The Coldwell complex represents a manifestation of Keweenaw igneous activity (Halls and West, 1971; Halls, 1966), which was characterized by emplacement of vast amounts of basic igneous material, presumably from the upper mantle, at high levels in the crust (Smith et al., 1966; White, 1966). The exact mechanism setting off Keweenaw igneous activity, and the details of its course, remain somewhat obscure, but most authors agree that tensional features in the crust were involved, perhaps similar to continental rift systems, (Hinze et al., 1971). According to these authors, basins could be expected to develop over the rifts, thus explaining the association of sedimentation and volcanism. Plate tectonic interpretations (Chase and Gilmer, 1974; Craddock, 1973) assume incipient rifting involving two or more plates, so that the Lake Superior basin represents a failed triple junction. The northern arm of this junction may connect in some way to the Kapuskasing gravity high (Garland, 1950). Although this high does not extend as far south as Lake Superior, a zone of alkaline and carbonatite intrusions continues southeastward toward Lake Superior. These intrusions give ages similar to that of the Coldwell complex (Siemiakowska and Martin, 1975). A zone of alkaline igneous activity appears to have extended from the Keweenaw basin to the Kapuskasing high during Keweenaw igneous activity.

The boundaries of the Keweenaw lava piles in the Lake Superior basin all appear to be faulted (Halls and West, 1971). The closest Keweenaw lavas to the Coldwell complex lie on the Slate Islands, 10 km southwest of Middleton. These lavas form part of an arm of Keweenaw igneous rocks extending north-northwest to Nipigon.

The Coldwell complex lies very close to the junction of three arms of Keweenaw igneous rocks, one trending southwest toward the Duluth gabbro and associated rocks, another trending south or southeast toward Michipicoten Island and northern Michigan, and the third trending north-northwest toward Nipigon. The complex lies on or close to the extension of the major Isle Royale and North Shore faults (Halls and West, 1971). The complex is the largest of a group of alkaline intrusions of similar age which extend some 300 km to the north and east.

CHAPTER 4

PETROLOGY OF THE COLDWELL COMPLEX

The location, age, composition and geophysical signature of the Coldwell complex show it to be a manifestation of late Precambrian Keweenawan igneous activity. Gravity data suggest that more than 80 per cent of the hidden part of the complex is composed of mafic rocks, compared to about 20 per cent of the exposed part. A generally gabbroic composition would accord well with the known character of other Keweenawan igneous products, but the mechanism by which large volumes of syenite can be derived from gabbroic parent magma remains obscure. In this chapter the development of syenitic rocks is discussed in terms of differentiation trends, physico-chemical conditions of development, and interactions with the wall rocks.

Differentiation trends in the complex

General considerations of the gravity signature of the complex, the nature of Keweenawan igneous activity, and petrogenetic theory suggest if one single magma composition is parental to the complex, that composition must be gabbroic. However analyses of fine grained mafic dykes (Tables 10, 18), which approximate liquid compositions, show a considerable range in content of TiO_2 , $\text{FeO}+\text{Fe}_2\text{O}_3$ and MgO . The differences are reflected in large variations in $\text{Fe}/\text{Fe}+\text{Mg}$ ratios. None of these compositions can be considered 'primitive' in the sense that other compositions can be derived from it by extraction of minerals known to occur in the gabbro. The most important minerals include biotite, olivine, plagioclase, calcite, apatite and magnetite. Given the compositions of these minerals, matrices can be constructed and solved relating the gabbroic compositions by means of adding and subtracting minerals of known composition. The selected mineral compositions (Table 19) are the average compositions obtained by electron probe analysis of minerals of the gabbroic rocks, except for apatite for which stoichiometric $\text{Ca}_3(\text{PO}_4)_2$ was assumed.

The gabbroic rocks of the complex fall into three groups; eastern gabbro, alkaline gabbro, and mafic dykes. The relations between the compositions of these groups can be expressed by the relations

$$\text{MD}+0.60 \text{ AM}+0.03 \text{ BI}+0.14 \text{ PX}=1.20 \text{ AG}+0.28 \text{ PL}+0.10 \text{ OL}+0.11 \text{ MT}+0.06 \text{ CC}+0.01 \text{ AP}$$

$$\text{EG}+1.10 \text{ AM}+0.01 \text{ CC}=1.22 \text{ AG}+0.43 \text{ PL}+0.03 \text{ BI}+0.10 \text{ OL}+0.14 \text{ PX}+0.18 \text{ MT}+0.01 \text{ AP}$$

where the abbreviations are as follows; PL-plagioclase, AM-amphibole, OL-olivine, BI-biotite, PX-pyroxene, MT-magnetite, CC-calcite, AP-apatite, AG-alkaline gabbro, MD-mafic dykes, EG-eastern gabbro. If one of the observed gabbro compositions were parental to the others, then all minerals could be placed on the same side of the equation and have the same sign. Neither of the above expressions approaches this condition. However the two compositions represented by the above equations approach each other, and approach the average alkaline gabbro, as determined by Nockolds (1954). This suggests a further calculation to obtain a parental composition from which all three gabbroic rocks can be derived by fractionation of the minerals observed in the gabbroic rocks. Table 19 shows the results of this calculation. The observed rock compositions can be matched within a few tenths of a per cent, except TiO_2 and H_2O . The TiO_2 discrepancies may result from disregard of the presence of ilmenite (Puskas, 1967), but no reasonable mineral compositions can duplicate the observed water contents. If gabbro is the parental magma, water must be regarded as a mobile component not controlled by crystal fractionation.

The deduced parental composition closely approaches average alkali gabbro, but shows higher $\text{Fe}/\text{Fe}+\text{Mg}$, lower Ca and Al, and High CO_2 . The discrepancies in $\text{Fe}/\text{Fe}+\text{Mg}$ and Ca and Al contents could be removed by assuming fractionation of a more magnesian olivine and anorthitic plagioclase in the hidden parts of the complex. Differentiation of the parental composition to give the gabbroic rocks observed in the complex followed two sharply contrasting paths. Fractionation of plagioclase and magnetite led to alkaline gabbro, while fractionation of amphibole led to the mafic dykes and eastern gabbro. This difference in fractionation paths could result from differing physical-chemical conditions at time of crystallization, as discussed below. The distinction between eastern gabbro and mafic dykes can be seen from the equation

$$\text{MD}+0.06 \text{ BI}+0.28 \text{ PX}+0.15 \text{ PL}+0.07 \text{ MT}=\text{EG}+0.50 \text{ AM}+0.07 \text{ CC}$$

If the composition represented by this equation is taken to be parental to eastern gabbro and mafic dykes, the composition of the former is reached by continued crystallization of amphibole, while the composition of the latter is reached by crystallization of pyroxene and plagioclase (and minor biotite and magnetite) instead of amphibole, that is by a switch from eastern gabbro type of fractionation to alkali gabbro type fractionation.

Table 19

Calculated composition of magma parental to gabbroic rocks of the Coldwell complex

	1	2	3	4	5	6	7	8	9	10**	11	12	13	14	15	16
SiO ₂	42.92	43.94	54.01	40.15	36.10	36.10	50.85	0.33	0.00	0.00	48.84	48.91	43.10	43.11	47.40	47.38
TiO ₂	2.16	2.86	0.01	1.43	5.50	0.60	0.60	26.76	0.00	0.00	2.70	2.04	2.11	1.85	0.15	0.58
Al ₂ O ₃	14.17	14.87	29.28	14.48	18.50	0.30	5.20	2.31	0.00	0.00	14.64	14.47	14.79	14.76	13.56	13.60
FeO*	13.38	11.88	0.15	14.10	24.69	32.40	8.70	65.21	0.10	0.10	12.75	13.46	10.92	11.03	9.29	9.10
MgO	8.73	9.31	0.02	10.77	8.70	29.60	11.40	1.93	1.13	0.25	5.31	4.48	6.37	6.23	9.75	9.97
CaO	11.10	12.37	11.05	11.95	0.00	0.60	22.20	0.59	54.43	58.84	7.75	7.81	9.02	9.02	10.19	10.17
Na ₂ O	2.79	2.32	4.77	2.54	0.20	0.00	1.00	0.00	0.00	0.00	3.88	3.92	3.57	3.56	2.99	2.77
K ₂ O	1.62	0.92	0.52	1.02	9.50	0.00	0.00	0.00	0.00	0.00	2.36	2.28	2.05	2.03	2.41	2.43
H ₂ O	1.26**	0.61	0.00	1.25**	3.00**	0.00	0.00	0.00	0.00	0.00	1.81	0.61	1.68	3.72	1.57	1.57
CO ₂	1.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	44.13	0.00	0.06	0.00	2.74	2.73	0.00	0.00
P ₂ O ₅	0.54	0.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	42.05	1.10	1.02	0.49	0.47	0.40	0.42

* Total Fe+Mn reported as FeO.

