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GEOLOGICAL SURVEY OF CANADA

DEPARTMENT OF MINES AND TECHNICAL SURVEYS

BULLETIN 70

ALKALINE ROCKS AND NIOBIUM DEPOSITS NEAR NEMEGOS, ONTARIO

R. W. Hodder

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By
R. W. Hodder

DEPARTMENT OF
MINES AND TECHNICAL SURVEYS
CANADA

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PREFACE

Several unusual deposits of niobium-bearing minerals associated with ring-like structures, and alkaline and carbonate rocks have been found in Ontario and Quebec. Some have been explored by companies to test the possibility of economic production of niobium and other metals, and all have aroused considerable academic interest.

The study of one such complex, near Nemegos, Ontario, was the subject of a doctorate thesis sponsored by the Geological Survey of Canada. The author spent the field season of 1956 on the complex and returned privately for shorter visits in 1957 and 1958. This report includes results of laboratory work carried out at the University of California and presents detailed data and conclusions that elucidate problems of all such deposits.

J. M. HARRISON,
Director, Geological Survey of Canada

OTTAWA, January 8, 1960

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These specimens and thin sections are stored with the Geological Survey of Canada, Ottawa.

ALKALINE ROCKS AND NIOBIUM DEPOSITS NEAR NEMEGOS, ONTARIO

Abstract

A ring complex of alkaline rocks with carbonate rock and magnetite-apatite bodies lies within the gneisses of the Timiskaming subprovince of the Canadian Shield near Nemegos, northern Ontario. The complex consists of three concentric rings of alkaline rock: an outer ring 3 miles in diameter and composed of coarse nepheline syenite; a middle ring of foliated malignite, and ijolite traversed by magnetite veins, and including an arcuate body of carbonate rock; and an inner ring of coarse nepheline syenite. Contacts between nepheline syenite and malignite and the foliation in the malignite dip nearly vertically. Bodies of carbonate rock and magnetite-apatite dip steeply towards the centre of the complex. Lamprophyre dykes cut all rocks and dip at low angles away from the centre of the complex. The gneiss surrounding the outer ring of nepheline syenite shows evidence of contact alteration. Of economic interest is magnetite and pyrochlore.

From chemical and petrographic studies and field evidence it is concluded that magma of nepheline syenite composition occupied steeply dipping ring-type fractures. Aqueous solutions rich in calcium, carbon dioxide, iron, fluorine, phosphate and iridium percolated into the wall rocks. These solutions are thought to have been derived directly from the parent magma of the nepheline syenite. Alteration of the gneiss outside the complex involved pyroxenization and desilication to form a rock with minerals characteristic of the igneous alkaline rocks. A septum of gneiss between the outer and inner rings of nepheline syenite was highly altered by percolating solutions to form a layer of malignite. Solutions of similar composition altered nepheline syenite to ijolite along fractures occupied by magnetite veins and deposited in cone-sheet fractures the minerals of the magnetite-apatite rock and of the carbonate rock.

Résumé

Un complexe annulaire de roches alcalines renfermant des masses de roches carbonatées et des amas de magnétite-apatite se rencontre au sein des gneiss de la sous-province géologique Timiskaming du bouclier canadien, à proximité de Nemegos (Nord de l'Ontario). Ce complexe se compose de trois anneaux concentriques de roches alcalines: un anneau extérieur, d'un diamètre de trois milles, constitué de syénite néphélinique à grain grossier; un anneau intermédiaire de malignite foliée et d'ijolite coupée de filons de magnétite, et comprenant également une masse arquée de roche carbonatée; et, finalement, un anneau intérieur de syénite néphélinique à grain grossier. Les contacts, entre la syénite néphélinique et la malignite, et la foliation au sein de la malignite, sont à pendage presque vertical. Les masses de roche carbonatée et de magnétite-apatite sont fortement inclinées vers le centre du complexe. Des dykes de lamprophyre coupent toutes les roches, et ils ont des pendages peu prononcés vers l'extérieur du complexe. Le gneiss, qui entoure l'anneau extérieur de syénite néphélinique, contient des indices d'une altération de contact. Du point de vue économique, il est intéressant de signaler la présence de magnétite et de pyrochlore.

Il ressort, des études chimiques et pétrographiques, et des résultats obtenus sur le terrain, qu'un magma de composition syénite néphélinique a rempli des fractures de type annelé à fort pendage. Des solutions aqueuses riches en calcium, en anhydride carbonique, en fer, en fluor, en phosphate et en iridium se sont infiltrées dans les roches encaissantes. On croit que ces solutions ont dérivé directement du magma originel de syénite néphélinique. L'altération du gneiss, à l'extérieur du complexe, a entraîné la pyroxénisation et la désilication, pour aboutir à une roche à minéraux propres aux roches ignées alcalines. Un segment de gneiss, situé entre les anneaux extérieur et central de syénite néphélinique, a été fortement altéré par les solutions d'infiltration, et il s'est transformé en une bande de malignite. Des solutions de composition semblable ont transformé la syénite néphélinique en ijolite, le long des fractures occupées par les filons de magnétite, et elles ont déposé, dans des fractures de forme conique et faiblement espacées, les minéraux qui composent les roches à magnétite-apatite et carbonatée.

INTRODUCTION

Alkaline plutonic rocks outcrop in a ring of hills that rise 1,000 feet above the hummocky surface of the Canadian Shield a few miles north of Nemegos in northern Ontario. The outstanding features of the area are the concentric distribution of the alkaline rocks (nepheline syenite, malignite, ijolite), isolated bodies of magnetite-apatite and carbonate rock within the alkaline rocks, and the local occurrence of pyrochlore (a radioactive, niobium-bearing mineral) in some of the alkaline rocks, magnetite-apatite bodies and carbonate rocks.

The geological problems investigated in the area include:

1. The distribution and genesis of the alkaline rocks.
2. The nature and significance of the alteration of country rock about the alkaline complex.
3. The distribution and genesis of magnetite-apatite bodies.
4. The distribution and genesis of carbonate rocks. The association of carbonate rocks and alkaline rocks is a problem of current geological interest (Smith, 1956; Pecora, 1956)[1].
5. The distribution and genesis of pyrochlore in the complex.
6. The sequence of events in the development of the alkaline complex at Nemegos and its bearing on the genesis of alkaline rocks in general.

The distribution of the rock types is described in the first part of this paper. The second part is a discussion of possible modes of origin of the complex.

The writer studied part of the alkaline complex during the summer of 1956 and parts of the summers of 1957 and 1958. The area was mapped on scales of 1 inch to 200 feet and 1 inch to 100 feet. Exposures are not plentiful and, wherever possible, surface mapping was supplemented by examination of diamond-drill cores. Specimens were collected for laboratory studies at the University of California, Berkeley.

Location

The alkaline rocks outcrop in McNaught and Lackner townships, Sudbury mining district, northern Ontario. Seven miles of gravel road connect the camp of Multi-Minerals Ltd., in the southwestern part of the area of alkaline rocks, with Nemegos station on the main line of the Canadian Pacific Railway. The town of Chapleau lies 15 miles northwest of the Multi-Minerals camp and may be reached from Nemegos by 18 miles of gravel road, part of which is highway 129 connecting Chapleau with highway 17 at Thessalon.

History and Development

The first claims staked in the area covered a magnetite vein northwest of the present Multi-Minerals camp, visible in an exploration-cut named the McVittie pit after the discoverer. Two claims covering the pit and other magnetite exposures

[1] Names and/or dates in parentheses are those of references cited in Bibliography at the end of this report.

in the vicinity were staked and patented early in the century. Relatively little work was done until 1949 when the deposits were found to be radioactive. This discovery prompted the formation of the Nemegos Uranium Corporation which acquired the original claims and staked seventy-two more—all on the west side of the alkaline complex. It was determined subsequently that radioactivity was caused by pyrochlore, a titano-columbate of calcium and rare earths that commonly contains minor amounts of uranium. In September 1953, Sudbury Northrim

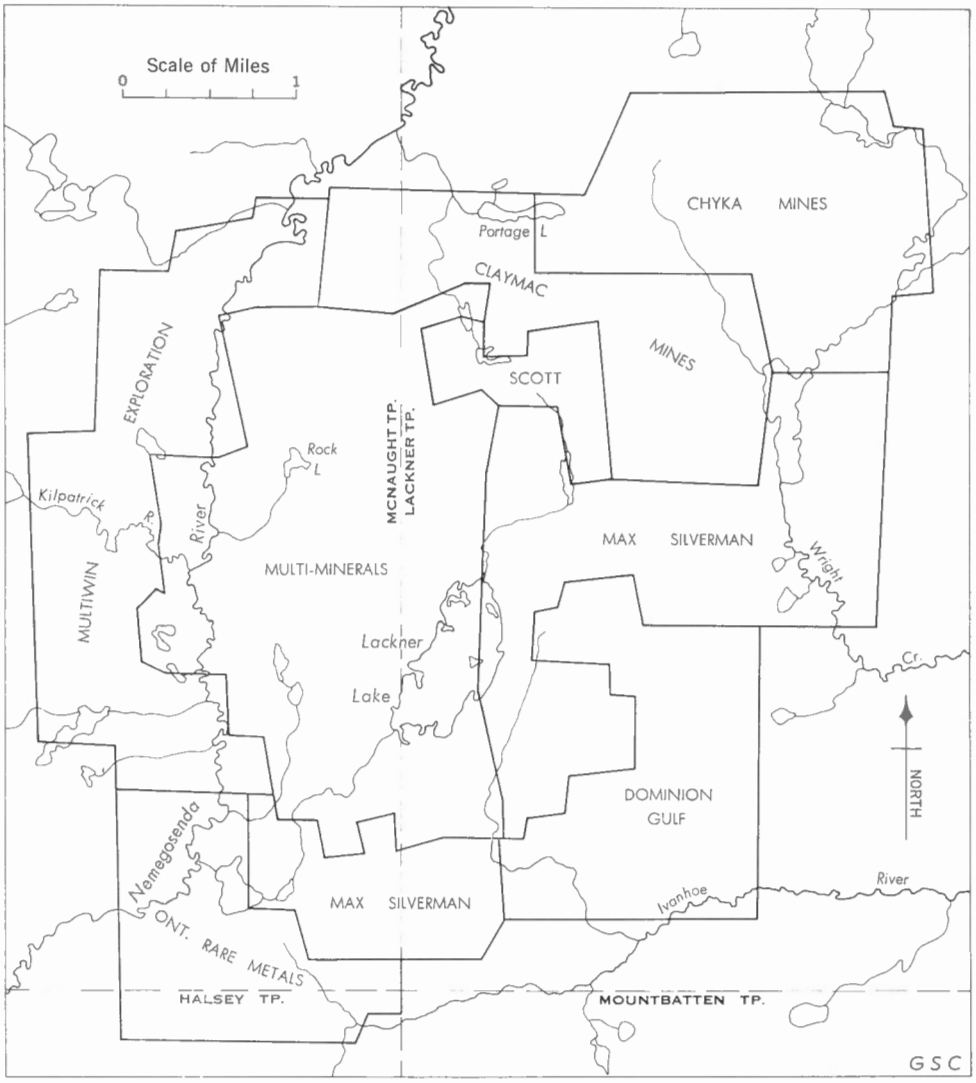

Figure 1. ***Property limits, Nemegos alkaline complex.***

Exploration Co. Ltd.[1] took an option on the property and in the same year it was sold to Multi-Minerals Ltd. (*see* Fig. 1). To date, the property has been mapped geologically, covered by magnetometer and scintillometer surveys, and 65,858 feet of diamond drilling has been done from the surface. Bulk samples have been sent to laboratories for ore dressing and metallurgical tests and in 1956 Multi-Minerals applied for patent of forty-nine claims.

Chyka Mines Limited, Dominion Gulf Company, Max Silverman of Sudbury and several other companies and individuals have conducted geophysical and geological surveys and have done some diamond drilling on the north and east sides of the alkaline complex. Multi-Minerals was the last company active in the area; its program of exploratory drilling was discontinued in October 1956. The district was idle throughout 1957 but in the spring of 1958 Multi-Minerals let a contract to Mannix Construction Company that called for the mining of 150,000 tons of magnetite-apatite from No. 6 orebody. The material was used in concrete mix to weigh down the Trans-Canada pipeline through the muskeg of northern Ontario.

Acknowledgments

Thanks for assistance and courtesies are tendered to the management of Multi-Minerals Ltd., especially to H. L. Garvie, consulting engineer, and to Lloyd Otto, resident manager; and to G. E. Parsons formerly of Dominion Gulf Company, R. W. Hutchinson of American Metal Climax Incorporated, and Frank Petroski of Brochu Diamond Drilling Limited. The writer benefited from unpublished plans and reports supplied by Multi-Minerals Ltd. and by the Dominion Gulf Company. The faculty of the University of California at Berkeley and in particular the thesis committee composed of F. J. Turner, Howel Williams and H. E. Hawkes kindly supervised the laboratory work and final compilation of data. L. E. Weiss advised the writer in the field for a week in 1958 and the Committee on Research of the university provided funds for chemical analyses.

[1] Sudbury Northrim Exploration Co. Ltd. and Sudbury Midzone Mines Ltd. were merged in April 1955 to form Midrim Mining Co. Ltd. Multi-Minerals is an affiliate of Midrim Mining Co.

GENERAL GEOLOGY

Regional Geology

The subject of this report lies within the Timiskaming subprovince of the Canadian Shield. The area had not previously been mapped geologically by federal or provincial surveys and the only mention of the general vicinity is in Bell's (1883) reconnaissance report on the Moose River basin, in which he noted in passing the presence of gneisses along Nemegos River and of erratic blocks of syenite on the shores of Nemegosenda Lake, 20 miles north of Nemegos. However, the Ridout area in Tooms township, which adjoins the southwest corner of Lackner township, was mapped for the Geological Survey of Canada by Emmons and Thomson (1929). They reported highly sheared and chloritized acid to basic flows and pyroclastic rocks in Tooms township. The volcanic rocks, believed to be of Keewatin age, are cut by granite. To the northwest, in Lackner and McNaught townships, where the alkaline complex lies, biotite gneiss outcrops in a few places and has been intersected by diamond-drill holes beyond the margins of the plutonic alkaline rocks. The gneiss is separated from the rocks of Ridout map-area by the Ivanhoe River fault, a structure about which little or nothing is known. Alkaline rocks with pyrochlore, similar to those of the Nemegos complex, have been discovered and explored by the Dominion Gulf Company at Nemegosenda Lake, where Bell first noticed syenite boulders (Parsons, 1957).

Local Geology

The most outstanding geological feature in the Nemegos area is a ring complex of plutonic alkaline rocks outlined topographically by hills, ponds and creeks (*see* Fig. 2). The outermost ring, 3 miles in diameter and marked by hills rising several hundred feet above the flat land outside the alkaline area, is composed of very coarse grained nepheline syenite. This syenite separates the gneissic country rock from an inner ring of dark alkaline rocks formed of ijolite and foliated malignite, which lies in a slight depression. Bodies of magnetite-apatite, carbonate rocks, and a few patches of alkorthosite lie within these dark coloured rocks. A ring of equigranular nepheline syenite, pinkish brown to grey, forms a ridge inside of the depression occupied by the dark rocks. The outcrop width of this layer of nepheline syenite is extremely variable. Similar syenite outcrops between the outer nepheline syenite and the dark rocks, in the northern part of the area. The core of the alkaline complex, within the ring of equigranular nepheline syenite, is a poorly exposed, coarse-grained, inequigranular nepheline syenite. In summary, the principal rock-units appear in the following order from the country gneiss towards the centre of the alkaline complex:

(*a*) Country gneiss.

(*b*) Very coarse nepheline syenite of the outer ring.

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(*c*) A layer of foliated malignites associated with ijolites, magnetite-apatite bodies, carbonate rocks and alkorthosite.

(*d*) Equigranular nepheline syenite.

(*e*) Inequigranular nepheline syenite of the core.

A sharp contact between the outer nepheline syenite and ijolite is exposed 600 feet south of the McVittie pit. On the west shore of Rock Lake the nepheline syenite of the outer ring intrudes the foliated malignites. The contacts between this nepheline syenite and the inequigranular nepheline syenite of the core are gradational wherever they are exposed. The magnetite-apatite bodies and carbonate rocks have sharp contacts with fragments which they include and with the malignites. All rock types are cut by lamprophyre dykes. The relative ages of the rocks commencing with the youngest are as follows: lamprophyre dykes, carbonate rock, magnetite-apatite bodies, ijolite, malignite, outer ring of nepheline syenite, inner core of equigranular or inequigranular nepheline syenite, country gneiss.

These age relationships have been determined from a study of the aforementioned intrusive relationships and a proposed order of development set forth with substantiating evidence in the second part of this paper.

An airborne magnetometer survey has outlined the Nemegos complex and has indicated a satellitic magnetic anomaly half a mile wide on the property of Chyka Mines, northeast of Portage Lake. Diamond drilling indicates a circular body of alkaline rock separated from the main Nemegos complex by a thin septum of pyroxene-biotite gneiss.

Structure

The rock types are arranged in concentric zones about a centre north of Lackner Lake. Foliations in the nepheline syenites, malignites, magnetite-apatite bodies and carbonate rocks strike concentrically, parallel with the contacts, and dip from 55 to 90 degrees towards the centre of the complex. Diamond-drill data show that the carbonate rocks dip towards the centre and suggest that the contacts of the other rock types may also have this attitude. The lamprophyre dykes dip at low angles away from the centre of the complex and are concentric with the major ring structure.

Five faults are believed to be present in the northern part of the area and two others appear to pass completely through the complex. These faults are inferred to explain the distribution of rocks and certain topographic features. The five faults in the north apparently strike northwest to north whereas the regional faults that pass completely through the complex strike northeast. Apparent displacements are small but the actual nature of the faults is unknown. Other faults may be present but unsuspected because of lack of outcrops and drill-hole data. Diamond-drill cores show many small fractures and narrow zones of gouge and breccia, especially within the ring of malignites. The faults are later than the intrusions and do not bear on the genesis of the alkaline complex. They are therefore not shown on the geological map.

DESCRIPTION OF ROCKS

The nepheline syenites are composed essentially of alkali feldspar and nepheline; the malignites of alkali feldspar, nepheline and aegerinaugite; and the ijolites of nepheline and aegerinaugite. The magnetite-apatite and carbonate rocks are what their names imply. Most of the rock-units are subdivided as to texture and grain size; fine grained meaning a grain diameter of less than 1 mm, medium grained of 1 to 5 mm, coarse grained of 5 mm to 3 cm, and very coarse grained meaning a grain diameter greater than 3 cm. Modal analyses are presented with the written descriptions and chemical analyses, and Niggli values are given where they are available. The properties of the various minerals are given in the section entitled *Mineralogy*.

'Outer' Nepheline Syenites

The nepheline syenites in the outermost ring of the alkaline complex can be divided into four types, on the basis of mineral-content and texture. Exposures of type 1 are distinct because of their very coarse and unequal-sized grains. Type 2 has a mineral-content similar to that of type 1 but tends to carry a higher percentage of feldspar and does not exhibit the very coarse grains of type 1. Type 3 contains more than 20 per cent dark minerals, which is considerably more than the other nepheline syenites. Type 4 outcrops only at Beaver Pond where it is characterized by the development of needle-like laths of feldspar in an equigranular matrix. Modal analyses of the four types are listed in Table I.

Type 1. The outer nepheline syenite that outcrops on the western and northern margins of the Multi-Minerals property is inequigranular, very coarse grained, and varies in colour from white to grey flecked with black. On the exposed surface nepheline crystals have weathered away, and the coarse laths of feldspar stand out, emphasizing the alignment of the long direction of the laths parallel with the contact between the nepheline syenite and the malignites.

This nepheline syenite is composed essentially of euhedral grains of nepheline, up to 7 mm in diameter, and simple twinned laths of a perthitic alkali feldspar that vary in length from 2 mm to 4 cm. The perthite may be coarse and the albite twins recognizable in the soda phase. Feldspar laths and nepheline grains are fresh, except for minor cloudy alteration of the feldspar and local development of cancrinite along fractures in the nepheline. Aegerinaugite, biotite, hornblende and magnetite are the dark constituents. The aegerinaugite is irregular in shape and poikilitically includes feldspar. Biotite occurs as ragged grains of many shapes; it replaces aegerinaugite or hornblende or occurs as interstitial grains between feldspar and nepheline. Small zircons surrounded by pleochroic halos occur within the biotite. Hornblende is always in and around the aegerinaugite and there are all degrees of replacement of aegerinaugite by hornblende. The rocks along the western

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Table I

Modes of Nepheline Syenites of the Outer Rim

	1	2	3	4
Alkali feldspar	37.9	28.1	33.9	53.8
Nepheline	50.5	57.4	38.9	34.9
Biotite	7.8	6.2	7.5	3.9
Aegerinaugite	2.6	1.3	9.1	6.2
Hornblende	—	5.1	9.8	—
Accessory minerals	1.2	3.8	0.8	1.2
	100.0	101.9	100.0	100.0
Points	2066	2081	2239	4343

Points were taken $\frac{1}{3}$ mm apart except in 455-I-4 where points were taken $\frac{1}{6}$ mm apart. Rows were $\frac{1}{3}$ mm apart.

