# THE OPEMISCA LAKE PLUTON

## A Petrological and Geochemical Study

by

L. E. Wolhuter

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Department of Geological Sciences,
McGill University,
Montreal.

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## ABSTRACT

The Opemisca Lake pluton is a Precambrian intrusive mass which has intruded into the core of an anticline of regionally folded and metamorphosed greenstones.

The intrusive is uncommonly sodic and is characterized by a core of uncontaminated granite, and a rather narrow rim of contaminated granite, syenite and melasyenite. It is possible to differentiate positively between contaminated and uncontaminated granite by means of variation diagrams.

The cooling history of the granite is inferred from petrographic studies of the pluton and some of its satellitic stocks, and from published results of experimental studies on silicate melts. The granite crystallized from a rather dry magma, and during most of its cooling period a fairly high degree of equilibrium was maintained between crystals and melt.

Isopleth maps of the pluton show a pronounced concentric chemical zoning which is attributed to a combination of the processes of differentiation and contamination.

Deformation in the wallrocks of the pluton suggest that forceful injection was the most important mechanism of emplacement.

CONTENTS

## CHAPTER VII



## CHAPTER VIII



## CHAPTER IX



## TABLES

## ILLUSTRATIONS

# CHAPTER I

# INTRODUCTION

## 1.01 General Statement

During the 1960 and 1961 field seasons, while mapping the country to the south and west of the Opemiska Copper Mine for the Department of Natural Resources, Quebec, the author became interested in the Opemisca Lake pluton as a possible source of the ore deposits at the mine. Reconnaissance traverses across the pluton during these years confirmed what had already been determined previously by Tolman (1932) and Norman (1938) during regional mapping: the pluton was, for the greater part, remarkably uniform in composition, it was not affected by multiple intrusion, and it had a relatively simple structure.

At the time, the Department of Natural Resources, Quebec, was contemplating a programme of geochemical research on granitic intrusives within the province. The possibility of a geochemical study of the Opemisca Lake pluton was brought to the attention of the Department, especially since the intrusive extended into the northwest quarter of Levy township, an area which was scheduled for detailed mapping (1:12,000 scale) by the writer during the 1962 field season.

The Department agreed to this suggestion with the proviso that the geochemical investigation should not impede the scheduled mapping in Levy township. Inasmuch as the field work was to be carried out by a crew of only two men, the writer and a junior assistant, it would not have been possible to make a thorough investigation of the entire pluton in the time available. However, in view of the known homogeneity of the intrusive, this was not considered to be a serious disadvantage, and it was decided to map in detail only that part of the pluton lying within northwest Levy township. Mapping elsewhere in the intrusive was to be confined to sampling and a description of the rocks in the immediate vicinity of the sample locality.

The material collected in the field was investigated at McGill University and in the laboratories of the Department of Natural Resources, Quebec. The primary purpose of this study was to determine the geochemical and petrological characteristics of the pluton and to see whether these would cast some light on the origin and genesis of the intrusive. An attempt was also made to relate deformation structures in the wallrocks to a mechanism whereby the pluton could have been emplaced.

The results of these labours are presented in this thesis.

## 1.02 Location and Access

The area to be described is centred on Opemisca lake in the electoral district of Abitibi East, Quebec. The village of Chapais and the Opemiska Copper Mine are situated about 2 miles south of the southeastern border of the intrusive, and the well known mining town of Chibougamau lies about 25 miles to the east.

An all weather gravel highway and branch lines of Canadian National Railways link Chapais with the larger population centres in the southern part of the province. A graveled landing strip is situated about one mile southeast of the village. At the time of writing, Hall's Air Service of Val d'Or, Quebec, provided a daily flight to and from Chapais.

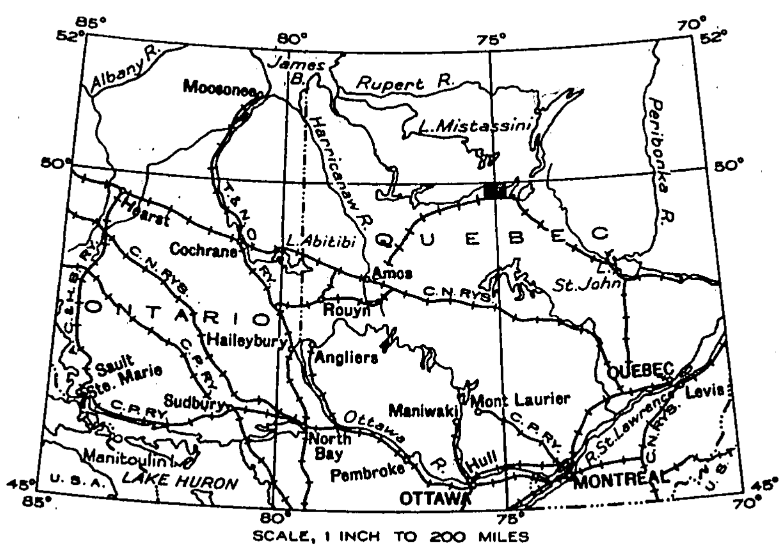



Figure 1. Location of area described in text.

West bay on Opemisca lake is connected by a short stretch of bush road to the Chapais-Senneterre highway. From West bay extensive areas of the pluton are readily accessible by canoe. The southeastern part of the intrusive is reached most easily on foot, along trails leading northward from Chapais.

## 1.03 Topography

The area underlain by the pluton is characterized by low hills and knolls of bedrock rising from less than 50 feet to as high as 350 feet above the surrounding lowlands. Two discontinuous belts of sand and gravel cross the eastern half of the pluton.

Well drained areas are heavily forested, whereas the lowlands are generally swampy and, in places, extensively covered with muskegs.

Opemisca lake lies at an altitude of 1176 feet above sea level.

## 1.04 Previous Work

Brief descriptions of the geology along the shores of Opemisca lake are given in reports by Brock (Bell, 1897) and Low (1906) who passed through the area during the early years of exploration of the Nottaway River basin and the Chibougamau Lake region.

During the 1930 field season, more detailed geological mapping of the area was undertaken by Tolman (1931). His map of the southern part of the Opemiska Quadrangle, at a scale of two miles to the inch, includes an extensive tract of country around the area under discussion in this study. In a subsequent publication, Tolman (1932) described the petrography and petrology of the Opemisca Lake pluton. Four chemical analyses were also presented. Unfortunately, Tolman erred in his interpretation of the structural setting of the pluton. He believed that the pluton was originally a sill-like body and that the southern border of the intrusive was the base of the sill when it was still in a horizontal position. He considered the hybrid basic xenoliths and contaminated granite near the southern margins of the pluton to be basic differentiates of the granite, and that they had formed by a process of gravitational differentiation.

During the late nineteen-thirties the area was mapped by Norman (1937, 1938) and Beach (1941) following the discovery of rich copper deposits to the south of the Opemisca Lake pluton. Their maps of the area (Geological Survey of Canada maps 401A, 602A and 623A) are still models of excellence, detail and accuracy. Norman (1938) recognized the nature of the Opemisca Lake intrusive, and was the first to comment on the zonal arrangement of minerals within the granite.

During the summers of 1959 to 1962, the writer mapped on behalf of the Department of Natural Resources, Quebec, an area of 100 square miles, partly along, but mostly to the south of the Opemisca Lake pluton. The area embraces the southeastern, southwestern and northwestern quarters of Levy township, and the southeastern quarter of Daubrée township. Preliminary accounts of this work have been published (Wolhuter, 1960, 1962), or are awaiting publication (Wolhuter, 1966).

## 1.05 Field and Laboratory Techniques

Sampling, and analytical techniques, precision and accuracy of data are described in Appendix I.

## 1.06 Acknowledgments

The author is deeply indebted to the Department of Natural Resources, Quebec, for enabling him to do the field work on which this study is based, and for defraying the cost of thin sections and many incidental expenses. The detailed geochemical work described in this thesis was done largely by the analytical laboratories of the Department. In particular, the author wishes to express his appreciation to Dr. J. R. Assad, Director of the Mineral Deposits Branch of the Department of Natural Resources, for his interest in the project when it was first conceived, and for his continued encouragement and cooperation subsequently.

Mr. K. Schrijver is thanked for many fruitful discussions pertaining to this work, for his reading of the manuscript, and for his stimulating suggestions and criticism. Mrs. Pat Grove provided many helpful hints relating to the intricacies of colourimetric analyses for trace elements, and Mr. Paul Girard assisted ably in the field.

A special debt of gratitude is owed to Dr. J. E. Gill who directed this study.

Finally, my sincere thanks are due to my wife for her constant inspiration, encouragement and help in preparing this thesis.

# CHAPTER II

## GENERAL GEOLOGICAL RELATIONS

The Opemisca Lake pluton is one of two large Precambrian intrusive masses that extend east-southeastwards from Michwacho lake to Chibougamau lake and beyond (fig.2). In contrast to the complex structure and heterogeneous lithology of the neighbouring intrusive body, the Opemisca Lake pluton is characterized by a relatively simple structure and a homogeneous composition. Both intrusives lie within the core of a major anticline which trends east-southeast as far as David lake, in adjacent Scott township, and then changes to a northeasterly course.

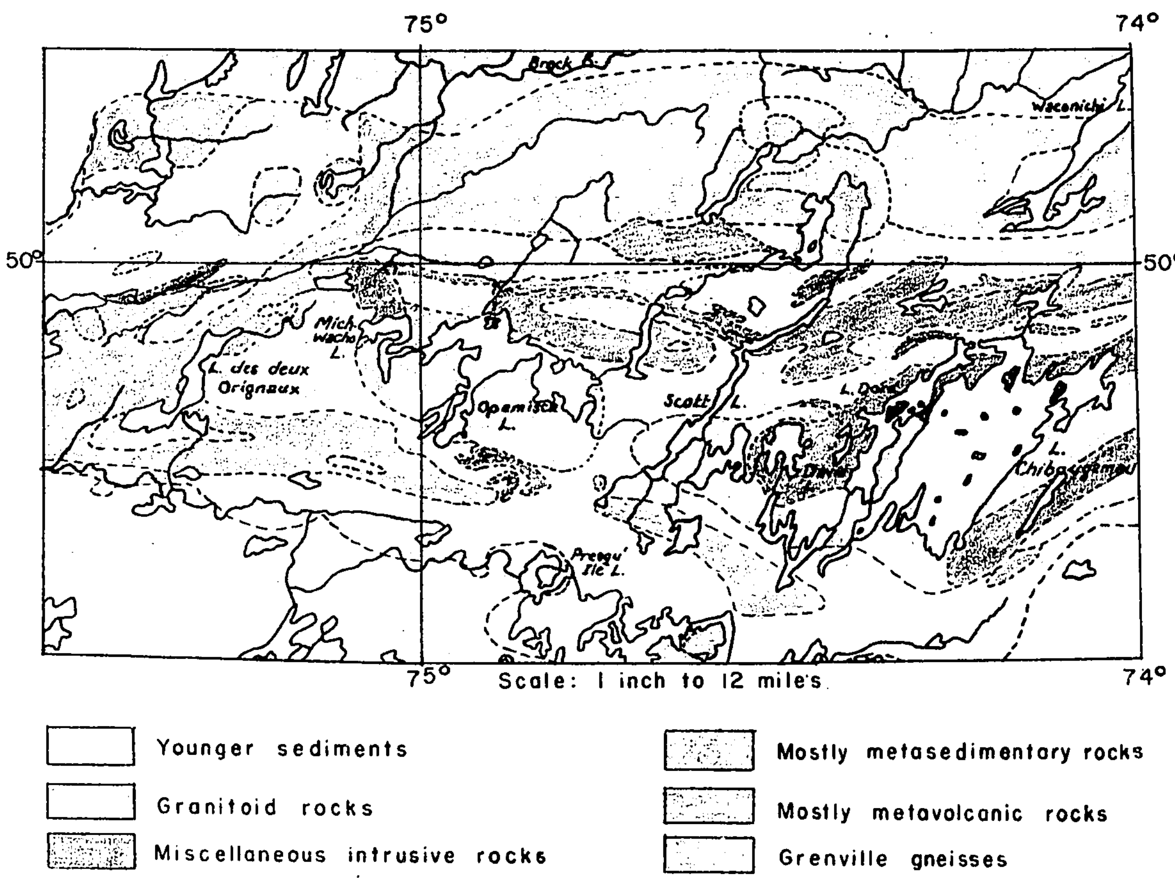



Figure 2. Regional geologic setting of the Opemisca Lake pluton

The Opemisca Lake pluton intrudes vertical to steeply-inclined sequences of volcanic, sedimentary, and layered intrusive rocks. The country rocks are folded into tight isoclines, and have been regionally metamorphosed to the greenschist facies.

The pluton and the rocks surrounding it form part of the Waswanipi-Chibougamau belt (Dresser and Denis, 1944, p.73), one of the major easterly-trending belts of the Superior geological province in southwestern Quebec.

## CHAPTER III

## STRUCTURAL FEATURES

The Opemisca Lake pluton is elliptical in outline and measures 15 miles in length and 7 miles in width. The long axis is parallel, or nearly so, to the regional trend. On a regional scale the contact between the pluton and the bordering rocks is concordant (fig.2) but locally, in detail, contacts are discordant (figs.3, 36). Areas of

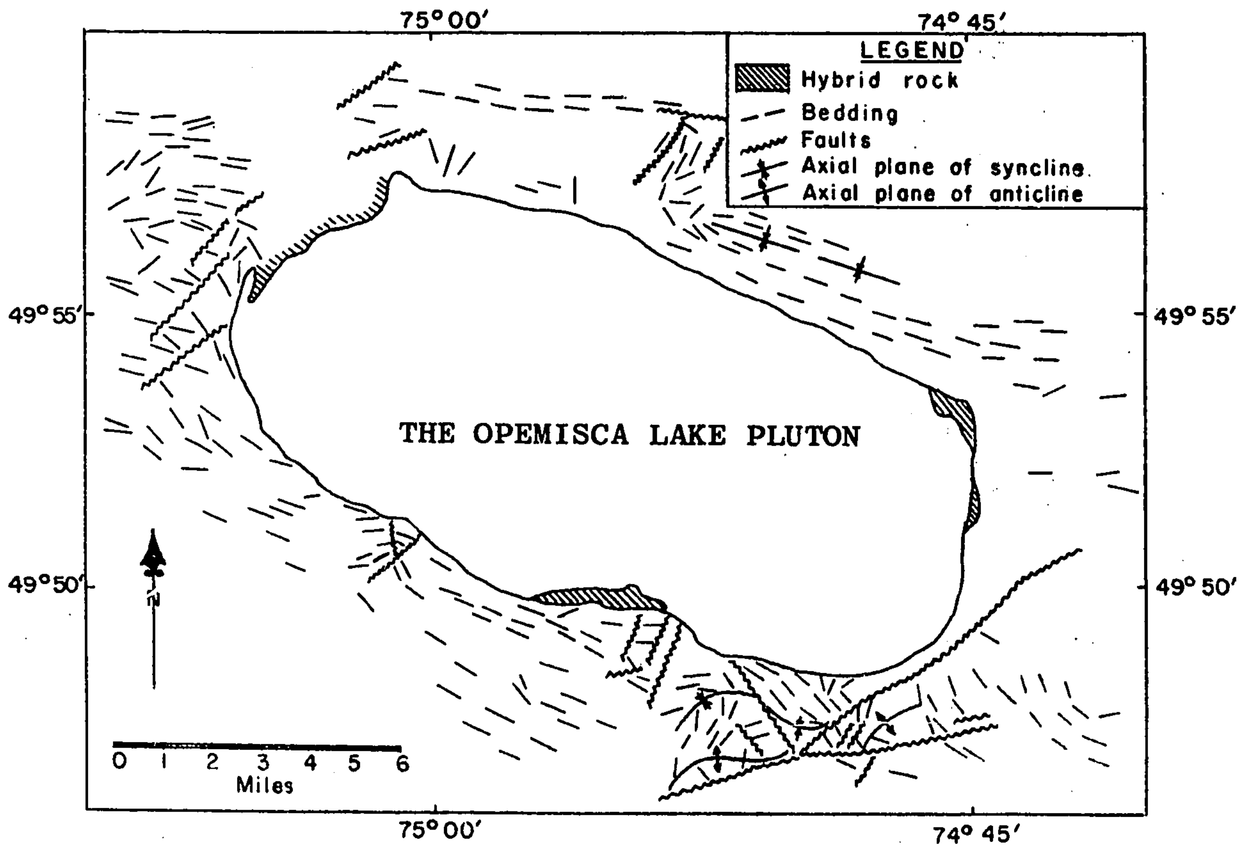



Figure 3. Structural trends in rocks surrounding the Opemisca Lake pluton.

greatest discordancy are along the north central border of the intrusive (Opemisca mountain area), around the western nose (Michwacho lake area), and around the southeastern extremity (Opemiska mine-Springer mountain area). Structural information about the rocks to the east of the pluton is lacking because of scarcity of outcrop in this area.

On the northern slope of Springer mountain, the strike of the greenstones changes from northwest to northeast as the margin of the Opemisca Lake pluton is approached (fig.36). Here the intruding mass seems to have wedged the layers of older rock apart and then forcibly pushed them aside to make room.

The nature of the contact between the pluton and the older rocks is not well known owing to the scanty exposures along the borders of the intrusive. The southern contact appears to be rather smooth with relatively few apophyses extending into the country rock. Tolman (1932, p.87) reports that the eastern edge of the intrusive is much less regular owing to the presence of a number of apophyses nearly parallel to the structure of the greenstones. The contact between the pluton and the older rocks was invariably knife-sharp where it could be seen and it had no pronounced chill zone. In a few places, though, the rocks along the contact are slightly finer in grain than elsewhere.

Dips in the wallrock are generally steep - vertical around the northwestern nose of the pluton and steeply inward along the southern, eastern and northeastern borders. This would suggest a possible funnel shape for the intrusive. The inward dip of the granitic rocks has also been confirmed by diamond drilling in northeast Levy township (Geisterfer, 1961, personal communication). The Opemisca Lake pluton intruded into the core of a major anticline. This structure is indicated by the orientation of beds in the wallrocks which, nearly everywhere, face away from the intrusive. Also, the same general stratigraphic sequence can be traced away from the pluton into the older rocks on both its northern and southern flanks.

Secondary foliation in the wallrocks can usually be attributed to low grade regional metamorphism and not to the intrusion of the granitic rocks. However, a rare and steeply-dipping mineral lineation in metagabbros bordering the intrusive in the disturbed area on the north slope of Springer mountain may have been induced by the rising pluton. A conspicuous foliation within the granitic rocks is noticeable at a few localities along the southern margin of the pluton. The planar structure is defined by tabular aggregates of mafic minerals, by chlorite flakes and by hornblende prisms. Generally it conforms closely in orientation to the trend of the contact of the intrusive but it is independent of foliation in the wall rocks. The planar structure is most likely a primary foliation caused by flowage in the magma. It decreases very abruptly towards the centre of the pluton, where the fabric is without any obvious preferred orientation.