** Values assumed

1.	Calculated parental magma composition.	13.	Column 1 less 7.09% PL, 26.36% AM, 4.10% OL, 1.02% PX, 1.77% MT, 0.39% CC, 0.76% AP. Residual 46.88% recalculated to 100%.
2.	Average alkali gabbro (Nockolds 1954).	14.	Average mafic dyke of the Coldwell complex (4 analyses)
3-10.	Assumed mineral compositions; 3-plagioclase, 4-amphibole, 5-biotite, 6-olivine, 7-pyroxene, 8-magnetite, 9-calcite, 10-apatite.	15.	Column 1 less 15.26% PL, 5.34% AM, 0.05% OL, 5.80% BI, 7.27% Mt, 3.32% CC, 0.70% AP. Residual 64.55% recalculated to 100%.
11.	Column 1 less 8.50% PL, 38.15% AM, 4.18% OL, 6.44% BI, 3.82% Px, 0.05% MT, 3.26% CC, 0.36 AP. Residual 35.28% recalculated to 100%.	16.	Average alkaline gabbro of the Coldwell complex (3 analyses).
12.	Eastern gabbro of the Coldwell complex (analysis of dyke rock)		

These calculations and deductions seem sufficiently plausible to justify further calculation. Therefore I attempted to derive various alkaline syenites from the basic rocks with which they seem to be connected, namely augite-amphibole syenite from eastern gabbro, nepheline syenites from alkaline gabbro, and alkaline salic dykes from mafic dykes. These calculations use mean compositions of mafic minerals from the pairs for compositions considered, plus some assumed compositions for minor phases such as apatite and magnetite. The known change in mineral composition with rock composition is ignored. The calculations cannot be expected to be very accurate but they are instructive.

Table 20 shows that augite-amphibole syenite composition cannot be derived from eastern gabbro simply by extraction of minerals from the latter. However the sign of the alkali feldspar and amphibole contributions can be understood, if they are assumed to cumulate in the syenite, that is, the gabbro fractionated mainly plagioclase and pyroxene, with lesser olivine and biotite, to give a liquid parental to the syenite. This liquid fractionated alkali feldspar and amphibole which collected as cumulate minerals. Since the syenite shows abundant evidence of cumulate textures, this interpretation seems reasonable.

On this model, the fractionation history of the eastern gabbro is similar to that of the dyke rocks in showing an initial phase dominated by amphibole fractionation, and a later phase dominated by plagioclase and pyroxene.

Similar calculations applied to the alkaline gabbro (Table 21) show a more complex pattern. If the mesocratic nepheline syenite derived from the alkaline gabbro, the syenite must contain substantial amounts of cumulate nepheline and alkali feldspar, and lesser amounts of cumulate olivine and magnetite. Alternatively the mesocratic nepheline syenite could derive directly from the primitive composition of Table 19 by initial fractionation of amphibole followed by fractionation of plagioclase, olivine and pyroxene. This latter pattern would parallel the derivation of the eastern gabbro and mafic dykes. Leucocratic nepheline syenite cannot be derived from mesocratic nepheline syenite by any plausible pattern of crystal fractionation. However the mesocratic nepheline syenite could be the result of cumulation of amphibole in an originally leucocratic rock.

Table 22 shows results for derivation of salic dykes from mafic dykes. The amount of amphibole required is far too large to consider as a cumulate in the salic dykes. It could be considered as modifying the composition of the mafic parent of the salic dykes before fractionation. In this model the parent of the salic dykes became enriched in amphibole component, presumably by accumulation of early crystallized amphibole. The later crystallization history was dominated by plagioclase, olivine and pyroxene, as previously deduced.

Source and significance of the parental magma

These chemical balance calculations show the complexity of the relations between the various units of the Coldwell complex. None of the observed compositions can be considered as parental to the others. The simplest possible parental composition is that of the alkaline gabbro of column 1, Table 19. Other possible parents could be generated by adding various hypothetical minerals to this composition and extracting them prior to appearance of any of the observed phases. In this sense all calculations of parental composition are ambiguous. However the deduced composition approaches a worldwide magma type and approaches compositions known to have been abundantly present in the general region during the emplacement of the Coldwell complex. These facts suggest that the deduced parental compositions probably lie fairly close to the correct values.

According to modern ideas of basalt genesis (Wyllie, 1971), alkali basalt liquids equilibrate at pressures of 8-18 kilobars, regardless of which one of several competing schemes of petrogenesis is chosen. Tholeiitic basalt magma equilibrates at somewhat lower pressures. Applied to Keweenawan igneous activity, these facts suggest that the magma parental to the Coldwell complex derived from rather greater depths than the magmas responsible for the generally tholeiitic magmatism of the Lake Superior basin.

These ideas fit well with the plate tectonic concept of the Lake Superior basin as a triple junction with a failed arm running north-northeast. On this model, basaltic magma would be expected near the surface in the successful arms, and at greater, but still anomalously shallow, depths along the failed arm. The deduced parental magma of the Coldwell complex is unusually

Table 20
Calculated fractionation from eastern gabbro to augite-amphibole syenite

	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	48.91	35.80	52.15	38.70	43.40	54.10	0.33	0.00	64.03	59.09	59.09
TiO ₂	2.04	0.00	0.75	2.80	2.20	0.05	26.76	0.00	0.00	0.74	0.74
Al ₂ O ₃	14.47	0.10	3.10	15.40	11.20	29.28	2.31	0.00	19.58	16.41	16.41
FeO*	13.46	35.20	7.80	14.00	10.80	0.15	65.21	0.29	0.32	8.29	8.29
MgO	4.48	28.30	11.80	17.50	15.50	0.02	1.93	0.32	0.16	0.32	0.32
CaO	7.81	0.10	28.15	0.00	12.30	11.09	0.59	55.84	0.33	2.78	2.78
Na ₂ O	3.92	0.00	1.05	0.60	3.10	4.77	0.00	0.00	3.02	5.38	5.38
K ₂ O	2.28	0.00	0.00	9.60	1.60	0.02	0.00	0.00	12.12	5.46	5.46
H ₂ O	0.61	0.00	0.00	3.00**	1.25**	0.00	0.00	0.00	0.00	0.69	1.73
CO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12
P ₂ O ₅	1.01	0.00	0.00	0.00	0.00	0.00	0.00	42.05	0.00	0.11	0.11

*Total Fe+Mn quoted as FeO

**Value assumed

1. Eastern gabbro.

2-9. Assumed mineral compositions; 2-olivine, 3-pyroxene, 4-biotite, 5-amphibole, 6-plagioclase, 7-magnetite, 8-apatite, 9-alkali feldspar

10. Column 1 less 9.40% OL, 13.30% PX, 9.37% BI, 20.98% PL, 5.28% MT, 2.23% AP, plus 10.89% AM and 17.20% alkali feldspar. Residual 67.50% recalculated to 100%.