1. East side of Camp Lake.
2. Due north of Rock Lake at the northern boundary of Multi-Minerals Ltd. property.
3. North of Rock Lake.
4. East side of Beaver Pond.

Accessory minerals include magnetite, calcite, apatite, zeolites, fluorite, cancrinite, sphene, perovskite, sodalite and pyrochlore.

side of Upper Lake show this particularly well. There, aegerinaugite is surrounded by hornblende which in turn is rimmed with biotite. Magnetite occurs in grains of irregular shape and extremely variable size and is most commonly grouped around the margins of the other dark minerals or included within them. Apatite, sodalite, sphene, calcite, cancrinite, perovskite and pyrochlore are present in minor amounts. Apatite rods are included in most of the minerals. Sodalite and sphene are generally euhedral, but sodalite may fill interstices between other minerals just as calcite does.

The distribution of the foregoing minerals is not uniform. For example, in the western exposures 1,000 feet south of the McVittie pit, there are concentrations of nepheline in areas 2 feet wide where nepheline forms 90 per cent of the rock, the remaining 10 per cent being composed of corroded grains of feldspar and a very few dark minerals.

Hornblende, in appreciable amounts, is present in the northern exposures but absent in the western. Oval patches of pyroxene and biotite as much as 8 inches long occur within the nepheline syenites near margins. They are considered to be xenoliths of other rocks that have been severely altered. Pleochroism of biotite is

not as intense as it is in other nepheline syenites and some biotite grains are strained. Accessory minerals are apatite, calcite, cancrinite, magnetite, amphibole, sphene and perovskite.

Type 2. The nepheline syenite of the northeastern and southeastern margin of the alkaline complex is an inequigranular, coarse-grained rock. It is either brown-grey with patches of black or almost black with patches of white, where dark minerals form clots. Nepheline grains are euhedral to subhedral and generally unaltered but some have cancrinite along cracks. The simple twinned alkali feldspar may be zoned and perthitic and slightly clouded by a dull alteration product. Aegerinaugite has intense pleochroism at the grain borders but the centres are pleochroic in shades of light green and the mineral is rarely rimmed with hornblende. Accessory minerals are apatite, calcite, cancrinite, magnetite, amphibole, sphene and perovskite.

Type 3. This nepheline syenite outcrops in the northwestern part of the Multi-Minerals property, for the most part due north of Rock Lake. The rock occupies an elliptical area between the western and northern exposures of type 1 nepheline syenite and the malignites. The extent of type 3 is defined by small outcrops and loose material; the contact with neighbouring rock types has not been observed. The rock is inequigranular, coarse grained, and mottled grey and black. The constituent minerals have the same optical properties as those of the other nepheline syenites but the nepheline is most commonly subhedral and the grains interlock with perthitic alkali feldspar. The feldspar laths do not exceed 1 cm in length. Rims of aegerinaugite grains are darker green than the centres and have smaller extinction angles (Z C), suggesting a higher content of the aegerine molecule at the grain boundaries. Replacement of aegerinaugite by hornblende is almost complete in some specimens, and many of the hornblende grains show only small blebs of aegerinaugite at their cores. Calcite is a very minor accessory.

Type 4. The type 4 nepheline syenite outcrops on the southeastern side of No. 6 mineral body and on the shores of Beaver Pond. It is inequigranular, coarse to medium grained, grey to brown, and composed essentially of alkali feldspar and nepheline. The feldspar forms needle-like laths up to 1 cm long with simple twins. The nepheline is medium grained, euhedral to subhedral, with patches of cancrinite, and with the medium-grained aegerinaugite and strongly pleochroic biotite it forms an equigranular background for the feldspar laths. Accessory minerals are zeolites, fluorite, zircon, calcite, very fine grained magnetite, and a few grains of pyrochlore within aegerinaugite. The rock is traversed by many magnetite veins flanked on either side by aegerinaugite and biotite. The width of the pyroxene selvage increases directly with increase in width of the magnetite vein. Where several magnetite veins cut the nepheline syenite, the accompanying development of aegerinaugite is sufficient to change the character of the rock from the nepheline syenite to ijolite.

Table II

Chemical Composition, Norm, and Mode of Inequigranular Inner Nepheline Syenite

Specimen 5
Location: South end of the western ravine.

Chemical Composition

SiO_2	51.22
TiO_2	0.22
Al_2O_3	23.55
Fe_2O_3	0.42
FeO	3.89
MnO	0.14
MgO	0.79
CaO	3.36
Na_2O	7.86
K_2O	7.02
H_2O+	1.02
H_2O-	0.11
P_2O_5	0.15
CO_2	0.18
	99.93

Weight %; Analyst: W. H. Herdsman

Norm

or	41.54
ab	2.62
an	10.74
ne	34.12
di	3.83
ol	5.08
mt	0.46
il	0.30
cc	0.40
H_2O	1.12
	100.21

Mode

Alkali feldspar	37.0
Nepheline	48.3
Aegerinaugite	4.2
Hornblende	3.0
Accessories	7.5
	100.0

Accessories include biotite, calcite, magnetite, cancrinite and apatite. 4184 points $\frac{1}{6}$ mm apart on rows $\frac{1}{3}$ mm apart.

Niggli Values

al	48.2
fm	12.0
c	9.1
alk	30.7
	100.0
si	131.

'Inner' Nepheline Syenites

The nepheline syenites at the centre of the alkaline complex are divided into an inequigranular type that forms the core and an equigranular type that rims the core. This difference in texture of the two kinds of inner nepheline syenites is the most striking difference in the field. It is not, however, the only distinction between these rocks, as the equigranular nepheline syenite has a higher feldspar and aegerinaugite content than has the inequigranular nepheline syenite. The contact between the two types is gradational over hundreds of feet. The equigranular type is believed to be a border facies of the inequigranular.

Inequigranular nepheline syenite. The best exposures are along the hillsides west of Lackner Lake and at the southern ends of the two ravines that run south from Tower Lake. The rock is inequigranular, coarse grained and brown-grey. The alkali feldspar is perthitic and tabular in habit with simple twins. Some perthites are coarse and multiple twins are distinguishable in one soda phase. Nepheline is euhedral to subhedral and is considerably altered to cancrinite. The dark minerals are poikilitic aegerinaugite with deep green margins, minor amounts of strongly pleochroic biotite replacing aegerinaugite, and hornblende replacing the pyroxene. Accessory minerals are calcite, magnetite and apatite (*see* Table II). Pyrochlore is a rare accessory mineral.

Equigranular nepheline syenite. This outcrops between the inequigranular nepheline syenite of the core and the layer of malignite. It is coarse grained, equigranular, and brown to grey flecked with black. The rock contains pod-shaped inclusions or segregations of dark minerals as much as 6 inches long oriented parallel with the poorly defined foliation produced by preferred orientation of feldspar grains. The alkali feldspar is perthitic and unaltered, and forms simple-twinned stubby laths that contain rings of inclusions of apatite and aegerinaugite. In a few localities the alkali feldspar includes small ragged grains of albite. Euhedral to subhedral nepheline grains are generally the coarsest grains in the rock and they are altered locally to cancrinite along cracks and at grain boundaries. A few nepheline grains contain rings of inclusions like those in the feldspar. Aegerinaugite forms irregularly shaped grains with rounded edges, although some grains, especially within the feldspar, are spherical. Aegerinaugite is replaced by biotite, hornblende and perhaps nepheline. Biotite occurs also around aegerinaugite and magnetite, extending out along cracks into the light coloured minerals. The minor constituents hornblende and magnetite replace the aegerinaugite and locally magnetite replaces biotite along cleavages. Calcite occurs in various amounts as irregularly shaped grains occupying interstitial positions and penetrating along cracks into other minerals especially biotite. Also present are apatite, zircon, sodalite and pyrochlore (*see* Table III). The pyrochlore forms subhedral octahedra in biotite and has inclusions of feldspar and nepheline.

Malignites

The malignites are dark rocks with pronounced foliation that occupy most of the area between the nepheline syenites of the outer ring and those of the core.

Table III

Chemical Compositions, Norms, and Modes of Equigranular Nepheline Syenites

	6	7	8	9
Chemical Compositions				
SiO_2	50.12	50.32	50.65	50.73
TiO_2	0.34	0.32	0.32	0.22
Al_2O_3	21.79	21.82	22.49	22.74
Fe_2O_3	2.51	1.96	2.17	1.19
FeO	4.76	5.61	4.62	5.06
MnO	0.28	0.28	0.21	0.18
MgO	1.12	0.83	0.65	1.08
CaO	3.86	3.58	3.33	3.19
Na_2O	8.19	7.97	7.49	7.61
K_2O	6.22	6.36	7.24	7.11
H_2O+	0.43	0.37	0.24	0.38
H_2O-	0.21	0.21	0.17	0.09
P_2O_5	0.23	0.17	0.17	0.18
CO_2	nil	0.19	0.19	0.12
	100.06	99.99	99.94	99.88

Weight %; Analyst: W. H. Herdsman

Norms				
or	36.70	37.81	42.81	41.70
ab	3.67	4.30	1.83	2.88
an	4.17	5.00	6.12	3.34
ne	35.10	34.02	33.37	33.09
di	12.53	9.75	7.87	11.44
ol	2.36	4.34	3.01	3.88
mt	3.48	2.78	3.25	1.62
il	0.61	0.61	0.61	0.30
cc	—	0.40	0.40	0.20
H_2O	0.64	0.58	0.39	0.47
	99.26	99.59	99.66	98.92
Modes				
Alkali feldspar	37.9	40.4	46.9	42.8
Nepheline	43.2	44.3	40.2	41.6
Biotite	5.3	1.0	3.4	1.4
Aegerinaugite	11.2	11.1	7.6	11.3
Accessories	2.4	3.0	1.9	2.9
	100.0	99.8	100.0	100.0
Points	4252	4210	4136	4223

All points $\frac{1}{6}$ mm apart and rows $\frac{1}{3}$ mm apart.

Niggli Values				
al	35.3	35.8	37.0	35.1
fm	20.8	20.9	20.0	19.3
c	11.2	10.5	9.8	9.6
alk	32.7	32.8	33.2	36.0
	100.0	100.0	100.0	100.0
si	138.	140.	142.	146.

They are outlined by ground and airborne magnetometer surveys as a crescent-shaped band with greater magnetic intensity than the surrounding nepheline syenites. Magnetometer mapping (*see* Fig. 2) and diamond drilling indicate that the malignites do not project past the southern end of Nine Mile Lake but are again present at the southern margin of the alkaline complex. Rocks at the outer edge of the crescent of malignites are well foliated, medium to fine grained, equigranular except for coarse feldspar and nepheline grains, and grey to black. They grade into the adjoining equigranular nepheline syenite by an increase in grain size and a lightening of the colour as the content of mafic minerals decreases. Type 1 nepheline syenite of the outer rim intrudes the malignites on the west shore of Rock Lake. Foliation results from the alignment of platy and tabular grains plus the segregation of light and dark minerals into distinct layers.

The malignites closest to the nepheline syenite contain coarse feldspar and nepheline grains that project across the foliation and push aside the dark minerals, but in general there are fewer coarse feldspar and nepheline grains towards the centre of the layer of malignite and foliation there is less pronounced in hand specimens. The foliation, defined by the preferred orientation of stubby feldspar laths, is still evident in thin section, but the texture is best described as hornfelsic. Rocks with less pronounced foliation may contain considerable melanite, which gives them a dense vitreous lustre.

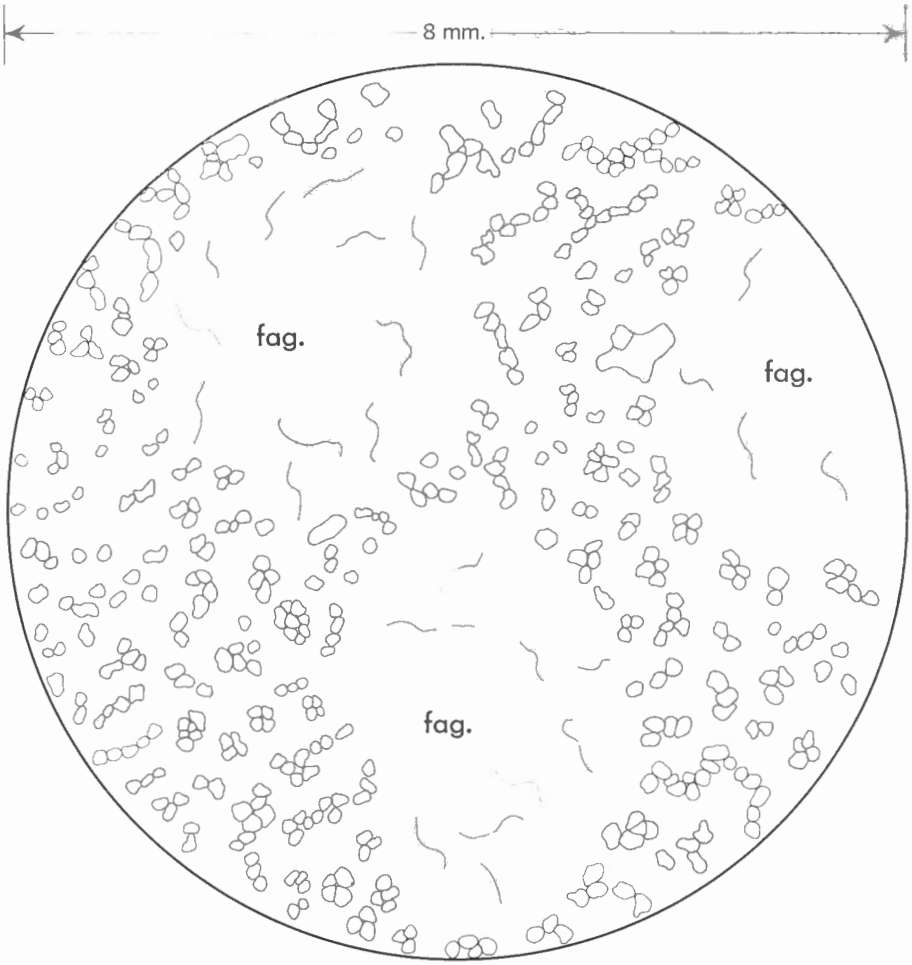
Strongly foliated rocks are not confined to the margins, near the nepheline syenites. Locally rocks with more than 20 per cent preferentially oriented biotite occur away from the margins of the malignites.

The malignites are composed essentially of alkali feldspar, nepheline, aegerinaugite and various amounts of magnetite, melanite, wollastonite, biotite and fayalite, and the accessory minerals calcite, apatite, sodalite, fluorite, zircon, albite, pyrochlore and a white mica. The coarse grains of feldspar that transect the foliation are perthitic and zoned and contain a ring of inclusions of fine grains of aegerinaugite and apatite. The outer rim of the zone has a larger $-2V$ and hence a higher Na content than the core. The coarse nepheline grains are euhedral to subhedral and contain rings of inclusions. Stubby laths of feldspar (which may or may not be perthitic) occur in the ground mass of the coarse grains and correspond in composition to the cores of the coarse feldspar grains. The fine nepheline grains are subhedral to anhedral throughout most of the malignite but become more euhedral towards the equigranular nepheline syenite. Both feldspar and nepheline grains are generally fresh, except for a brownish alteration along curved cracks in the feldspar and the development of cancrinite along cracks in the nepheline (*see* Pl. I). Melanite replaces aegerinaugite and varies in colour from dark brown to bright yellow.

Analyses of three specimens of malignites with their norms and modes are given in Table IV. The modes indicate that the differences in chemical composition between these three rocks are caused by varying proportions of the same mineral constituents. For example, specimen 11 has the lowest silica and alumina content and the highest calcium, sodium and total iron content of the three rocks; it also

has the highest pyroxene content. Specimen 10 has the highest silica and highest potash content and the lowest calcium content, and correspondingly it has the largest percentage of alkali feldspar and lowest of pyroxene.

Specimen 11 has normative leucite, wollastonite and calcium orthosilicate because of the very low silica content and high percentage of lime with respect to total iron and magnesium in the rock.



fag. — fine aggregation of feldspar and nepheline in a very fine-grained groundmass of nepheline, aegirine-augite, and feldspar. The rounded grains in the sketch are aegirine-augite.

GSC

Figure 3. *Sketch of nepheline-feldspar blebs in the ijolite selvages along magnetite veins traversing nepheline syenite.*

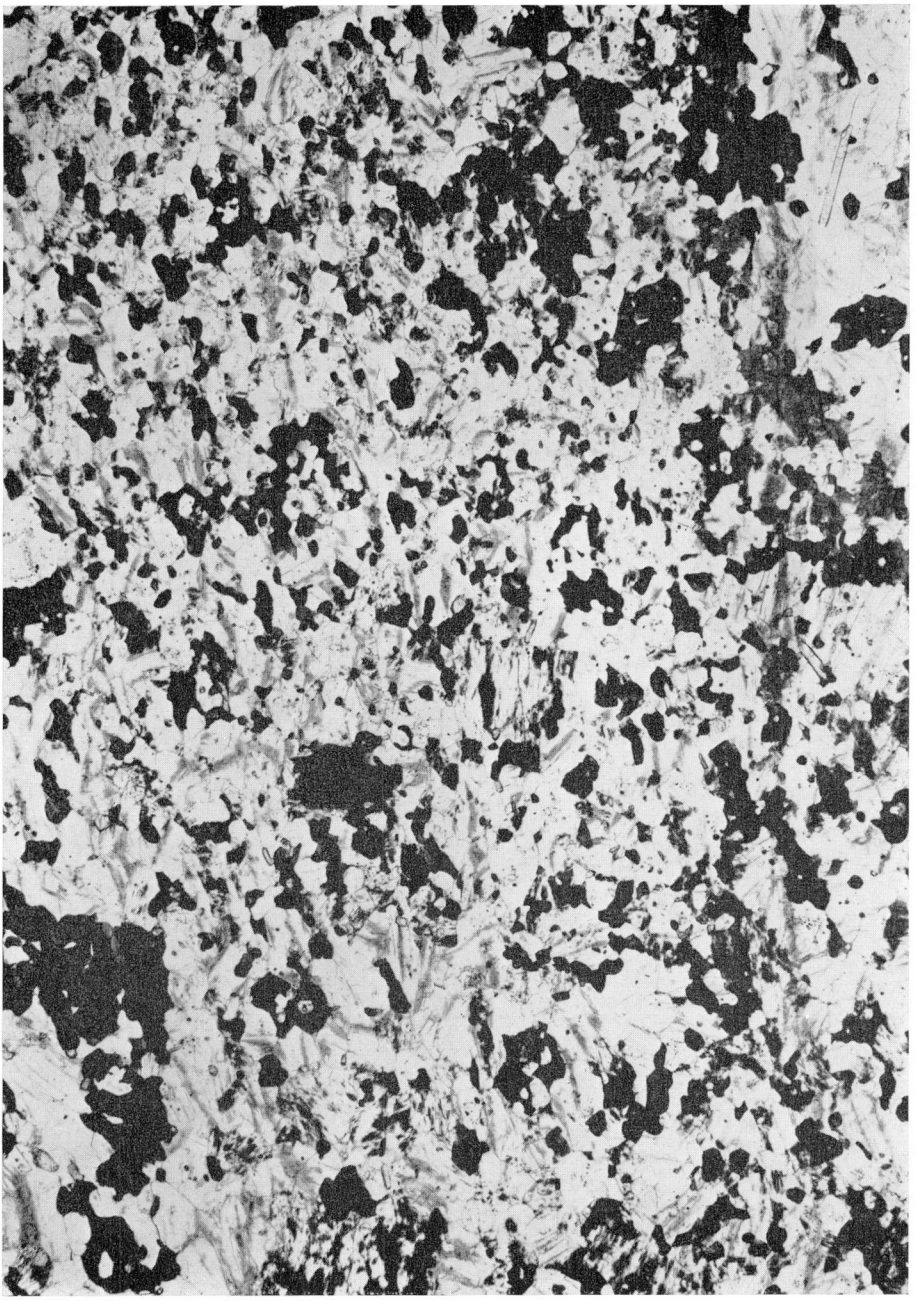


Plate I. *Photomicrograph of malignite from specimen 10, western ravine. Note irregular outlines of the pyroxene grains (grey). Black grains are magnetite and the white area is composed of feldspar and nepheline with alteration along curved cracks.* × 16

Table IV

Chemical Compositions, Norms, and Modes of Malignites

Chemical Compositions

	10	11	12
SiO_2	52.42	42.02	51.32
TiO_2	0.22	0.96	0.28
Al_2O_3	17.91	16.59	19.36
Fe_2O_3	5.46	7.72	4.74
FeO	5.78	5.06	5.78
MnO	0.36	0.46	0.32
MgO	1.81	3.98	1.23
CaO	3.28	10.72	4.23
Na_2O	3.68	7.07	6.34
K_2O	7.55	4.15	6.08
H_2O+	1.21	0.03	0.22
H_2O-	0.19	0.19	0.05
P_2O_5	0.09	1.08	0.21
CO_2	nil	0.19	0.04
	99.96	100.22	100.20

Weight %; Analyst: W. H. Herdsman

Norms

or	44.80	—	35.58
ab	16.40	—	13.26
an	10.01	2.78	6.67
lc	—	19.18	—
ne	7.87	31.47	21.78
di	5.10	25.35	12.06
ol	5.82	—	2.80
wo	—	−5.45	—
cs	—	1.54	—
mt	7.89	11.13	6.73
il	0.30	1.82	0.46
ap	—	1.12	—
cc	—	0.40	—
H_2O	1.40	0.21	0.27
	99.59	100.45	99.61

Modes

Alkali feldspar	55.2	49.1	48.4
Nepheline	26.1	15.9	27.8
Aegerinaugite	14.2	31.5	17.7
Accessories	4.5	3.5	8.2
	100.0	100.0	102.1
Points	6724	7852	8485

All points $\frac{1}{10}$ mm apart and rows $\frac{1}{3}$ mm apart.