In its gross internal pattern the pluton shows a distinct concentric zonal structure, brought about by mineralogical and chemical veriations. The core or inner zone, which makes up the bulk of the intrusive, consists of a leucocratic hornblende-bearing soda granite. It is almost monotonously uniform in texture and composition. By decrease of quartz and increase of mafic minerals the granite grades almost imperceptibly into the narrow marginal zone of contaminated syenite and melasyenite. During the mapping of the pluton, the quartz content was estimated visually in order to differentiate in broad outlines between the granite (more than 10 percent quartz) and the syenite (less than 10 percent quartz). Despite inaccuracies attributable to weather conditions and the direction of traverses across the pluton, subsequent modal analyses show that estimates on the majority of samples were surprisingly close. The main source of error was the very small grain size of the quartz in the peripheral zones of the pluton. Microscopic study revealed that in these areas the quartz is intensely granulated and intergrown with feldspar. The intergrowth is so fine in grain that the component minerals cannot be differentiated with a hand lens. Consequently, estimates of the quartz content in the marginal rocks tend to be low, but generally not so much in error as to invalidate the approximate boundary between the granite and the marginal syenite shown on the detailed map of the northwest quarter of Levy township (Wolhuter, 1966).

Inclusions are uncommon in the central part of the intrusive but become more plentiful and also larger towards and in the marginal zone. They range in size from xenoliths, several thousand feet across, to mere schlieren and xenocrystic hornblende, biotite and chlorite.

A few small syenitic dykes, none of which exceeds 10 feet in width, intrude the country rocks surrounding the pluton in northwest Levy township. All of these dykes occur within 2,000 feet of the main intrusive mass but farther south, on the Opemiska Copper Mines property in southwest Levy township, the Black pyroxenite is pierced by small satellitic stocks of porphyritic quartz syenite at a distance of at least 7,000 feet from the pluton.

Locally narrow, medium- to coarse-grained quartz-feldspar veins cut the granite or syenite, but in general the pluton is singularly free of pegmatitic phases. More common, but still rare, are whitish to pinkish veins or dykes of fine- to medium-grained sugary aplite and veinlets of pink feldspar. The aplites generally average about 2 to 3 inches in width, although in one outcrop dykes as much as 3 feet across were seen.

# CHAPTER IV

# PETROGRAPHY

## 4.01 Nomenclature

Because of the strongly sodic composition of the plagioclase in the Opemisca Lake pluton, some difficulty was experienced in the choice of a suitable system of classification. In most of the samples investigated the plagioclase grains are slightly zoned and range in composition from sodic oligoclase cores to albitic rims. Where the plagioclase shows little or no zoning, the composition is almost invariably albitic.

According to the classifications proposed by Johannsen (1939) and Travis (1955), the rocks of the Opemisca Lake pluton containing more than 10 percent quartz by volume rank as (soda) granodiorites. Quartz-poor varieties are known as syenodiorites, in Johannsen's terminology. Lindgren (quoted in Johannsen, 1939, p.254), who originated the term granodiorite, specified that the plagioclase should be either calcic oligoclase or andesine. According to him, the average granodiorite has a colour index of approximately 20 (Williams and others, 1955, p.129). The Opemisca rocks do not meet either of Lindgren's specifications.

In the classification of Williams, Turner and Gilbert (1955) albite is included with the potash feldspars as an alkali feldspar. No difficulty is experienced in grouping those rocks in which the plagioclase is unzoned and composed entirely of albite. However, it is in the specific group of granitic rocks dealt with in this study that this particular classification proves to be rather awkward. If the average composition of the zoned plagioclase is taken as a criterion, the rocks of the Opemisca Lake pluton, with an average slightly on the sodic side of $An_{10}$, would be classed as granite or syenite, depending on the quantity of quartz present. If, on the other hand, the abundances of oligoclase and albite in the zoned plagioclase serve as a basis of classification, most of the quartz-rich rocks would probably rank as adamellites and others as granites. The equivalent quartz-poor varieties would be monzonites and syenites.

Despite mineralogical variations within the Opemisca Lake pluton, the intrusive as a whole is a fairly uniform body of rock and a multiplicity of names is unwarranted. For this reason, and also because it is eminently suited to the present study, the author has chosen what is essentially the classification advocated by Moorhouse (1959). In this system, silicic feldspar includes the potash feldspars, albite and sodic oligoclase, whereas plagioclase includes only those varieties more calcic than $An_{20}$. This eliminates any confusion as to the status of the zoned acid oligoclase-albite crystals. The only difference between the classification used in this work and that of Moorhouse is in the volume percentage of quartz chosen to mark the boundary between the oversaturated (quartz-rich) and saturated (quartz-poor) groups of rocks. In this study the critical percentage of quartz is 10 rather than 5 as used by Moorhouse.

According to this classification the interior of the Opemisca Lake pluton is composed of a leucocratic soda granite which grades outward into a rather narrow rim of sodic syenite and melasyenite.

## 4.02 Granitic Rocks

### 4.021 Mineralogy

As seen in hand specimens, the typical granite is a mottled pink and white medium-grained porphyritic granular rock composed essentially of plagioclase, potash feldspar, quartz and hornblende. Sphene, magnetite and yellowish-green epidote are common accessories. The mottled colouring is caused by an irregular pink hematite stain along cleavage and twin planes and grain boundaries of the feldspars.

Large pink to white poikilitic microcline phenocrysts are characteristic. In some outcrops the microcline crystals attain a length of 2.5 cm and a width of 1.2 cm, but in general they do not exceed 1 cm in length. Despite their large size, the phenocrysts are not at all conspicuous in hand specimens, owing to the large number of smaller plagioclase tablets poikilitically enclosed within them. Only where it has broken cleanly along a cleavage plan is the microcline readily seen. A very rare but conspicuous porphyritic phase of the granite contains large pink or white subhedral potash(?) feldspar phenocrysts devoid of any inclusions and measuring as much as 3.5 cm in length and 2.5 cm in width.

Blackish-green hornblende and brown sphene both usually show good idiomorphic outlines and are easily visible to the naked eye.

The syenite and melasyenite are rather similar in appearance to the granite, except that they contain little or no quartz and generally have a higher content of dark minerals (20 percent or more for melasyenites). Small dark-green fine-grained granular aggregates of mafic minerals are common, especially in the melasyenites. In some places along or near the southern border of the intrusive the syenites and melasyenites are distinctly foliated.

Point counts of thin sections show the granite to have the following range in composition: plagioclase (including myrmekite), 50 to 60 percent; perthitic microcline, 15 to almost 30 percent; quartz, 10 to 25 percent in the granites and less than 10 percent in the syenitic rocks; hornblende, generally less than 5 percent in the granites and as much as 25 percent in the melasyenites. Accessory minerals commonly present are pistacite, sphene, opaque iron oxide, apatite and zircon. Secondary minerals include saussurite and chlorite. The modes of some of the several varieties of granitoid rocks in the pluton are shown in table 1.

Plagioclase is the dominant constituent of the granite. Although the borders of the grains may be somewhat corroded by quartz and potash feldspar, the plagioclase is typically hypidiomorphic. In the granite proper many of the plagioclase grains show good idiomorphic outlines (plate I), but in the marginal zones of the intrusive the plagioclase tends toward a more xenomorphic outline (plate II).

The plagioclase grains average about 2 mm in diameter. A smaller generation of idiomorphic to xenomorphic crystals ranging in size from less than 0.5 mm to almost 1 mm are enclosed poikilitically in the large microcline phenocrysts.

Nearly all plagioclase grains show multilamellar twinning according to the albite law. Most sections also contain a fair number of complex twins featuring combined albite and Carlsbad twinning. Pericline or acline twinning is rare.

Zoning of the plagioclase is on the whole a pronounced feature of most of the samples studied. Generally the zoning is progressive from cores as high as $An_{15}$ to rims of $An_4$ but oscillatory zoning is also fairly common. In

TABLE 1. MODAL COMPOSITION OF GRANITOID ROCKS OF THE OPEMISCA LAKE PLUTON

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Sample number | NL-82 | NL-2 | NL-74 | NL-20 | NL-59 | NL-11 | NL-17 | NL-31 | NL-64 |
| Plagioclase[1]...... | 47.6 | 57.1 | 55.4 | 58.5 | 54.3 | 54.2 | 58.5 | 54.1 | 51.7 |
| Perthitic microcline...... | 19.9 | 15.9 | 21.1 | 16.6 | 18.4 | 26.9 | 17.9 | 15.2 | 15.0 |
| Quartz............ | 2.9 | 4.8 | 8.6 | 8.7 | 12.9 | 13.0 | 17.3 | 21.0 | 25.1 |
| Myrmekite......... | 2.1 | 0.7 | 4.4 | 2.2 | 5.1 | 1.3 | 1.2 | [5]---- | 1.6 |
| Hornblende........ | [3]24.3 | 15.9 | 8.7 | 12.4 | 6.8 | 2.9 | 2.9 | 3.4 | 1.8 |
| Epidote........... | 1.1 | 1.6 | 0.6 | 0.7 | 1.6 | 0.5 | 0.8 | 4.0 | 3.7 |
| Chlorite.......... | 0.6 | [4]3.7 | 0.1 | 0.1 | 0.2 | 0.2 | 0.9 | 0.9 | 0.4 |
| Opaque minerals........ | 0.4 | 0.2 | 0.7 | 0.7 | 0.5 | 0.3 | 0.2 | 0.5 | 0.4 |
| Sphene............ | 0.8 | tr | 0.4 | 0.2 | 0.1 | 0.2 | 0.3 | 0.7 | tr |
| Apatite........... | 0.3 | 0.2 | 0.1 | tr | 0.1 | tr | tr | tr | 0.1 |
| Other accessories[2].... | tr | tr | tr | tr | tr | 0.3 | tr | 0.2 | 0.2 |
| TOTAL....... | 100.0 | 100.1 | 100.1 | 100.1 | 100.0 | 99.8 | 100.0 | 100.0 | 100.0 |
| Number of points counted.......... | 1000 | 1200 | 1400 | 1225 | 1000 | 3443 | 1000 | 1000 | 1000 |
| Area counted ($mm^2$). | 700 | 540 | 630 | 480 | 700 | 450 | 660 | 500 | 700 |
| Distance from margin of pluton... (thousands of ft.) | 0 | 0.6 | 4.4 | 4.5 | 1.4 | 16.3 | 14.4 | 0.1 | 16.0 |
| Colour Index[6]...... | 26.4 | 19.9 | 9.9 | 13.3 | 7.7 | 3.7 | 4.3 | 5.7 | 2.9 |

[1]Includes secondary saussurite
[2]Mostly zircon, rarely muscovite
[3]Includes a few pyroxene relics
[4]Includes a little relic biotite
[5]Included with plagioclase
[6]Excludes epidote

Explanation of table 1.

1. Melasyenite, strongly contaminated.
2. Syenite, strongly contaminated.
3. Quartz syenite, moderately contaminated.
4. Quartz syenite, little or no contamination.
5 to 9. Granites, generally uncontaminated.

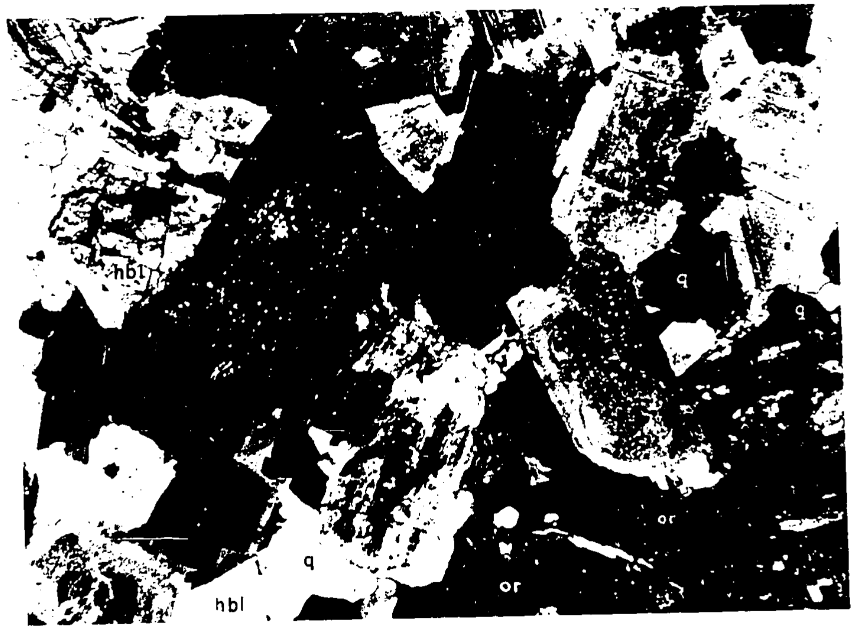



Plate I. Typical texture of normal granite. Hypidiomorphic plagioclase grains form the fundamental framework. K-feldspar (or) and quartz (q) are interstitial to the plagioclase. Some idiomorphic hornblende (hbl) is present. Crossed nicols, X17.

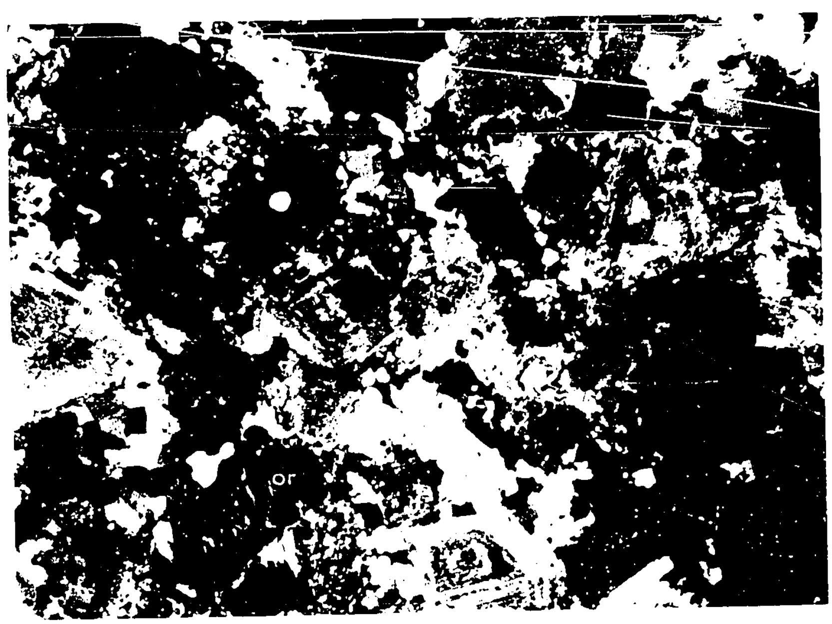



Plate II. Protoclastic texture in granite of marginal zone. A finely crushed and recrystallized interstitial aggregate surrounds rounded plagioclase grains. Crossed nicols, X17.

fresh or relatively unaltered plagioclase grains the zoning is vague and, owing to the small variation in composition, it is difficult to see. In the more altered grains oscillatory zoning is usually emphasized by selective saussuritization of alternating shells of different composition.

Slight to moderate saussuritization of the plagioclase is characteristic but the intensity and pattern of alteration varies considerably from grain to grain. Most commonly the saussurite is uniformly distributed throughout the grain or else it forms irregular patches alternating with fresh, unaltered feldspar. Elsewhere a strongly saussuritized core is surrounded by clear or relatively unaltered feldspar whereas in other grains the saussurite may define oscillating compositional zones as outlined above. The saussurite is made up of fine sericite flakes and tiny clinozoisite granules. The relative proportions of the two minerals vary considerably, not only from one sample to the next but also from grain to grain in the same thin section. As a rule, clinozoisite is more abundant in the more intensely saussuritized plagioclase. Also, the intensity of saussuritization tends to increase towards the margin of the intrusive, reflecting an increase in the lime content of the original unaltered plagioclase.

Most plagioclase grains show evidence of strain by their undulatory extinction and, in places, by bent twin lamellae.


Plate III. Highly irregular borders of K-feldspar megacryst (or) penetrating surrounding framework of plagioclase crystals. Crossed nicols, X16

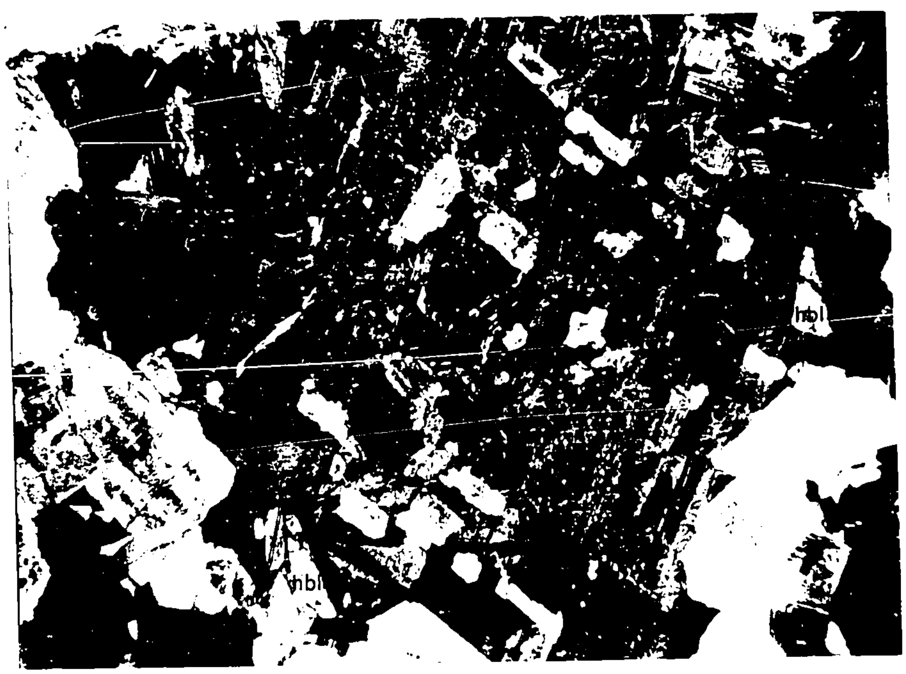



Plate IV. Tiny plagioclase tablets and some hornblende (hbl) poikilitically included in K-feldspar. Inclusions are arranged along definite crystallographic planes in megacryst. Crossed nicols, X11.

The bulk of the potash feldspar in the Opemisca Lake pluton occurs as microcline crystals which are considerably larger than the surrounding minerals. The microcline usually shows grid twinning, is almost invariably perthitic and contains only a slight dusting of secondary alteration products. Generally the albitic element in the perthite occurs as tiny parallel stringers or blebs which, in some grains, have coalesced to form irregular patches or anastomosing veinlets.

Typically the microcline is poikilitic and highly irregular in outline, owing to interference between the borders of the phenocryst and the surrounding framework of plagioclase grains (plate III). However, in two samples collected near the southern margin of the pluton, and in another from one of the small satellitic stocks to the south, the microcline occurs as rudely subhedral to euhedral crystals bounded by relatively smooth unbroken faces against which the surrounding minerals or matrix abut sharply (plate V). Smaller grains of microcline are invariably interstitial to the plagioclase. In many places the microcline has replaced the adjoining plagioclase.