11. Augite-amphibole syenite (average of 3, excluding analysis 2 of Table 12).

Table 21
Calculation of fractionation to nepheline syenite

	1	2	3	4	5	6	7	8	9**	10	11	12	13	14	15	16	17	18	19	20	21
SiO ₂	42.92	54.01	40.15	36.10	36.10	50.85	0.33	0.00	0.00	51.08	51.13	50.80	42.10	36.10	36.10	0.33	65.90	65.80	41.60	56.50	56.50
TiO ₂	2.16	0.01	1.43	5.50	0.60	0.60	26.76	0.00	0.00	1.66	0.81	0.95	2.60	0.60	5.50	26.76	0.00	0.00	0.00	0.35	0.34
Al ₂ O ₃	14.17	29.28	14.48	18.50	0.30	5.20	2.31	0.00	0.00	16.01	15.87	2.00	11.50	0.30	18.50	2.31	20.47	18.60	34.90	19.53	19.53
FeO*	13.38	0.15	14.10	24.69	32.40	8.70	65.21	0.10	0.29	7.23	7.59	10.34	15.55	32.40	24.69	65.21	0.58	0.20	0.40	6.16	6.16
MgO	8.73	0.02	10.77	8.70	29.60	11.40	1.93	1.13	0.25	6.44	6.00	11.60	13.00	29.60	8.70	1.93	0.00	0.00	0.00	0.45	0.45
CaO	11.10	11.09	11.95	0.00	0.60	22.20	0.59	54.63	55.84	7.33	7.34	23.35	9.20	0.60	0.00	0.59	1.54	0.50	1.20	2.30	2.30
Na ₂ O	2.79	4.77	2.54	0.20	0.00	1.00	0.00	0.00	0.00	4.79	5.02	0.85	2.40	0.00	0.20	0.00	9.91	2.70	17.10	6.93	6.93
K ₂ O	1.62	0.02	1.02	9.50	0.00	0.00	0.00	0.00	0.00	2.99	3.00	0.00	1.75	0.00	9.50	0.00	1.09	12.00	4.60	6.07	6.07
H ₂ O	1.26**	0.00	1.25**	3.00**	0.00	0.00	0.00	0.00	0.00	3.09	1.57	0.00	1.25**	0.00	3.00**	0.00	0.00	0.00	0.00	1.14	0.92
CO ₂	1.46	0.00	0.00	0.00	0.00	0.00	0.00	44.13	0.00	0.76	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.75	0.75
P ₂ O ₅	0.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	42.05	0.45	0.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.43

*Total Fe+Mn quoted as FeO

**Assumed value

1. Calculated parental magma composition
- 2-9. Assumed mineral compositions; 2-plagioclase, 3-amphibole, 4-olivine, 5-biotite, 6-pyroxene, 7-magnetite, 8-calcite, 9-apatite.
10. Column 1 less 11.80% PL, 22.75% AM, 0.04% BI, 12.90% OL, 12.49% PX, 4.75% MT, 2.98% CC, 0.77% AP. Residual 31.52% recalculated to 100%.
11. Mesocratic nepheline syenite (average of 3).
- 12-19. Assumed mineral compositions (in nepheline syenite); 12-pyroxene, 13-amphibole, 14-olivine, 15-biotite, 16-magnetite, 17-plagioclase, 18-potash feldspar, 19-nepheline.
20. Column 11 less 126.06% AM, plus 24.98% PX, 15.33% OL, 38.21% BI, 1.40% MT, 25.44% PL, 6.95% KS, 11.06% NE. Residual 99.12% Recalculated to 100%.
21. Leucocratic nepheline syenite (average of 4).

Table 22
Calculated fractionation from mafic dykes to salic dykes

	1	2	3	4	5	6	7	8**	9	10	11
SiO ₂	43.11	54.01	40.15	36.10	36.10	50.85	0.33	0.00	0.00	50.89	50.94
TiO ₂	1.85	0.05	1.43	5.50	0.60	0.60	26.76	0.00	0.00	0.99	0.00
Al ₂ O ₃	14.76	29.28	14.48	18.50	0.30	5.20	2.31	0.00	0.00	19.72	19.67
FeO*	11.03	0.15	14.10	24.69	32.40	8.70	65.21	0.10	0.29	5.28	5.73
MgO	6.23	0.02	10.77	8.70	29.60	11.40	1.93	1.13	0.25	0.72	0.25
CaO	9.02	11.09	11.96	0.00	0.60	22.20	0.59	54.43	55.84	3.12	3.19
Na ₂ O	3.56	4.77	2.54	0.20	0.00	1.00	0.00	0.00	0.00	8.47	8.43
K ₂ O	2.03	0.2	1.02	9.50	0.00	0.00	0.00	0.00	0.00	5.04	4.98
H ₂ O	3.72	0.00	1.25**	3.00**	0.00	0.00	0.00	0.00	0.00	-	5.31
CO ₂	2.73	0.00	0.00	0.00	0.00	0.00	0.00	44.13	0.00	1.32	1.28
P ₂ O ₅	1.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	42.05	0.13	0.17

*Total Fe+Mn quoted as FeO

**Assumed value

- Calculated value impossible (13.46).

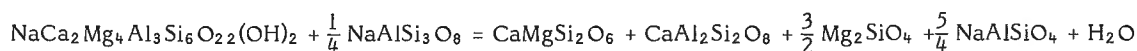
1. Average mafic dyke (4 analyses).
- 2-9. Assumed mineral compositions; 2-plagioclase, 3-amphibole, 4-biotite, 5-olivine, 6-pyroxene, 7-magnetite, 8-calcite, 9-apatite.
10. Column 1 less 43.51% PL, 10.93% BI, 26.41% OL, 21.63% PX, 5.05% MT, 5.30% AP, plus 49.30% AM. Residual 29.48% recalculated to 100%.
11. Average salic dyke (3 analyses).

rich in volatiles. High volatile content may have been the only source of sufficient energy to bring the magma to high levels in the crust. The Prairie Lake complex, 20 km north of the Coldwell complex, consists mainly of carbonatite and ijolite (Ferguson, 1971). Presumably this small intrusion, whose isotopic age of 1112 m.y. resembles that of the Coldwell complex, was only able to reach high levels in the crust because the process of CO₂ enrichment, visible in the Coldwell magma, had proceeded to extremes.

Chemical balance considerations suggest that a key factor in the development of the Coldwell complex was the replacement of amphibole as a cumulate phase by pyroxene+plagioclase+magnetite. This factor can be used to gain quantitative information concerning the conditions of emplacement of the complex.

Physical chemical conditions of emplacement

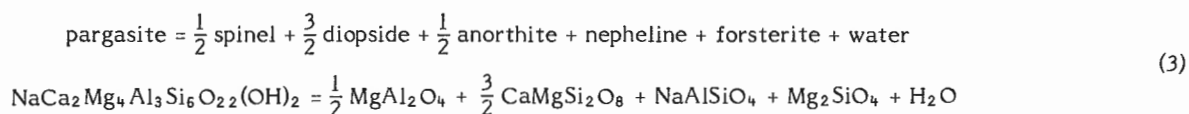
The magma parental to the Coldwell complex underwent two contrasting courses of differentiation, one dominated by crystallization of amphibole, the other by crystallization of plagioclase+ pyroxene. If balanced chemical reactions can be written among the components of these minerals, then the physical chemical conditions controlling the various assemblages can be deduced from the equilibrium conditions for the reaction. One such reaction is the following:



In order for this reaction to be relevant, the mineral assemblage in the rocks should be amphibole-plagioclase-pyroxene-nepheline-olivine. This assemblage occurs in many, if not most of the alkaline rocks. A condition for equilibrium of this reaction can be written in the form:

$$\Delta G = G_d^0 + G_a^0 + \frac{3}{2} G_f^0 + \frac{5}{4} G_n^0 + G_w^0 - G_p^0 - \frac{1}{4} G_{ab}^0 + RT \ln f_w + P (v_d + v_a + \frac{3}{2} v_f + \frac{5}{4} v_n - v_p - \frac{1}{4} v_{ab}) = 0 \quad (2)$$

where ΔG is the change in Gibbs free energy on reaction, G_i^0 is the standard free energy of phase i at temperature T and 1 bar, v_i the volume of i , and f_i its fugacity. The subscripts are as follows; d-diopside, a-anorthite, f-forsterite, w-water, n-nepheline, p-pargasite, ab-albite. All of the quantities in equation (2) can be found in standard tabulations of thermodynamic data, with the exception of the standard free energy of pargasite. This quantity can be deduced from a reaction studied experimentally by Boyd (1959), namely