Niggli Values

al	30.7	20.6	31.5
fm	34.6	35.0	28.5
c	8.9	24.3	12.4
alk	24.5	20.1	27.5
	98.7	100.0	99.9
si	153.	89.4	141.

Alkorthosite

The alkorthosites are white to grey rocks composed mostly of alkali feldspar with nepheline and a very minor amount of biotite, aegerinaugite, apatite, magnetite, calcite, cancrinite, melanite and albite. These rocks outcrop within the layer of malignites north of Tower Lake, near the contact between equigranular nepheline syenite and malignite, and have been observed in drill-cores from just north of the Multi-Minerals camp. They grade into foliated malignites with the increase in the content of dark minerals and nepheline; their texture is hornfelsic. Nepheline is subhedral to anhedral and fresh except for minor cancrinite. Perthitic alkali feldspar is in stubby laths that have microcline twinning, show an alignment with respect to one another, and are rimmed with multiple-twinned albite which appears to have exsolved from perthite. Albite may occur as individual grains. The pyroxene is very irregular in grain outline and in grain size, and fine-grained magnetite is dusted through the rock. Calcite is interstitial.

Ijolites

Ijolites are best exposed in the McVittie pit where the initial exploration in the area opened a cut in the ijolites around a large magnetite vein. The ijolites are dense black rocks, fine grained and equigranular except where pocked by round clusters of alkali feldspar and nepheline that average 3 mm in diameter. Dominant minerals are nepheline and aegerinaugite. Nepheline occurs as fresh euhedral grains as much as 1 mm wide and as scattered grains as much as 3 mm wide with or without rings of inclusions of small aegerinaugite grains. Late nepheline veinlets cut the rock and are almost completely altered to cancrinite or zeolite. The aegerinaugite grains are irregular in outline and extremely variable in size; the larger grains are formed of coalescing smaller grains (*see* Pl. II) and are poikilitic with inclusions of nepheline, biotite and magnetite. They have pale green centres and dark green margins. Fine- to medium-grained, non-perthitic alkali feldspar is present in accessory amounts as fresh grains with simple twins. Biotite and magnetite occur as fine-grained octahedra or large poikilitic grains enclosing nepheline. Pyrochlore is dispersed through the rock in fine stringers along cracks, or as individual octahedra either around the margins of pyroxenes or in the surrounding light coloured minerals. Apatite occurs in medium-grained ijolites. Melanite, sphene and calcite do not occur in the type of ijolites from the McVittie pit but are found in the ijolites due east of the Multi-Minerals camp. Unlike the ijolites from the McVittie pit, these ijolites carry considerable alkali feldspar.

Round blebs or clots of nepheline and alkali feldspar, which occur in some of the ijolite associated with the magnetite vein of the McVittie pit, suggest a possible connection between these rocks and the pyroxene-rich borders of the magnetite veins traversing the type 4 nepheline syenite of the outer ring. In the type 4 exposures flanking Beaver Pond, veins of magnetite cut the nepheline syenite and the wall rock alongside these veins is enriched in aegerinaugite (*see* Pls. III

Plate II. *Photomicrograph of ijolite from McVittie pit. Note the coalescing pyroxene grains.* × 16

Plate III. *Photomicrograph of magnetite vein and pyroxene selvage. Magnetite is black material at foot of photograph. Grey grains and spongy material is aegerinaugite, and white is nepheline. Magnetite veins traverse outer nepheline syenite of type 4.* × 16

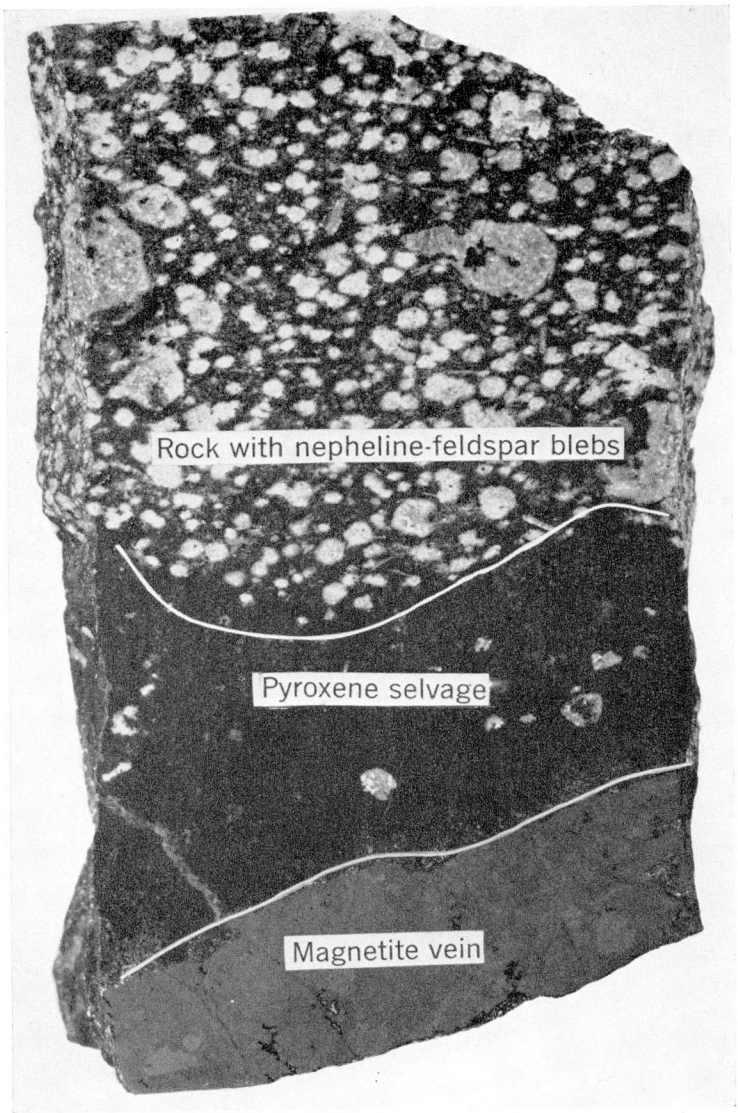


Plate IV. *Photograph of hand specimen showing pyroxene selvage along a magnetite vein passing into rock with blebs of nepheline and feldspar. The rock with nepheline-feldspar blebs passes into 'outer' nepheline syenite of type 4. East shore of Beaver Pond.* × 1

and IV). These basic selvages contain blebs of nepheline and alkali feldspar and correspond very closely in composition and texture to ijolites of the McVittie pit. A sequence away from the centre of a magnetite vein is as follows: 1, magnetite of the vein; 2, ijolite composed of nepheline, aegerinaugite, magnetite and biotite; 3, an ijolite with blebs of feldspar and nepheline. With increasing amount of the light coloured blebs, the ijolite grades into homogeneous nepheline syenite. The width of the pyroxene margin is directly proportional to the width of the magnetite vein and is two to three times wider than the vein. In a thin section of a magnetite vein half an inch wide (*see* Pl. III) nepheline is seen to be the dominant light coloured mineral next to the magnetite vein, although feldspar occurs in minor amounts. The nepheline is fresh and euhedral to subhedral. Small grains of aegerinaugite coalesce into larger grains and appear to replace the nepheline, but there are euhedral nepheline grains in contact with aegerinaugite. Biotite may be present between the magnetite and aegerinaugite grains and the magnetite vein may have a thin core of alkali feldspar. Thin section examination of the rocks with feldspar-nepheline blebs farther away from the magnetite vein shows that the blebs are round patches of close-packed feldspar and nepheline grains with minor aegerinaugite, biotite, magnetite and calcite. The blebs are set in a fine-grained hornfelsic groundmass composed of nepheline, some alkali feldspar in fine equant grains and medium-sized laths, and an abundance of fine aegerinaugite. The edges of the blebs mark the limit of the pyroxene and of the larger grains of nepheline and feldspar (*see* Pl. III). Pyrochlore grains are present in a number of these blebs.

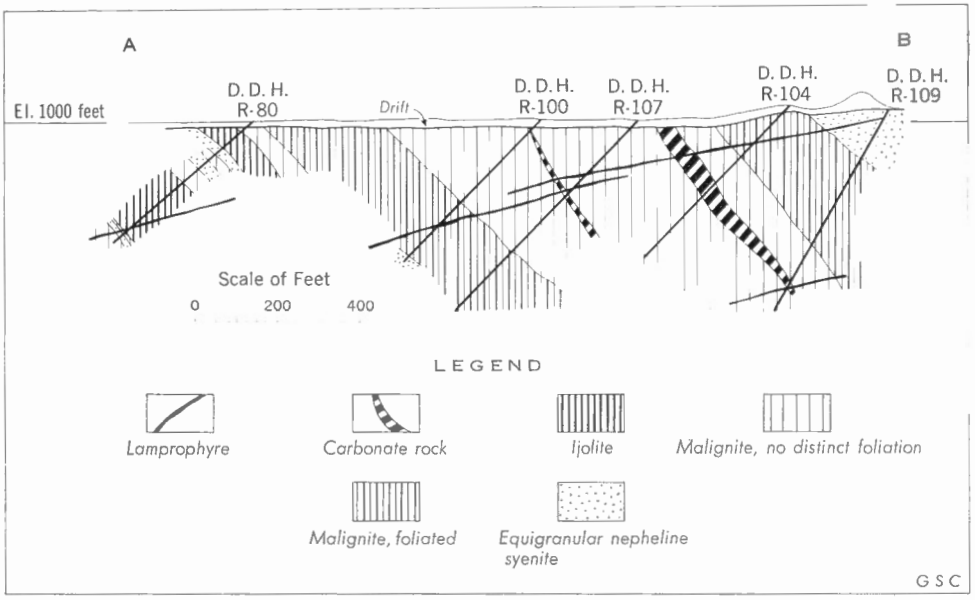


Figure 4. **Diagrammatic section A-B (see Figure 2).**

98011-0—3

Carbonate Rock

Only two outcrops of carbonate rock are known in the area. One of these lies within malignites 200 yards east of Rock Lake, and the other is on the property of Dominion Gulf at the east side of the alkaline complex. However, a body of carbonate rock 650 feet long and 50 feet wide and proven to a depth of 500 feet has been outlined by diamond drilling on the Multi-Minerals property north of Camp Lake (*see* Figs. 4 and 5).

The outcrop at Rock Lake is of a dense grey rock, composed of approximately 20 per cent coarse- to fine-grained calcite, 15 per cent poikilitic alkali feldspar, 20 per cent fine-grained nepheline, 15 per cent magnetite, and accessory amounts of melanite, aegerinaugite, pyrochlore and biotite. The rock is surrounded by nepheline syenite. The carbonate body outlined by diamond drilling is lenticular in plan and cross-section. It is enclosed principally within malignites but in

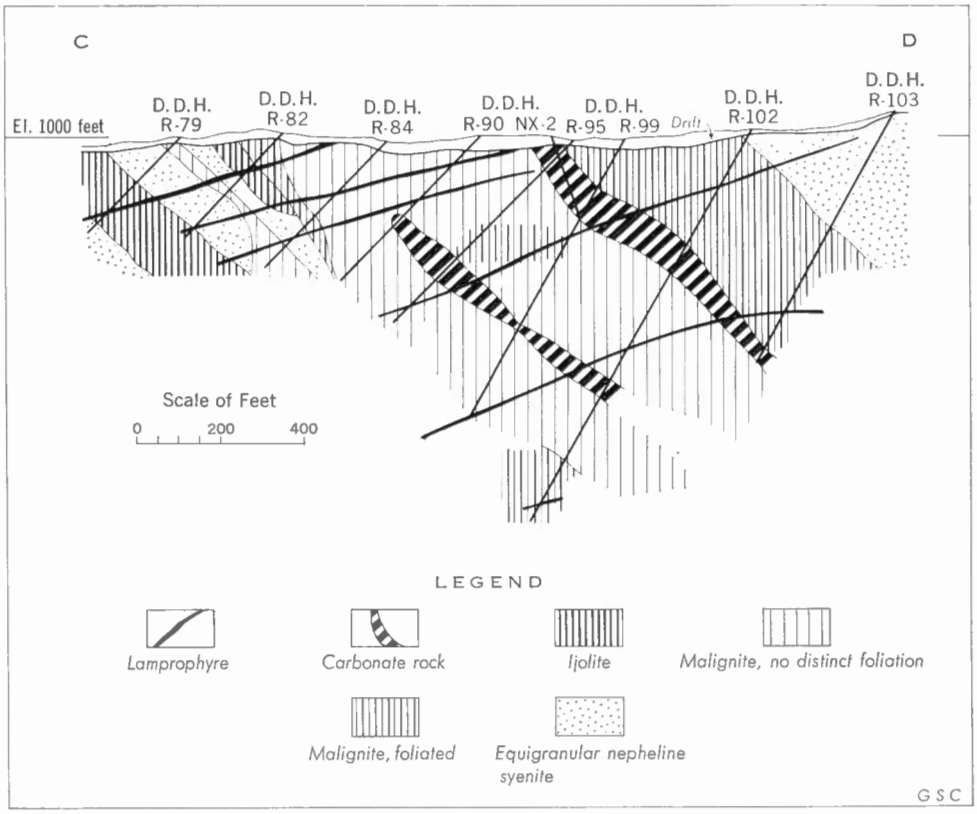


Figure 5. ***Diagrammatic section C-D (see Figure 2).***

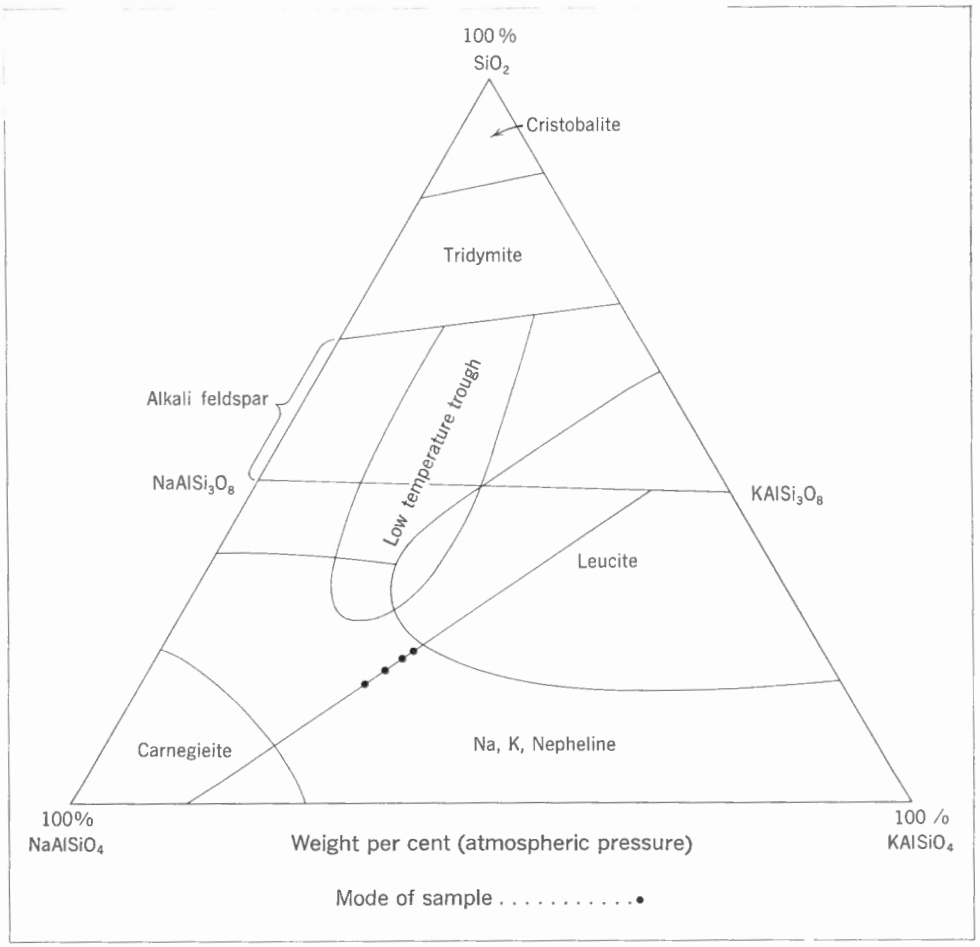


Figure 6. *Nepheline syenites of the Nemegos alkaline complex plotted on the equilibrium diagram of the system $NaAlSiO_4$-$KAlSiO_4$-SiO_2 (Schairer and Bowen; 1935, p. 326; Schairer, 1950, p. 514.) for comment on more recent work in this system at higher pressures see page 40.*

drill-holes it has been observed to intersect ijolite and nepheline syenite. The contacts of the main mass with the wall rocks are sharp. The wall rock has patches of calcite and the biotite and pyroxene content of the malignite is highest within 2 feet of the malignite-carbonate rock contact. The foliation in the malignite is not distinct about the carbonate body. Narrow veinlets of calcite penetrate the enclosing rock beyond the margin of the main mass. The calcite includes angular fragments of rock that are noticeable along the large diameter core as pink to grey patches from a few centimetres to several inches long. The appearance of the fragments corresponds most closely to that of equigranular nepheline syenite.