The poikilitic inclusions in the microcline phenocrysts are usually tiny plagioclase tablets and, more rarely, idiomorphic hornblende and sphene (plates IV, V). In some microcline grains these inclusions are haphazardly arranged, whereas in others they lie with their long axes parallel to


Plate V. Large K-feldspar phenocryst from granite porphyry in satellitic stock. Inclusions are mostly plagioclase with some hornblende (hbl) and sphene (sph). Inclusions generally increase in size towards borders of phenocryst. Crossed nicols, X17.

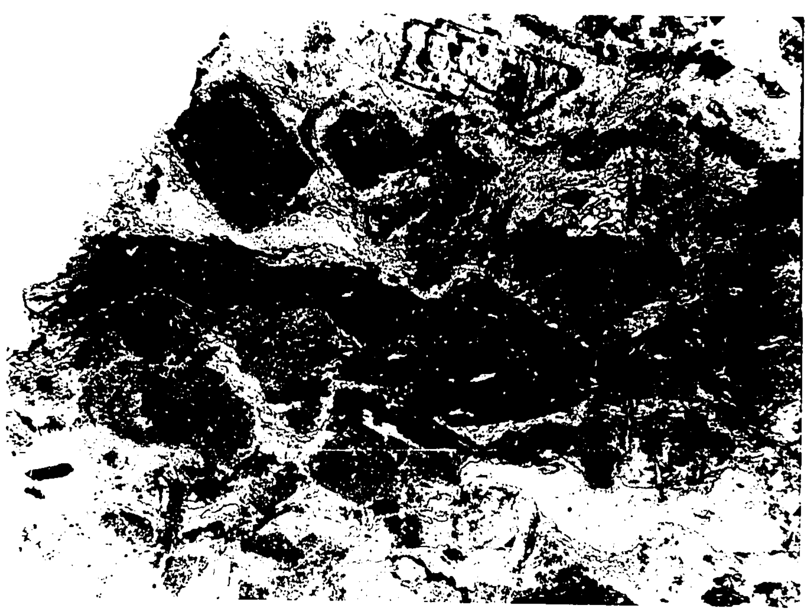


Plate VI. Mafic inclusion composed of an aggregate of hornblende, chlorite, opaque iron oxide and minor apatite. The inclusion is bent around framework plagioclase grains. Plane-polarized light, X15.

definite zones or crystallographic directions (plate IV). Where a sufficiently large number of such inclusions are present, they may define a distinct trapezoidal outline. Most microcline grains have an undulatory extinction ranging from weak to strong; others extinguish sharply.

Quartz is most abundant in the centre of the pluton and, as a rule, less abundant towards the margins. (See table 1 and fig.15B). Typically it occurs in anhedral interstitial grains or mosaics. Where quartz has not been granulated, the grains are about the same in size as the plagioclase. Towards the margin of the batholith, however, the rocks show evidence of considerable crushing and the feldspars are surrounded by intensely granulated and recrystallized mosaics of quartz in which the grains range in size from less than 0.01 mm to as much as 0.2 mm (plate II). The granulated quartz is intergrown with fine-grained potash feldspar, plagioclase and myrmekite and all these minerals show pronounced strain shadows. Quartz was one of the last minerals to crystallize and in many places replaces the earlier-formed plagioclase. Its relationship to microcline, however, is not so clear. In most thin sections the contacts between the two minerals offer inconclusive evidence as to the relative age of each. In a few sections quartz is seen to have replaced the microcline, whereas in other sections the reverse is true. Apparently the crystallization of the two minerals overlapped considerably during the magmatic stage. The seemingly anomalous relationship between quartz and potash feldspar could also be ascribed to autometasomatism during deuteric alteration of the granite. For reasons to be given in a later section, these phenomena are not attributed to alteration during regional metamorphism.

Hornblende is the most abundant mafic mineral in the pluton. It is pleochroic from blue green or light olive green (Z) to green (Y) and pale brown (X). The extinction angle $Z \wedge c$ exceeds $20^{\circ}$ in contrast to the actinolite in the greenstones in which the extinction angle is less than $20^{\circ}$. The hornblende generally has two distinct habits. In the interior of the pluton it occurs as well-shaped idiomorphic to hypidiomorphic, stubby to elongated prisms. Although some of these crystals are of approximately the same size as the plagioclase grains, the average size of the hornblende is noticeably smaller than that of the plagioclase. Locally the hornblende completely encloses smaller plagioclase grains and partially encloses larger ones. Generally, however, the larger plagioclase crystals tend to abut sharply on hornblende. A marked increase in hornblende content takes place towards the margin of the intrusive, as irregular to elongated aggregates composed mostly of small xenoblastic hornblende grains (plate VII) become increasingly abundant. The aggregates are in general conspicuously larger than the plagioclase grains and in places are bent around them (plate VI). In some of the aggregates the hornblende is poikilitic and is sieved with tiny quartz and plagioclase

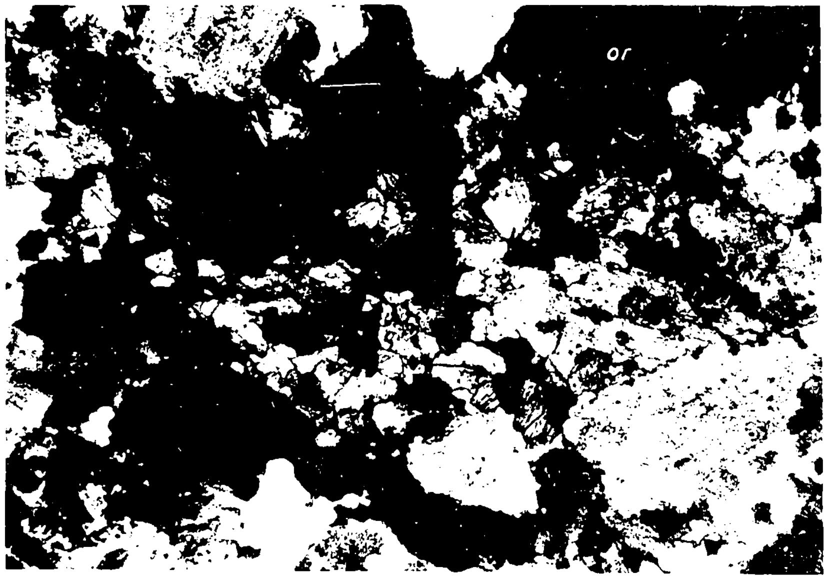



Plate VII. Mafic inclusion in granite composed of xenoblastic hornblende, opaque iron oxide (black) and a few minute granules of apatite. Crossed nicols, X25.

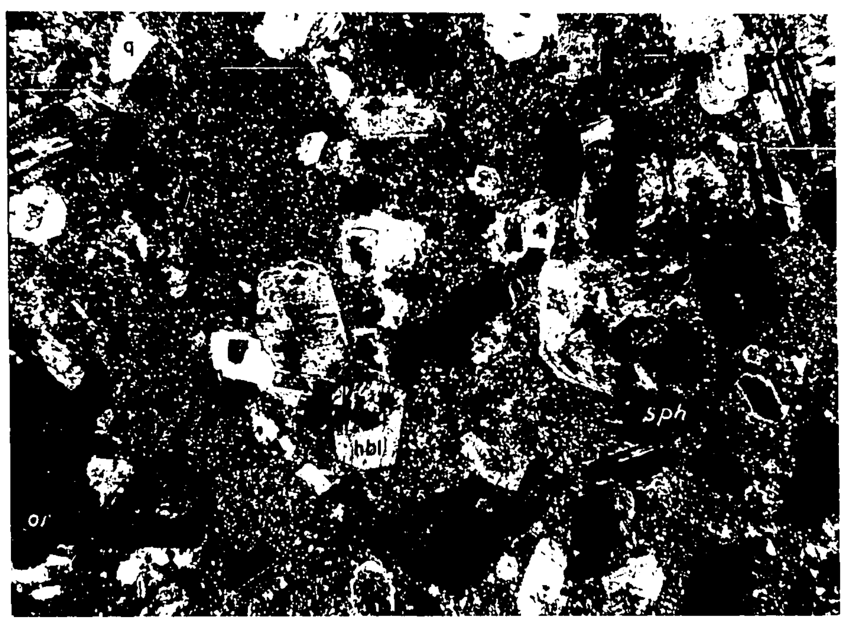



Plate VIII. Porphyritic texture of granite porphyry from satellitic stock. Phenocrysts are mostly plagioclase, but some K-feldspar (or), hornblende (hbl), sphene (sph) and quartz (q) are present. Crossed nicols, X11.

granules. Very rarely the hornblende encloses a core of vestigial clinopyroxene. One or more of the minerals epidote, sphene, magnetite, chlorite and apatite almost invariably accompanies the hornblende, particularly where it occurs in aggregates.

Myrmekite in characteristic fashion forms partial fringes or protuberances on plagioclase where it is in contact with microcline. Locally, within the plane of the section, the myrmekite is seen to be completely surrounded by either plagioclase or microcline. Most typically, the feldspar component of the myrmekite outgrowth consists of one individual only. In some specimens, especially those that have been deformed, the myrmekite occurs as granular aggregates of xenomorphic grains between the larger remnant microcline and plagioclase crystals, and also within the finely crushed intergrowth of quartz and feldspar. The myrmekite does not necessarily form only at the expense of the potash feldspar. Occasionally, small euhedral tablets of polysynthetically twinned plagioclase, poikilitically enclosed in microcline phenocrysts, and also larger plagioclase grains elsewhere in the section are seen to be penetrated by irregular vermiform growths of quartz.

Like hornblende, epidote occurs in a variety of ways. The bulk of it is present in the form of tiny clinozoisite granules in saussurite. Locally these tiny granules have aggregated and recrystallized to form larger irregular grains. Elsewhere, large clear xenomorphic crystals of a colourless to pale yellow pistacitic epidote seem to have crystallized independently of the plagioclase. Still another xenomorphic variant is associated with the clusters of mafic minerals and has presumably resulted from reaction between the granite magma and lime-rich mafic inclusions.

Chlorite is commonly found in the presence of other mafic minerals and only rarely independently. The chlorite is pleochroic from light green or bluish green to pale brown or greenish brown. Several lines of evidence indicate that most if not all of the chlorite is pseudomorphic after biotite:

1) the anomalous blue and dusky purple interference colours of some chlorite grains are faintly streaked with higher order colours where slivers of only partially altered biotite remain;
2) tiny, semi-opaque granules of sphene crowd the cleavage planes and borders of the chlorite grains. These probably represent the titanium contained in the former biotite which was excreted when the biotite altered to non-titaniferous chlorite;
3) zircon grains with pleochroic haloes are enclosed in some chlorite flakes; an association which strongly suggests the zircon was inherited from former biotite;

4) very rarely the chlorite carries sagenitic rutile or small irregular relics of biotite.

Common accessory minerals in the granitic rocks are sphene, apatite, magnetite, ilmenite(?) and zircon. Sphene characteristically forms wedge-shaped euhedrons, but in the marginal zones of the pluton some anhedral grains are present. It also occurs in a fine-grained granular form in chlorite as described above. Apatite rarely occurs anywhere but in or around the edges of the hornblende or mafic aggregates (plate VII).

4.022 Texture

The dominant textural feature of the granitic rocks is the framework of hypidiomorphic plagioclase (plate I) studded with large poikilitic potash feldspar phenocrysts. Although the degree of euhedrism of the plagioclase varies somewhat from the core of the pluton to the margin, this fundamental texture remains essentially unchanged throughout the intrusive.

The mafic mineral content of the granitic rocks is generally too low to have had much influence on the texture. Even in the more melanocratic contaminated border zones the hornblende crystals and mafic aggregates interfered only with the growth of the plagioclase grains in their immediate vicinity. A more pronounced modification which locally affects the marginal zones is the development of protoclastic texture. Not only is the interstitial quartz and potash feldspar extensively crushed and recrystallized, but the plagioclase grains too have a more xenomorphic outline as a result of the crystal edges being rounded by granulation (plate II).

The small satellitic stocks to the south of the pluton are of particular interest in that they provide an insight into the crystallization behaviour of the magma. Rapid chilling has preserved the texture and mineral composition of the granite in the stocks at a stage when it still contained a substantial quantity of liquid. Although mineralogically identical to the granite in the pluton, the granite in the satellitic stocks has a porphyritic texture (plate VIII). The phenocrysts are, in order of abundance: albite, perthitic microcline, hornblende, quartz, opaque minerals and sphene. With the exception of quartz, which is xenomorphic, the other minerals are idiomorphic to subidiomorphic. Staining shows the matrix to be made up largely of very fine-grained quartz, potash feldspar, and minute granules of epidote. Albite is probably present in the matrix but could not be identified on account of its small grain size. Potash feldspar encloses tiny tablets of plagioclase, and rarely idiomorphic hornblende or sphene, in the same manner as in the pluton (plate V). Judging visually, the potash feldspar phenocrysts in the stocks seem to be slightly smaller, on the average, than those in the pluton. Nonetheless, they are larger by far than the remaining phenocrysts which are of about the same size as their counterparts in the pluton.

The mineralogical compositions of two different samples from one of the satellitic stocks are shown in table 2. The first column shows the results obtained by micro point - counting one standard thin section.

The mode of rocks as coarse-grained as the granite porphyry cannot be determined reliably from a single thin section (Chayes, 1956, p.93). In order to get a more precise estimate of the mineralogical composition of the porphyry, the second hand specimen was cut into 7 slabs, each of which was polished and then stained with sodium cobaltinitrite. The stained slabs were point-counted on a large mechanical stage fitted with a binocular microscope (Schrijver, 1968).

The average matrix content of the seven slabs is 45.1 $\pm$ 1.6 percent at the 95 percent confidence level. The good agreement between the point counts of the thin section and the slabs indicates the uniform composition of the stock. It may therefore be assumed with reasonable confidence that the average matrix content of the stock as a whole is also about 45 percent.

TABLE 2. MODAL COMPOSITIONS OF PORPHYRITIC GRANITE FROM SATELLITIC STOCK

| | | 1 | 2 |
|---|---|---|---|
| Sample Number | | A-86 | L-40 |
| PHENOCRYSTS: | Albite........ | 41.2 | 42.6 |
| | K-feldspar.... | 3.3 | 5.3 |
| | Quartz........ | 0.7 | 2.1 |
| | Hornblende.... | 3.8 | ) |
| | Sphene........ | 0.5 | ) |
| | Epidote....... | 1.0 | ) 5.0 |
| | Magnetite..... | 0.1 | ) |
| MATRIX: | Quartz ) Feldspar)..... Epidote ) | 49.4 | 45.1 |
| | TOTAL | 100.0 | 100.1 |

Explanation of table 2.

1. Thin section point count; 960 points counted over 2.2 $cm^2$.

2. Stained slab point count; average of 7 slabs; 5770 points counted over 117.2 $cm^2$.

In order to positively identify the satellitic stocks with the Opemisca Lake pluton, a bulk sample from the stock for which the modes are shown above, was analyzed for $Al_2O_3$, $Na_2O$ and $K_2O$ by rapid chemical methods. To avoid discrepancies attributable to differences in analytical techniques, a control sample from the pluton which had been analyzed previously by classical chemical methods, was included. The results are shown in table 3. It is clear that the satellitic stock has the same peculiarly distinctive features as the pluton, that is, high alumina and soda, and a low potash/soda ratio. The identity of the granite from each of the two rock bodies can hardly be doubted.

TABLE 3. PARTIAL CHEMICAL ANALYSES OF GRANITIC ROCKS

| | 1 | 2 | 3 |
|---|---|---|---|
| | SY-W | NL-14 | NL-14 |
| $Al_2O_3$..... | 16.0 | 16.2 | 16.41 |
| $Na_2O$...... | 5.9 | 5.6 | 6.18 |
| $K_2O$....... | 2.4 | 3.1 | 2.93 |

Explanation of table 3.

1. Bulk sample of satellitic granite porphyry stock. Rapid chemical analysis. Analyst: J. R. Stevenson.
2. Control sample of granite from Opemisca Lake pluton. Rapid chemical analysis. Analyst: J. R. Stevenson.
3. Same as (2) above. Classical chemical analysis. Analyst: Geochemical laboratory, Department of Natural Resources, Quebec.

Whether potash feldspar megacrysts in granitic rocks are porphyroblasts or phenocrysts has been hotly debated by many who have worked in granitic terrains. Tolman (1932, p.101) concluded that the microcline was a normal pyrogenetic mineral because of the perthitic structure (which he accepted as being due to exsolution) and because it was contemporaneous with or earlier than quartz. The writer agrees with Tolman's conclusion, but not with his reasoning. Other characteristics of the potash feldspar offer perhaps better evidence as to its origin. Firstly, the preferred orientation and regular zonal arrangement of poikilitically included plagioclase and other minerals within the microcline suggest that the growing phenocryst exerted sufficient force on small objects in its path to rotate them into a position where they lay with their long axes parallel to the crystal faces of the microcline before it enveloped them. It is difficult to visualize this happening in the solid state. Secondly, in the porphyritic quartz syenite from the satellitic stock, slightly elongated plagioclase crystals lie in a similar parallel arrangement along the crystal faces of the phenocryst (plate V). Again the implication is that this structure could only have originated if the phenocryst grew in a liquid medium. Admittedly, certain metamorphic minerals such as chiastolite, cordierite, staurolite and garnet growing in the solid state are capable of brushing aside finely divided foreign matter (Harker, 1939, p.42), but it seems obvious beyond debate that a mineral growing in the solid state is incapable of picking up, realigning and pushing ahead of it foreign crystals of substantial size that happen to be in its way. Finally, if one accepts the common explanation of porphyritic texture (and this is indisputably verified by porphyritic texture in lava flows), then it is clear from the textural evidence in the satellitic stocks that potash feldspar did crystallize fairly early and had already attained a substantial size at a time when as much as half of the original magma was still in a liquid state.

The poikilitic texture of potash feldspar has been cited by Nockolds (1932, p.446) as evidence of contamination. He considered the smaller crystals enclosed in the potash feldspar to have been liberated in the magma by the mechanical disintegration of xenoliths. This argument is not valid in the present case for the following reasons:

1) The poikilitic inclusions, particularly the plagioclase are of a more or less uniform size and shape throughout the pluton. It is extremely difficult to visualize any process involving incorporation and disintegration of xenoliths whereby the liberated crystals would achieve such a uniform distribution and then become enclosed only in potash feldspar.

2) No rocks in the area, with the exception of some porphyritic rhyolites, contain plagioclase crystals of the same size and shape as those in the potash feldspar phenocrysts. It is obviously impossible for the granite to have assimilated the vast quantities of rhyolite necessary to have released the requisite number of feldspar phenocrysts.

3) In the satellitic stocks and also in the pluton the plagioclase crystals caught up along the outer edges

of the potash feldspar phenocrysts are generally larger than those in the interior (plate V). This clearly suggests concurrent crystallization of the two minerals and an increase in size of the plagioclase between the time the first small crystals were enclosed in the potash feldspar and the time the marginal ones were captured.