The condition for equilibrium for this reaction can be written in the form

$$G_p^0 = 0.5G_s^0 + 1.5G_d^0 + 0.5G_a^0 + G_n^0 + G_f^0 + G_w^0 + RT \ln f_w + P(0.5v_s + 1.5v_d + 0.5v_a + v_n + v_f - v_p) \quad (4)$$

All terms on the right hand side of this reaction can be taken from standard data compilations, the G_i^0 from Robie and Waldbaum (1968), fugacity from Burnham et al. (1969), or from the higher temperature values of Pistorius and Sharp (1960) and volume values from Robie and Waldbaum (1968) and Ernst (1968). Boyd (1959) determined that the equilibrium for reaction (3) passed through the four points 850°C, 240 bars, 900°C, 330 bars, 950°C, 480 bars, and 1000°C, 670 bars. Substituting these values into equation (4), and using the data sources listed above, produces four values for $-G_p^0$; 850°C, 234383 cal, 900°C, 231458 cal, 950°C, 228456 cal, 1000°C, 225408 cal. It is convenient to fit this data to an equation of form $G_p^0 = a + bT$, where a and b are constants. In this case $-G_p^0 = 3016967 - 599.08T$ (± 350 cal). The equilibrium curve for reaction (1) can now be calculated from equation (2). Taking the data from the sources referenced above, and recasting the G_i^0 in the form $a + bT$, the result can be written

$$24060 - 30.755T + 0.072P + RT \ln f_w = 0 \quad (5)$$

Along this curve in P-T space pure pargasite, albite, diopside, anorthite, forsterite, nepheline and water coexist. This curve is of little practical significance, since the minerals coexisting in actual rocks are complex solid solutions not pure members. However by taking account of the activity of each component in the complex solid solutions (King, 1969, p. 311-355) the equation can be made to apply to natural mineral assemblages. For such assemblages equation (5) should be re-written

$$24060 - 30.76T + 0.072P + RT \ln f_w + RT (\ln x_d \gamma_d + \ln x_a \gamma_a + 2 \ln x_f \gamma_f + \frac{3}{2} \ln x_n \gamma_n + \ln x_w \gamma_w - \ln x_p \gamma_p - \frac{1}{2} \ln x_{ab} q_{ab}) = 0 \quad (6)$$

where x_i is the mol fraction of component i in the solution of which it forms a part, and γ_i its activity coefficient. In the case of ideal solutions the value of the activity coefficient is 1.0. Most of the solutions involved in equation (6) are known to be almost ideal at magmatic temperatures. Orville (1973) showed that plagioclase solid solutions containing less than 60 mol per cent anorthite component acted essentially ideally at temperatures of 700°C. At higher temperatures the departures from the ideal would be even smaller. Currie and Curtis (1976) showed that nepheline departed very slightly from ideal solid solution, even at metamorphic temperatures, and that pyroxene could be treated as ideal in the absence of jadeite component. Nafziger and Muan (1967) showed that olivine could be considered as an almost ideal solution at magmatic temperatures. For all the solid solutions except amphibole, experimental evidence suggests that the activity coefficients can be taken as 1.0 without significant error. The writer assumes ideal solution for pargasite is amphibole. This assumption undoubtedly introduces an error, but the error is probably small. The equation for coexistence of pargasitic amphibole, pyroxene, plagioclase, nepheline and forsterite can therefore be written:

$$24060 - 30.755T + 0.072P + RT \ln f_w + RT \ln (x_d x_a x_f^{1.5} x_n^{1.25} / x_p^{0.25} x_{ab}) = 0 \quad (7)$$

The calculation of mol fractions of diopside, anorthite, nepheline and forsterite from mineral analysis data is straight forward, but calculation of pargasite content offers difficulties because neither volatile content nor $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio is known directly from analytical data. The writer has adopted the procedure of calculating the analytical data to a standard cell of 46 charges, and then assigning sufficient Al to the Z position to make $Z=800$. If this quantity is denoted Al^{IV} , and the rest of the aluminum designated Al^{VI} , then the mol fraction of pargasite can be computed from the standard cell as $(\text{Al}^{\text{IV}}/2)(\text{Al}^{\text{VI}})(\text{Na})(\text{Mg}/4)$. This procedure avoids difficulties with the oxidation state of iron, but tacitly assumes no iron in the tetrahedral site. It does not distinguish between hydrous, oxidized and fluor-amphiboles, which are tacitly assumed to have the same thermodynamic properties.

In Table 23 the computed mineral compositions for gabbroic rocks are shown. The lamprophyric dykes contain large proportions of pargasite component in the amphibole, and are therefore suitable for applying equation (7). On Figure 16 a curve is plotted for the coexistence of amphibole, pyroxene, plagioclase, olivine and nepheline, assuming water pressure equal to total pressure. This assumption seems rather implausible, since the rocks contain a significant amount of H₂O, and the initial magma may have been undersaturated in volatiles.

Variations in water pressure can be considered by noting that fugacity $f = P_w f^*$ where f^* is the fugacity coefficient and P_w the water pressure. If water and CO₂ mix ideally $P_w = P \cdot x_w$, where x_w is the mol fraction of water in the vapour phase. For the lamprophyres $x_{H_2O}/x_{H_2O} + x_{CO_2} = 0.7$. This seems likely to be a lower limit for the gabbroic rocks, since the fenitized rocks are enriched in water relative to CO₂. Presumably fenitization should deplete the fenitizing magma in water relative to CO₂ leaving relatively high residual CO₂/H₂O ratios. In Figure 16 the stability of the amphibole-pyroxene-plagioclase-olivine-nepheline assemblage is plotted for $P_{volatile} = P_{total}$ and $P_w = 0.7 P_{total}$. This curve is roughly coincident with that for the vapour deficient case in which P_w is about $0.7 P_{total}$. The two curves in Figure 16 are thought to bound the most likely pressure-temperature area for the crystallization of the gabbroic rocks.

Using the mineral compositions for alkaline gabbro in Table 23 causes the equilibrium boundary to be raised about 10 per cent in temperature for a given pressure, since the value of the bracket in the last term of equation (7) goes from 0.300 to about 1.310. At the same pressure, a magma of the composition of the lamprophyric dykes could therefore be crystallizing amphibole, while an alkaline gabbroic magma would be crystallizing pyroxene, olivine and nepheline.

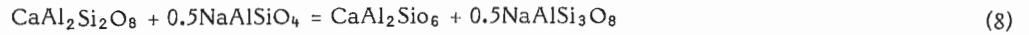
In principle the procedure outlined above could be followed for ferropargasite component of amphibole, using the experimental data of Gilbert (1966). The condition of equilibrium for a given assemblage would be uniquely fixed by the intersection of the two stability curves. In practise this procedure leads to poor results because it requires a knowledge of the oxygen fugacity, and the two curves intersect at a very low angle, giving a poorly defined intersection with a very large uncertainty. Rather than relying on this inaccurate estimation, some data from

Table 23
Compositions of coexisting minerals from units of the Coldwell complex

	olivine x_{fo}	pyroxene x_{ct}	x_{di}	amphibole x_{pa}	nepheline* x_{ne}	plagioclase* x_{an}	x_{ab}	alkali feldspar* x_{kf}	x_{ab}	calculated temperature (at 1 kilobar pressure)
lamprophyre	0.38	0.04	0.75	0.38	0.81	0.65	0.35	-	-	925°C
alkaline gabbro	0.56	0.03	0.69	0.10	0.82	0.58	0.42	-	-	920°C
eastern gabbro	0.54	0.03	0.69	0.10	-	0.55 ⁺	0.45 ⁺	-	-	930°C
mesocratic nepheline syenite	-	0.02	0.75	0.08	0.82	0.42	0.58	0.70	0.30	790°C
leucocratic nepheline syenite	-	0.02	0.66	0.00	0.78	-	-	0.75	0.25	780°C
"laurvikite"	0.04	0.01	0.50	0.08	-	0.34	0.66	0.61	0.39	815°C
barkevikite syenite	0.05	0.00	0.11	0.00	-	0.22	0.78	0.65	0.35	640°C
ultra-fenite	-	0.00	0.46	0.01	-	0.22	0.78	0.66	0.34	635°C
fenite	-	-	-	0.01	-	0.23	0.77	0.71	0.29	605°C
* recalculated to assumed binary solution										
⁺ optical determination										