98011-0—3½

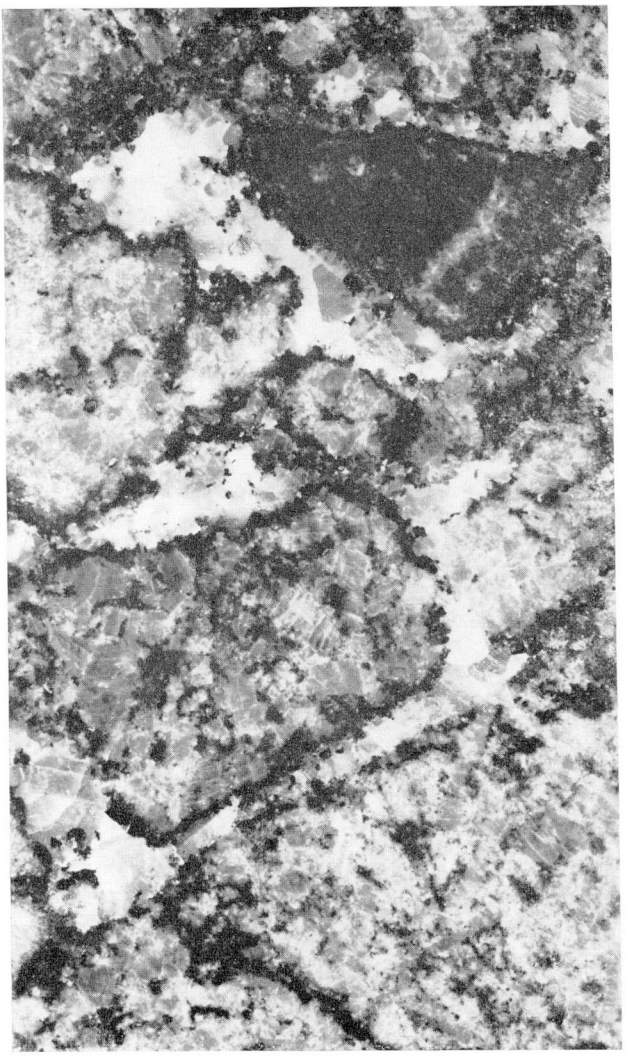


Plate V. *Photograph of drill-core showing rims on inclusions within carbonate rock. Main carbonate mass, Multi-Minerals property.* × *1.5*

They are now fine-grained masses of recrystallized feldspar in rosettes and anhedral grains of nepheline. Irregular grains of aegerinaugite replace the feldspar, and magnetite in turn replaces the aegerinaugite. Calcite is dispersed through the inclusions. The rims of the inclusions are marked by borders of coarse aegerinaugite and biotite, and sometimes by a murky brown alteration (*see* Pls. V and VI). The pyroxene appears to have replaced the biotite and the murky brown

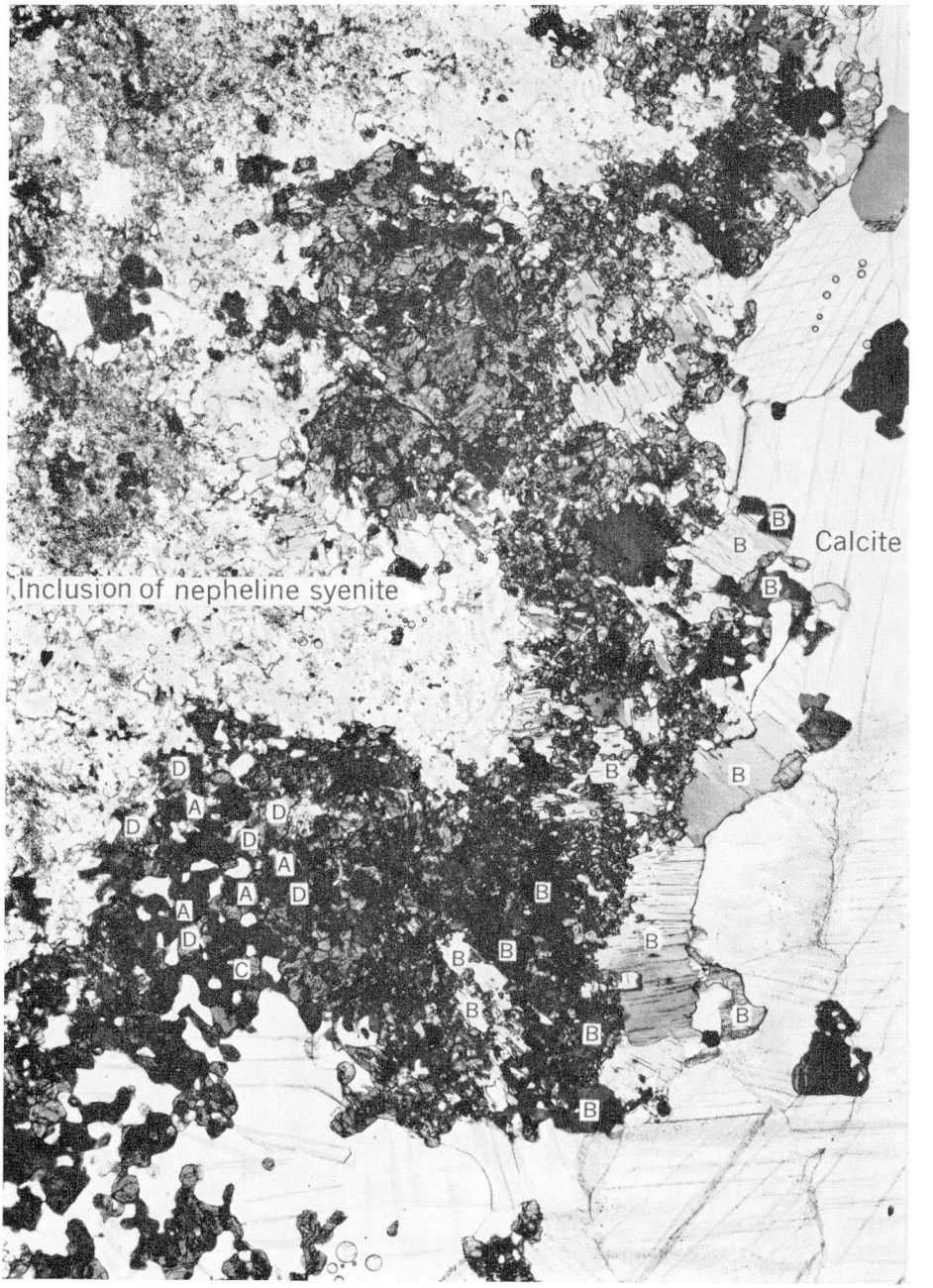


Plate VI. *Photomicrograph of dark coloured rims about inclusions of nepheline syenite in carbonate rock. Main mass of carbonate rock, Multi-Minerals property. A, patches of murky brown alteration material; B, biotite; C, calcite; D, grains of aegerinaugite.* × 16

Plate VII. Photograph of layers of dark coloured minerals within carbonate rock. Main mass of carbonate rock, Multi-Minerals property. × 1.4

alteration. The calcite content of the lenticular body varies; in places bands of aegerinaugite, apatite, magnetite, biotite, sulphides, pyrochlore, albite and alkali feldspar (Pl. VII) that conform with the walls of the body account for 40 per cent of the rock; elsewhere specimens consist of almost pure white or pink calcite. The calcite grains are very coarse and show no signs of deformation.

Lamprophyre Dykes

Lamprophyre dykes do not outcrop but dykes from a few inches to 20 feet thick are cut by diamond-drill holes. The dykes strike conformably with the circular nature of the alkaline complex and dip at angles of 15 to 20 degrees away from the centre of the complex. They cut all alkaline rocks and intrude the enclosing gneisses. The rock is fine grained, inequigranular to equigranular,

and dark grey spotted with white patches as much as 3 mm wide. The white patches are clots of calcite or calcite with plagioclase and alkali feldspar, in a matrix consisting of euhedral colourless pyroxene grains, an altered alkali feldspar, albite, dark brown biotite, magnetite, calcite, chlorite and zeolite. The pyroxene is altered to chlorite. The albite is unaltered, but the alkali feldspar grains are generally altered to a flaky mineral with high birefringence. However, they may be fresh, and younger alkali feldspar may have crystallized along grain boundaries and cracks. Fine magnetite is dusted through the rock and forms wormy intergrowths in the altered pyroxene. Single grains of calcite are crowded between other grains or are collected together in the clots that fleck the rock.

Regional Gneiss

Gneiss outcrops sporadically on the north and northeast sides of the alkaline complex and is intersected by diamond-drill holes on the Multiwin and Multi-Minerals claims west of Nemegosenda River and on the claims of Ontario Rare Metals to the south of the Multi-Minerals camp. Outcrops to the west and south are totally obscured by sand that covers the area to depths of 50 feet. There is no detailed description of the gneisses in the literature and sparse outcrops preclude a continuous examination of changes in the gneiss towards the outer ring of nepheline syenite. No diamond-drill holes penetrate the gneiss closer than 2,000 feet from the outer ring of nepheline syenite and yet no specimens of gneiss were found that did not carry either a soda amphibole or aegerinaugite.

In hand specimens the rock is seen to be essentially a biotite-pyroxene gneiss with a strong foliation and a segregation of light and dark minerals into layers. It is medium to coarse grained with augen of feldspar and quartz up to 1 inch long. Many of these augen are shattered and veined with dark minerals and sulphides. The colour of the gneisses varies from black streaked with white to buff-grey streaked with black. Diamond-drill holes have intersected sections that are mottled white and black and are composed of dark minerals and interstitial calcite. The gneisses are cut by lamprophyre dykes at all localities and by zoned pegmatites with quartz cores on the Multiwin claims. Microscopically their texture is allotriomorphic granular and the essential minerals are alkali feldspar, plagioclase and quartz. Other minerals include aegerinaugite, riebeckite, biotite, calcite, apatite, pyrite, magnetite and zircon. Alkali feldspar is present as coarse grains, commonly perthitic and mostly fractured and veined with dark minerals. Although some grains are fresh, most are altered to a flaky mineral with low birefringence. Alkali feldspar also occurs with albite as fine, ragged grains that have crystallized around the margins of the aegerinaugite or as aggregates of fine grains associated with irregularly shaped biotite, pyroxene, calcite and amphibole. A rim of fine alkali feldspar and albite may be arranged around the aegerinaugite or between the aegerinaugite and biotite. These fine grains are not perthitic. In one specimen the alkali feldspar is replaced by a pale green pyroxene that forms a wormy intergrowth. The coarse plagioclase is more often fresh than is the coarse alkali feldspar. Quartz

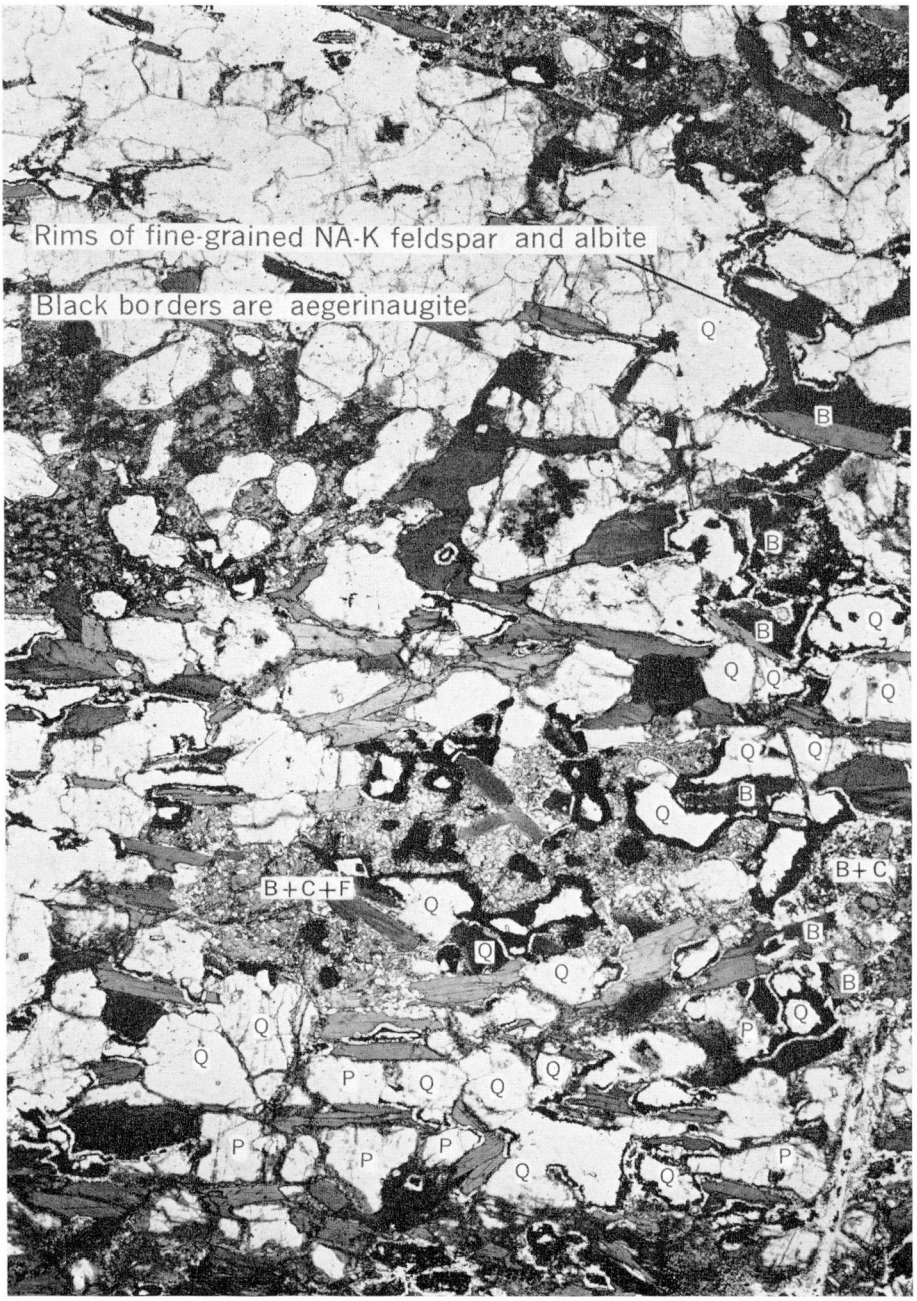


Plate VIII. *Photomicrograph to show occurrence of aegerinaugite in regional country gneiss. Specimen from drill-hole, west side of Nemegosenda River. Q, quartz; B, biotite; C, calcite; P, original plagioclase of the gneiss.* × 16

Table V

Chemical Composition, Norm, and Mode of Pyroxenized Regional Gneiss

Specimen 13 from drill-hole R–83.

Chemical Composition

SiO_2	53.59
TiO_2	0.68
Al_2O_3	16.51
Fe_2O_3	0.87
FeO	7.08
MnO	0.28
MgO	4.34
CaO	6.69
Na_2O	5.52
K_2O	2.51
H_2O+	1.36
H_2O-	*nil*
P_2O_5	0.47
CO_2	0.16
	100.06

Weight %; Analyst: W. H. Herdsman

Norm

or	15.01
ab	31.86
an	12.76
ne	8.01
di	18.54
ol	9.69
mt	1.16
il	1.22
ap	0.49
cc	0.30
H_2O	1.36
	100.40

Mode

Alkali feldspar	36.5
Quartz	18.8
Biotite	22.1
Aegerinaugite	9.6
Plagioclase	9.9
Soda amphibole	102.8
	199.7

9210 points were counted at intervals of $\frac{1}{20}$ mm on rows $\frac{1}{3}$ mm apart. Four thin sections of the analyzed material were used in the counting, because the extent of alteration of the feldspars and quartz and the development of the pyroxene are variable.

Niggli Values

al	33.7
fm	30.2
c	18.3
alk	17.8
	100.0
si	137.

grains may be strained or unstrained and many are rimmed with small grains of aegerinaugite (Pl. VIII). Undulatory extinction of the strained grains decreases with increasing replacement by pyroxene. The aegerinaugite is paler in the outer margins

of these rims around the quartz and is itself rimmed with riebeckite. Aegerinaugite also occurs in masses of small grains in a fine-grained groundmass of feldspar. Many of these small grains of aegerinaugite coalesce to give one big poikilitic grain. The riebeckite appears around aegerinaugite or in clots with aegerinaugite, biotite, feldspar and calcite. In some specimens it is the dominant dark mineral and is readily recognized under crossed nicols because of the extreme dispersion of its bisectrices. A brown amphibole is seen to be associated with the pyroxene in one thin section. Biotite forms stubby grains, pleochroic for the most part in light browns and yellows and commonly in clusters separated from the aegerinaugite by a rim of fine-grained feldspar. Calcite forms interstitial grains especially in clots of fine-grained pyroxene, feldspar, biotite and riebeckite, and calcite stringers through the rock are bordered by riebeckite. Apatite, zircon and sphene are accessory minerals.

Chemical Composition of the Rocks

Comparison of the chemical analyses of the nepheline syenites and malignites from Nemegos with the analyses of the average silic igneous rock (794 analyses) and the average intermediate igneous rock (810 analyses) by Nockolds (1954, p. 1032) permits the following conclusions:

1. Silica is low to moderate in the nepheline syenites.
2. Alumina is high in the alkaline rocks and low to *nil* in the other rocks as compared to the average silic igneous rock and slightly high as compared to the average intermediate igneous rock.
3. Ferrous iron is more abundant than ferric iron in the alkaline rocks and total iron is high with respect to the average silic igneous rock and both lower and higher than that of the intermediate igneous rock. The lowest values occur in the nepheline syenites.
4. Magnesium is average with respect to average silic igneous rocks and low with respect to average intermediate igneous rock.
5. Calcium is high with respect to the average silic igneous rock and low with respect to the average intermediate igneous rock.
6. Sodium is equal to or in excess of potash in most instances and total alkali is very high with respect to all other average igneous rocks.
7. Minor constituents of the silicate rocks such as titanium, carbon dioxide and phosphorus are low with respect to all other average igneous rocks.

MINERALOGY

Six principal minerals are widely distributed in the rocks of the alkaline complex, namely, aegerinaugite, nepheline, alkali feldspar, biotite, magnetite and apatite. In all the silicate rocks these minerals account for at least 90 per cent of the mineral content and only in the carbonate rock are they not the dominant constituents. Aside from these six minerals, the alkaline rocks are characterized by an absence of quartz, of plagioclase, other than albite as a component of perthite, and of primary amphibole and by the presence of the following accessory minerals: primary calcite, fluor-apatite and magnetite. In the following descriptions of the minerals, the optical properties have been determined with the universal stage except where otherwise indicated.

Aegerinaugite

Aegerinaugite is the most abundant mineral in the alkaline rocks. It is never euhedral but rather occurs as fine subspherical grains, as grains with most irregular outlines, and as rounded lobes projecting into adjacent minerals and along grain boundaries. It is rarely twinned and poikilitically encloses apatite, magnetite, biotite, nepheline, alkali feldspar and calcite. Aegerinaugite is replaced by brown hornblende in the nepheline syenites and by melanite in the malignites. Pyrochlore occurs within the aegerinaugite or at its grain boundaries. Groups of fine grains of aegerinaugite coalesce into a clot which in turn recrystallize into one large anhedral crystal with optical continuity. The mineral is fresh in all rocks and strongly pleochroic in greens (*see* Table VI). The colours may be strong at the edges of grains and pale to colourless at the centres, indicative of an enrichment of the aegerine molecule towards the margins.

In the zoned crystals, the extinction angle, X C, of the core of the crystal is less than that of the rim. Aegerinaugites of the malignites and the equigranular nepheline syenite have the largest 2V's in the alkaline suite and the smallest 2V's were recorded from the ijolites.

Nepheline

Nepheline is a constituent of all the silicate rocks except the regional gneiss, and it occurs also as veinlets and breccia fillings. It is readily recognized on the exposed surfaces of the coarse-grained rocks because it weathers faster than the other constituents to leave subhexagonal pits. It is fresh or slightly altered to cancrinite along cracks. An approximate chemical formula of the nephelines determined from X-ray data and partial chemical analyses is $Ne_{85}Kp_{15}$ for the mineral as an essential constituent of the silicate rocks, and $Ne_{75}Kp_{25}$ for the nepheline of the veinlets and breccia fillings. No particular trend in the Ne/Kp ratio was observed in passing outward from the inner nepheline syenite through the equi-

Table VI

Chemical Composition and Optical Properties of Aegerinaugite from Nepheline Syenite of the Outer Rim

Chemical Composition

SiO_2	43.29
TiO_2	0.84
Al_2O_3	5.27
Fe_2O_3	8.09
FeO	16.69
MnO	1.36
MgO	3.26
CaO	11.65
Na_2O	3.92
K_2O	1.77
H_2O+	3.25
H_2O-	*nil*
P_2O_5	0.42
CO_2	*nil*
	99.91

Calculated chemical formula
$(Na_{36}K_{12}Ca_{63})\ (Fe_{30}Fe_{69}Mg_{30}Ti_{33}Mn_6)$
$(Si_{226}Al_{30})\ (O_{751}OH_{108}P_2)$
$(Na,K,Ca)_1\ (Fe,Mg,Ti,Mn)_{1.3}\ (Si,Al)_2\ (O,OH,P)_7$

Weight %; Analyst: W. H. Herdsman

Optical Properties

=1.721		$2V_z=85$
=1.731	(.002)	X C=35
=1.741		r v strong

Absorption X Y Z
X=dark green, Y=light green-yellow
Z=pale green

granular nepheline syenite and the malignites, although the small variations in the Ne/Kp do correspond to variations in the Na/K of the associated alkali feldspars.