Many of the quartz monzonites and granodiorites of the Sierra Nevada batholith are characterized by large potash feldspar phenocrysts similar to those of the Opemisca Lake pluton (Bateman et al, 1963). To account for the uncommonly large size of these phenocrysts, Bateman and his co-workers have suggested that they might have formed in a manner proposed by Jahns and Burnham (1962). Jahns and Burnham attributed the discrepancy in size between coarse pegmatite and much finer-grained aggregate to concomitant crystallization from a silicate melt and a coexisting aqueous gas. Bateman and his co-workers reasoned that prolonged crystallization in a magma would eventually leave it over-saturated with water and this should result in the separation of an aqueous gas phase from the mixture of crystals and silicate melt. When this takes place large potash feldspar phenocrysts presumably could crystallize simultaneously with the finer-grained granitoid matrix.

Whether it is necessary to invoke the presence of a gas phase to explain the large size of the potash feldspar is debatable. Textural evidence from two different domains, the main intrusive mass and the satellitic stocks, suggest the following sequence of events in the genesis of potash feldspar phenocrysts:

1) Potash feldspar started to crystallize fairly early. Judging by the small size of the plagioclase crystals caught up and enclosed poikilitically by the growing microcline phenocryst, the latter may have started to crystallize not long after the plagioclase had commenced doing so.

2) Plagioclase crystallized around a great many nuclei whereas potash feldspar grew from only a few isolated centres. The smaller number of potash feldspar crystals may be one reason why they are so much larger than the plagioclase crystals, but why they should have crystallized in so few places is not known.

3) By the time approximately half the magma had crystallized (indicated by the proportions of phenocrysts and matrix in the stocks), the bulk of the plagioclase had already been formed, whereas only a small fraction of the potash feldspar and quartz had solidified. Moreover, the plagioclase crystals were almost the same in size and shape as if crystallization had proceeded to completion under plutonic conditions. On the other hand, quartz and potash feldspar still had to increase considerably in size even though the potash feldspar

was already much larger than the plagioclase. At this stage the various crystals were still dispersed in the liquid and, with the exception of quartz, tended to have fairly good crystal outlines.

4) In the late stages of the long and slow crystallization process taking place in the pluton, but not in the smaller stocks, the unhindered expansion of the large microcline phenocrysts was impeded by the surrounding crystalline aggregate. As a result the outer portions of the microcline crystallized in the interstices of the plagioclase framework, thus giving rise to the characteristic highly irregular borders of the microcline phenocrysts.

### 4.03 Hybrid Xenolithic Rocks and Mafic Xenocrysts

Several large but poorly exposed xenoliths of hybridized basic rocks are strung out along the southern margin of the Opemisca Lake pluton. Owing to the scarcity of outcrop, the sizes and shapes of these bodies could not be defined. The larger ones are several thousand feet across whereas the smaller ones may be no more than a few tens of feet in diameter. A peculiar feature of the pluton is the noticeable lack of inclusions intermediate in size between these large hybrid xenoliths and the small xenocrystic mafic aggregates which range in size from less than 1 mm to several centimeters.

Very rarely an inclusion is found which is 6 or 8 inches in diameter, but of the many hundreds of outcrops examined within the pluton proper, not one contained inclusions in the size range from about one foot to several feet in diameter. However, the small syenitic apophyses cutting the amphibolitic pyroxenites near the southwest end of Knife lake (fig.36) do carry angular slabs of wallrock measuring as much as two feet in length. These slabs were pried loose from the walls immediately adjacent.

For the sake of convenience in the ensuing discussion the large inclusions which generally form mappable units will be referred to as xenoliths, whereas the small mafic aggregates will be termed xenocrysts.

Compared to the surrounding granitic rocks the characteristic features of the xenoliths are their extreme inhomogeneity and their abundance of dark minerals - mostly amphibole, chlorite and biotite and, more rarely, pyroxene. In the more extreme cases a rock may vary within a few feet from porphyritic (porphyroblastic ?) to non-porphyritic, or from medium-grained to coarse-grained, or the colour index may decrease from as high as 60 to less than 20. Generally the xenoliths have an isotropic fabric, but others are distinctly lineated. Quartz is rare or absent in all of them. Tiny granitic or syenitic dykes, usually not more than a few inches in width commonly penetrate the xenoliths.

Nearly all xenoliths seen in the map area appear to have been gabbroic rocks originally. Some may have been included in a relatively fresh or unaltered state, whereas others evidently had been subjected to regional metamorphism prior to being incorporated in the pluton. The granite seems to have had little effect on most of the large xenoliths but some reacted more extensively with the magma and were converted to rocks of dioritic composition.

To illustrate the variability in the degree of alteration of the inclusions, five typical examples will be discussed.

A slab of metapyroxenite included in a syenitic dyke in the area southwest of Knife lake (fig.36) is composed of clinopyroxene, pale green amphibole and magnetite and is in no way different from the normal metapyroxenites of the area. Inclusion in the syenite has obviously had no noticeable effect upon it.

A sample from the xenolith straddling range line IV in the southeastern part of northwest Levy (fig.36) is medium- to coarse-grained, has a pronounced lineation and consists of dark-green amphibole and white earthy feldspar. The colour index is greatly variable. The more leucocratic varieties resemble the melasyenites. Under the microscope the rock is seen to be made up of a typical greenschist facies assemblage: pale-green uralitic amphibole (actinolite), epidote, albite and muscovite. Epidote and muscovite are both more abundant than in the regional greenstones. A few tiny veinlets of epidote cut the section and suggest that at least part of the epidote has been introduced from elsewhere. Nockolds (1932, p.439) postulated that aqueous solutions derived from the magma might be responsible for the epidotization of xenoliths. These solutions were presumably released just after final consolidation of the granite. Whether the primary source of the lime required for the formation of epidote was the granite itself or whether lime was merely redistributed from one part of the xenolith to another is not specified. Not uncommonly, outcrops of some of the greenstones in the region are characterized by an abundance of small pods and blind veinlets of epidote. The general impression given by these outcrops is that the epidote originated in place during metamorphism, as tiny granules of saussurite in the plagioclase, and that these granules eventually recrystallized and segregated into larger masses. It would seem then that redistribution of epidote within the basic xenoliths is the most likely process. Muscovite makes up about 10 to 15 percent of the inclusion and is coarser grained and more abundant than in the typical greenstones. Like the epidote it may represent material originally present in the xenolith but it may also have formed in response to the introduction of potash gained from the granite during reciprocal reaction. If this is so, then the muscovite probably formed at temperatures and pressures below the lower limit of stability of biotite, which is the characteristic mineral formed elsewhere as a result of reaction between the minerals in the xenolith and introduced potash.

A slightly more advanced stage of reaction between granite and inclusion is exemplified by a sample from the large xenolith straddling the boundary line between northwest Levy and northeast Daubrée townships (figs. 17, 36). These rocks consist essentially of heavily saussuritized plagioclase and pale-green uralitic amphibole. The relative proportion of the two minerals varies considerably. Biotite, almost wholly converted to chlorite, is usually very closely associated with amphibole and leaves little doubt that it was derived from that mineral. The potash necessary to form the biotite was evidently introduced from the magma. Patches of perthitic potash feldspar occur locally in the interstices of the plagioclase and amphibole. The amphibole and particularly the plagioclase are usually replaced by the perthite and, in places, a little myrmekite has developed around the plagioclase. Nockolds (1932, p.445) does not think that potash feldspar normally replaces the minerals in a xenolith. Instead, he visualizes a process whereby the potash feldspar starts to crystallize along cracks, grain boundaries and other openings in and among the xenolithic minerals. It is the force exerted by these growing crystals which pries apart and ultimately disintegrates the xenoliths. However, where there was little time for reciprocal reaction and where the mineral assemblage of the inclusion was markedly out of equilibrium with that of the granite, as in the present case, potash feldspar might replace the xenolithic minerals (Nockolds, 1935, p.297).

About 1,000 feet west of Knife lake (fig.36) three small outcrops jutting out from underneath a thick blanket of sand mark the site of the most extensively hybridized xenolith seen within the Opemisca Lake pluton. In hand specimen, the rock is characterized by porphyroblastic plates of biotite, as much as 10 mm in diameter, set in a grey medium-grained granular matrix. The essential minerals in order of abundance are plagioclase, clinopyroxene, biotite and orthopyroxene. Accessory minerals include magnetite, potash feldspar, amphibole, talc, sericite and apatite.

The plagioclase is hypidiomorphic to xenomorphic. Most grains are lath-shaped and are generally well twinned on the albite law. Zoning is common and the composition ranges from cores as calcic as $An_{52}$ to rims as sodic as $An_{30}$. In the majority of zoned grains the spread in composition does not range far on either side of $An_{40}$. The plagioclase is generally clear and only a few grains contain dense patches of fine sericite. Tiny, highly irregular vermicular granules and blind veinlets of plagioclase locally occur within clinopyroxene. It is possible that this plagioclase originated as a result of the alteration of pyroxene to biotite - a reaction entailing the loss of lime and silica which may be ejected in the form of plagioclase. Significantly, plagioclase and biotite are common associates within altered pyroxene.

The pyroxenes are generally xenomorphic, but a few grains show very good crystal outlines. They vary considerably in size from a fraction of a millimetre to as much as 5 mm. Some aggregates are even larger. The clinopyroxene is very pale brown in colour and has a barely discernible pleochroism. The orthopyroxene is distinctly pleochroic from pinkish to neutral. Many of the pyroxenes have been altered to a fine scaly mass of talc laced with dendritic or mosslike aggregates of magnetite.

Two types of biotite are present: a reddish-brown to dark-brown variety occurring as clearly defined anhedral plates and commonly forming at the expense of pyroxene and, a pale-green to green bladed variety usually based on the talcose aggregates and penetrating the surrounding minerals. In several places the two varieties of biotite are completely gradational. The paler variety tends to acquire a darker colour and stronger pleochroism where it is in contact with opaque iron oxide. Xenomorphic microperthite is usually interstitial to the other minerals. It replaces plagioclase very extensively where the two minerals are in contact but very rarely replaces pyroxene.

Amphibole is rare. Small irregular grains locally replace pyroxene. The amphibole in turn may be replaced by biotite.

Because of the extremely poor exposure of the xenolith little can be learned in the field about its relationship to the surrounding granite. Interpretation of the origin and development of the mineral assemblage is limited largely to thin section study and must therefore remain conjectural.

The texture of the two dominant minerals, plagioclase and clinopyroxene, is clearly igneous. The original rock may have been either gabbroic or dioritic. The present composition of the plagioclase is centred at about $An_{40}$ and is too sodic for a typical gabbro. Anorthite content of plagioclase, however, is of doubtful diagnostic value in hybrid rocks inasmuch as introduction of material from the enclosing granite may have brought about a considerable shift towards a more sodic plagioclase (Nockolds, 1935; Deer, 1938). The high combined total of Mg, Fe and Ca oxides and the rather low $SiO_2$ content (2, table 6) also are commensurate with an original gabbroic rather than a dioritic composition. Although $K_2O$ and $Na_2O$ are higher than in normal gabbros, the excess most likely was acquired from the granite.

Transfusion of K from the granite into the xenolith, particularly a basic xenolith, would result in the fixation of the K by the Fe and Mg silicates (Goldschmidt, 1922) and minerals such as pyroxene and amphibole would be converted to biotite. The deep reddish-brown colour of the biotite (Hall, 1941) replacing the pyroxene and the absence of sphene and other titanium-bearing minerals suggest that the Ti in the pyroxene has entered the biotite lattice.

At some stage during the reconstitution of the xenolith, pyroxene was partially converted to aggregates of talc and magnetite (probably a titaniferous variety). Subsequently, instead of the reddish-brown biotite, blades of pale-green biotite started to form at the expense of the talc from where they grew out into the surrounding mineral aggregate. The pale-green colour of the bladed biotite suggests not only a lack of iron and titanium (Hall, 1941) but also a lower temperature of formation than the reddish-brown biotite (Tilley, 1926; Turner, 1938; Taubeneck, 1964). A significant feature of the biotite in this xenolith is that it successfully withstood conversion to chlorite, unlike the biotite elsewhere in the pluton.

The most advanced stage in the alteration of inclusions caught up in the granite is shown by the many small xenocrysts in the marginal zones of the pluton. Hornblende is the dominant constituent in all of these tiny aggregates. It is almost invariably accompanied by one or more of the minerals epidote, sphene, opaque iron oxide and apatite. Locally the hornblende is partly altered to brown biotite which in turn is almost wholly or entirely converted to pale-green chlorite and granular sphene. Nockolds (1931) has shown clearly how similar clots of minerals in the Dhoon granite represent the remains of inclusions of metamorphosed basic rocks which have been absorbed by the granitic magma.

The most obvious sources for the inclusions are the abundant greenstone lavas and gabbros and the layered ultramafic rocks surrounding the Opemisca Lake pluton.

Minerals such as albite, muscovite and quartz, which are at the low end of the reaction series tend to go into solution if they are immersed in a magma which is not yet saturated with respect to these phases (Bowen, 1928, p.221). Now quartz, muscovite and albite, particularly the latter, are common constituents of the greenstones. It follows, therefore that if fragments of greenstone were to be caught up in a granitic magma, especially one in the initial stages of crystallization and still precipitating phases higher in the reaction series, then these three minerals could be dissolved by the magma. The removal by solution of such a major constituent as albite from greenstone inclusions could be a cogent factor in the disintegration of these xenoliths (Nockolds, 1933, p.584).

The mafic remnants consisting of actinolite, epidote, chlorite, sphene and iron-titanium oxides are released and strewn through the adjacent contaminated magma. If, under the prevailing conditions, they are not in chemical equilibrium with the magma, they would react with it to form new minerals which are in equilibrium with the contaminated magma (Nockolds, 1933, p.571).

Very rarely some of the xenocrystic hornblende in the granite is seen to have cores of relict pyroxene. It is possible that these may represent inclusions derived from the ultrabasic rocks which are in contact with the Opemisca Lake pluton along part of its border. These inclusions, being composed for the greater part of pyroxene and amphibole, would not be subject to solution as were the greenstone fragments but would react with the magma in essentially the same way as the mafic remnants of the greenstone. Whatever the origin of these small basic clots in the Opemisca Lake pluton, it seems that the granite managed to a greater or lesser extent to convert these inclusions to stable assemblages of hornblende with or without sphene and opaque minerals.

As temperature and pressure decreased, biotite became the stable ferromagnesian mineral. The presence of zircon in some biotite grains, particularly in the interior of the pluton, suggests that part of the biotite may have crystallized directly from the magma (Nockolds, 1935, p.300), but in most places it formed at the expense of hornblende. Either the granite cooled quickly through the stability range of biotite, or else the reaction was extremely sluggish, because only a small proportion of the hornblende was replaced. In contrast, the little biotite that had formed, whether in the inclusions or in the magma, was subsequently converted almost entirely to pale green chlorite as a further decrease in temperature and pressure took place.

The abundant apatite concentrated around the small xenocrystic aggregates is in accord with Nockolds' inference (1931, p.506; 1933, p.563) that volatile material played an essential part in the transfer of material to and fro between the granite and the inclusion.

The small size of the xenoblastic hornblende grains in the mafic aggregates may have been inherited from the parent rock. It may also be the result of reaction between inclusion and magma, a process which, under certain circumstances, leads to a reduction in the grain size of the inclusion (Joplin, 1935; Poldervaart, 1953).

With the general exception of the small xenocrystic aggregates, the inclusions in the Opemisca Lake pluton are characterized by an almost complete lack of equilibrium between the phases present in the inclusion and those in the granite. It would seem that only in the smaller xenocrysts did reaction proceed to a state of equilibrium or near-equilibrium. In the larger xenoliths, the very size of the inclusions may have prevented the reaction between xenolith and magma from going to completion. Likewise, the xenoliths may have been included in the magma at such a late stage in its cooling cycle that reaction rates were altogether too sluggish to bring about any appreciable change in the mineral composition of the xenoliths.

## 4.04 Contact Metamorphic and Metasomatic Rocks

A notable feature of the Opemisca Lake pluton is the absence of any collar of contact metamorphosed rocks around it. Contacts with the wallrock are sharp and nowhere could any evidence be found of mineralogical reconstitution of the wallrock to a higher grade of metamorphism than the prevailing regional greenschist facies.

The implication is that by the time the granite arrived at its presently exposed level it was probably in a fairly advanced state of crystallization and therefore relatively cool and free of volatile constituents. As such it did not have the necessary reserve of heat and volatiles to recrystallize the wallrock.

The only exposure in which the metasomatic action of the granite on the wallrocks is clearly shown is on the property of Canamiska Copper Mines Limited in northwest Levy township. Here, an outcrop of metapyroxenite, not more than 60 feet from the contact of the pluton is cut by veins and dykelets of granitic rock. The medium-grained pyroxenite alongside the veinlets has been impregnated with quartzo-feldspathic material and converted to a slightly reddened fine-grained granoblastic dioritic (?) rock.