Yoder and Tilley (1962) on the crystallization of alkaline basalt magma have been added to Figure 16. This curve gives the lowest temperature at which alkaline basalt liquid could be expected to exist (water saturated conditions). An additional curve showing the calculated position of the minimum melting curve for $P_w=0.7P_{total}$ is plotted. The intersection of the curves lies in the general region of 950° and 1 kb. Slightly higher pressures, but not significantly higher temperature, are obtained if it is assumed that the magma was more undersaturated in water. According to the data of Yoder and Tilley (1962) these conditions are reasonable for an alkaline basalt magma crystallizing amphibole. As previously noted, slight differences in composition could result in the appearance of the assemblage pyroxene-plagioclase-olivine-nepheline under the same pressure-temperature conditions.

A further confirmation of the conditions of emplacement of the gabbroic rocks can be obtained from the aluminous pyroxenes of the complex. Consider the reaction

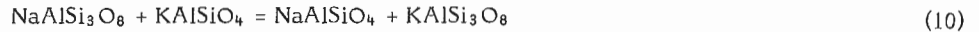


This equilibrium can be evaluated directly from data tabulated by Robie and Waldbaum (1968). With the assumption that all species dissolve ideally, the condition for equilibrium can be written

$$4.526T + 20.39 - 0.345P + RT \ln (x_t x_{ab} / x_a x_n) = 0 \quad (9)$$

where x_t is the mol fraction of $CaAl_2SiO_6$ component in pyroxene. This curve is plotted in Figure 16 for the values of $x_a = 0.58$, $x_n = 0.42$, $x_t = 0.81$, $x_{ab} = 0.04$ (Table 22). The resulting straight line intersects the other curve in the region of 950° and 1 kb, confirming that the gabbroic rocks crystallized in this general region of pressure and temperature.

Amphiboles and pyroxenes of the more salic rock units contain insufficient pargasite or tschermakite component to make equations (5) or (9) useful. For rocks containing nepheline and alkali feldspar, Perchuk and Ryabchikov (1968) pointed out that temperatures can be estimated from the equilibrium



where the components occur in feldspar and nepheline solid solutions. Data for the standard free energies of these components are tabulated by Robie and Waldbaum (1968). Fitting the data for standard free energies to a straight line, the equilibrium can be described by the equation

$$2400 + 0.072P + RT \ln (x_n x_k / x_{kp} x_{ab}) + RT \ln (\gamma_n \gamma_k / \gamma_{kp} \gamma_{ab}) = 0 \quad (11)$$

where k refers to $KAlSi_3O_8$ component, and kp to $KAlSiO_4$. The activity coefficients for nepheline have been investigated by Currie and Curtis (1976) who found that

$$RT \ln \gamma_n = (3.035T - 2830 + 0.288P)x_{kp}^2 + (5952 - 0.854T - 0.579P)x_{kp}^3$$

$$RT \ln \gamma_{kp} = (6098 + 1.745T - 0.160P)x_n^2 + (0.845T - 5952 + 0.579P)x_n^3$$

The activity of alkali feldspar components in disordered alkali feldspar has been investigated by Thompson and Waldbaum (1969) who showed, that to a good approximation,

$$RT \ln \gamma_k = (8.504T - 6530 + 0.131P)x_{ab}^2 + (8859 - 7.974T - 0.019P)x_{ab}^3$$

$$RT \ln \gamma_{ab} = (20050 - 15.420T + 0.074P)x_k^2 + (7.974T - 8859 + 0.019P)x_k^3$$

Substitution of these expressions into (11) leads to a complex expression, which can be considerably simplified by assuming alkali feldspar and nepheline to be binary solutions, so that $x_{ab}=1-x_k$ and $x_n=1-x_{kp}$. With these simplifications, (11) can be reduced to

$$\begin{aligned} -13737 + 4.838T + 0.117P + RT \ln (x_k x_n / x_{kp} x_{ab}) + (6.070T - 5660 + 0.577P)x_{kp} + (8928 - 1.281T - 0.451P)x_{kp}^2 + \\ (13523 - 6.918T + 0.205P)x_{ab} = 0 \end{aligned} \quad (12)$$

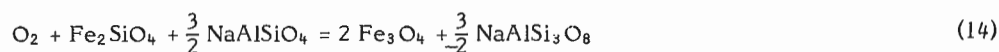
The nepheline composition of the mesocratic nepheline syenite (Table 23) falls outside the Burger-Morozewicz convergence field. It probably represents the original igneous composition, rather than a composition later equilibrated toward the convergence field. The results of pressure-temperature calculations on the gabbroic rocks suggest that pressures lay in the range of 1 to 1.5 kilobars. Assuming a pressure of 1 kilobar, the nepheline-alkali feldspar pair in the mesocratic nepheline syenite suggests a temperature of 790°. The nepheline of the leucocratic syenite lies closer to the convergence field, and may therefore be secondary. However the indicated temperature is almost identical, 780°C.

Stormer (1975) has proposed a geothermometer based on the coexistence of plagioclase and alkali feldspar. I have assumed an emplacement pressure of 1 kb and applied this thermometer to the mesocratic nepheline syenite and to the other syenitic rocks lacking nepheline. The result for the mesocratic nepheline syenite, 810°, accords reasonably well with the nepheline-alkali feldspar estimation, and with the estimate for the augite-amphibole syenite, 815°. The temperatures given for the other syenitic rocks are much lower, ranging from 605 to 640° (Table 23). The estimates of temperature and pressure derived by these methods are given in Table 23 and Figure 16. The temperature of emplacement of the gabbroic rocks appears to have been in the range 900 to 950° at pressures of 1 to 1.5 kb. The nepheline syenite and augite-amphibole syenite were emplaced at noticeably lower, but still magmatic, temperatures in the range of 780 to 820°. The temperatures of equilibration of the other syenites, thought to have developed by hydridization and metasomatism, lie in the subsolidus range for saturated syenites, about 600 to 640°. Morse (1969) pointed out that syenites containing neither quartz nor nepheline have relatively high solidus temperatures, and it is difficult to see how they could exist for long periods as magmas.

Knowing the pressure-temperature conditions of emplacement, the oxygen fugacity during emplacement can be estimated from one of the several buffered assemblages present in the rocks. The augite-amphibole syenite locally contains the assemblage quartz-fayalite-magnetite. Assuming that olivine forms an ideal solid solution, the calibration of Huebner (1971) can be used,

$$\ln f_{O_2} = 20.723 - 59624/T + 0.212P/T - 3 \ln x_f \quad (13)$$

where x_f is the mol fraction of Fe_2SiO_4 in the olivine. Substituting the values of P , T and $x_f(0.96)$ from Table 23, the calculated value of $f_{O_2} = 1.31 \times 10^{-15}$ bars. The alkaline gabbro contains the buffered assemblage nepheline-olivine-magnetite-albite. This buffer operates by the reaction



Assuming ideal solid solution in all phases, substituting thermochemical data from Robie and Waldbaum (1968), and fitting the results to the form of (13), gives

$$\ln f_{O_2} = 2.1734 - 65177/T + 0.216P/T - \ln(x_{ab}^{1.5} x_{mt}^2 / x_f^{1.5} x_n^{1.5}) \quad (15)$$

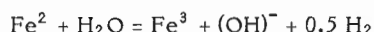
where x_{mt} is the mol fraction of Fe_3O_4 on magnetite. As previously noted, nepheline, olivine and plagioclase can be reasonably treated as ideal solutions at magmatic temperatures. Magnetite is not ideal, since a solvus with ulvospinel is known to exist, but the correction due to non-ideality is very small in eq. 15. For the alkaline gabbro eq. 15 predicts an oxygen fugacity of 1.02×10^{-14} bars using the data in Table 23. Many of the more silicic syenites contain both hematite and magnetite in complex relations suggesting that their formation was almost simultaneous. According to Huebner's calibration, at 625°C the oxygen fugacity of the hematite-magnetite buffer would be about 3.93×10^{-14} bars. The oxygen fugacities prevailing during formation of the Coldwell complex all fall close to 10^{-14} bars. This could not result from internal source. The nature of this external buffer cannot be specified, but it might have been circulating water.