Alkali Feldspar

Alkali feldspar grains of the alkaline suite are euhedral, elongate the 'a' axis, simply twinned, perthitic, and fresh except for minor alteration along cracks. The optical properties do not vary greatly from one rock to another with $2V_x$ measured on the potash component varying from 75 to 80 degrees in the nepheline syenites and gneiss and in the 80's in the malignites. The dispersion is r v. Partial chemical analysis, X-ray and optical data indicate a feldspar that is a microcline-microperthite $OR_{60-90}\ Ab_{40-10}$, $2V_x 75°$ to 80° on the potash component and a spacing for (201) of 4.19 to 4.20.

Biotite

The biotite is typically in stubby laths with ragged ends, and is crowded with fine-grained inclusions surrounded by pleochroic halos. Pleochroism of the biotite is intense with X Y Z: X yellow-brown, Y dark brown, and Z very dark brown to opaque. A biotite with pleochroism in paler browns occurs in the malignites that have a high content of melanite. The biotite is most frequently associated with aegerinaugite and in clots with other dark minerals.

Magnetite

Magnetite is a pervasive accessory and in some rocks a major constituent. It occurs in good octahedral inclusions in poikilitic calcite and pyroxene, but more often it forms roughly rounded and irregular masses from fine to coarse grained, poikilitically enclosing the other minerals. Magnetite, like the nepheline, is not restricted to the position of a component mineral in a rock but can also form crosscutting veins. Partial analyses from the veins and from the magnetite-apatite bodies are given in Table IX. The present laboratory studies have not revealed ilmenite lamellae in the magnetite but Nickel (1955), using magnifications up to $\times 1{,}500$ in his metallurgical studies, described and photographed such structures in magnetite from the malignites.

Apatite

Apatite is the most persistent accessory mineral. It is enclosed within other minerals and exhibits the typical rod-shaped form with a hexagonal cross-section. It is emerald green in the magnetite-apatite rock and dark green to yellow-green in the silicate and carbonate rocks. Partial analyses taken from company reports on the commercial potentiality of this apatite as a source of phosphate indicate that this is a fluor-apatite.

Melanite

Melanite, a black andradite garnet, is a major constituent in the malignite, where it occurs with pale biotite and replaces pyroxene, with wollastonite, or with the more standard association in the malignites of aegerinaugite, nepheline, alkali feldspar and strongly pleochroic biotite. It also occurs sporadically in the carbonate rock. In hand specimens melanite is visible as black, poorly developed dodecahedra and in thin sections under plane polarized light it is brown to bright yellow. The grain boundaries are irregular and the melanite includes aegerinaugite, magnetite, biotite and calcite.

Wollastonite

In the malignites, wollastonite forms laths up to 3 mm long with simple twins. It has a $2V_x$ of 40 degrees and can be readily distinguished from apatite,

the only other mineral at all similar in appearance, by the twins and the two good cleavages. Wollastonite is associated with the six major minerals and with brown melanite.

Riebeckite

Riebeckite occurs as a major component in some of the regional gneisses cut by diamond-drill holes on the west margin of the alkaline complex. The mineral is in fine laths alone or in sprays and it commonly surrounds or is enclosed by aegerinaugite. It is pleochroic with X deep blue, Y violet, and Z light yellow-green. The dispersion of the bisectrices is extreme, the extinction angle $X \wedge C$ is approximately 5 degrees and the 2V is large.

Hornblende

The inner nepheline syenites and the northwestern exposures of the other nepheline syenite, type 1, contain brown hornblende replacing aegerinaugite. The hornblende is strongly pleochroic with X olive-brown, Y dark olive-green, and Z dark brown-green. The $2V_x$ is 40 degrees and the extinction angle $Z \wedge C$ is 15 degrees.

Fayalite

Fayalite occurs sparingly in the equigranular nepheline syenites and in the malignites. Its distribution is erratic and although it is not a common mineral it may account for 12 per cent of some specimens. The mineral is anhedral, poikilitic, colourless to faint yellow, and irregularly cracked. Magnetite has advanced along these cracks as has a brown to red alteration product. The $2V_x$ is 60 degrees and there is strong dispersion $r > v$. Fayalite is associated with aegerinaugite and magnetite and appears to be replaced by the former.

Plagioclase

Plagioclase occurs in the nepheline syenites only as a constituent of perthite. Its composition there, determined in coarse specimens by extinction angles, is albite. Albite is also present in the alkorthosites as multiply twinned rims on alkali feldspar. In the regional gneisses both albite (An_{0-5}) and andesine (An_{30}) are present. Albite is generally in fine, clean grains outside the aegerinaugite grains that surround quartz. Andesine forms large primary grains; some fresh and some replaced by pyroxene. There are also tattered plagioclase grains in the carbonate rock.

Pyrochlore

Euhedral to subhedral octahedra of pyrochlore, yellow-brown to red-brown—honey-yellow under reflected light—are most often concentrated at grain boundaries of the minerals, generally at the margins of the aegerinaugite grains. However, it is not unusual to see pyrochlore enclosed in nepheline, feldspar, biotite, apatite, mag-

netite or melanite. The grains of pyrochlore are commonly centres for radiating cracks in the enclosing mineral. Where melanite encloses pyrochlore it takes on a brown alteration. Where pyroxene is immediately adjacent to the pyrochlore grain the pyroxene is a lighter colour. Pyrochlore also occurs as segregations of grains, clusters of euhedral sugary grains, pale yellow and set in nepheline stringers that traverse the rock or act as breccia fillings (Pl. IX).

Two chemical analyses of pyrochlore from the Multi-Minerals property are given in Table VII. From these analyses it is evident that the composition of the pyrochlore varies considerably. The relationship between chemical compostion and colour is not clear. In Interim Report 710ML of the Mines Branch, Nickel (1955) described alpha track exposures where the darker pyrochlore produced more tracks than the lighter pyrochlore, but in Interim Report 716ML he stated that the different coloured grains did not produce distinguishable alpha tracks. Nickel also noted that the pyrochlore is metamict and produces an X-ray diffraction pattern only after ignition.

Table VII

Analyses of Pyrochlore from Multi-Minerals Property

	Weight %	
	Sample A	Sample B
Nb_2O_5	46.1	58.1
Ta_2O_5	1.4	2.8
U_3O_8	12.6	1.2
ThO_2	4.7	—
CaO	27.0	16.9
MnO	0.2	0.3
Fe_2O_3	3.0	11.0
ZrO_2	0.5	—
TiO_2	2.5	9.1
MgO	0.4	0.28
Ce_2O_5	1.3	—
La_2O_5	0.3	0.32
Dy_2O_3	0.1	—

Source rocks A, ijolite; B, foliated malignite.
Methods: Recalculated, semiquantitative spectrographic analyses of pyrochlore concentrates.
Sample A: Nickel, E. H.: Interim M.D. Test Rept. No. 710ML; Mines Branch, Dept. Mines and Tech. Surv., 1955.
Sample B: Nickel, E.H.: Interim M.D. Test Rept. No. 716ML; Mines Branch, Dept. Mines and Tech. Surv., 1955.
Calculated formula:

Sample A, $(Ca_{1205}Mg_{25}Mn_{70}Ce_{38}La_{40}DyTh_{43}Zr_{1015}U_{105})\ (Nb_{865}Ta_{15}Ti_{78}Fe^{+++}_{90})\ O_{6324}$
$A_{4.6}\ B_1\ O_{11.5}$

Sample B, $(Ca_{301}Mg_7Mn_{42}La_2U_3)\ (Nb_{436}Ta_{12}Ti_{113}Fe^{+++}_{138})\ O_{1916}$
$A_1\ B_2\ O_{5.4}$

Plate IX. *Photomicrograph of pyrochlore grains in a nepheline stringer traversing ijolite. Note the cracks radiating from the pyrochlore grains. Between Beaver Pond and Camp Lake.* × 16

Cerianite

Cerianite was described by Graham (1955) of Dominion Gulf Company as radioactive octahedra, translucent, greenish amber, and occurring in samples of carbonate rock from the east side of the complex. The mineral is found at the borders of silicate inclusions in the carbonate rock. Results of a quantitative spectrochemical analysis by the Ontario Provincial Assay Laboratories are shown in Table VIII.

Table VIII

Oxide	Weight %	Oxide	Weight %
CeO_2	80 ±20	Yb_2O_3	1.1±0.1
ThO_2	5.1± 0.5	Ta_2O_5	0.6±0.05
Nb_2O_5	1.8± 0.2	ZrO_2	0.6±0.05
La_2O_3	1.5± 0.2	U_3O_8	N.D.
Y_2O_3	1.2± 0.2		

Specific gravity is 3.18. It has a cubic (Fm3m) lattice with cell edge 5.42±0.01 A°. From the X-ray and chemical data, Graham concluded that this was a cerium dioxide in mineral form, isostructural with thorianite and uraninite. For it he proposed the name cerianite.

Other accessory minerals are sphene, zircon, perovskite, calcite, cancrinite, and the sulphides pyrrhotite, pyrite, chalcopyrite and sphalerite. The last two minerals were identified by Nickel (1955) in his metallurgical studies.

98011-0—4

PETROGENESIS OF THE ALKALINE COMPLEX

During the past 25 years considerable attention has been focused on petrography and structure of ring complexes in New England (Billings, 1943, 1945), the Hebredean region of Great Britain (Richey, 1935; Anderson, 1936), Fennoscandia (von Eckerman, 1948), and, more recently, in Africa (Dixey, *et al.*, 1955, and Jacobson, *et al.*, 1958). A number of petrogenic problems arise in connection with these structures and in particular with the ring structures containing alkaline rocks (von Eckerman, 1948; Dixey, 1955). These same problems apply to the petrogenesis of the alkaline rocks in the Nemegos ring complex. They are briefly enumerated below, and are then considered in more detail.

1. Nepheline syenite is the major rock-unit at Nemegos. Is it of magmatic or metasomatic origin? If it is of magmatic origin, what is the nature of the magma? If it is a product of metasomatism, then what were the agents of metasomatism?

2. What is the significance of the development of aegerinaugite at the expense of quartz and feldspar in the enclosing gneiss? Why has this gneiss the chemical composition of an alkaline rock?

3. What is the origin of the malignites? Are they an intermediate fraction of a basic alkaline magma or are they products of metasomatic alteration of the country rock?

4. What is the significance of the ijolite and the magnetite veins that traverse ijolite at Nemegos? Are ijolites members of a magmatic series with malignite and nepheline syenite or are they of metasomatic origin?

5. What is the origin of magnetite-apatite bodies and how are they related to alkaline rocks?

6. What is the significance of carbonate rock within the complex?

7. What is the significance of pyrochlore in alkaline complexes and why is its greatest concentration in the carbonate rock and more basic members of the alkaline suite?

8. What is the significance of the lamprophyre dykes that intrude all other rocks in the area?

9. What bearing do problems of alkaline ring complexes, and in particular the Nemegos structure, have on the genesis of alkaline rocks?

Origin of Nepheline Syenite

Nepheline syenite is the most abundant member of the alkaline suite exposed at Nemegos. It is also a major rock-unit at Alno Island, Sweden (von Eckerman, 1948), Spitzkop, Eastern Transvaal (Strauss and Truter, 1950), and at Mauze Hill and Tundulu in the Chilwa series of Nyasaland (Dixey, *et al.*, 1955). In the Fen district of Norway (Brogger, 1921) nepheline syenite is a minor rock-unit and at Napak, Uganda (King, 1949) it has not been observed.

98011-0—4½

Two origins have been proposed for the ring complexes of nepheline syenite and they are best expressed with reference to areas for which they have been vigorously proposed.

1. At Alno Island, von Eckerman noted that nepheline syenites outcrop about a carbonate core and that they grade, mineralogically and structurally, into a pyroxenized gneiss. On the basis of the gradational contacts and because this view is in accord with his proposed origin for associated carbonate rocks, von Eckerman concluded that the nepheline syenites are produced by metasomatic action of carbonate magma on regional gneiss.

2. At Spitzkop, Eastern Transvaal, nepheline syenites occupy ring-dyke and cone-sheet type structures. They are clearly intrusive into one another and into other rocks of the complex. They are accompanied by contact metamorphism of surrounding granite in the form of a pyroxenization, and inclusions of quartzite within the nepheline syenite have been impregnated with albite and soda pyroxene. A preferred orientation of feldspar laths in the porphyritic nepheline syenite is interpreted as flow banding. Strauss and Truter (1950) concluded that nepheline syenites at Spitzkop have crystallized from a magma.

Nepheline syenite at Nemegos outcrops at the core of the structure and as an outer ring between country gneiss and the malignites, which are adjacent to the core. The nepheline syenites of the outer rim occupy a ring-type structure and this configuration is advanced as evidence of the magmatic origin for these rocks. Granites and volcanic rocks occupy such structures in New England (Billings, 1943, 1945), the British Tertiary province (Richey, 1935), and the Younger Granite Province of Nigeria (Jacobson, *et al.,* 1958). The intrusive igneous nature of ring-dykes is an established concept.

Nepheline syenite of the outer rim extends an apophysis into malignite at the west shore of Rock Lake and stringers of nepheline syenite up to a foot wide, with sharp contacts that cut across the foliation of malignite, were observed in drill-cores. Very coarse feldspar laths in the western exposures of the outer nepheline syenite are aligned parallel with the boundaries of the ring structure and are believed to be a flow banding.

The ring-dyke configuration, the intrusive appearance of offshoots and the alignment of feldspar laths constitute the field evidence for the magmatic origin of nepheline syenite at Nemegos.

The nepheline syenites at Nemegos, like all members of their clan, are high in alkalis, relatively high in volatile constituents, and have a high FeO/MgO ratio. They are low in combined CaO, MgO and FeO. In this respect they are similar to granites. Moreover, the nepheline syenites have the petrographic characteristics of the hypersolvus igneous granites assigned by Tuttle and Bowen (1958, pp. 129, 137) and of the hypersolvus nepheline syenites of Tilley (1957, pp. 326 and 327) as follows:

1. They have virtually no plagioclase except as a component of perthite.
2. They have an amphibole of the Na-Fe species.

3. They have a pyroxene that is an Na-bearing variety.
4. They occur as small intrusions.
5. They do not show widespread metamorphism.
6. They have a high temperature feldspar.

Laboratory experiments of silicate melts by Tuttle and Bowen (op. cit., p. 138) suggest that these are the properties of a rock that crystallized at high temperature from a magma.

In Figure 6, four modes of the Nemegos nepheline syenites are plotted. The modes all fall near the end of the low temperature trough, the Na-K nepheline region, of the equilibrium diagram published by Schairer in 1950 for the dry system SiO_2-$NaAlSiO_4$-$KAlSiO_4$. Subsequent work at water pressures of 1,000 atmospheres in the system SiO_2-$NaAlSi_3O_8$-$KAlSi_3O_8$ by Tuttle and Bowen (1952, 1958), shows that under high-water pressures this low temperature trough changes its configuration drastically, the leucite field disappears and potash feldspar melts congruently. However, the feldspar thermal barrier, a ridge lying along the feldspar join, still exists, and probably there is a low temperature region below the feldspar join near the plotted modes of the nepheline syenites. These diagrams suggest that the nepheline syenites represent residual liquids of a crystallizing and fractionating magma. It is also significant that these nepheline syenites have chemical compositions similar to phonolites, flow rocks of indisputable magmatic origin.

With the recognition of the magmatic origin for the nepheline syenites at Nemegos, attention can be turned to the composition of the magma, and to the temperature and prevailing pressures at time of crystallization. The magma that crystallized as nepheline syenites was essentially deficient in silica and high in alkalis and lime. The temperature of crystallization of the alkali feldspar must be considered. In the nepheline syenites all the soda feldspar occurs as a component of perthite, which formed by unmixing during cooling. This indicates crystallization in the binary system $NaAlSi_3O_8KAlSi_3O_8$ (Bowen and Tuttle, 1950) above the solvus, that is above 660°C for 2,000 atmospheres water pressure, and in the ternary system $NaAlSi_3O_8$-$KAlSi_3O_8$-H_2O (Yoder, *et al.,* 1957) above 695°C for 5,000 atmospheres water pressure.

Very little can be said about prevailing pressures at the time of crystallization. There is no stratigraphic information about the intruded rocks that would allow an estimate of the depth of cover at time of intrusion. There is also no way of estimating pressures exerted by the volatile content of the magma during crystallization.

Patches high in nepheline in the western exposures of type 1 nepheline syenite of the outer rim are attributed to a deuteric attack by late emanations high in alkali and lime and low in silica. The feldspar was leached of silica to form nepheline with the alkali of the emanations. The biotite and hornblende associated with pyroxene in type 2 of the outer nepheline syenite and in the inner nepheline syenite suggest that water was retained during crystallization. The absence of hornblende

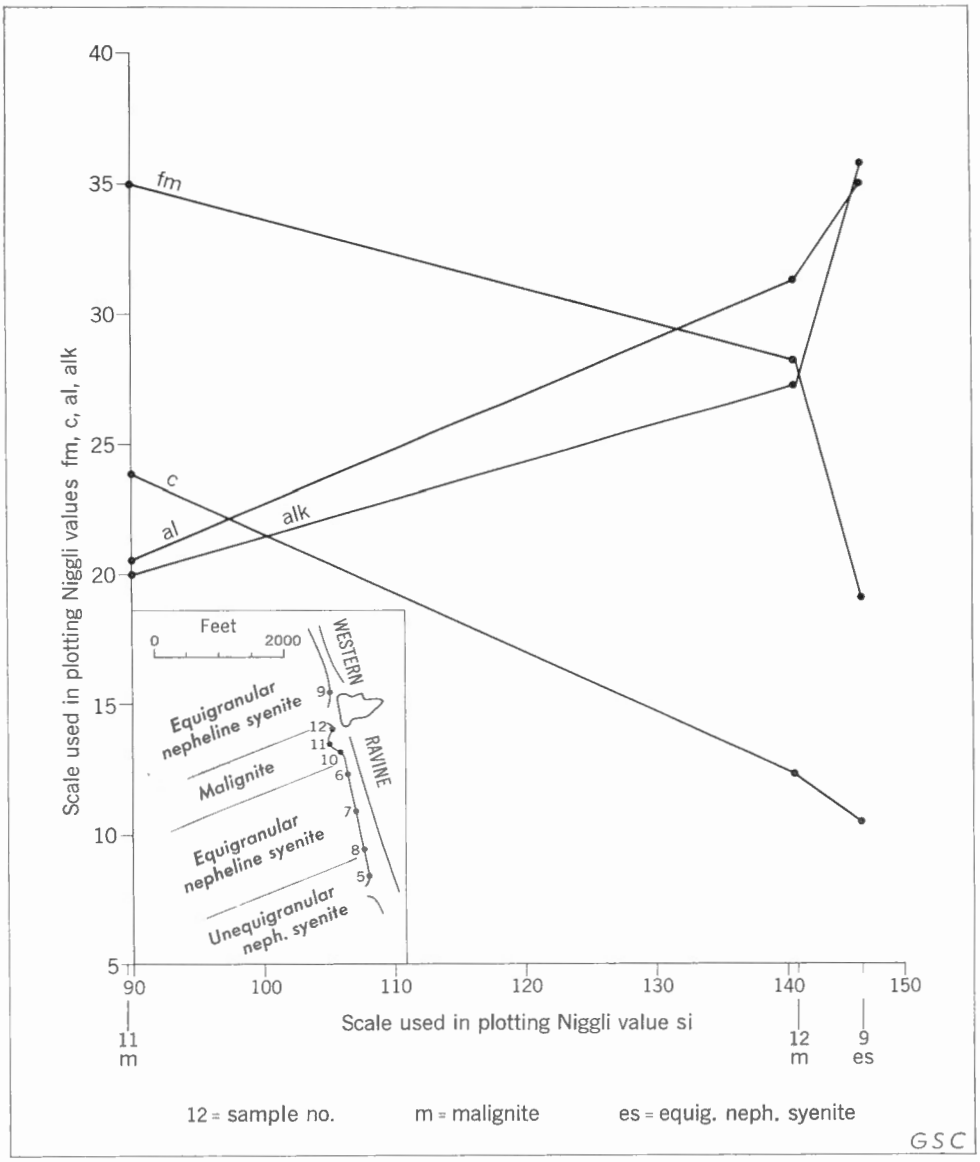


Figure 7. *Variation of Niggli values al, fm, c, alk with increase of Niggli value si for a series of samples taken along the western ravine starting within equigranular nepheline syenite adjacent to inequigranular nepheline syenite of the outer ring and proceeding into the malignites.*

in type 1 of the outer nepheline syenite suggests that water was released rapidly during crystallization. The angular patches high in biotite and pyroxene in type 1 of the outer nepheline syenite are inclusions of the gneiss that have been sub-

jected to a pyroxenization, a feature that is discussed in the next section. Significance of the ring of equigranular nepheline syenite about the core of inequigranular nepheline syenite is also considered in a later section. It is a border facies of the inequigranular nepheline syenite, and its peculiar texture is discussed, along with the development of the malignites which it adjoins.