# CHAPTER V

# CHEMICAL AND MINERALOGICAL TRENDS

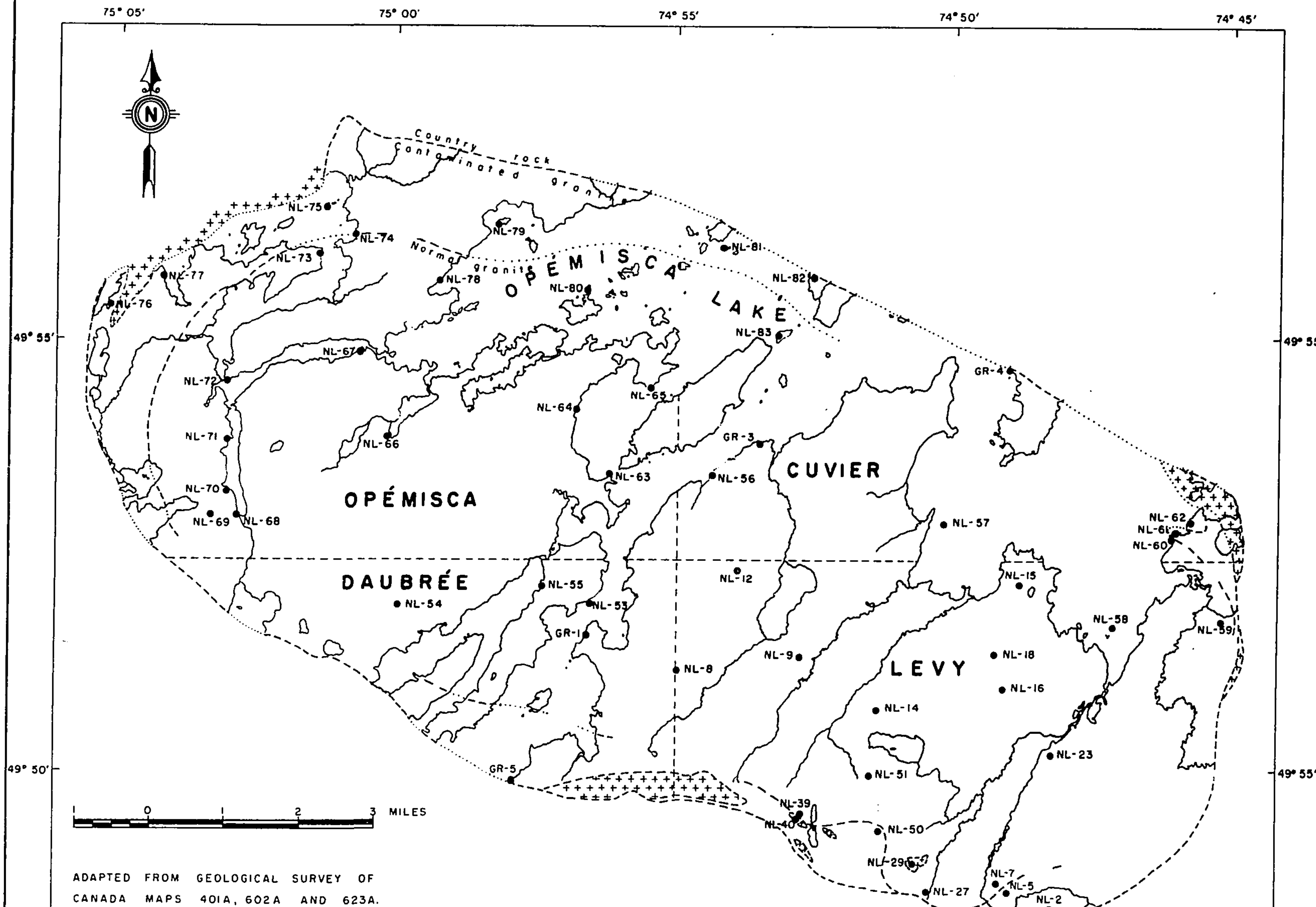
## 5.01 General Statement

A geochemical survey of the Opemisca Lake pluton was undertaken to investigate the variation in the composition of the granitic rocks, and the manner of distribution, within the pluton, of a selected group of elements.

Fifty-two samples were collected and analysed for the following elements or oxides: Ag, B, Ba, Be, Bi, Ca, Co, Cu, $CO_2$, Fe, $H_2O$, $K_2O$, $Li_2O$, Mo, Mn, $Na_2O$, Ni, $P_2O_5$, Pb, S, Sn, Sr, Ti, V, W, and Zn. The results are summarized in tables 4, 5 and 6. The elements Ag, B, Be, Bi and Sn were not detected in any of the samples and have been omitted from the tables. Sample localities are shown in figure 4.

Complete chemical analyses were carried out on 17 of the samples, the results of which are shown in table 4. With the exception of sample NL-76 (16, table 4), the analyses listed reflect the range in composition from the silica-rich granite in the interior of the pluton to the contaminated syenite and melasyenite along or near the margin of the intrusive.

Sample NL-76 from the western extremity of the pluton was later found to be penetrated by numerous fine




ADAPTED FROM GEOLOGICAL SURVEY OF CANADA MAPS 401A, 602A AND 623A.

Figure 4. Location of chemically analyzed samples in the Opemisca Lake pluton.

75° 05' 75° 00' 74° 55' 74° 50' 74° 45'

TABLE 4. COMPLETE CHEMICAL ANALYSES OF GRANITIC ROCKS FROM THE OPEMISCA PLUTON

| Analysis Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample number | NL-82 | NL-77 | NL-5 | GR-5 | NL-79 | NL-62 | NL-39 | NL-59 | GR-1 | NL-72 | NL-14 | NL-68 | GR-3 | NL-66 | NL-57 | NL-76 | NL-63 | NL-7 | | |
| $SiO_2$ | 59.90 | 59.98 | 64.69 | 62.75 | 63.48 | 66.05 | 65.30 | 66.84 | 68.20 | 67.70 | 67.86 | 67.94 | 69.40 | 68.61 | 68.40 | 68.87 | 70.31 | 76.01 | 66.53 | 69.25 |
| $TiO_2$ | 0.52 | 0.53 | 0.62 | 0.58 | 0.50 | 0.33 | 0.20 | 0.28 | 0.22 | 0.20 | 0.18 | 0.10 | 0.12 | 0.18 | 0.12 | 0.22 | 0.12 | 0.04 | 0.29 | 0.20 |
| $Al_2O_3$ | 16.16 | 16.80 | 17.10 | 16.46 | 17.38 | 16.94 | 17.56 | 16.80 | 16.30 | 16.37 | 16.41 | 16.34 | 15.74 | 16.23 | 15.87 | 15.90 | 15.75 | 13.73 | 17.02 | 16.42 |
| $Fe_2O_3$ | 1.92 | 1.98 | 1.93 | 1.77 | 1.80 | 1.38 | 1.47 | 1.28 | 1.30 | 1.27 | 1.14 | 1.30 | 1.08 | 1.22 | 1.25 | 1.25 | 1.13 | 0.43 | 1.17 | 0.95 |
| FeO | 2.34 | 2.22 | 1.12 | 2.30 | 1.22 | 1.00 | 0.85 | 0.86 | 0.58 | 0.53 | 0.67 | 0.49 | 0.56 | 0.50 | 0.57 | 0.53 | 0.36 | 0.18 | 1.20 | 0.75 |
| MnO | 0.06 | 0.06 | 0.05 | 0.07 | 0.07 | 0.04 | 0.03 | 0.04 | 0.01 | 0.04 | 0.03 | 0.04 | 0.02 | 0.03 | 0.02 | 0.05 | 0.03 | 0.01 | ---- | ---- |
| MgO | 3.71 | 3.22 | 1.23 | 2.80 | 1.09 | 1.33 | 0.98 | 1.12 | 0.96 | 1.08 | 1.00 | 1.04 | 0.79 | 0.97 | 0.91 | 0.56 | 0.49 | 0.15 | 1.33 | 0.94 |
| CaO | 4.46 | 4.36 | 3.53 | 2.74 | 3.17 | 2.56 | 2.66 | 2.27 | 2.45 | 2.13 | 2.09 | 1.84 | 1.93 | 1.86 | 1.76 | 2.14 | 1.16 | 0.64 | 2.70 | 1.92 |
| $Na_2O$ | 5.45 | 5.72 | 5.84 | 5.96 | 5.74 | 6.63 | 6.57 | 6.66 | 5.99 | 6.03 | 6.18 | 6.05 | 6.01 | 6.00 | 6.28 | 5.61 | 6.16 | 3.65 | 6.08 | 6.05 |
| $K_2O$ | 3.34 | 2.89 | 2.52 | 3.44 | 3.18 | 2.78 | 2.96 | 2.80 | 2.84 | 3.02 | 2.93 | 3.04 | 2.94 | 3.22 | 3.07 | 3.14 | 3.40 | 5.08 | 3.07 | 2.73 |
| $H_2O+$ | 0.89 | 0.77 | 0.65 | 0.97 | 0.68 | 0.50 | 0.33 | 0.45 | 0.40 | 0.44 | 0.57 | 0.53 | 0.46 | 0.47 | 0.54 | 0.32 | 0.53 | 0.03 | 0.39 | 0.41 |
| $H_2O-$ | 0.02 | 0.01 | 0.03 | 0.03 | 0.01 | 0.02 | 0.05 | 0.01 | 0.02 | 0.02 | 0.01 | 0.04 | 0.01 | 0.01 | 0.01 | 0.03 | 0.02 | 0.01 | 0.04 | 0.04 |
| $CO_2$ | 0.03 | 0.02 | 0.03 | 0.03 | 0.02 | 0.02 | 0.03 | 0.03 | 0.01 | 0.00 | 0.04 | 0.00 | 0.01 | 0.00 | 0.05 | 0.00 | 0.02 | 0.03 | | 0.06 |
| F | 0.14 | 0.13 | 0.14 | 0.11 | 0.12 | 0.11 | 0.11 | 0.12 | 0.11 | 0.12 | 0.11 | 0.10 | 0.09 | 0.11 | 0.11 | 0.10 | 0.08 | ---- | ---- | ---- |
| Cl | 0.04 | 0.04 | 0.03 | 0.12 | 0.07 | 0.03 | 0.03 | 0.01 | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 | ---- | ---- | ---- |
| TOTAL...% | 98.98 | 97.76 | 99.51 | 100.13 | 98.53 | 99.72 | 99.13 | 99.57 | 99.41 | 98.97 | 99.24 | 98.86 | 99.18 | 99.43 | 98.98 | 98.73 | 99.58 | 99.99 | 99.82 | 99.72 |
| MINOR ELEMENTS *(PPM)* | | | | | | | | | | | | | | | | | | | | |
| Ba | 1255 | 1400 | 1015 | 990 | 1025 | 1150 | 1565 | 1155 | 1060 | 1225 | 1235 | 1145 | 1025 | 1160 | 1285 | 875 | 1090 | 280 | ---- | ---- |
| Co | 2.5 | 5 | 3.8 | 2.5 | 7.5 | 3.8 | 3.1 | 3.8 | 3.8 | 5 | 3.8 | 3.1 | 3.1 | 3.8 | ---- | 5 | 2.5 | 2.5 | ---- | ---- |
| Cu[1] | 5.0 | 5.5 | 2.5 | 33 | 15 | tr[2] | 2.5 | tr | 2.5 | 12.5 | 2.5 | tr | tr | 3 | 5 | tr | tr | tr | ---- | ---- |
| Mo | 16 | 2.5 | 2 | 2 | 3 | 3 | 1 | 3 | nd | nd | 1 | 4 | 2 | 4 | nd | 6 | 3 | nd | ---- | ---- |
| Mn | 510 | 465 | 385 | 520 | 535 | 285 | 235 | 280 | 110 | 345 | 205 | 325 | 170 | 250 | 175 | 375 | 235 | 120 | ---- | ---- |
| Ni | 21.3 | 22.5 | 11.3 | 37.5 | 10 | 8.8 | 10 | 12.5 | 12.5 | 10 | 12.5 | 15 | 10 | 11.3 | 15 | 7.5 | 15 | 7.5 | ---- | ---- |
| Pb | 5 | 5 | 12.5 | 15 | 17.5 | 5 | 17.5 | 10.0 | 15 | 12.5 | 12.5 | 5 | 15 | 5 | 5 | 15 | 50 | 15 | ---- | ---- |
| Sr | 1250 | 1800 | 1115 | 680 | 1350 | 1350 | 1700 | 1030 | 1030 | 1115 | 940 | 850 | 1050 | 940 | 700 | 930 | 600 | 285 | ---- | ---- |
| V | 89 | 89 | 70 | 95 | 62 | 50 | 35 | 45 | 38 | 45 | 42 | 33 | 44 | 33 | 36 | 44 | 38 | nd | ---- | ---- |
| W | 4 | nd[3] | nd | 4 | 4 | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | ---- | ---- |
| Zn[1] | 12 | 16 | 15 | 24 | 39 | 7 | 9 | 8 | 8 | 8 | 6 | 11 | 4 | 8 | 13 | 13 | 14 | 8 | ---- | ---- |
| NORMS | | | | | | | | | | | | | | | | | | | | |
| Quartz | 2.16 | 2.88 | 12.66 | 5.46 | 10.32 | 10.50 | 9.18 | 11.76 | 16.44 | 15.42 | 15.12 | 15.78 | 18.54 | 16.38 | 15.30 | 19.50 | 18.54 | 33.42 | 12.06 | 17.88 |
| Orthoclase | 19.46 | 17.24 | 15.01 | 20.02 | 18.90 | 16.68 | 17.79 | 16.68 | 16.68 | 17.79 | 17.24 | 17.79 | 17.24 | 18.90 | 18.35 | 18.35 | 20.02 | 30.02 | 18.35 | 16.12 |
| Albite | 46.11 | 48.21 | 49.25 | 50.30 | 48.21 | 55.54 | 55.54 | 56.07 | 50.83 | 50.83 | 52.40 | 51.35 | 50.83 | 50.83 | 53.45 | 47.16 | 51.87 | 31.44 | 51.35 | 51.35 |
| Anorthite | 10.01 | 11.68 | 13.07 | 8.34 | 12.51 | 8.34 | 9.73 | 7.78 | 9.17 | 8.90 | 8.34 | 8.34 | 7.23 | 7.78 | 5.84 | 9.17 | 5.56 | 3.06 | 10.01 | 9.45 |
| Diopside | 9.69 | 7.94 | 3.46 | 4.20 | 2.62 | 3.49 | 2.59 | 2.59 | 2.38 | 1.30 | 1.73 | 0.65 | 1.73 | 1.08 | 2.16 | 1.08 | 0.22 | ---- | 2.65 | 1.33 |
| Hypersthene | 6.69 | 6.06 | 1.50 | 6.85 | 1.60 | 1.80 | 1.30 | 1.60 | 1.30 | 2.10 | 1.70 | 2.30 | 1.20 | 1.90 | 1.30 | 0.90 | 1.10 | 0.40 | 2.70 | 1.33 |
| Magnetite | 2.78 | 3.02 | 1.86 | 2.55 | 2.55 | 2.09 | 2.09 | 1.86 | 1.16 | 1.16 | 1.62 | 1.39 | 1.62 | 0.93 | 1.62 | 1.16 | 0.93 | 0.70 | 1.86 | 1.39 |
| Ilmenite | 0.91 | 0.91 | 1.22 | 1.22 | 0.91 | 0.61 | 0.46 | 0.61 | 0.46 | 0.46 | 0.46 | 0.15 | 0.15 | 0.46 | 0.15 | 0.46 | 0.15 | ---- | 0.61 | 0.46 |
| Hematite | ----- | ---- | 0.64 | ---- | ---- | ---- | ---- | ---- | 0.48 | 0.48 | ---- | 0.32 | ---- | 0.64 | 0.16 | 0.48 | 0.48 | ---- | ---- | ---- |
| Corundum | ----- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 0.92 | ---- | ---- |
| Normative plagioclase | $An_{18}$ | $An_{20}$ | $An_{21}$ | $An_{14}$ | $An_{21}$ | $An_{13}$ | $An_{15}$ | $An_{12}$ | $An_{15}$ | $An_{15}$ | $An_{14}$ | $An_{14}$ | $An_{12}$ | $An_{13}$ | $An_{10}$ | $An_{16}$ | $An_{10}$ | $An_9$ | $An_{16}$ | $An_{16}$ |
| DIFFERENTIATION INDICES $(\frac{1}{3}Si+K) - (Ca+Mg)$ | | | | | | | | | | | | | | | | | | | | |
| | 6.82 | 6.85 | 9.04 | 9.09 | 9.84 | 10.07 | 10.28 | 10.56 | 10.77 | 11.06 | 11.07 | 11.37 | 11.56 | 11.60 | 11.60 | 11.67 | 12.79 | 15.52 | 10.25 | 11.20 |

[1]Average of duplicate analyses by the Department of Natural Resources, Quebec and by the writer.
[2]Tr denotes detectable quantities of copper but too low for quantitative measurement (less than 2.5 ppm).
[3]nd Indicates element sought but not detected.

1 to 5. Contaminated granites.
6 to 17. Normal (uncontaminated) granites.
18. Aplite.
19 to 20. Normal granites (after TOLMAN, 1932b).

Analyses 1 to 18 by the Department of Natural Resources, Quebec, except for Co, Cu, Mo, Ni, Pb, W and Zn which were determined by the writer.

stringers of secondary quartz, and its composition should be considered spurious. Apart from the introduction of quartz, the rock does not appear to have been altered in any other way. Even if allowance is made for the amount of introduced

TABLE 5. PARTIAL CHEMICAL ANALYSES OF GRANITIC ROCKS FROM THE OPEMISCA LAKE PLUTON

| Analysis Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample Number | NL-2 | NL-50 | NL-61 | NL-74 | NL-75 | NL-81 | GR-4 | NL-8 | NL-9 | NL-12 | NL-15 | NL-16 | NL-18 | NL-23 | NL-27 | NL-51 |
| MAJOR ELEMENTS (WEIGHT PERCENT) | | | | | | | | | | | | | | | | |
| $Na_2O$ | 6.03 | 5.73 | 6.46 | 6.14 | 5.81 | 5.59 | ---- | 5.90 | 5.84 | 5.65 | 6.15 | 6.39 | 6.08 | 6.27 | 5.83 | 6.60 |
| $K_2O$ | 3.20 | 3.77 | 3.26 | 3.18 | 3.42 | 3.56 | ---- | 2.78 | 2.83 | 3.26 | 2.86 | 2.86 | 3.06 | 2.83 | 3.34 | 2.70 |
| $Li_2O$ | 0.006 | 0.00 | 0.00 | 0.002 | 0.004 | 0.00 | ---- | 0.003 | 0.003 | 0.00 | 0.003 | 0.004 | 0.002 | 0.001 | 0.001 | 0.003 |
| Ca | 3.4 | 2.1 | 2.5 | 2.1 | 2.1 | 2.6 | ---- | 1.9 | 1.6 | 1.3 | 1.8 | 1.6 | 1.5 | 1.8 | 1.5 | 2.1 |
| Fe | 3.7 | 1.9 | 2.1 | 1.8 | 2.3 | 1.7 | ---- | 1.3 | 0.99 | 0.89 | 1.0 | 1.0 | 1.0 | 1.4 | 1.2 | 1.5 |
| Ti | 0.33 | 0.20 | 0.205 | 0.16 | 0.28 | 0.17 | ---- | 0.07 | 0.075 | 0.07 | 0.06 | 0.09 | 0.08 | 0.17 | 0.15 | 0.14 |
| $P_2O_5$ | 0.14 | 0.08 | 0.12 | 0.11 | ---- | 0.07 | ---- | ---- | ---- | 0.015 | 0.04 | 0.025 | 0.04 | 0.04 | 0.03 | 0.08 |
| S | 0.055 | 0.034 | 0.037 | 0.035 | ---- | 0.035 | ---- | ---- | ---- | 0.023 | 0.023 | 0.027 | 0.023 | 0.029 | 0.024 | 0.027 |
| $H_2O+$ | 1.50 | 0.58 | 0.53 | 0.43 | ---- | 0.56 | ---- | ---- | ---- | 0.51 | 0.30 | 0.40 | 0.50 | 0.45 | 0.52 | 0.30 |
| MINOR ELEMENTS (PARTS PER MILLION) | | | | | | | | | | | | | | | | |
| Ba | 750 | 1460 | 1205 | 1225 | 970 | 1150 | ---- | 1330 | 1210 | 1080 | 1335 | 1235 | 1175 | 1190 | 990 | 1190 |
| Co | 11.3 | 3.1 | 5 | 5 | 3.8 | 5 | 3.1 | 4.4 | 5 | 2.5 | 2.5 | 5 | 3.1 | 1.3 | 3.8 | 3.1 |
| Cu[1] | 63 | 5.5 | 2.5 | 7.5 | tr[2] | 2.5 | 8 | tr | 4 | 4 | 2.5 | 3.5 | 10 | tr | 2.5 | 3 |
| Mo | 2 | 2 | 2 | 2 | 3 | 2 | 4 | 3 | 4 | 3 | 4 | 4 | 1 | 2 | 2 | 2 |
| Mn | 655 | 600 | 420 | 450 | 715 | 510 | ---- | 397 | 200 | 225 | 170 | 280 | 300 | 350 | 420 | 410 |
| Ni | 25 | 16.3 | 12.5 | 11.3 | 22.5 | 10 | 8.8 | 10 | 10 | 12.5 | 10 | 10 | 10 | 15 | 8.8 | 11.3 |
| Pb | 30 | 5 | 17.5 | nd | 7.5 | 12.5 | 5 | nd | 5 | 5 | 15 | 5 | 15 | nd | 12.5 | 20 |
| Sr | 900 | 1160 | 1000 | 1280 | 1000 | 900 | ---- | 1030 | 3300 | 740 | 940 | 790 | 840 | 850 | 830 | 1350 |
| V | 82 | 47 | 46 | 44 | 61 | 57 | ---- | 24 | 41 | 41 | 41 | 43 | 41 | 42 | 43 | 47 |
| W | nd[3] | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd |
| Zn[1] | 35 | 6 | 7 | 11 | 15 | 8 | 10 | 8 | 15 | 12 | 13 | 14 | 12 | 9 | 15 | 6 |