Trends of metasomatic alteration in the complex

The complex nature of metasomatic alteration around the Coldwell complex suggests that at least two distinct processes were involved. One resembled the fenitization process described in the literature, for example by Currie and Ferguson (1971, 1972), in which the silica values of the rocks converge toward a rather low value and the alkali content increases. This process results from the circulation of alkali-rich brines through fractures in the rocks, although the exact composition of the brines remains doubtful (Currie and Ferguson, 1971; Siemiakowska and Martin, 1975). Fenitic alteration demonstrates that the alkaline complex was saturated in water at the moment the fenitizing solutions were released.

The other type of metasomatic alteration (Table 4) resulted in addition of silica and alkalis, particularly potassium. Such a process does not resemble fenitization but rather the formation of "sweats" in high grade metamorphic rocks and the metasomatism associated with granitic rocks. Currie (1968, 1969) showed experimentally that in sealed rocks material can be transported toward a heat source. If the emplacement of the Coldwell complex fractured the wall rocks sufficiently to permit appearance of a free aqueous phase, but did not fracture them sufficiently to vent to the surface, then an originally water-undersaturated intrusion could soak up water from its surroundings.

This hypothesis explains a number of otherwise puzzling features of the complex. The two types of metasomatism could date from different periods. During the earlier, water-undersaturated, period, the intrusion soaked up water from the wall rocks, much of it probably of meteoric origin. This influx could help to buffer oxygen fugacity by reactions of schematic form:



When crystallization of the complex proceeded far enough that a free aqueous phase was evolved, the direction of transport of water reversed, so that solutions migrated outward, mainly through pre-existing cracks and fissures. This stage of fenitization overprinted the early stage of metasomatism.

Geothermometric considerations suggest that even the later stages of magmatic crystallization took place at temperatures above 750°C. Temperatures of the fenitizing solutions were initially near this value, that is above the melting temperature of granitic rocks at the 1 kilobar pressure assumed for the intrusion. Leakage of volatiles into the country rocks during fenitization would therefore produce a complex mixture of metasomatism and melting. As metasomatism proceeded to desilicate the country rocks, the melting temperatures of the resultant syenites would be substantially higher than those of the initial granitic compositions (Morse, 1969). Hence less metasomatized, quartz-bearing, rocks would appear younger and intrusive into more syenitic metasomatic rocks. These considerations may explain the very complex relations among the quartz syenites, fenites, and various hybrid phases termed 'nordmarkite' by Puskas (1967).

Summary and conclusions

The Coldwell alkaline complex resulted from emplacement of a large mass of alkaline basalt magma in the crust. This mass may extend through most of the thickness of the crust. The magma was originally undersaturated in water, but at the level of exposure contained sufficient water that amphibole was the major crystallizing phase. The exposed igneous rocks crystallized in the range 800 to 950°C at about 1-1.5 kb. These conditions lay very close to those at which amphibole becomes unstable, so that some parts of the magma crystallized pyroxene+olivine+plagioclase, leading to a more markedly alkaline differentiation trend. During crystallization the magma took up water from its surroundings, buffering the oxygen fugacity at about 10^{-14} bars. This increase in water content caused amphibole to reappear on the liquidus, so that all the late magmatic rocks contain amphibole. Water saturation was reached at a relatively late stage. The expulsion of aqueous fluids from the complex produced a complicated pattern of melting and metasomatism in the wall rocks. Although the temperatures in the wall rocks surpassed melting temperatures for granitoid compositions, they lay nearly 150° below temperatures of the primary igneous rocks.

CHAPTER 5

ECONOMIC GEOLOGY

Various parts of the Coldwell complex have been examined as prospects for the mining of iron, vanadium, copper and nickel, nepheline, and building stone. No special examination of these prospects was made during the present study, and the following brief summary is based on the work of Puskas (1967).

The eastern gabbros contain magnetite-rich lenses up to 20 m wide and 1.2 km long. The bodies are composed of ilmenomagnetite with accessory olivine, apatite and chalcopyrite. The chemical composition of the larger bodies approaches 40 per cent iron, 30 per cent silica, 5 to 8 per cent sulphur, and 0.3 to 1.0 per cent P_2O_5 . The composition does not appear attractive either as a source of iron or titanium. The largest bodies are listed by Puskas (1967) as follows. A conformable segregation 15 m wide and 1.2 km long crosses Highway 17 about 1.2 miles west of Pic River (Zebe Renshaw property). A number of layers of limenomagnetite occur in a belt extending from 1.5 km north of Bamooos Lake west to Skipper and Lacobeer Lake (George Olsen property). This property also exhibits significant sulphide mineralization. A similar property (H. England property) at the east end of Bamooos Lake contains both ilmenomagnetite layers and sulphide mineralization. A magnetite specimen from an island in the lake east of Bamooos Lake assayed 0.48 per cent vanadium, probably present in the mineral pintadoite, a hydrous calcium vanadate.

Significant copper mineralization occurs in the coarser grained phases of the eastern gabbro underlying the layered and foliated gabbros. Assay results indicate copper values ranging from 0.17-1 per cent, varying erratically both horizontally and vertically. Nickel values are low. Anaconda American Brass Ltd. investigated a claim group about 22 km long extending from Lake Superior north to Bamooos Lake and northwest to Skipper Lake and beyond. Sulphide mineralization occurs scattered throughout the gabbro with significant concentrations in some separated localities. Assays indicate a variation in copper content from 0.05 to about 2 per cent. The area has some potential as a low-grade, large tonnage, open pit operation. Watkinson et al. (1973) reported pyrrhotite and chalcopyrite to be the most abundant sulphides, with lesser amounts of cobaltian pentlandite, cubanite, pyrite, bornite, arsenopyrite, and mackinawite.

Conwest Exploration Company has examined a similar property straddling Highway 17 at the gabbro-felsic volcanic contact. Lakehead Mines Ltd. examined a property west of

Willie Lake centred around Milepost 8 on the boundary of Township 79. All of these properties include magnetite-rich lenses, and the sulphide mineralization is found in or near these lenses.

Moneta Porcupine Mines in 1954 examined a slightly different type of mineralization on the west side of the Coldwell complex, located in Highway 17 1.3 km west of Little Pic River. A gabbro body here interfingers with metavolcanic rocks, and is intruded by a very complex assemblage of pegmatitic nepheline syenite, quartz syenite and granitoid rocks. The gabbro exhibits rude east dipping layering, and the coarser grained zones are enriched in sulphides, magnetite and apatite. The best drilling results graded 0.46 per cent copper over 12 m.

All of the known copper mineralization occurs in zones very close to the gabbro contact, and rich in metavolcanic xenoliths. The zones all display the assemblage pyrite-pyrrhotite-magnetite, diagnostic of very low sulphur fugacities. It seems unlikely that there was sufficient sulphur available to form major sulphide deposits. The observed mineralization may result from mobilization of material from the surrounding metavolcanic rocks.

Building stone has been quarried sporadically from the 'laurvikite' since construction of the Canadian Pacific Railway about 1880. Commercial operations were carried on by Peninsula Granite Quarries Ltd. from 1927 to the late 1930's, in a series of quarries along the railway extending about 4 km north from the old Peninsula station. Two varieties of stone were produced, a 'black granite' with spectacular Carlsbad twinning and schiller, and a 'red granite' with much subdued twinning and schiller. Despite the attractive appearance and high quality of the stone, marketing difficulties forced the closure of the operation in the late thirties. A late attempt to quarry stone in 1960 was unsuccessful.