Significance of the Alteration in the Gneiss

All specimens of the regional gneiss available from drill-holes, which are 2,000 to 3,000 feet from the outer rim of nepheline syenite, have certain common characteristics. These characteristics in turn are similar to those of the altered rocks surrounding the alkaline complexes at Fen (Brogger, 1921), Alno (von Eckerman, 1948), Spitzkop (Strauss and Truter, 1950), Turja, Kola Peninsula (Kranck, 1929), and Messum, South West Africa (Mathias, 1956); this despite the fact that the original rocks at Fen and Alno are gneisses and migmatites, whereas they are granites at Spitzkop, quartzite at Turja, and tuff and agglomerate at Messum. These characteristics are listed below:

1. The gneiss contains aegerinaugite and generally a soda amphibole, calcite, fluorite, apatite, magnetite, zircon and sulphides—all minerals of the adjacent alkaline rocks.

2. Aegerinaugite developed in the gneiss at the expense of quartz, enclosing grains and penetrating along cracks. Fine grains of aegerinaugite coalesce into coarse grains.

3. Coarse grains of alkali feldspar and plagioclase (An_{30}) in the gneiss are embayed and there is a new generation of fresh, nonperthitic, fine-grained alkali feldspar and albite.

4. Biotite grains in the gneiss are embayed and rounded.

5. The chemical composition of the specimen of Table V, p. 29, is that of an alkaline rock, and 8.01 per cent normative nepheline.

Regrettably there is no description of the regional gneisses round Nemegos, other than Bell's notes on his reconnaissance of 1881 and a brief description by Parsons in 1957. Both authors described granite-gneiss with various proportions of quartz, feldspar, biotite, hornblende and augite. However, it is reasonable to conclude that the alkaline nature of the chemical composition and mineral constituents of the gneiss adjacent to the alkaline complex is related to the intrusions of alkaline igneous rocks.

The significance of the contact alteration adjacent to intrusions of alkaline rocks is, of course, the fenite problem described most thoroughly by Brogger (1921) from the Fen area, Norway, and by von Eckerman (1948) from Alno Island, Sweden. Brogger attributed the pyroxenization of the regional gneiss and other alterations at Fen to metasomatism related to an alkaline magma and he called the process "fenitization" (1921, p. 171). Since the publication of Brogger's descriptions and conclusions similar contact phenomena have been noted wherever ring complexes of alkaline rocks and the surrounding rocks have

been studied, and Nemegos is no exception. The conclusion is unanimous that the contact alteration is caused by aqueous residual fluids of a magma escaping into the adjacent rocks.

Even though specimens of unaltered gneiss are not available for comparison at Nemegos, it is probable that the development of aegerinaugite, albite, non-perthitic alkali feldspar, apatite and magnetite, together with the destruction of intermediate plagioclase, quartz, biotite and alkali feldspar, and the deficiency in silica and the high lime content can be attributed to an addition of lime, iron, fluorine and phosphorus in an aqueous solution high in carbon dioxide. This solution escaped outward from the body of nepheline syenite, along a pressure gradient, into the adjoining rock.

The reactions between this solution and the country rock were governed by the chemical potential of the various components in solution relative to the chemical potentials of the same components in the crystalline phase. For development of aegerinaugite in the gneiss the sum of the chemical potentials of components of aegerinaugite in solution must be greater than those in the mineral phase, for a fixed temperature and pressure. Moreover, for a fixed temperature and pressure the chemical potential of components in the crystalline phase remains constant, where the composition of the crystalline phase is constant. Under similar conditions in the fluid phase the chemical potential is dependent on the concentration of each component. If the concentration of the constituent components in solution is such that, for this particular temperature and pressure, the chemical potential is greater than that of the same components in the crystalline phase, the reaction will proceed in such a way as to produce the crystalline phase with the lower chemical potential. The concentration of CaO in solution, which is so important in this metasomatism, increases with increased CO_2 content of the solution. Garrels and Richter (1955) show that the amount of CO_2 in solution does not decrease rapidly with falling temperature and pressure if there is abundant CO_2 in the system. Hence, if sufficient CO_2 is available the solubility of CaO will remain high during the metasomatism.

Material must be removed from the gneiss during this metasomatism so that the same volume of rock can be retained and so that the final product will be a rock of the observed chemical composition. Material to be removed, in this instance silica, must have a concentration limit low enough so that the chemical potential of this component, for a particular temperature and pressure, is lowest in solution. Equilibrium is attained when the chemical potential of components in solution is the same as it is in the mineral phase.

The reaction between introduced material in solution and original minerals in the gneiss, plus the extraction of silica, produced a rock so low in silica that nepheline appears in the norm. No nepheline was actually observed in the gneiss outside the alkaline complex, but it has been reported by Parsons (1957, p. 84), von Eckerman (1948, p. 40), and Mathias (1956, p. 46) replacing feldspar in the zone of contact metasomatism.

Origin of Malignite

Most alkaline complexes described in the literature do not have rocks called malignites, but they do have dark alkaline rocks of malignitic composition that are referred to by names such as melanocratic fenite. Malignites have been reported to be intermediate differentiates of an ijolite magma or alternately to be products of intensified fenitization.

At the type locality, Poohbah Lake, Ontario (Lawson, 1896), malignite outcrops in an elliptical body unattended by other members of the alkaline suite. Lawson recognized three facies of this rock, garnet-pyroxene, amphibole and pyroxene-nepheline malignite. Locally these rocks are foliated. All the malignites are intrusive into Coutchiching schists and Lawson believed that they are of magmatic origin. Kranck (1929) described the petrography of malignites from Turja, Kola Peninsula, but not their field relationships. From a study of thin sections and chemical analyses of malignites and other members of the alkaline suite he concluded that malignites are magmatic in origin and an intermediate differentiate, between ijolite and aegerine syenite, from an ijolite magma. No rocks are called malignite in the description of the Spitzkop complex (Strauss and Truter, 1950), but rocks are present that range in composition from fayalite diorites to theralites and are very similar in mineralogy and chemical composition to the malignites at Nemegos. These rocks at Spitzkop grade into the outer zone of fenites and lie against the ijolites of the core. They are foliated and contain more calcium and iron than the fenites that lie outside them, and they are intruded by many other rocks of the complex. The authors conclude that these rocks are the most mafic of the metasomatic rocks at Spitzkop.

From Alno Island, von Eckerman (1948, p. 47) described minor occurrences of malignite intrusive into other alkaline rocks, but the main body of malignites lies at the gradational contact between homogeneous alkaline rocks and the outer fenites. He preferred to call these rocks malignitic fenites and believed that they formed at the inner fenite boundary through metasomatism of country rock. In this metasomatism, nepheline replaced feldspar. The few intrusive contacts are attributed to a mobilization of material during metasomatism.

From the Messum complex, South West Africa, Korn and Martin (1954, p. 108) and Mathias (1956, pp. 44 and 46)) described rocks with the composition of malignites under the heading of melanocratic fenites. These rocks are included within the nepheline syenite at the core of the complex. Because of their attitude, shape, texture and composition they are believed to be xenoliths and sheets of basic lavas, tuffs and gabbros that have been altered by metasomatism. Gradations of this alteration are recorded from Messum and there also nepheline replaces feldspar (Mathias, 1956, p. 46).

Parsons (1957) reported a malignite or pyroxenitic fenite lying between the central alkaline intrusion and the altered gneisses at Nemegosenda. The data gathered from drill-cores indicate that malignite occurs in dykes and stringers. Parsons concluded that these rocks are metasomatically altered country rock, a

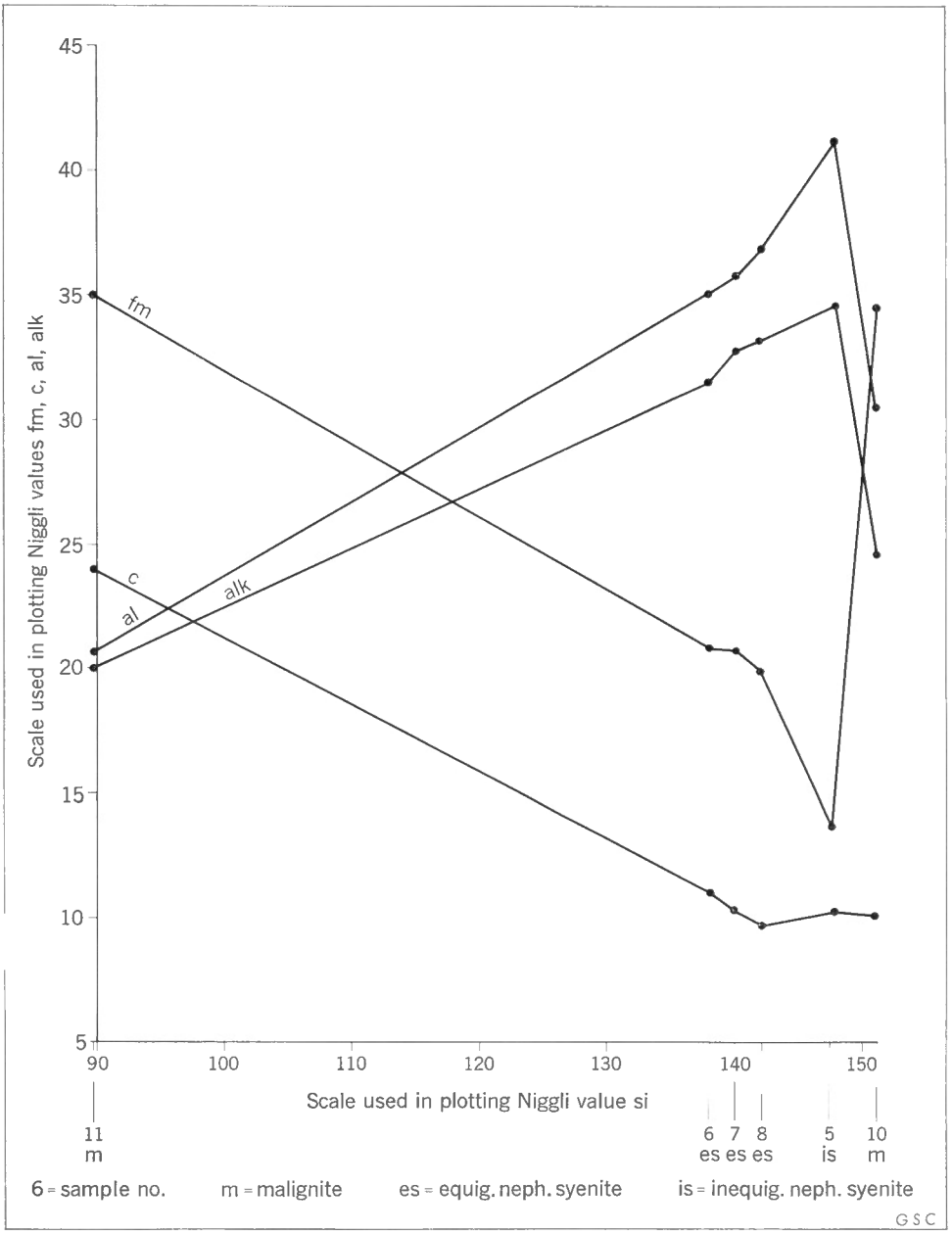


Figure 8. *Variation of Niggli values al, fm, c, alk with increase in Niggli value si for a series of samples taken along the western ravine starting within the inequigranular nepheline syenite at the centre of the complex and proceeding through equigranular nepheline syenite into the malignites.*

basic front about the central intrusion and that some of the metasomatized rock has become mobilized and intruded into fractures. In those rocks, Parsons (1956, p. 84) reported that nepheline replaced feldspar.

The malignites at Nemegos lie in a band separating the outer ring of nepheline syenites from the core of nepheline syenites. They are composed of alkali feldspar, nepheline, aegerinaugite, magnetite, and locally melanite, wollastonite and olivine, plus accessory amounts of apatite, sodalite, sphene, calcite and zircon. Except for melanite, wollastonite and olivine, all these minerals occur in the second generation of minerals in the metasomatized gneiss. Large aegerinaugite grains form by coalescence of smaller grains and melanite replaces aegerinaugite. Coarse grains of alkali feldspar and nepheline near the contact of malignites with the nepheline syenites transect the foliation.

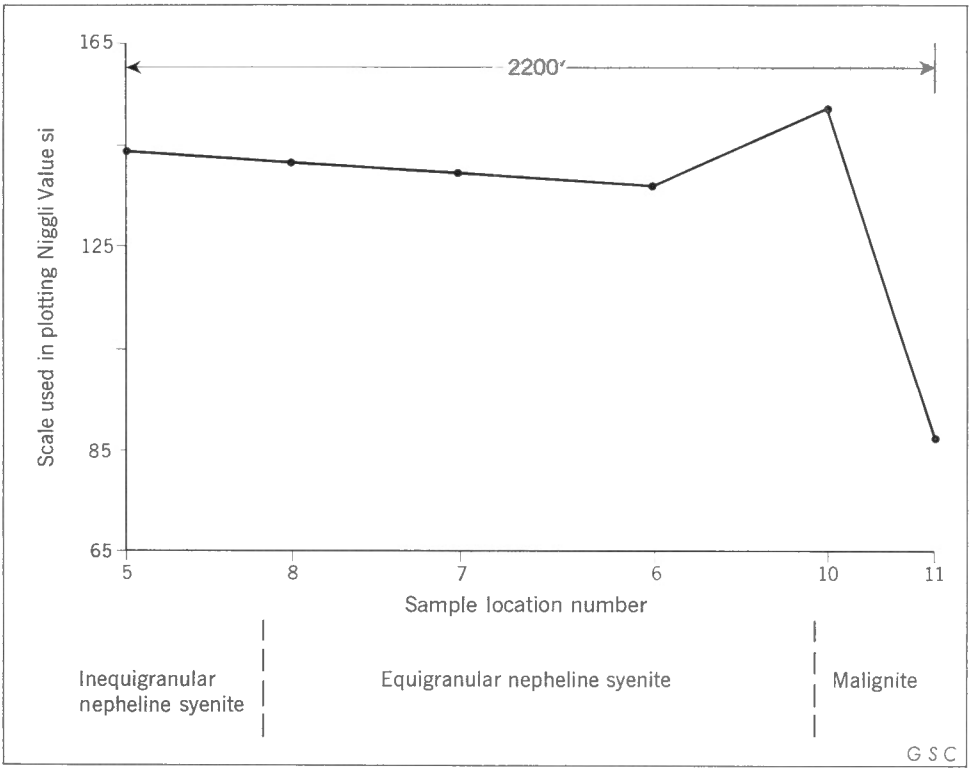


Figure 9. *Variation in Niggli value si along the western ravine from inequigranular nepheline syenite at the centre of complex through equigranular nepheline syenite and into malignites.*

Variation diagrams (Figs. 7 and 8) have been constructed from analyses of a suite of samples collected along the western ravine in the northern part of the area. These specimens give a section from the inner inequigranular nepheline

syenite, through the equigranular nepheline syenite and malignites, and into the edge of the outer equigranular nepheline syenite. The silica content increases gradually from the centre of the band of malignite south along the ravine to its contact with the equigranular nepheline syenite. At the malignite side of this contact, specimen 10 silica content rises rapidly to the highest value in the section. South of the contact, the silica content of equigranular nepheline syenite is lower than that of specimen 10 but it resumes its gradual rise towards the centre of the complex (*see* Fig. 9). The increase in silica is accompanied by an increase in alkali and alumina and a decrease in lime, iron and magnesia, except again in the instance of the contact between malignite and nepheline syenite where the peak in silica content is accompanied by slightly higher lime content and high iron. The Fe^{+++}/Fe^{++} ratio increases into the malignites. These variations in chemical composition are consistent with the decrease in dark minerals and increase in feldspar from the centre of the malignites to the equigranular nepheline syenite.

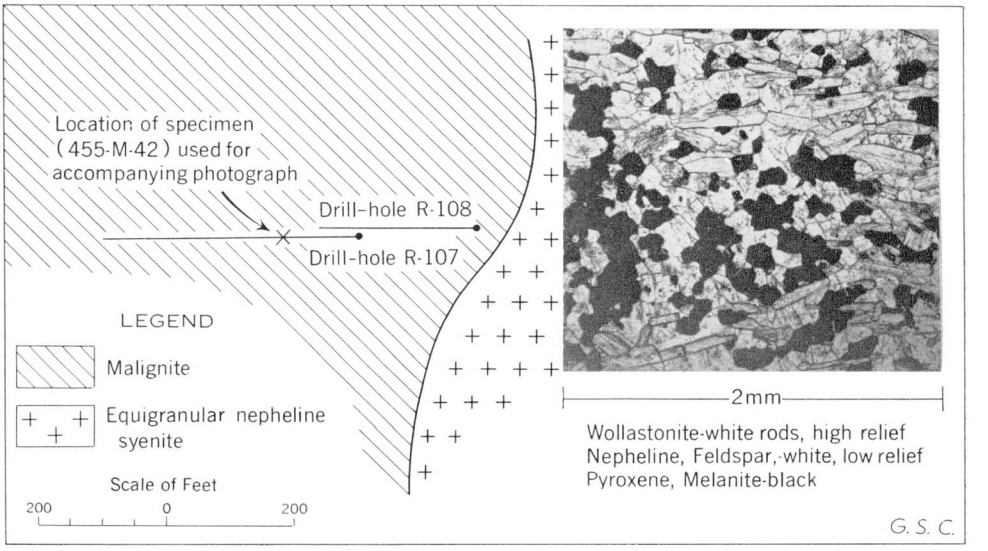


Figure 10. *Sketch map to show the position of wollastonite-bearing malignite with respect to the contact between malignite and equigranular nepheline syenite, located one-half mile north of Multi-Minerals camp.*

The hypothesis favoured here is that the malignites at Nemegos represent a crescent-shaped septum of the regional gneiss that has been trapped between two rings of nepheline syenite. This septum has been subjected to extensive metasomatism identical with the metasomatism of the gneiss outside the outer ring of nepheline syenite. Samples of gneiss display the effects of metasomatism at a distance of thousands of feet from the intrusion, but malignites represent the most intense products of this alteration. It is the writer's opinion that an inner ring of nepheline

syenite was intruded, and emanations escaped from it into the country rock. Shortly thereafter or almost simultaneously the outer ring of nepheline syenite was emplaced, and it too contributed solutions to the rocks that surrounded it. These were aqueous solutions, high in lime, iron, phosphorus, carbon dioxide and fluorine. Because of the proximity of the source of the solutions, the temperature, pressure and concentration of components in solution remained high for a considerable time. The next result was an approximation to equilibrium between solution and rock. Aegerinaugite developed to the exclusion of quartz, silica was withdrawn, and nepheline replaced the albite. The composition of the nepheline was controlled by the chemical potential of potash and soda in solution and in the crystalline phases of the rock.

The removal of silica by solution proceeded until the formation of melanite was favoured over the formation of aegerinaugite. Silica must have been removed by diffusion in solution or by a movement towards the intrusion of silica-rich solutions, in order to maintain equal volume relationships during metasomatism. The result of these phenomena was the presence at the contact of intrusion with the intruded gneiss of a solution with highest concentration of silica, moving from the gneiss to the intrusion, and one with a high concentration of calcium, moving from the intrusion to the gneiss. The highest possible temperatures and pressures in the gneiss were reached at this contact. It is also at this contact that wollastonite is stable and though wollastonite was not found in the section from which the variation diagrams were constructed, it is present in specimens from the same relative position in the complex, that is within the malignites but close to the contact with equigranular nepheline syenite (*see* Fig. 10). Wollastonite and calcite are stable together at 1,000°C and 2,000 atmospheres (Bowen, 1940). The large porphyroblasts of feldspar and nepheline near the contact are also products of the prevailing chemical potentials, controlled by a high concentration of alumina near the contact.

The foliation of the malignites may be explained by the observation that crystals grow with the axis of best thermal conductivity perpendicular to the isotherms and with the largest compressibility along the pressure gradient (Barth, 1952, p. 231). In this manner biotite acquires a preferred orientation with [001] parallel with the pressure and temperature gradients.

Compositional Variations within Malignites

The malignites are relatively homogeneous except for local occurrences of a rock with 30 to 40 per cent biotite and for an alkorthosite composed of feldspar and nepheline. These two distinctive rocks within the band of malignites are attributed to either differences in the composition of the original gneiss or irregularity in the distribution of material during metasomatism. The latter hypothesis is preferred because lime, one of the major components added during metasomatism, is apparently low, as there is virtually no aegerinaugite in these rocks.