| Analysis Number | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample Number | NL-53 | NL-54 | NL-55 | NL-56 | NL-58 | NL-60 | NL-64 | NL-65 | NL-67 | NL-69 | NL-70 | NL-71 | NL-73 | NL-78 | NL-80 | NL-83 |
| MAJOR ELEMENTS (WEIGHT PERCENT) | | | | | | | | | | | | | | | | |
| $Na_2O$ | 5.98 | 6.25 | 6.14 | 6.14 | 7.00 | 6.94 | 6.22 | 5.87 | 6.34 | 6.01 | 6.14 | 6.22 | 6.12 | 6.11 | 5.93 | 6.85 |
| $K_2O$ | 2.87 | 2.82 | 2.86 | 3.13 | 2.75 | 2.59 | 2.92 | 3.27 | 2.80 | 3.00 | 2.84 | 3.00 | 3.34 | 2.91 | 2.69 | 2.26 |
| $Li_2O$ | 0.003 | 0.002 | 0.003 | 0.002 | 0.002 | 0.00 | 0.005 | 0.002 | 0.002 | 0.006 | 0.003 | 0.005 | 0.002 | 0.001 | 0.003 | 0.002 |
| Ca | 1.7 | 1.9 | 1.6 | 1.2 | 1.7 | 1.4 | 1.5 | 1.4 | 2.0 | 1.6 | 1.9 | 1.4 | 1.8 | 2.1 | 1.7 | 1.4 |
| Fe | 1.1 | 1.1 | 0.93 | 0.91 | 2.0 | 1.3 | 0.82 | 0.97 | 1.2 | 1.2 | 1.1 | 1.2 | 1.5 | 1.3 | 1.1 | 1.1 |
| Ti | 0.05 | 0.088 | 0.14 | 0.10 | 0.10 | 0.175 | 0.083 | 0.13 | 0.22 | 0.20 | 0.14 | 0.17 | 0.17 | 0.10 | 0.053 | 0.14 |
| $P_2O_5$ | 0.04 | ----[4] | 0.02 | ---- | 0.10 | 0.045 | 0.05 | 0.05 | 0.06 | 0.07 | 0.07 | 0.08 | 0.10 | 0.09 | ---- | 0.11 |
| S | 0.023 | ---- | 0.027 | ---- | 0.013 | 0.034 | 0.029 | 0.027 | 0.029 | 0.018 | 0.023 | 0.035 | 0.032 | 0.031 | ---- | 0.024 |
| $H_2O+$ | 0.45 | ---- | 0.48 | ---- | 0.49 | 0.62 | 0.53 | 0.43 | 0.44 | 0.29 | 0.47 | 0.55 | 0.41 | 0.34 | ---- | 0.69 |
| MINOR ELEMENTS (PARTS PER MILLION) | | | | | | | | | | | | | | | | |
| Ba | 1470 | 1295 | 1090 | 1010 | ---- | 1175 | 980 | 1265 | 1370 | 1225 | 1300 | 1410 | 1280 | 1225 | 1200 | 1035 |
| Co | 3.8 | 3.8 | 3.8 | 2.5 | 3.8 | 5 | 3.1 | 3.1 | 7.5 | 3.1 | 3.8 | 5 | 2.5 | 2.5 | 5 | 7.5 |
| Cu[1] | 3.5 | 2.5 | 5 | 3 | 2.5 | tr | 2.5 | 5 | 2.5 | 2.5 | 2.5 | 2.5 | 3.5 | 5 | 5 | 10 |
| Mo | 3 | 4 | nd | 1 | 3 | 1 | 1 | 1 | 3 | 5 | 3 | 5 | 2 | nd | 2 | 3 |
| Mn | 320 | 305 | 365 | 240 | ---- | 495 | 330 | 470 | 420 | 440 | 310 | 340 | 445 | 470 | 495 | 300 |
| Ni | 10 | 8.8 | 10 | 12.5 | 10 | 10 | 8.8 | 10 | 10 | 8.8 | 8.8 | 17.5 | 15 | 15 | 8.8 | 16.3 |
| Pb | 25 | 12.5 | 12.5 | nd | 10 | 10 | 5 | nd | 10 | 12.5 | 10 | nd | 12.5 | 12.5 | 15 | nd |
| Sr | 880 | 980 | 790 | 700 | 870 | 880 | 800 | 760 | 1310 | 1210 | 1550 | 850 | 1400 | 1400 | 980 | 690 |
| V | 47 | 41 | 51 | 46 | 47 | 41 | 63 | 48 | 44 | 54 | 43 | 52 | 39 | 36 | 18 | 46 |
| W | nd | 4 | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | nd | 4 | nd | nd |
| Zn[1] | 10 | 8 | 8 | 13 | 7 | 14 | 9 | 11 | 11 | 7 | 10 | 12 | 15 | 10 | 13 | 27 |

[1]Average of duplicate analyses by the Department of Natural Resources, Quebec, and by the writer.
[2]Tr denotes detectable quantities of copper but too low for quantitative measurement (less than 2.5 ppm).
[3]nd Indicates element sought but not detected.
[4]A dashed line denotes element not determined.

Explanation of Table 5.

Analyses 1 to 6 : Contaminated granites, syenites and melasyenites.

Analyses 7 to 32: Normal (uncontaminated) granites.

quartz, the overall composition of this particular sample is still anomalous, considering its proximity to the border

TABLE 6. ANALYSES OF HYBRID XENOLITHS FROM THE OPEMISCA LAKE PLUTON

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Sample Number | NL-29 | NL-40 | --- | --- |
| $SiO_2$ | 53.95 | 51.90 | 55.85 | 50.52 |
| $TiO_2$ | 0.57 | 0.57 | 0.76 | 0.61 |
| $Al_2O_3$ | ---- | ---- | 16.56 | 14.95 |
| $Fe_2O_3$ | [1]8.29 | [1]7.43 | 1.98 | 2.63 |
| FeO | | | 4.41 | 6.10 |
| MnO | 0.10 | 0.19 | ---- | ---- |
| MgO | 4.10 | 9.94 | 5.51 | 9.02 |
| CaO | 7.56 | 7.42 | 5.37 | 7.98 |
| $Na_2O$ | 4.85 | 3.02 | 4.69 | 2.92 |
| $K_2O$ | 2.13 | 2.51 | 3.12 | 2.78 |
| $H_2O+$ | 1.51 | 1.44 | 1.26 | 2.11 |
| $H_2O-$ | 0.04 | 0.04 | 0.05 | 0.07 |
| $P_2O_5$ | 0.11 | 0.28 | ---- | ---- |
| S | 0.027 | 0.035 | ---- | ---- |
| $CO_2$ | 0.14 | 0.04 | ---- | ---- |
| TOTAL | 83.377 | 84.745 | 99.56 | 99.69 |

MINOR ELEMENTS

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Ba | 505 | 485 | ---- | ---- |
| Co | 6.3 | 21.3 | ---- | ---- |
| Cu | 27.5 | 93 | ---- | ---- |
| Mn | 780 | 1450 | ---- | ---- |
| Mo | 1 | 2 | ---- | ---- |
| Ni | 16.3 | 18.8 | ---- | ---- |
| Pb | 27.5 | 10 | ---- | ---- |
| Sr | 930 | 750 | ---- | ---- |
| V | 195 | 179 | ---- | ---- |
| W | nd | nd | ---- | ---- |
| Zn | 28 | 45 | ---- | ---- |

NORMS

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Orthoclase | ---- | ---- | 18.35 | 16.68 |
| Albite | ---- | ---- | 39.82 | 23.06 |
| Anorthite | ---- | ---- | 15.01 | 19.46 |
| Nepheline | ---- | ---- | ---- | 0.85 |
| Diopside | ---- | ---- | 9.36 | 16.25 |
| Hypersthene | ---- | ---- | 4.06 | ---- |
| Olivine | ---- | ---- | 7.39 | 16.35 |
| Magnetite | ---- | ---- | 3.02 | 3.71 |
| Ilmenite | ---- | ---- | 1.52 | 1.22 |
| Normative plagioclase | ---- | ---- | $An_{27}$ | $An_{45}$ |

DIFFERENTIATION INDICES $(\frac{1}{3}Si+K) - (Ca+Mg)$

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| | 2.31 | -1.13 | 4.21 | -0.99 |

[1]Total Fe as $Fe_2O_3$

Explanation of table 6.

1. Hybrid hornblende-biotite diorite.
2. Hybrid pyroxene-biotite diorite.
3. Diorite (Tolman, 1932b).
4. Diorite (Tolman, 1932b).

of the intrusive. It is possible that the granite in this area presents an injection of magma from the interior of the pluton after the margin had solidified.

The alumina content of sample NL-7 (18, table 4) was not determined, neither does the analysis differentiate between ferrous and ferric iron. In order to calculate the norm, the 0.44 percent Fe in the sample was arbitrarily estimated to be made up of 0.30 percent $Fe^{3+}$ and 0.14 percent $Fe^{2+}$. Alumina content was then calculated by subtracting the sum of all the remaining oxides from 100. There is little possibility that these assumed quantities are significantly in error, and the norm may be considered to be substantially correct.

## 5.02 Geochemical Behaviour of Major and Trace Elements

Chemical variation in the Opemisca Lake pluton is illustrated by means of diagrams in which the content of the various elements, the ratios of certain element pairs and water content are plotted against the function $(\frac{1}{3}\,Si + K) - (Ca + Mg)$ as the main ordinate of reference (figs. 5, 6 and 10). This function, hereafter referred to as the differentiation index (D.I.), is indicative of the degree of differentiation reached by a magma and was first used in its present form by Nockolds (Nockolds and Allen, 1953). It is a modification of the one originally proposed by Larsen (1938).

The use of these particular diagrams has been criticized on the grounds that the ordinate is a highly artificial variable, and that it tends to smooth out

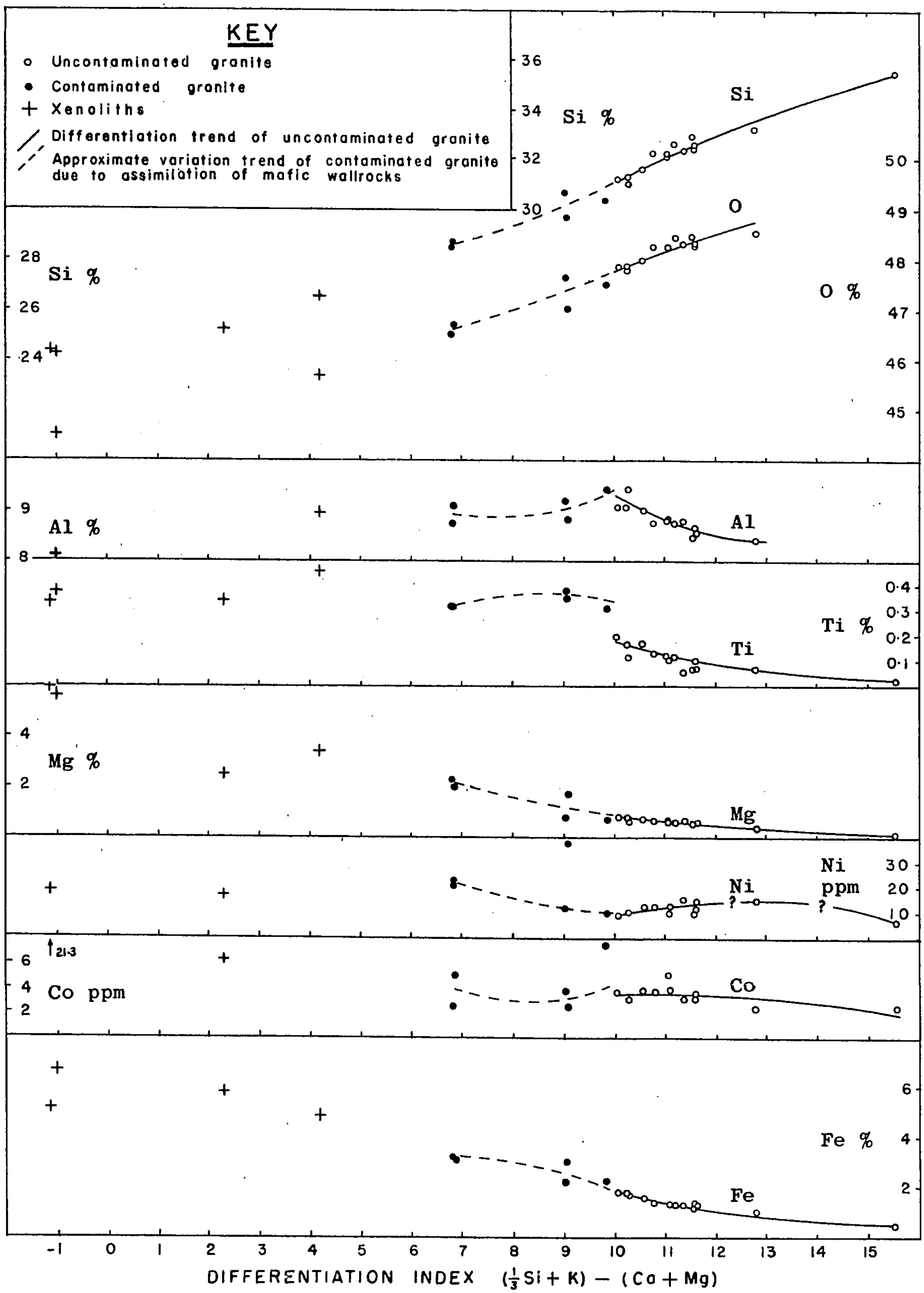



Figure 5. Nockolds variation diagram for Si, O, Al, Ti, Mg, Ni, Co and Fe in the Opemisca Lake pluton.

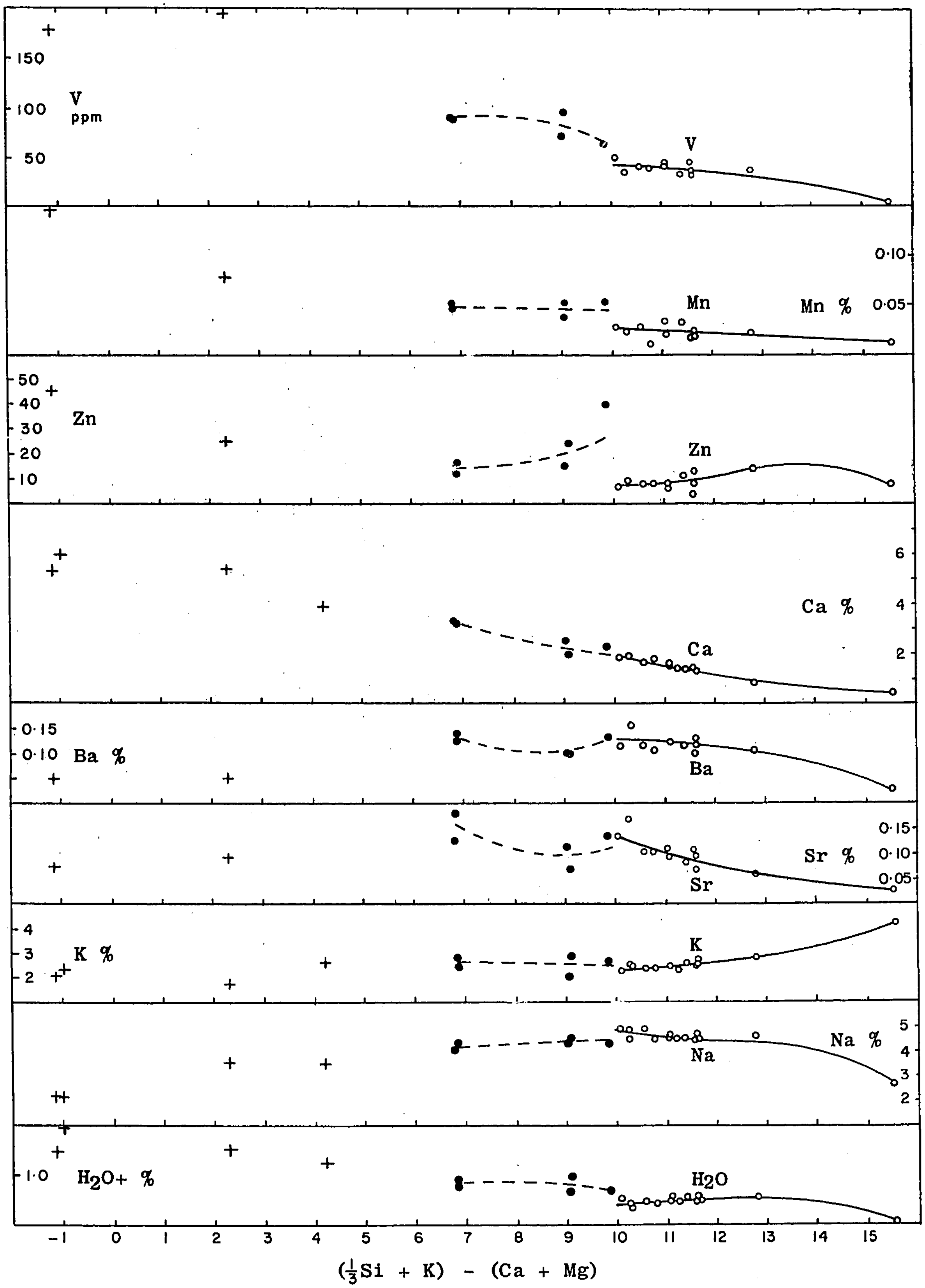



Figure 6. Nockolds variation diagram for V, Mn, Zn, Ca, Ba, Sr, K, Na, and $H_2O$ in the Opemisca Lake pluton.

differences in acid rocks and emphasize them in basic rocks (Nockolds, 1941, p. 510). To see whether this is really so, the author plotted the same data shown in figures 5 and 6 on the well known Harker diagrams which use $SiO_2$ content as ordinate. For some elements, notably Mg, Ca and K the Nockolds diagrams did tend to reduce scatter of the points. This is to be expected as each of these elements appears in the ordinate function. On the other hand, Al, Ba and V gave a notably smoother array of points on the Harker diagram. The remaining elements showed much the same degree of scatter in both diagrams.