Denison Mines Ltd. in 1960 shipped a number of samples of various types of nepheline syenite from the west side of Red Sucker Cove to Lakefield Research, to test the potential for nepheline concentration. The 'nepheline' in this region is a mixture of nepheline, thompsonite, natrolite and other minerals. The attempt was unsuccessful because the iron content of the concentrates could not consistently be reduced below 0.08 per cent.

REFERENCES

- Anderson, E.M.
1951: The dynamics of faulting and dyke formation, with applications to Britain (2nd ed.), Edinburgh, Oliver and Boyd.
- Ayers, L.D., Lumbers, S.B., Milne, V.G., and Robeson, D.W.
1970: Ontario Geological Map, East Central Sheet, Ont. Dep. Mines Northern Affairs, Map 2198A.
- Baragar, W.R.A.
1972: Some physical and chemical aspects of Precambrian volcanic belts in the Canadian Shield, in *The Ancient Oceanic Lithosphere*, ed. E. Irving; Can. Earth Phys. Br. Publ., v. 42, no. 3, p. 124140.
- Boyd, F.R.
1959: Hydrothermal investigations of amphiboles, in *Researches in Geochemistry*, ed. P.H. Abelson, John Wiley and Sons Inc., New York, p. 377-396.
- Burnham, C.W.
1967: Hydrothermal fluids at the Magmatic Stage, in H.L. Barnes, ed. *Geochemistry of Hydrothermal Ore Deposits*, Holt, Rinehart, Winston, New York, p. 34-76.
- Burnham, C.W., Holloway, J.R., and Davis, N.F.
1969: Thermodynamic properties of water to 1000°C and 10 000 bars; *Geol. Soc. Am. Spec. Paper* 132.
- Chase, C.G. and Gilmer,
1974: Precambrian plate tectonics; the Mid-continent gravity high. *Earth Planet. Sci. Lett.*, v. 21, p. 70-78.
- Chaudhuri, S., Brookins, D.G., and Fenton, M.D.
1971: Rubidium-strontium whole rock and mineral ages of the Coldwell, Ontario syenites. *Geol. Soc. Am., Abstr.*, v. 3(4), p. 255.
- Coleman, A.P.
1900: Copper and Iron Regions of Ontario. Report of the Bureau of Mines of Ontario for 1900 (9th rep.), p. 143-191.
- Corbett, J.D., Hinze, W.J., and Secor, G.B.
1967: A regional geophysical study of the Port Coldwell complex, Ontario; 13th Ann. Inst. Lake Superior Geology, p. 8.
- Craddock, C.H.
1973: Structural evolution of the Keweenaw province; *Geology* v. 1, p. 190.
- Currie, K.L.
1968: On the solubility of albite in supercritical steam; *Am. J. Sci.*, v. 266, p. 321-341.
1969: Differentiation phenomena in the system quartz-albite-orthoclase-water; in *Report of Activities, Part B*, *Geol. Surv. Can.*, Paper 68-1B, p. 69-70.
1971: A study of potash fenitization around the Brent crater-a Paleozoic alkaline complex; *Can. J. Earth Sci.*, p. 481-497.
- Currie, K.L. and Curtis, L.W.
1976: An application of multi-component solution theory to jadeitic pyroxenes; *J. Geol.*, v. 84, p. 179-194.
- Currie, K.L. and Ferguson, J.
1970: The mechanism of intrusion of lamprophyre dykes indicated by "off-setting" of dykes; *Tectonophysics*, v. 9, p. 525-535.
- Currie, K.L. and Ferguson, J. (cont.)
1971: A study of fenitization around the alkaline carbonatite complex at Callander Bay, Ontario. *Can. J. Earth Sci.*, v. 8, p. 498-518.
1972: A study of fenitization in mafic rocks with special reference to the Callander Bay complex. *Can. J. Earth Sci.*, v. 9, p. 1254-1261.
- Ernst, W.G.
1968: *Amphiboles*. New York, Springer-Verlag.
- Fairbairn, H.W.
1959: Age investigations of syenites from Port Coldwell, Ontario. *Geol. Assoc. Canada* 11, p. 141-144.
- Farrand, W.R.
1960: Former shorelines in western and northern Lake Superior basin; unpub. Ph.D. thesis, Univ. Michigan, Ann Arbor.
- Ferguson, S.A.
1971: Columbium (Niobium) deposits of Ontario; Ont. Dep., Mines; *Min. Resour. Circ.* 14.
- Ferguson, J. and Currie, K.L.
1971: Evidence of liquid immiscibility in alkaline basic dykes from Callander Bay, Ontario; *J. Petrol.* v. 12, p. 561-585.
1972: The geology and petrology of the Callander Bay alkaline-carbonatite complex, Ontario; *Geol. Surv. Can., Bull.* 217.
- Foster, M.D.
1960: Interpretation of the composition of tri-octahedral micas; *U.S. Geol. Surv., Prof. Paper* 354-B.
- Froese, E.
1973: The assemblage quartz-K feldspar-biotite-garnet-sillimanite as an indicator of P_{H_2O} -T conditions; *Can. J. Earth Sci.*, v. 10, p. 1575-1579.
- Garland, G.D.
1950: Interpretations of gravimetric and magnetic anomalies on traverses in the Canadian Shield in Northern Ontario; *Can. Dominion Observatory, Publ.*, v. 16, no. 1.
- Gilbert, M.C.
1966: Synthesis and stability relationships of ferropargasite; *Am. J. Sci.*, v. 264, p. 698-742.
- Halls, H.C.
1966: A review of the Keewenaw geology of the Lake Superior region, in *The earth beneath the continents*, *Am. Geophys. Union, Geophys. Monogr.*, v. 10, p. 3-27.
- Halls, H.C. and West, G.F.
1971: A seismic refraction survey in Lake Superior; *Can. J. Earth Sci.*, v. 8, p. 610-630.
- Hamm, H.M. and Vieten, K.
1971: Zur Berechnung der Kristallchemischen Formel und des Fe^3 Gehaltes von Klinopyroxen aus Elektronenstrahlen-Mikroanalysen, *Neues Jb. Mineral. Monatsh.* p. 310-314.
- Herdman, D.J.
1974: Chemical petrology of the Port Coldwell alkali intrusion; unpub. M.Sc. thesis, McMaster Univ., Hamilton, Ont.
- Hinze, W.J., Davidson, D.M., and Roy, R.F.
1971: Continental rifts (abstract), 17th Inst. Lake Superior Geol., p. 29.