Alternative Explanation for Malignites

The writer's preferred hypothesis, advanced above, is that the malignites are screens of metasomatized regional gneiss left between nepheline syenite ring-dykes. However, as the unaltered gneiss is not exposed and a continuous transition from gneiss to malignite could not be observed, an alternative explanation must be considered, although it is less satisfactory to the writer.

Metasomatism of the regional gneiss outside the alkaline complex is established, and there is no other obvious explanation for the mineralogy and chemical composition of the gneiss. However, the malignites within the complex could be differentiates of an alkaline magma of which nepheline syenites represent the leucocratic fraction. The evidence in favour of a magmatic origin for the malignites is as follows:

1. Their component minerals are also those of the nepheline syenites, except for wollastonite, melanite, olivine and pyrochlore, which might be peculiar to this phase of differentiation.

2. Variation diagrams show that the malignites, with the exception of those immediately adjacent to the equigranular nepheline syenites, are low in silica, alumina and alkali, and high in iron and calcium as compared to the nepheline syenites. Both the nepheline syenites and malignites could have crystallized from a common magma, the malignites crystallizing first so as to become enriched in the mafic constituents. Rocks within the body of malignites that are rich in biotite or feldspar could be attributed to segregation of the necessary components within the magma; the alkorthosites could be patches from which the mafic minerals settled out. The foliation could be a flow banding and the rocks could occupy a ring- or cone-type fracture in the complex and any evidence of metamorphism in the malignites could be attributed to the effects of enclosure by the later intrusion of the outer nepheline syenite. There is however no field evidence that the malignites were ever intrusive.

Relationship of the Equigranular Nepheline Syenites to the Malignites

The equigranular nepheline syenite, in contrast to the adjacent malignites, has euhedral nepheline, nepheline and alkali feldspar grains that contain rings of inclusions that mimic the grain outline, and zoned alkali feldspar. The nepheline is euhedral in this rock because, as in the inequigranular nepheline syenite of the core, it crystallized from a magma before the feldspar and pyroxene. Compositions of the nepheline syenites plotted on the equilibrium diagram for the system SiO_2-$NaAlSiO_4$-$KAlSiO_4$ (Schairer, 1950) fall in the Na-K nepheline field, indicating that upon cooling nepheline would crystallize before feldspar.

Assimilation of fragments of country rock in the course of intrusion and exchange of material with the malignites during the contact metasomatism must have increased the SiO_2 and Al_2O_3 content of the residual magma. These and alkalis concentrated in the residual magma presumably contributed to the late growth of the feldspar. In regions where the silica content was low, late growth of nepheline took place and fine grains of other minerals were included in the

nepheline. The final product was an equigranular rock with almost equal amounts of feldspar and nepheline that show evidence of secondary growth by zoning and rings of inclusions. The equigranular nepheline syenite has more magnetite than the nepheline syenite of the core, because CO_2 presumably moved from the interior of the intrusion out through the crystallizing margin, oxidizing the available iron (Lasky, 1931). The equigranular nepheline syenite is regarded as a border facies of the inequigranular nepheline syenite of the core.

Significance of Ijolite and Associated Magnetite Veins

Ijolite is not an abundant rock within the Nemegos complex yet its mineral composition and texture are distinctive and it is everywhere associated with magnetite veins. On the other hand, ijolite is commonly the most abundant alkaline rock mentioned in descriptions of complexes in other parts of the world, and there is no mention in the literature of the association of ijolite with magnetite veins. Three different modes of origin have been suggested for the ijolites:

1. It is suggested that ijolite crystallized from a magma. In some areas it is considered to be the parent magma for the suite of alkaline rocks. At Iron Hill, Colorado (Larsen, 1942), ijolite composed of nepheline, pyroxene, and garnet in euhedral grains shows an igneous texture. Moreover, the rock forms sharp-edged dykes and a large intrusive body. The chemical and mineralogical composition of these ijolites corresponds closely to the mixtures of Bowen's (1922) equilibrium diagrams for the binary system diopside-nepheline. Larsen concluded that the ijolites crystallized from a magma.

A similar origin has been suggested for the central ijolites at Napak (King, 1949). There the contacts with other rocks are obscured but there is a continuous variation in chemical composition between ijolites and other intrusive and extrusive rocks of the complex. Kranck (1928) offered a similar reason for suggesting that ijolite represents the parent magma at Turja.

2. The ijolites may be a reaction product between an intrusion of nepheline syenite and limestone. This hypothesis was tendered by Shand (1921) for the ijolites of Spitzkop. The ijolites there grade into alkali syenites and partly enclose carbonate rock at the core. It is well to note that a more detailed study by Strauss and Truter (1950) revealed three distinct ijolites on the basis of texture, mineralogy and contact relationships with enclosing rocks. They believed that two of these are metasomatized country rock at the fenite boundary and a nephelinized pyroxenite. The third ijolite, the coarse one at the centre of the body, intrudes other rocks and they consider it to be of magmatic origin.

3. The ijolites may be of metasomatic origin. This origin has already been referred to above, where ijolite grades into fenite and pyroxenite at Spitzkop (Strauss and Truter, 1950). Von Eckerman (1948) reported ijolites in a similar position at Alno Island; that is, they occur at the boundary between fenite and homogeneous alkaline rock. There is no mention of intrusive relationships there and von Eckerman (op. cit., p. 48) stated that these rocks have resulted from the metasomatism of the surrounding malignites.

Pulfrey (1950), describing the rocks of Homa Bay, Kenya, recorded a mass of ijolite 1½ miles wide and intrusive into fenites on the west side of the complex. All other contacts are obscured. Constituent minerals, especially pyroxene and nepheline, are rarely euhedral and the nepheline has been partly replaced by aegerinaugite. Pulfrey pictured the intrusion of an alkaline magma that started to crystallize and separate nepheline crystals. Nepheline crystals rose to the top of the magma chamber where they were subjected to attack by rising fluids rich in calcium, titanium, phosphorus, fluorine, carbon dioxide and water. Potash, alumina, and possibly iron and soda were removed. The product of reaction between the mass of nepheline crystals and the solutions is nepheline-aegerinaugite rock—an ijolite.

At Nemegos the best exposures of ijolite flank a magnetite vein in the McVittie pit. Contacts between ijolite and surrounding rocks were not observed at the surface because of the overburden, but where seen in drill-cores they are gradational. Magnetite stringers that traverse the outer nepheline syenite, type 4, have borders composed of aegerinaugite, nepheline and biotite, two to three times as wide as the magnetite vein. These borders have the mineral composition and the allotriomorphic granular texture of ijolite. Rocks described earlier in this report include an aegerinaugite of this border replacing the constituents of the nepheline syenite. The conclusion reached is that ijolites of the Nemegos complex are products of pyroxenization along fractures that now contain magnetite.

The development of the ijolites is similar to the pyroxenization of the regional gneiss outside the ring of nepheline syenites, in that aqueous solutions rich in iron, calcium, fluorine and phosphate apparently entered fractures in the nepheline syenites and reacted with the constituent minerals to form dark minerals. Silica was withdrawn from alkali feldspar and used, together with components from solution, in the formation of aegerinaugite. Quartz and plagioclase were not components of the nepheline syenite as they were of the gneiss, so that silica and soda must have been furnished by the alkali feldspar. Nepheline and aegerinaugite may form by the following reaction:

$$\underset{\text{(alkali feldspar)}}{K_2O\ Na_2O\ Al_2O_3\ SiO_2} + \underset{\text{(added material)}}{CaO\ (\overset{++}{Fe},\ \overset{+++}{Fe},\ Mg)O}$$

$$\underset{\text{(aegerinaugite)}}{CaO\ Na_2O\ (Fe\ Fe\ Mg)O\ Al_2O_3\ SiO_2} + \underset{\text{(nepheline)}}{Na_2O\ K_2O\ Al_2O_3\ SiO_2}$$

The actual composition of nepheline will depend on the Na/K ratio in the solution and rock minerals at the given particular pressure and temperature.

In order to maintain the same volume of rock alongside the fracture there must have been a movement of material out of nepheline syenite during the process of replacement to compensate for the added material. Thus SiO_2, Al_2O_3, and K_2O, moving into the fractures provided the necessary concentrations of components at suitable temperatures and pressures for the formation of biotite at the edge of the magnetite veins forming in the fractures. Some even reached the centre

of the crystallizing magnetite where they formed the alkali feldspar cores of the magnetite veins. Veinlets of nepheline and magnetite can be attributed to local concentrations of soda, potash and silica under conditions favouring the crystallization of nepheline in fractures.

The ijolites east of the Multi-Minerals camp differ from those of the McVittie pit in that they contain melanite and alkali feldspar, and that magnetite veins are not exposed at the surface. A low concentration of SiO_2 must have favoured the development of melanite over aegerinaugite in the late stages of metasomatism.

Campbell-Smith, in his review of African carbonatites (1956, p. 208), wrote: "The connection of the nepheline syenites with the carbonatites does not seem as constant as is the carbonatite-ijolite-pyroxenite association and nepheline syenite is sometimes not present at all. On examining the published accounts on European and American carbonatites it appears that, contrary to prevalent opinion, nepheline syenite is not the rock type most commonly associated with carbonatites, but rather the association pyroxenite-ijolite-carbonatite is more frequent. This observation if substantiated may be of importance in the theory of carbonate formation." The conclusion that may be drawn from the Nemegos area is that this association of carbonatites with ijolites is a function of the alteration of the nepheline syenite to more basic alkaline rock, through introduction of aqueous carbonate solutions. These solutions, rich in iron, lime and other constituents, have been concentrated in the residual stages of magmatic differentiation. The ijolites are related to the carbonatites but not as a source of carbonate material. On the contrary, the ijolites were produced by attack of carbonate fluids on leucocratic alkaline rocks.

Origin of Magnetite-Apatite Bodies

Von Eckerman (1948, p. 57) described concentrations of magnetite and apatite rimmed with homogeneous basic alkaline rocks, lying within the metasomatically altered migmatites of Alno Island. The magnetite is titaniferous and the apatite is a fluorapatite. Apatite may account for 20 per cent of the rock. Von Eckerman believed that magnetite-apatite bodies are metamorphosed deposits of iron that were contained within the Precambrian migmatites prior to emplacement of the alkaline rocks. On the other hand, concentrations of magnetite and apatite within the carbonate rock is attributed to a gravitational concentration of crystal differentiates in carbonate magma.

Bodies of magnetite and apatite, with biotite, pyroxene and nepheline in varying proportions, are present with carbonate and alkaline rocks at Jacupiranga, Brazil (Derby, 1891). The iron orebodies have sharp, dyke-like margins and include fragments of a schistose alkaline rock of the area. Derby concluded that the magnetite-rich rocks are of magmatic origin.

The magnetite-apatite bodies at Nemegos are pod-shaped and lie within malignite. The walls of the bodies are vertical or dip steeply and the strike of contacts and foliation conforms roughly to that of the foliation in the malignite. Blocks of malignite are included within the orebodies and bear no evidence of

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alteration. Unaltered nepheline syenite is also present within magnetite-apatite but whether it is intrusive into the magnetite-apatite or included within it, is not clear. The minerals of these orebodies, magnetite, apatite, sulphides, pyrochlore, aegerinaugite, are also common to ijolite, malignite and carbonate rock and to the metasomatized gneiss outside the nepheline syenite.

The hypothesis is proposed that the magnetite-apatite bodies were intruded into steeply dipping cone-sheet fractures and zones of brecciation within the malignite. Foliation is attributed to flow banding and their mineral composition to crystallization from fluids very similar to those responsible for the alteration of the regional gneiss and the formation of ijolites and malignites. It is concluded that magnetite-apatite bodies formed from aqueous solutions rich in iron, lime, and components of the accessory minerals and some CO_2. These solutions may have collected in the magma chamber just below more calcic and carbonate-rich solution at the top of the magma chamber. Steeply dipping cone-fractures might there have tapped this magma chamber at the level of the iron-rich solution. The solution would thus invade the fractures and, with an escape of carbon dioxide in this low pressure region, the iron of the solution would crystallize as magnetite and the calcium would contribute to apatite and pyrochlore. Intergrowths of magnetite and ilmenite indicate that crystallization of the magnetite took place at temperatures above 700°C (Ingerson, 1955, pp. 361, 365). Contact effects are at a minimum because the solutions contributing to the magnetite-apatite bodies were similar to those that caused the development of the enclosing malignites, except that they carried more iron and less CO_2. The contact effects are confined to an introduction of iron into the wall rocks to form magnetite along the contact.

Significance of Carbonate Rock

The world-wide association of carbonate rocks with alkaline rocks has prompted several hypotheses for their mutual origin. A satisfactory proposal must explain this association, the structural position of the carbonate rock, and its mineral composition.

King (1949), reviewing the Napak structure in Uganda, supported the hypothesis of a magmatic origin for the carbonate rock. The complex there has a core a quarter of a mile wide composed of calcite with disseminated siderite and magnetite. The contacts are obscured, but veins of calcite intersect the ijolite. King believed the rock to be a product of direct fractional crystallization from an ijolitic magma rich in lime and carbon dioxide. The magmatic origin hypothesis for carbonate rocks associated with alkaline rocks is supported by von Eckerman (1948) in his study of Alno Island. There, alkaline rocks are arranged about a core of calcite and are traversed by cone sheets and radial dykes of calcite and dolomite. Some of the dykes are enclosed by country rock and, though they have sharp contacts, are associated with fenitization and semi-digested inclusions of country rock (op. cit., pp. 66 and 127). The wider the dyke the greater the wall-rock alteration. Accessory minerals in the carbonate rock are apatite, mag-

netite, biotite and pyroxene. Because of their cone-sheet structure and contact effects, and because it fitted his general hypothesis of a metasomatic development of the alkaline rocks, von Eckerman believed that the carbonate rock at Alno represents fracture filling by a carbonate magma at 400 to 600°C. The carbonate magma must have been rich in potash, magnesium, calcium, carbon dioxide and fluorine. This magma would have produced the accompanying alkaline rocks by metasomatism and finally crystallized as carbonate rock.

Shand believed that carbonate rocks in alkaline complexes are xenoliths of limestone caught in a rising magma. The reaction of granitic magma with limestone would result in a desilication and the formation of alkaline rocks. This hypothesis was stated in his account of the Spitzkop complex (1921) in which he described a circular area of marble three quarters of a mile wide and composed of calcite with accessory magnetite, apatite and pyroxene. The contacts of the calcite body with the surrounding rocks are obscured. However, a more recent and more detailed study of Spitzkop by Strauss and Truter (1950) revealed that the marble contains xenoliths of nepheline syenite; that there is no evidence of metamorphism of the marble; that the alkaline rocks do not intrude it; that there are no other members of a sedimentary series accompanying this limestone; and that the carbonate dykes, one of which is a ring-dyke, clearly cut the alkaline rocks of the complex. They concluded that the carbonate rock is intrusive, of magmatic origin, and has as its parent a peridotite magma.

Bowen (1924) suggested that the carbonate rocks of the Fen area, Norway, were the result of the replacement of the alkaline rocks. His examination was primarily petrographic and he cited as evidence of replacement the mixed silicate-carbonate rocks that form a transition between pure carbonate and pure silicate rocks, and the successive replacement of silicates by carbonates observed in thin section. This hypothesis is supported by Pulfrey (1951) in his study of Kavirondo, Kenya, where carbonates, present as plugs and ring-dykes, show a successive replacement of calcite by dolomite and by siderite. Because of the abundance of replacement phenomena in the accompanying ijolites and syenites he concluded that the carbonates are a product of the replacement of silicate rock by a carbonate magma of unknown origin.

Larsen (1942) suggested that carbonate rocks associated with alkaline rocks are fracture fillings by hydrothermal solution rich in lime. At Iron Hill, Colorado, the main mass of carbonate covers an area of 2 square miles and is composed mostly of dolomite with minor calcite and ankerite. Apatite, magnetite, pyroxene and sulphides are the accessory minerals. Dykes of dolomite with the same accessory minerals traverse the intrusive rocks of the complex and the Precambrian sediments outside the complex. The dykes have sharp contacts and are not associated with contact metamorphism. Larsen, viewing the shape, contacts, and vein-like nature of these dykes, believed the carbonate dyke rocks to be intrusive, and because the composition of the central mass is very similar to that of the dykes, suggests one mode of origin for both. He ruled out the possibility of a carbonate

magma on the basis of laboratory experiments on the melting of calcite, claiming that the temperature required for such a magma would be too high to be reasonable. He dismissed replacement, first, because there are no mixed silicate-carbonate rocks and hence no evidence of a gradation from silicate rock to carbonate rock, and secondly, because the carbonate rocks have the same composition regardless of the rock type they traverse. He observed that the minerals of the carbonate rock are similar to those widely distributed among the alteration products around the alkaline stock and that the carbonate rocks appear to be intrusive fracture fillings. He concluded that the dykes within the alkaline rocks and out in the country rock are hydrothermal veins and that the central mass is a hydrothermal filling in the throat of an old volcano.

The main body of carbonate rock at Nemegos is composed of calcite, is dyke-like in form, and appears to occupy an arcuate cone-sheet structure within malignites. The contacts are sharp and well defined and are marked by an alteration zone consisting of a border of aegerinaugite, and biotite and calcite in the surrounding rock. Sharp-edged stringers of calcite project into the wall rocks. Inclusions of nepheline syenite within the carbonate rock are rimmed with aegerinaugite, biotite, magnetite and sulphides. The principal minerals of the body are similar in habit and composition to those produced in the metasomatism of the regional gneiss and in the formation of malignites and ijolites. The magnetite, apatite and pyroxene of the carbonate rock are arranged in streaks and layers parallel to the contact with the wall rocks. The calcite shows no sign of deformation. It is concluded that the carbonate rock at Nemegos was introduced into an open fracture and has altered the wall rocks and inclusions. The mineral composition of the carbonate rock indicates that it is related to the alkaline rocks of the complex and to the associated metasomatism.

The carbonate rock is not believed to be an inclusion of limestone carried in by the magma because it bears no evidence of metamorphism, and because the nearest known outcrop of limestone is in the Grenville province of the Canadian Shield, 100 miles south of Nemegos. Neither is it considered to be a block of limestone from overlying sediments that foundered in the alkaline intrusion. It is difficult to visualize such a block of limestone assuming the position of a cone-sheet structure. If a limestone block did assume such a position through plastic flow then there must have been complete recrystallization after emplacement to erase all signs of deformation in the calcite.

An origin by replacement of silicates by carbonates must be considered but it does not seem probable in the light of a deficiency of mixed silicate-carbonate rocks that would represent an intermediate stage in the replacement. Moreover, there are replacement textures around the inclusions within the calcite, but no evidence that calcite was produced by the replacement. It would need to have been a most complete replacement to produce a carbonate rock such as the one at Multi-Minerals.

The only hypothesis that fits the field relationship and the petrography of carbonate rocks at Nemegos is that fractures were filled by carbonate solution

rich in lime, and carrying iron, sulphur, phosphate, niobium and copper, and that these solutions were genetically related to the alkaline intrusion. This solution might have been a calcite magma, a residual melt from an alkaline magma. The chief objection to the hypothesis of a magma has been that the melting temperature of calcite is 1,340°C at 1,000 atmospheres pressure (Smyth and Adams, 1923) in the presence of carbon dioxide. However, Paterson (1958, p. 603) showed that calcite will melt at temperatures above about 900°C in an atmosphere of water and carbon dioxide at a total pressure of 50 atmospheres, and Wyllie and Tuttle (1959) reported a minimum liquidus temperature in the system CaO-CO_2-H_2O at 665°C and 27 atmospheres pressure of water vapour. Hence, a calcite magma could exist at reasonable temperatures, especially if the other volatile constituents further depress the melting point of calcite.

The alternative to the calcite magma is a hydrothermal solution of appropriate composition, and this is the hypothesis preferred by the writer. Deposition in an open fracture by a mobile hydrothermal solution satisfies the field conditions and mineral composition. It also provides an origin for carbonate rocks that requires solutions similar to those contributing to the formation of ijolite and malignite, and to the alteration of the regional gneiss.

Origin of Pyrochlore

Niobium minerals, principally pyrochlore, occur most abundantly in the basic alkaline rocks and carbonate rocks of ring complexes (von Eckerman, 1948; Fawley and James, 1955). The other prominent occurrence of niobium minerals is in acid pegmatites (Rowe, 1958). Two problems arise in connection with these occurrences of niobium minerals:

1. The genetic significance of the affinity of niobium for rocks as chemically distinct as alkaline rocks and acid pegmatites.
2. The concentration of niobium in both the basic members of the alkaline suite and in the associated carbonate rocks.