More recently, Chayes (1962, 1964) has shown that on statistical grounds a strong negative correlation is to be expected between $SiO_2$ and some other oxides, and that linearity of data in Harker diagrams by itself is not evidence of crystal fractionation. Regrettably, the writer is not sufficiently familiar with statistics to evaluate Chayes' statements critically. Moreover, Chayes deals only with the common Harker diagrams, and specifically excludes Larsen diagrams. By inference this also excludes the Nockolds diagrams used in this work. Should Chayes' statements prove to be correct, the data presented in the following pages may need to be re-evaluated.

In computing the differentiation indices, all complete chemical analyses were recalculated to 100 percent on a volatile-free basis (without $H_2O$, $CO_2$, F, Cl). The following elements and oxides are not shown in the diagrams: W because it was detected in only 4 samples; $P_2O_5$ because of an insufficient number of analyses; Cu, Mo, Pb and S because of their extremely erratic behaviour, and $CO_2$ because it has no bearing on the problems to be discussed.

In the key to the diagrams shown in figures 5, 6 and 10, reference is made to "contaminated" and "uncontaminated" granites, and trends associated with each type are shown. Although the reasons for this terminology are explained later, it is necessary to introduce these terms at this stage to facilitate interpretation and explanation of the diagrams.

Except for slight variations, the point patterns of the major elements are regular and give rise to smooth trend lines with a high coefficient of correlation for differentiation indices over 10. The differentiation indices between 10 and 13 increase with increasing distance from the margin of the pluton (figs. 7A, 7B). In effect, therefore these segments of the curves picture the changes that took place in the chemical composition of the magma as it cooled from the margin inwards. For indices less than 10 the points generally tend to be more erratic, and for several elements the trend of the curve has been noticeably disrupted.

Only Si, O and K of the major elements increase as the differentiation index (D.I.) increases, and consequently they generate curves with positive slopes. The Si and O curves continue uninterruptedly and with a more or less constant slope for differentiation indices less than 10. In contrast, the curve for K is noticeably displaced at this point and below 10 it has a much lower slope.

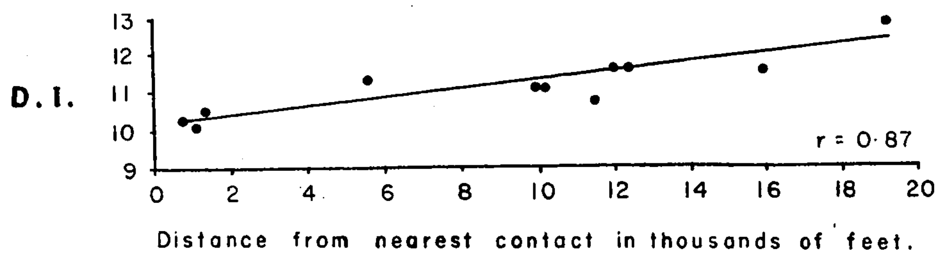



Figure 7A. Variation of differentiation index with distance from nearest contact of pluton (r is the correlation coefficient).

The remainder of the major elements all give rise to curves with negative slopes. Mg, Fe, and Ca are characterized by curves which are continuous and fairly uniform in slope over the entire range of differentiation indices depicted. The curves for Al, Ti and Na not only undergo pronounced changes in slope at D.I. = 10, but the two segments of each curve, above and below this point, are also sharply offset.

Only Ni and Zn of the seven trace elements plotted on the diagram give rise to curves which have positive slopes between the differentiation indices of 10 and 13. However, both these curves appear to be second order inasmuch as they peak at about D.I. = 13 or slightly beyond and then decline toward the aplite at D.I. = 15.52. Below D.I. = 10 the curve for Ni shows a sharp reversal in slope and the Ni content increases erratically towards the

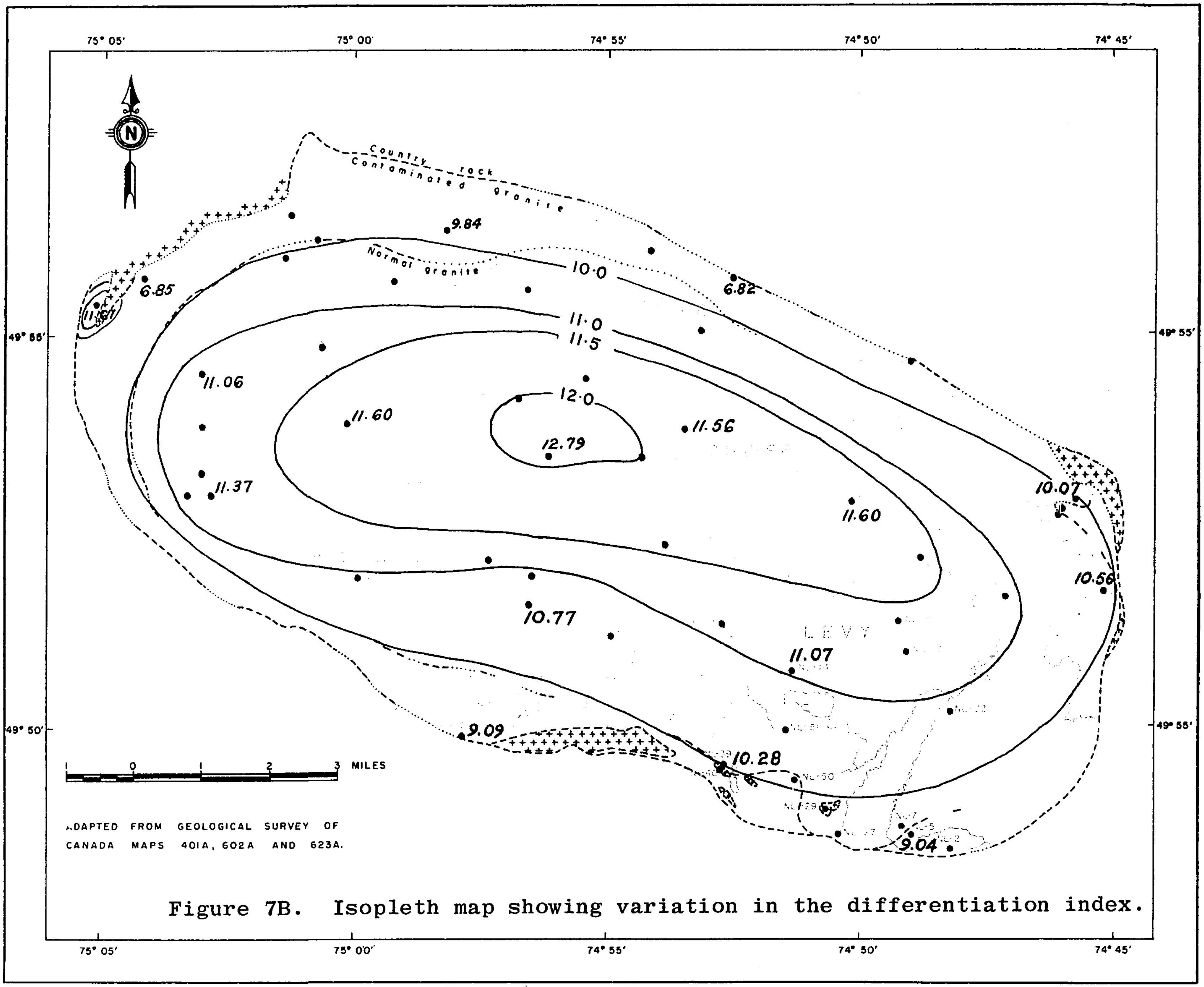



Figure 7B. Isopleth map showing variation in the differentiation index.

more basic members of the granite. The Zn contents in the range below 10 are highly erratic but they seem to diminish towards the lower indices.

Co maintains a fairly uniform level over the entire range of granitic rocks. Mn remains reasonably constant (average 483 ppm) for differentiation indices below 10, decreases sharply at this point and then again maintains a fairly constant level (average 228 ppm) for indices above 10.

The V, Ba and Sr curves all decline progressively as differentiation indices above 10 increase. Below 10 all three of these elements behave erratically.

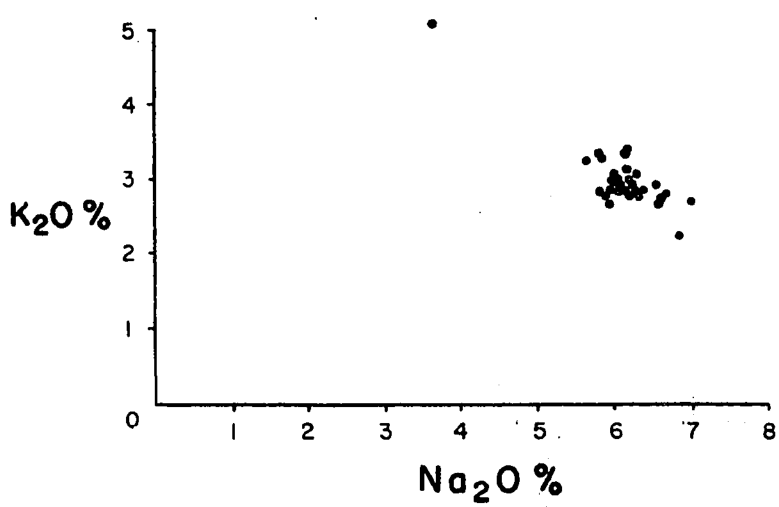



Figure 8. Reciprocal variation of $Na_2O$ and $K_2O$ in Opemisca Lake pluton.

The water content of the granite decreases gradually from the more mafic to the more felsic members in the region below D.I. = 10. From D.I. = 10 to D.I. = 13 water content remains fairly constant around 0.5 percent and then decreases rapidly to almost zero in the aplite at D.I. = 15.52.

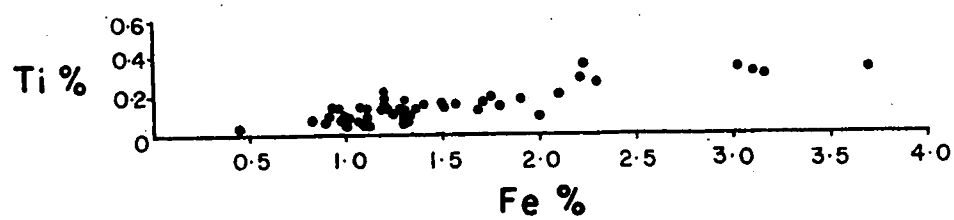



Figure 9. Covariation of Fe and Ti in Opemisca Lake pluton.

The trends of the curves representing the major elements in the range above D.I. = 10 are in agreement with the generally accepted principles of magmatic differentiation: early crystallization of ferromagnesian and lime-rich minerals coupled with fractionation, leading to a progressive enrichment in silica and potash, and impoverishment in Ca, Fe and Mg in the residual liquids and later rocks. Fe becomes enriched relative to Mg in the later differentiates as is shown by the positive slope of the curve depicting the Fe:Mg ratio (fig. 10). K increases somewhat erratically as Na decreases (fig. 8), and likewise the ratio Na:K declines as the differentiation index increases (fig. 10). Ti is clearly covariant with Fe (fig. 9) and the Ti/Fe ratio decreases, albeit erratically, from the earlier to the later granites (fig. 10).

The reasons for the irregular trend and the disruption of the curves for certain elements below D.I. = 10

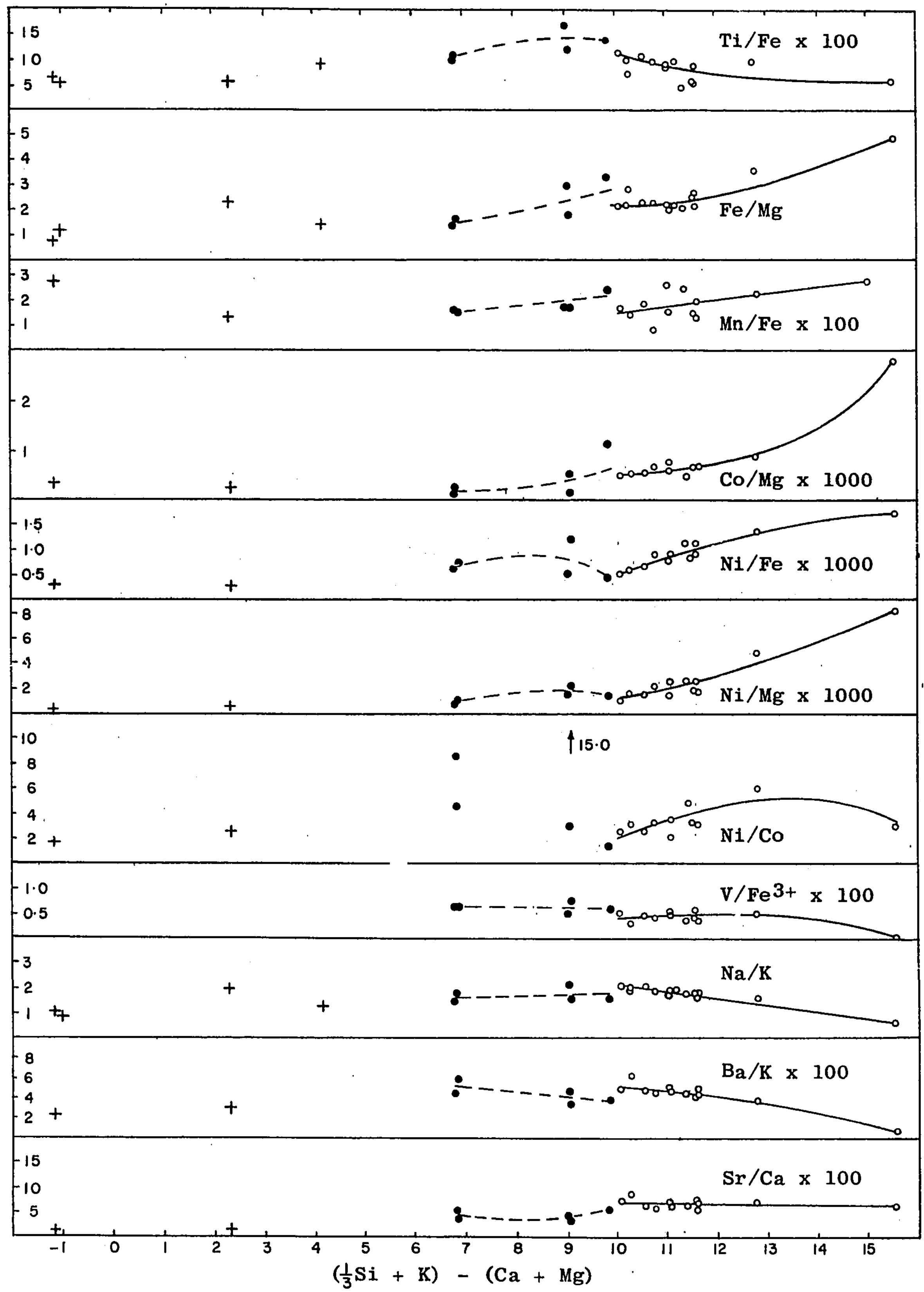



Figure 10. Variation in the ratios of certain element pairs in the Opemisca Lake pluton.

are more complex. The erratic distribution of points representing chemical analyses in a variation diagram or their departure from smooth curves is generally attributed to crystal accumulation (Bowen, 1928, p. 94). Whether accumulation can be of any importance in a steep-sided granitic intrusive is debatable. The pluton cools from the exterior inward and early-formed crystals presumably grow by accretion on the walls. Considering the extremely high viscosity ascribed to siliceous magmas (Clark, 1966, p. 299), it is doubtful whether significant sinking of crystals can take place in the cooler marginal phases of the granite magma where prevailing temperatures are close to the freezing point.

Contaminated rocks will have a composition intermediate between the original magma and the contaminating material (Nockolds, 1933, p. 576). Theoretically then, on a variation diagram, the contaminating, contaminated and uncontaminated rocks should all be on a straight line. However, this assumption is only valid if the contaminating substance is of a more or less uniform composition. Where an igneous mass such as the Opemisca Lake pluton has been intruded into and reacted with a wide variety of wallrocks the products can be expected to show a considerable diversity in chemical composition. This effect should be most pronounced in the marginal zones of the intrusive where it cooled relatively quickly and where the greatly increased viscosity and subsequent solidification of the magma would inhibit homogenization of the various types of contaminated granite. The fact that each of the 5 granites with differentiation indices less than 10 is located close to the border of the pluton, and that each is characterized by an abundance of tiny fine-grained mafic inclusions, lends credence to the hypothesis that contamination is the major factor responsible for the more mafic nature and irregularities in the chemical compositions of these rocks as compared to those of the other granites.

From the foregoing one may conclude that granitic rocks in the Opemisca Lake pluton with differentiation indices less than 10 have resulted from contamination and that differences among them are attributable to the same cause. In contrast, in rocks with indices in excess of 10, contamination has had little or no influence, and differentiation has been the main factor leading to diversity. In addition to the differentiation index, four elements, Si, Ti, Ca and Fe appear to be the most sensitive indicators of the rock type. Unfortunately, Si content is not available for the large number of partially analysed samples and the Ti content by itself is not an altogether reliable indicator. A careful analysis of the field and laboratory data and the distribution pattern of the various elements permitted the following empirical rule to be formulated: in the Opemisca Lake pluton, contaminated granites contain at least 1.95 percent Ca and not less than a combined total of 3.9 percent Ca and Fe. Further evidence confirming this rule is presented in the section dealing with strontium (p. 84).

The behaviour of the trace elements during the crystallization and differentiation of the granitic magma is generally more difficult to interpret than that of the major elements. Not only are the results of analyses for such minute quantities of elements less precise and subject to greater inaccuracy than for the major elements, but it is not always possible to correlate variations in the trace element content with variations in gross mineralogy.

The behaviour of most of the trace elements can be explained in terms of empirical laws formulated by Goldschmidt (1937) and Ringwood (1955). The seemingly anomalous behaviour of certain trace elements may be due to their being associated with or contained in phases which are dispersed through the rock in submicroscopic particles (Neumann, 1949). It may also be caused by trace elements being weakly fixed to irregularities or discontinuities in crystal structures by a process of adsorption rather than being incorporated into lattice sites (Devore, 1955).