- Huebner, J.S.
1971: Buffering techniques for hydrostatic systems at elevated pressures, in *Research Techniques for High Pressure and High Temperature*, ed. G.C. Ulmer, p. 123-178, Springer-Verlag, New York.
- Kerr, H.L.
1910: Nepheline syenites of Port Coldwell, 19th Ann. Rep., Bur. Mines Ont., p. 194-232.
- Kerrick, D.M. and Darken, L.S.
1975: Statistical thermodynamic models for ideal oxide and silicate solid solutions, with application to plagioclase; *Geochim. Cosmochim. Acta*, v. 39, p. 1431-1442.
- King, M.B.
1969: *Phase equilibrium in mixtures*; Pergamon Press, Oxford.
- Leszczyszn, W.
1959: *Geology of Pic Island*, unpub. B.Sc. thesis, Univ. Western Ontario, London.
- Logan, W.E., Murray, A., Hunt, T.S., and Billings, E.
1863: *Geological Survey of Canada, from its commencement to 1863*. Dawson Brothers, Montreal.
- Lum, H.K.
1973: *Petrology of the eastern gabbro and associated sulphide mineralization of the Coldwell alkalic complex, Ontario*; unpub. B.Sc. thesis, Carleton Univ., Ottawa, Ont.
- Marmo, V.
1971: *Granite petrology and the granite problem*. Elsevier Publishing Co., Amsterdam.
- McGlynn, J.C.
1970: Superior Province; in *Geology and Economic Minerals of Canada*, ed. R.J.W. Douglas, p. 54-71, *Geol. Surv. Can. Econ. Geol. Rep. 1*, 5th ed.
- Milne, V.G.
1967: *Geology of the Cirrus Lake-Bamoos Lake Area*; Ont. Dep. Mines, Geol. Rep. 43.
- Morse, S.A.
1969: Syenites; *Carnegie Inst. Wash. Yearbk.*, v. 67, p. 112-120.
- Nafziger, R.H. and Muan, A.
1967: Equilibrium phase compositions and thermodynamic properties of olivines and pyroxenes in the system $MgO-FeO-SiO_2$, *Am. Mineral.* v. 52, p. 1364-1385.
- Nockolds, S.R.
1954: Average chemical composition of some igneous rocks; *Bull. Geol. Soc. Am.*, v. 65, p. 1007-1032.
- Orville, P.M.
1972: Plagioclase cation exchange with aqueous chloride solutions: results at 700°C and 2000 bars in the presence of quartz. *Amer. J. Sci.* 272, p. 234-272.
- Perchuk, L.L. and Ryabchikov, I.D.
1968: Mineral equilibria in the system nepheline-alkali feldspar-plagioclase and their petrological significance. *J. Petrol.*, v. 9, p. 123-166.
- Philpotts, A.R.
1968: Igneous structures and mechanism of emplacement of Mount Johnson, a Montereian intrusion; *Can. J. Earth Sci.*, v. 5, p. 1131-1137.
- Pistorius, W.F.T. and Sharp, W.E.
1960: Properties of water, Part VI. Entropy and Gibbs free energy of water in the range 10-1000°C and 1-250 000 bars. *Am. J. Sci.*, v. 258, p. 757-768.
- Puskas, F.P.
1967: *Geology of the Port Coldwell area, District of Thunder Bay*; Ont. Dep. Mines, Geol. Br., Open File Rep. 5014.
1970: *The Port Coldwell alkali complex. 16th. Inst. Lake Superior Geol., Abstracts and Field Guide*, p. 85-100.
- Robie, R.A. and Waldbaum, D.R.
1968: Thermodynamic properties of minerals and related substances at 298.15°K (25.0°C) and one atmosphere (1.013 bars) pressure and at higher temperatures; *U.S. Geol. Surv., Bull.* 1259.
- Siemiatkowska, K.M. and Martin, R.F.
1975: Fenitization of Missisagi quartzite, Sudbury area, Ontario; *Bull. Geol. Soc. Am.*, v. 86, p. 1109-1122.
- Smith, T.J., Steinhart, J.S., and Aldrich, L.T.
1966: Crustal structure under Lake Superior. p. 181-197, in *The earth beneath the continents.*, *Am. Geophys. Union, Geophys. Monogr.* 10.
- Stormer, J.C.
1975: A practical two-feldspar geothermometer, *Am. Mineral.*, v. 60, p. 667-674.
- Thompson, J.B. and Waldbaum, D.R.
1969: Mixing properties of sanidine crystalline solutions. III. Calculations based on two-phase data; *Am. Mineral.*, v. 54, p. 811-838.
- Von Eckermann, H.
1948: The alkaline district of Alno Island; *Sver. Geol. Unders., Ser. Ca. No.* 36.
- Walker, J.W.R.
1956: Preliminary Report on the geology of the Jackfish-Middleton area; Ont. Dep. Mines; *Geol. Circ.* 4.
1967: *Geology of the Jackfish-Middleton area*; Ont. Dep. Mines, Geol. Rep. 50.
- Wanless, R.K.
1969: Isotopic Age Map of Canada; *Geol. Surv. Can. Map* 1256A.
- Watkinson, D.H., Mainwaring, P.R., and Lum, H.K.
1973: Petrology and copper mineralization of the Coldwell complex, Ontario; *Geol. Soc. Am. Abstr.*, v. 5, p. 856.
- White, W.S.
1966: Tectonics of the Keewenawan basin, western Lake Superior. *U.S. Geol. Surv., Prof. Paper* 524E.
- Wyllie, P.J.
1973: *The dynamic earth; Textbook in geosciences*. John Wiley and Sons, New York.
- Yoder, H.S. and Tilley, C.E.
1962: Origin of basalt magmas; an experimental study of natural and synthetic rock systems; *J. Petrol.* 3, v. 3, p. 342-532.

APPENDIX

Recalculation of Electron Probe Data

Electron probe analyses have been recalculated into standard cells, assuming that the oxygen framework of the mineral is continuous, and that electrical neutrality prevails. Thus olivine and nepheline analyses have been normalized to 8 charges (4 oxygens), and feldspar to 16 charges (8 oxygens). Biotite has been normalized to 22 charges (Foster, 1960), which tacitly assumes that all the iron is ferrous. However some of the amphiboles and pyroxenes are so iron-rich and ferric that recalculation into end members requires account to be taken of ferrous/ferric ratios. An approximate correction has been made by requiring that the sum of ions in the X, Y and Z positions in pyroxene be 4.00 (Hamm and Vieten, 1971), and that the sum $(Y+Z)=13.00$ in amphiboles. The sum of charges is then adjusted to 12.00 in pyroxenes, and to 46.00 in amphiboles, by converting Fe^2 to Fe^3 . These procedures give apparently reasonable results, but they cannot be expected to be very accurate since they deal with differences, and hence the sum of all the errors in the analysis. Application to electron probe analyses for which Fe^2/Fe^3 ratios are known independently (Curtis and Currie, in press) suggests that the error in calculated Fe^2/Fe^3 ratio is probably less than 10 per cent in pyroxene and less than 25 per cent in amphibole. The assumptions require that the presence of Ti is not associated with vacancies; hence pyroxene must contain Ti in the form of $\text{CaAl}_2\text{TiO}_6$ and NaTiAlO_6 , but not as TiSi_2O_6 . Similarly, in amphibole Ti in the Y position must be balanced by replacement of Ca by Na in the x position. The analyses of titaniferous amphiboles in this work commonly show $\text{Na}+\text{K} > 1/2 \text{Ca}$, suggesting that the method of calculation is reasonable.

The mol fraction of end members has been calculated from the standard cell by finding the occupancy of each cell site individually, and multiplying them together. Thus in a pyroxene containing in the standard cell 0.8Ca, 0.2Na, 0.1 Fe^2 , 0.4Mg, 0.3 Fe^3 , 0.5Al, 1.7Si charge balance considerations require it to consist of 0.3Ca(Fe^3 ,Al)AlSiO₆, 0.2Na(Al, Fe^3)Si₂O₆ and 0.5Ca(Fe,Mg)Si₂O₆. Within these groupings the proportion of end members is found by multiplying by the site occupancy. Thus the proportions of $\text{CaAl}_2\text{SiO}_6$ and CaFeAlSiO_6 are $(0.2/0.2+0.3)$ and $0.3/0.2+0.3$ respectively. The final statement of mol fractions would thus be 0.18CaFeAlSiO₆, 0.12CaAl₂SiO₆, 0.12NaFeSi₂O₆, 0.08NaAlSi₂O₆, 0.10CaFeSi₂O₆, and 0.4CaMgSi₂O₆. In the case of hydrous minerals, this procedure takes species. It therefore amounts to assuming either that all of the end members are pure hydroxylated phases, or that the chlorinated, fluorinated and oxidized phases have properties identical to those of the hydroxylated phase.

It might seem preferable to avoid the above calculations by assuming a Temkin model (Froese, 1973) whereby the activity of components of solid solutions can be calculated without calculating the mol fraction of end members. Temkin models give numbers very similar to the present method in the case of pyroxenes, but in the case of amphiboles and micas the proper definition of a "site" as used in the Temkin model becomes difficult, and different decisions give very different answers (compare Kerrick and Darken, 1975). In these circumstances it seemed best to avoid the problem.