The chemical composition of the pyrochlore is an essential factor in any consideration of its origin, and, though two analyses of the mineral from the Multi-Minerals property are given in the section on mineralogy, it is advisable to examine its general chemistry. Pyrochlore is the niobium-rich end-member of the pyrochlore-microlite series that has the general formula $A_2B_2O_6$ (O, Oh, F) where

A is Na, Ca, K, Mg, Fe^{++}, Mn, Sb, Pb, Ce, La, Dy, Er, Y, Th, Zr, U, and
B is Nb, Ta, Ti, Sn, Fe^{+++}, W.

Essentially pyrochlore is $(Na, Ca)_2\ Nb_2O_6F$ where the Nb_2O_5 percentage ranges from 26.22 to 63.64. Niobium has a charge of +5 and an atomic radius of 0.69A°, and the average niobium content of igneous rocks is 0.0024 per cent by weight, a concentration that does not allow early formation of niobium minerals in most igneous rocks. Niobium that is present is incorporated into minerals of titanium and zirconium.

At Nemegos the niobium content is greatest in malignites, less in carbonate rock, ijolite, and magnetite-apatite rock, and least in the nepheline syenites. This distribution is consistent with the study of Borodin (1955) in which he recorded the following relative percentages of Nb_2O_5:

	Weight %
Massive nepheline syenite	0.007–0.008
Poikilitic nepheline syenites	0.008–0.009
Foyaites (nepheline syenite with equal parts nepheline and feldspar)	0.018–0.021
Ijolites-urtites, composed essentially of nepheline and pyroxene	0.025–0.031

Assays from the regional gneiss about the Nemegos alkaline complex show only trace amounts of niobium. Pyrochlore was not observed in the thin sections of gneiss. Parsons (1957, p. 86) however noted that at the Nemegosenda Lake complex there is no detectable niobium in the unaltered gneiss, but that on approaching the homogeneous alkaline rocks of the complex through the altered gneiss 0.2 to 0.5 per cent of Nb_2O_5 was found where alteration is slight and up to 1.0 per cent where the pyroxenization is greatest near the intrusion. He believed that the pyrochlore was introduced in the early stages of contact metasomatism.

Rowe (1958, p. 84) recognized four different niobium-bearing minerals in the carbonate rocks and silicate rocks at Oka, Quebec. Their distribution and association he attributes to hydrothermal or pneumatolytic introduction of material. A similar origin is proposed by Rowe (op. cit., p. 62) for the pyrochlore in the mixed silicate-carbonate rocks of the Newman deposit, Lake Nipissing, Ontario. The source of these agents of metasomatism is an alkaline magma.

The conclusion drawn from the Nemegos occurrence is that niobium, because of its high charge and low concentration in the parent magma, and because it forms a volatile fluoride (Saether, 1950, p. 128) was not incorporated in the early forming minerals but became concentrated with lime, carbon dioxide, iron, fluorine, phosphate, sulphur, copper and water in a residual magma fraction. Niobium was then carried out from the body of nepheline syenite by the aqueous carbonate solutions during contact metasomatism, and pyrochlore formed.

In answer to the two questions proposed at the start of this section it can be suggested that niobium minerals are associated with both alkaline rocks and acid pegmatites because niobium is concentrated in residual fractions of any fractionating magma. Furthermore, the greatest concentrations of niobium are found in the basic members of the alkaline series and in the carbonate rock at Nemegos because the basic alkaline rocks are products of a metasomatism by solutions rich in niobium and because of the carbonate rock crystallized from similar solutions.

Significance of Lamprophyre Dykes

Lamprophyre dykes are common in the alkaline complexes of North America (Oka and Newman, Rowe, 1958, pp. 52, 75), in Fennoscandia (Alno Island, von Eckerman, 1948, p. 48), and in Africa (Dixey, *et al.*, 1955, p. 27).

They are for the most part radial dykes that cut both the alkaline rocks of the complex and the enclosing country rock. Their width varies from several inches to several feet and their composition from melilite-rich to carbonate-rich lamprophyre (von Eckerman, 1948, p. 98). The dykes are rarely accompanied by wall-rock alteration. Without exception, the lamprophyres are considered to be products of crystallization from a magma related to the alkaline intrusion, but no author specifies the actual genesis.

At Nemegos, lamprophyre dykes occupy ring-dyke fractures that dip at low angles away from the centre of the complex. They are the youngest rocks in the area. The principal minerals are a colourless pyroxene, albite, alkali feldspar, biotite, magnetite and calcite. The larger grains are cracked. It is concluded that the dykes formed by the crystallization of a residual magma in flat-lying ring-type fractures that formed when the roof of the magma chamber collapsed after the last major intrusion.

Genesis of the Alkaline Rocks at Nemegos

In conclusions drawn from the consideration of the foregoing eight problems in petrogenesis of the Nemegos alkaline complex, it has been suggested that the nepheline syenites have crystallized from a magma. This magma has also provided the fluids responsible for metasomatic development of other alkaline rocks and for both the magnetite-apatite rock and carbonate rock of the complex. If the presence of a magma is admitted, several questions arise that bear not only on the development of the Nemegos area but on fundamental problems of alkaline rock paragenesis. For example: how can a magma undersaturated in silica, high in lime, alkalis, alumina and carbon dioxide be derived by fractionation of primary magmas of basalt and granite? These magmas commonly give rise to residual differentiates that are quartzose. If such a magma were available how could it have remained undersaturated in the course of intrusion? It would have every opportunity to incorporate silica from the surrounding rocks. And, granted that even if such a magma existed and remained undersaturated, how could it have further differentiated to give the various rock types that are undeniably associated chemically and spatially in the Nemegos complex? In answer to these questions, workers have proposed three main groups of hypotheses:

1. Alkaline magma could be derived by fractionation of a basaltic or peridotitic magma and the diverse rocks of the association generally attained by further fractionation (Barth, 1936; Smyth, 1943; Fenner, 1937; Holmes, 1950; Strauss and Truter, 1950; Tomkeieff, 1938; Saether, 1950; and Backlund, 1933). Barth is the only one who appealed to simple fractionation; the others preferred the help of gases or thermodiffusion in segregation of the alkaline phase.

2. Alkaline magma might be the product of desilication of a magma saturated with silica by assimilation of limestone and the subsequent formation of lime-silicates (Daly, 1910, 1933; Shand, 1930, 1945).

3. Carbonate magma of unknown origin might have picked up silica as it rose through the crust at the same time desilicating the surrounding rocks and transforming them into alkaline rocks. The left-over carbonate could have contributed to the carbonatites (von Eckerman, 1948).

Although the alkaline rocks receive continuous attention in the literature they account for only 1 per cent of the igneous rocks exposed today, and it is reasonable to assume that they are a special variety of more common rock types. The comparison of the mineralogical composition of the nepheline syenites at Nemegos with an experimental system indicates that they are the members of an alkali-alumina-silicate system that crystallized late in the history of the melt (*see* Fig. 6).

In support of this is a concentration of alkalis, volatiles, niobium, uranium, zirconium, phosphorus, etc., all associated with late stages of differentiation from silicate magma in the same manner as in the genesis of pegmatites and hydrothermal solutions. The composition and habit of the rocks of the Nemegos alkaline complex also support the contention that this process of differentiation and concentration eventually contributed the CaO and CO_2 of the carbonate rocks after separation of SiO_2 and Al_2O_3 and various other constituents into a fraction that formed the silicate rocks of the alkaline complex. It is concluded therefore that alkaline rocks are a fraction of one of the established primary magmas—basalt or granite.

The problem narrows down to whether or not a primary magma, saturated with silica, will differentiate to give a fraction low enough in silica to crystallize a feldspathoid and be attended by a solution rich in calcium, water and carbon dioxide. As the alkaline rocks intrude Precambrian gneisses, the alkaline magma must have been generated before it intruded the Precambrian basement and this makes it most unlikely that desilication was by reaction of the magma with a foundered block of Palæozoic limestone. There is no evidence of Precambrian limestone in the area.

The study of the Nemegos area offered no indication of how fractionation proceeded and the hypothesis tendered here is speculative. Granted that a parent magma with the appropriate components, including juvenile carbon dioxide, existed in a magma chamber in a stable area like the Canadian Shield, then fractionation may have proceeded in the following stages:

1. Water, carbon dioxide and other volatile materials would have gathered at the top of the magma chamber where the temperatures and confining pressures were least.

2. Carbon dioxide would dissolve in water in accord with prevailing temperatures and pressures (Garrels and Richter, 1955) to form carbonic acid.

3. The magma would begin to cool slowly and crystals would form and settle downward. At the same time elements with low concentrations, or charges and radii unsuitable for their incorporation in early forming minerals, would collect at the top of the magma chamber with the volatiles. Phosphorus, titanium, zirconium

and niobium form volatile fluorides (Saether, 1950, p. 128). The acid environment at the top of the magma chamber would attract the bases K^+, Na^+, and Ca^{++}. The calcium ion in particular would concentrate at the top because, as the carbon dioxide content of the solution increased, so would the solubility of Ca^{++} (Garrels and Richter, 1955). Carbon dioxide would be the concentrating agent and would be responsible for the formation of a carbonic acid and the solubility of Ca^{++}. Hence, the fraction at the top of the magma chamber containing the greatest CO_2 content would have a greater tendency to differentiate because there the concentrator would be most abundant.

4. Basic ions rising through the magma towards the carbonic acid environment would eventually neutralize the acid in the region below the zone of highest CO_2 content, and actually establish a slightly alkaline environment. Ferrous iron that had not been incorporated into early forming minerals would form a hydrosol in this water-rich, slightly alkaline zone (Shand, 1945).

5. Below the zone where the iron hydrosol was concentrated the composition of the magma would reflect the upward movement of Na^+, K^+, Ca^{++}, CO_2, Fe^{++} and minor elements, and would have the composition of nepheline syenite. It would grade downward into a magma with the composition of ijolite.

Hence through fractionation, controlled by accumulation of water and carbon dioxide, the magma over a long period of time would take on a layered appearance. Cone-sheet fractures would result from an upward thrust of the accumulating volatiles and the ring-dyke fractures would form by subsidence of the roof of the magma chamber. These fractures would tap the magma at different levels to draw off (a) aqueous solutions rich in calcium and carbon dioxide; (b) the iron hydrosol, which oxidizes quickly to magnetite upon loss of water; (c) or alkaline rocks. Silication of the magma would be minimized by the rapidity of intrusion.

Proposed Sequence of Events in the Development of the Nemegos Complex

1. Fractionation of the parent magma to provide an aqueous solution rich in carbon dioxide, water and calcium at the top of the magma chamber, an iron-rich layer below, and an alkaline magma below that.

2. Fracturing and releasing of aqueous fluids responsible for the metasomatism of the regional gneiss. Development of ring-type fracture by collapse, followed by intrusion of the nepheline syenite magma that formed the core of the complex.

3. Another collapse and the formation of a ring-type structure outside the previous fracture. This fracture developed after the first fracture was formed and was occupied by the nepheline syenite of the outer ring. The sheet of regional gneiss caught between the two intrusions of nepheline syenite was altered to the malignites. The intrusion was accompanied by alteration of the regional gneiss beyond the outer ring of nepheline syenite.

4. Build up of pressures in the magma chamber through further concentration of carbon dioxide and water with subsequent cracking of the outer nepheline syenite

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and the development of cone-sheet fractures. Aqueous solutions high in iron and calcium entered the cracks in the outer nepheline syenite, altering the rock to ijolite and crystallizing along the fractures as magnetite veins. Steeply dipping cone-sheet fractures tapped the iron-rich layer in the magma and the material of the magnetite-apatite bodies occupied the fractures. Cone-sheet fractures with shallow dip tapped at the top of the magma chamber and almost pure aqueous solutions of calcium carbonate entered and crystallized in the fracture to form a carbonate rock.

5. Finally a slight subsidence produced the flat-lying fractures that were filled by the lamprophyre dykes.

Conclusions

1. Nepheline syenites of the Nemegos alkaline complex have crystallized from a magma. The equigranular nepheline syenite is a border facies of the inequigranular nepheline syenites.

2. Development of aegerinaugite in the regional gneiss at the expense of quartz and feldspar, and the alkaline chemical composition of the gneiss is the result of a metasomatic alteration of the gneiss by fluids derived from the parent magma of the nepheline syenites.

3. Malignite is produced by metasomatism of a sheet of regional gneiss caught between two rings of nepheline syenite. The agents of metasomatism are aqueous solutions rich in calcium, carbon dioxide, iron phosphorus and niobium. The fluids were derived from the parent magma of the nepheline syenites.

4. Ijolite at Nemegos results from the pyroxenization of the nepheline syenite that flanks the magnetite veins. The agents of metasomatism were similar to those responsible for the development of the malignites. Magnetite veins also formed from these solutions.

5. Magnetite-apatite bodies are intrusive rocks that occupy steeply dipping cone-sheet fractures. They crystallized from aqueous solutions rich in iron and calcium and lower in carbon dioxide than the solutions responsible for altering the gneiss and forming the malignites and ijolites.

6. The carbonate rock is an intrusion formed by the crystallization of calcium carbonate from a hydrothermal solution. This hydrothermal solution was derived by fractionation from the parent magma of the nepheline syenites. The carbonate rock is a product not a cause in the development of the alkaline rocks.

7. Niobium is concentrated in a residual fraction of a differentiating magma, because of its low concentration in the primary magma and because of its high charge. It is present in pyrochlore in the basic alkaline rocks and in the carbonate rock at Nemegos, because it was introduced with the solutions involved in the metasomatic development of the malignites and ijolites and the solutions from which the magnetite-apatite and carbonate rocks crystallized.

8. Lamprophyre dykes are the youngest rocks in the area and they occupy gently dipping ring-dyke fractures formed by the last subsidence of the roof of

the magma chamber. Their association with the alkaline complex and their composition indicate a genetic relationship with the alkaline magma but the position in the differentiation series is not clear.

9. It may be speculated that all the rocks at Nemegos are genetically related to an alkaline magma formed by differentiation of either a granite or a basaltic parent magma; that the nepheline syenites are parts of the alkaline magma and that the other rocks crystallized from hydrothermal solutions derived from this magma or formed through metasomatism of rocks in place by the hydrothermal solutions; that fractionation of the parent magma was primarily controlled by the concentration of carbon dioxide at the top of the magma chamber over a long period of time and in a stable area.

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MINERAL DEPOSITS

Magnetite, apatite and pyrochlore are the minerals with potential economic value in the rocks of the Nemegos area. These minerals commonly occur together and all but one of the known mineral deposits are within the property limits of Multi-Minerals in the southwestern part of the alkaline complex.

Magnetite-Apatite Deposits

The magnetite-apatite deposits that have been most fully explored in the Multi-Minerals claims are elliptical in plan, up to 200 feet wide and 500 feet long, and they have been probed to a depth of at least 500 feet by diamond drilling. These deposits are composed principally of coarse-grained magnetite and apatite with minor amounts of pyroxene and pyrochlore. Foliation is caused by orientation of apatite crystals and segregation of apatite and magnetite into layers up to 3 inches wide. The apatite is emerald green and contrasts with the shiny black magnetite in hand specimen. Ilmenite lamellae occur within the magnetite grains. Large fragments of ijolite and small fragments of nepheline syenite are included within the magnetite-apatite rock, but it is difficult to decide if these patches of silicate rock are true inclusions or independent intrusions. The contact between the apatite-magnetite rock and the ijolite is sharp where encountered in drill-core, but is not well exposed at the surface. The contact between the nepheline syenite patches and the magnetite-apatite rock is exposed in several places in the open pit at the No. 6 orebody. There, it is sharp with no reduction in grain size of either rock type at the contact. Considerable magnetite in the syenite occurs at the contact, and feldspar is present in the magnetite-apatite rock. Diamond-drill hole R-65 penetrated a short section of brecciated rock cemented solely by apatite.

Magnetite Veins

In addition to the bodies of magnetite-apatite, veins of solid magnetite are exposed in the McVittie pit and in most of the outcrops eastward to Beaver Pond. In the McVittie pit the magnetite veins traverse ijolite and show sharp boundaries. There is one major vein 3 feet wide that strikes north, is almost vertical, and is attended by many smaller stringers, averaging 2 inches across, scattered through the wall rock. In the outcrops around Beaver Pond there is also one major vein that averages 3 feet in width and that strikes northwest with a dip of 50°NE. At Beaver Pond the magnetite veins cut the nepheline syenite of the outer ring, type

4, and pyroxene is developed in the wall rock. Analyses of the magnetite from the two types of occurrence are as follows:

Table IX

Average of fourteen analyses of the magnetite fraction from the No. 6 magnetite-apatite orebody at Beaver Pond

	Weight %
Total iron	48.95
Phosphorus	2.65
Titanium oxide	6.40
Silica	1.69
Manganese	0.79
Sulphur	0.43

Average of twelve analyses of magnetite from the largest vein at Beaver Pond

	Weight %
Total iron	62.20
Phosphorus	0.04
Titanium oxide	9.18
Silica	0.76
Manganese	1.34
Sulphur	0.03
Lime	0.03
Alumina	1.31
Magnesia	0.19

Analyses are taken from the annual report of Multi-Minerals Limited. Titanium in the analyses confirms the petrographic evidence that the intergrowths in the magnetite are ilmenite. The phosphorus, silica, manganese and sulphide indicate that the magnetic fraction used for analysis was not solely magnetite. From magnetic separations of the magnetite-apatite rock and sieving at minus 48 mesh, minus 65 mesh, and minus 100 mesh the average was 64 per cent total iron, 6 per cent titanium, 0.27 per cent phosphorus and less than 1 per cent silica. The apatite concentrates average 16.6 per cent phosphorus or 83 per cent bone phosphate-lime, with approximately 1.0 per cent iron and 0.05 per cent titanium. A commercial analysis of the apatite is given below in weight per cent. BPL means bone phosphate of lime, $Ca_3P_2O_8$.

P_2O_5	BPL	Acid. sol. iron	Total Fe	CaO	F	SiO_2	Al_2O_3
35.1	76	1.6	1.9	49.1	2.7	4.3	1.1

Pyrochlore

Pyrochlore occurs in three different ways:

1. As separate fine grains or clusters in the alkaline silicate rocks, principally in the ijolites and malignites, but also in very minor amounts in the equigranular

nepheline syenites and nepheline syenite of the outer ring, type 4. Pyrochlore grains are mostly associated with grain boundaries of aegerinaugite but they may also be enclosed within any of the rock-forming minerals.

2. In fine, disseminated grains in the magnetite-apatite bodies such as No. 6 orebody and also in carbonate rock.

3. As euhedral grains in nepheline stringers that traverse malignites and ijolites and the pink nepheline fillings in the brecciated ijolite at the southeast end of Beaver Pond. As pyrochlore is most abundant in the more basic members of the alkaline suite and the carbonate rocks that generally lie within these basic rocks possible orebodies can be outlined by magnetic surveys.

The principal deposits known on the Multi-Minerals property have been tested by diamond drilling and estimates of tonnages and grade to a depth of 500 feet made by officers of the company are as follows:

Number 6 body. This consists of magnetite, apatite and disseminated pyrochlore. Diamond drilling indicated 5,024,250 tons averaging 69.60 per cent magnetite, 21.88 per cent apatite and 0.173 per cent Nb_2O_5.

Number 8 body. This consists of disseminated pyrochlore in ijolite and malignite. Diamond drilling indicated more than 50,000,000 tons of rock averaging 0.26 per cent Nb_2O_5.

Number 3 and Number 4 bodies. These consist of magnetite, apatite and pyrochlore in ijolite. Diamond drilling indicated a combined total of 10,000,000 tons of rock averaging 15.5 per cent magnetite, 19.5 per cent apatite and 0.226 per cent Nb_2O_5.

Main mass of carbonate rock. Diamond drilling of this mass north of Camp Lake indicated 1,610,000 tons composed of 80 per cent calcite and averaging 0.16 per cent Nb_2O_5.

One deposit in claims held by Dominion Gulf Company, covering the southeastern part of the complex has been partly explored by diamond drilling. This company drilled three holes, one of which intersected a pyrochlore-bearing magnetite-apatite body in malignite. The width of this body was estimated by company officials to be 75 to 100 feet, with an average tenor of 39.04 per cent Fe (soluble), 5.04 per cent P, and 0.15 per cent Nb_2O_5. The rocks at each side of this body contain pyrochlore for widths estimated at 25 to 50 feet, the average content being estimated at 0.15 per cent Nb_2O_5.

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