TABLE 7: IONIC RADII AND ELECTRONEGATIVITIES OF CERTAIN MAJOR AND TRACE ELEMENTS (After Ahrens, 1952 and Ringwood, 1955)

| Cation | Ionic Radius (Å) | Electro-negativity | Cation | Ionic Radius (Å) | Electro-negativity |
|---|---|---|---|---|---|
| $Ba^{2+}$ | 1.34 | 0.85 | $Mo^{4+}$ | 0.70 | - |
| $Ca^{2+}$ | 0.99 | 1.0 | $Mn^{2+}$ | 0.80 | 1.4 |
| $Co^{2+}$ | 0.72 | 1.7 | $Ni^{2+}$ | 0.69 | 1.7 |
| $Cu^{2+}$ | 0.72 | 2.0 | $Pb^{2+}$ | 1.20 | 1.6 |
| $Fe^{2+}$ | 0.74 | 1.65 | $Sr^{2+}$ | 1.12 | 1.0 |
| $Fe^{3+}$ | 0.64 | 1.8 | $Ti^{4+}$ | 0.68 | - |
| $K^{+}$ | 1.33 | 0.8 | $V^{3+}$ | 0.74 | 1.35 |
| $Mg^{2+}$ | 0.66 | 1.2 | $Zn^{2+}$ | 0.74 | 1.7 |

a. Barium

Barium (fig. 6) behaves somewhat erratically in the contaminated granite. In the normal granite it initially maintains more or less the same level of concentration and then starts diminishing rapidly. Barium becomes notably impoverished in the very late residual melts and reaches its lowest concentration of 280 ppm in the aplite.

The behaviour of barium is attributed to its concentration in early potassic minerals (von Engelhardt, 1936). $K^{+}$ is the only ion comparable in size to $Ba^{2+}$; it is also very similar to $Ba^{2+}$ in electronegativity. Because of its higher charge $Ba^{2+}$ can be expected to enter appropriate lattice sites more readily than $K^{+}$ and it will therefore be impoverished in the later potassium-bearing rocks and minerals. This trend is well shown by the Ba/K ratio (fig. 10) which diminishes noticeably with higher differentiation indices.

It is interesting to note that the two samples of hybrid basic xenoliths NL-29 and NL-40 (1, 2, Table 6) have an appreciably lower Ba content (505 and 485 ppm respectively) than the granites, although their potash content (2.13% and 2.51% respectively) is comparable to that of the least potassic normal granites. There can be little doubt that these xenoliths were originally Ba- and K-poor basic rocks. During hybridization, substantial quantities of K from the granite transfused into the inclusions where it became fixed, mainly as biotite. However, Ba does not appear to have entered the inclusions in comparable quantities despite the fact that the biotite lattice can accomodate an even greater content of Ba than can the potash feldspar lattice (Rankama and Sahama, 1950, pp. 472 - 473). Von Engelhardt (1936) noticed that Ba was unusually low in greisens associated with tin deposits. Greisens are considered to be the products of reaction between a host rock and volatile substances introduced by gaseous igneous emanations (Holmes, 1920). Nockolds (1935, p. 573) has emphasized the importance of volatiles in the transfer of material between granite magma and xenoliths during reciprocal reaction. From the foregoing, it would seem then that whereas $Ba^{2+}$ can compete freely with $K^{+}$ for lattice sites in the feldspar structures during igneous crystallization, it is not capable of moving with the same facility as K where transfer of material involves being carried as volatile substances, or in the presence of volatiles, into or through solid rock.

b. Cobalt

Cobalt behaves erratically in the contaminated granites. In the normal granites it remains fairly constant in the early, more basic varieties and tends to diminish slightly in the late granites and the aplite veins (fig. 5).

The radii of $Co^{2+}$ and $Fe^{2+}$ ions are very close, whereas those of $Co^{2+}$ and $Mg^{2+}$ differ by a slightly larger margin. In basic rocks $Co^{2+}$ apparently will substitute for both of these elements, whereas in granitic rocks it is strongly coherent with $Mg^{2+}$ (Carr and Turekian, 1961, p. 40). This is contrary to the behaviour predicted from Ringwood's data (1955, p. 201). It seems that the effective radius of $Co^{2+}$ is somewhat less than the accepted value, and rather close to that of $Mg^{2+}$ (Mason, 1966, p. 136). As a result $Co^{2+}$ will show a greater affinity for $Mg^{2+}$ than for $Fe^{2+}$. On account of its higher electronegativity and larger ionic radius $Co^{2+}$ would be admitted to magnesian minerals and thus become enriched in the later fractions. This is confirmed by the rise in the Co/Mg ratio with increasing differentiation (fig. 10).

c. Copper

The trend of copper in the rocks of the Opemisca Lake pluton is completely erratic and it is therefore not shown in any of the diagrams. This erratic distribution of copper is not a unique phenomenon. Putnam and Burnham (1963) have observed similar tendencies in several plutons in Arizona.

Copper is a chalcophile element and can be expected to be present in igneous rocks, mainly in the sulphide phase (Rankama and Sahama, 1950). On the other hand, the close similarity in ionic radii of $Cu^{2+}$ and $Fe^{2+}$ suggest that some of the copper may substitute for iron in silicates. Wager and Mitchell (1951) found that prior to the separation of an immiscible sulphide phase copper enters essentially into the silicates only. Recent work has established that in many rocks the highest concentration of copper occurs in magnetite. Cornwall and Rose (1957) found that magnetite in basic Keweenawan lavas contained 880 ppm Cu, nearly three times the concentration of Cu in augite. Magnetite from the late Precambrian Deloro granite pluton in eastern Ontario holds 14 ppm Cu, slightly more than biotite-chlorite (Azzaria, 1963). In a study of four Precambrian granitic intrusives in north-western Ontario, Vollrath (1964) found the copper content of magnetite to range from 203 ppm in quartz diorite, to 40 ppm in granodiorite and 11 ppm in quartz monzonite. According to Walker (1966) the copper content of magnetite in the Opemisca Lake pluton ranges from less than 0.1 percent to more than 0.7 percent, and averages 0.3 percent (3000 ppm). Unfortunately, Walker's results are based on semi-quantitative estimates, and there is strong evidence that they are much too high. If Walker's data are correct, the average quantity of Cu in the Opemisca Lake granite (contaminated as well as uncontaminated varieties) contributed by magnetite alone is 24 ppm. In comparison, the average <u>total</u> Cu content of the

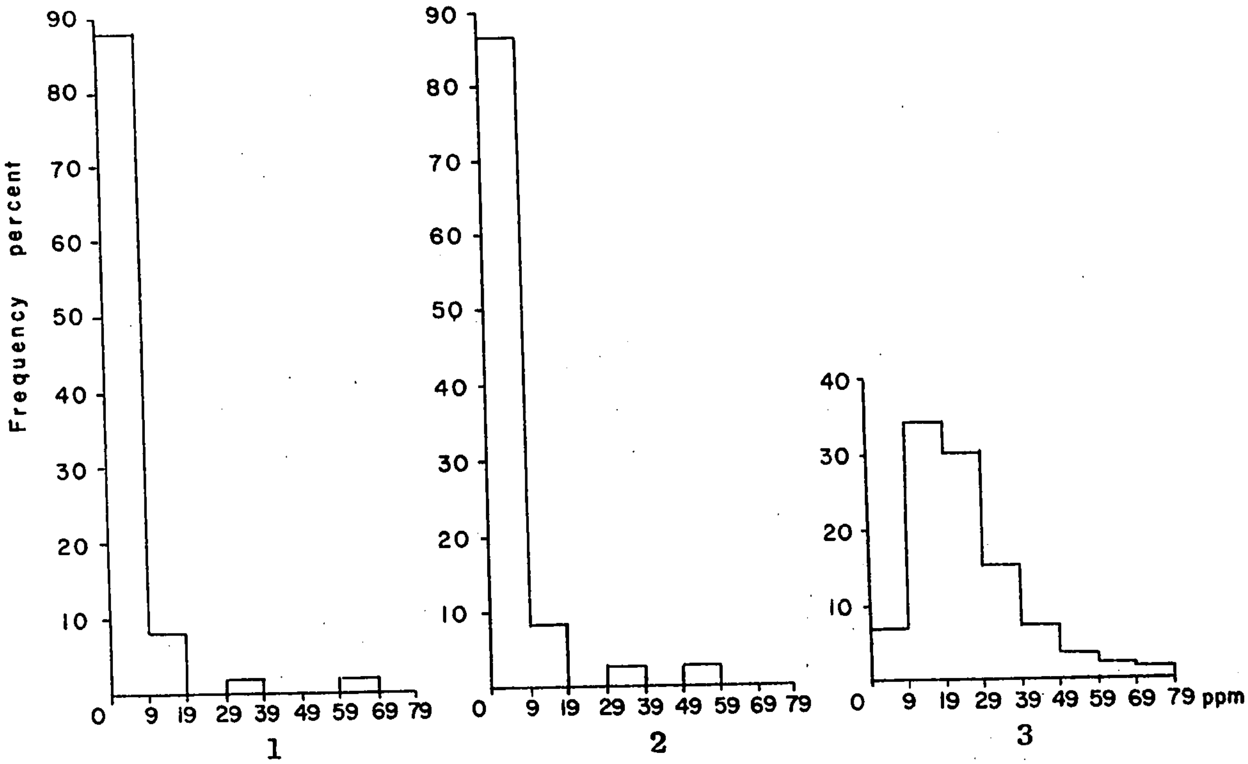



Figure 11. Frequency distribution of Cu in the Opemisca Lake pluton as determined by various analysts: 1. The writer. 2. Department of Natural Resources, Quebec. 3. W.B.G. Walker (1966).

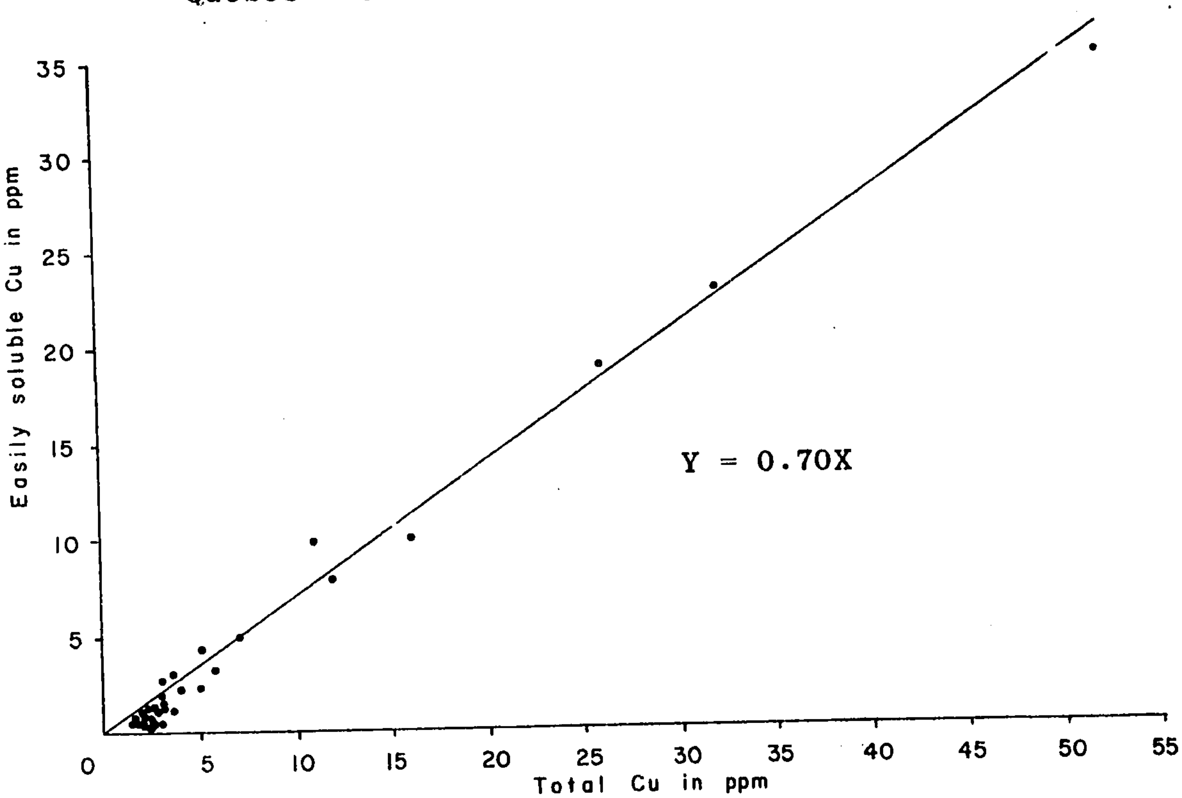



Figure 12. Ratio of easily soluble Cu to total Cu in the Opemisca Lake pluton. Regression line fitted by least squares method.

granite as determined by the writer is only 5.5 ppm. Duplicate analyses of 37 of the writer's samples carried out by the Department of Natural Resources, Quebec, averaged 5.8 ppm Cu. For these same 37 samples, the writer's average was 6.4 ppm Cu. A comparison of the frequency distribution diagrams (fig. 11) clearly indicates the lack of correlation between Walker's results and the other two sets of data which are virtually identical.

In order to find out to what extent copper is concentrated in the magnetite, Walker (1966, p. 4) determined the copper content in two granite samples as well as in the magnetite fractions from these two samples. In the first sample, 1.0 percent magnetite contributed about 30 ppm Cu to the overall content of 68 ppm. In the second sample, 1.5 percent magnetite contributed about 45 ppm Cu to the total content of 85 ppm. If it may be assumed that these results are representative, and if estimates of copper content are consistent in all samples, then it would appear that magnetite contributes roughly half the total amount of copper in the rock.

About 70 percent of the copper content of those granites containing more than 3 ppm Cu is in an easily soluble form (fig. 12). For copper contents of less than 3 ppm the ratio of easily leachable copper is significantly lower and much more erratic. This may be due to greater analytical errors at such extremely low concentrations of Cu, but it may also reflect a smaller percentage of readily soluble Cu relative to that being held in the lattice sites of the silicate minerals. Magnetite is soluble in HCl and it is possible that the readily leachable copper represents to a large extent that fraction of the total copper which proxies for $Fe^{2+}$ in the magnetite lattice. The remaining copper is probably contained in the ferromagnesian minerals and in sulphides. Although no sulphides were observed in any of the samples, the prevalence of minute quantities of sulphur in the analyses (table 5) attest to their presence.

Several factors may be responsible for the non-uniform distribution of copper in the Opemisca Lake pluton - lack of precision and accuracy of analytical methods at low concentration, erratic distribution of magnetite (fig. 16), the erratic distribution of sulphides (as indicated by the sulphur content) and the possibility of widespread leaching during deuteric (?) chlorite-sericite alteration of the granite (Putnam and Burnham, 1963).

d. Molybdenum

The molybdenum content of most of the granitic rocks ranges from 2 - 4 ppm and it shows no noticeable trend. Because of its marked affinity for sulphur, molybdenum is rarely found in any mineral other than molybdenite (Rankama and Sahama, 1950, p. 627). No molybdenite was seen in any of the samples, but in view of the extremely low concentrations that could possibly be present, it is most unlikely to be detected.

e. Manganese

Manganese remains at roughly the same level of concentration (about 500 ppm) in the contaminated granites, decreases sharply to about 250 ppm in the normal granite and then declines gradually but somewhat erratically with increasing differentiation index (fig. 6). The ionic radius of $Mn^{2+}$ is greater than that of $Fe^{2+}$ but, in contrast, it has a lower electronegativity. The increase in the Mn/Fe ratio with increasing differentiation (fig. 10) suggests that Mn is enriched relative to Fe in the later fractions. It seems therefore that the lower electronegativity of $Mn^{2+}$ is not sufficient to compensate for its larger radius, and relative size remains the determining factor in the distribution of manganese and iron.

f. Nickel

The trend of nickel is altogether unexpected (fig. 5). Instead of decreasing in the later stages as do Fe and Mg, the two elements which nickel follows most closely, it increases with higher differentiation indices before decreasing in the aplite phase. Nickel characteristically diminishes as the host rocks become more siliceous (Rankama and Sahama, 1950) and it is not clear why it should behave differently in the Opemisca Lake pluton. A somewhat similar trend was observed in the Skaergaard intrusion (Wager and Mitchell, 1951) where nickel, after decreasing progressively throughout the basic sequence until almost depleted, starts increasing again in the late stage granophyres. Wager and Mitchell (1951, p. 184) postulated that the late ferromagnesian minerals and iron ores removed so little Ni from the melt that it began to accumulate again in the residual liquids, but the reasons for this particular behaviour are not known.

The Ni/Mg ratio (Mason, 1966, p. 136) and the Ni/Co ratio (Rankama and Sahama, 1950, p. 682) generally are highest in the early-formed rocks and decrease toward the later rocks. Ringwood (1955) argues convincingly that the ionic radius and electronegativity of $Ni^{2+}$ are such that it should substitute for $Fe^{2+}$ rather than $Mg^{2+}$ in the lattice sites of the ferromagnesian minerals, and that the Ni/Fe ratio should decrease from the earlier to the later-formed rocks and minerals. In the Opemisca Lake pluton, the Ni/Fe, Ni/Mg and Ni/Co ratios all rise with increasing differentiation (fig. 10). The Ni/Co rise is not sustained and falls off after peaking at about D.I. = 13, but the trend of this curve as a whole is uncertain. The unexpected increase in the nickel content in the later granites is of course largely responsible for the increase in the Ni/Mg, Ni/Co and Ni/Fe ratios. Somewhat similar trends were observed in the four Precambrian granitic plutons studied by Vollrath (1964). She found that the Ni/Co and Ni/Mg ratios increased from the more mafic to the more silicic plutons, whereas the Ni/Fe ratio behaved erratically. It should be pointed out that Vollrath studied the variation from pluton to pluton and no data are given for within pluton variation. Strictly speaking, therefore, it may not be altogether correct to compare her results with those of the present study.

The possibility that the increase of Ni with rising differentiation indices could have arisen by chance is suggested by the distribution pattern of Ni within the pluton (fig. 31). An irregular area of low nickel content ( $<$ 10 ppm Ni) coincides with the central part of the intrusive which is underlain by the more siliceous and more highly differentiated granites. The isopleth map for Ni is based on 49 analyses, and is clearly in contrast to the differentiation curve, which is based on only 13 analyses. The reason for this contradiction seems to lie in the extremely erratic increase in Ni from the core of the pluton outwards. This gives rise to complexly shaped isopleth lines. As a result, the area of low Ni content near the centre of the intrusion is highly irregular in outline and extends almost to the border of the intrusive in some places. By chance, the analyses chosen to represent the trend of Ni during differentiation are of samples so located that they do not reflect the decrease of Ni from the margin inwards. Instead, they emphasize the reverse trend. Analytical errors can also be misleading in trying to determine the distribution pattern of an element such as

Ni, which shows a relatively small quantitative variation in the pluton. The slightest error in estimating the intensity of the colour of the solutions during analysis is greatly magnified in calculating the Ni content subsequently. (See Appendix I.) This can affect the shape of the isopleth lines on the map or trend lines on the variation diagram to a very considerable extent.

In the contaminated granites the nickel behaves as expected and decreases somewhat irregularly from the more basic to the less basic rocks.

g. Lead

Lead behaves erratically and has no discernible trend within the Opemisca Lake pluton. Its concentration appears to be completely independent of that of potassium, the element for which lead is most likely to substitute (Wedepohl, 1956). According to Holman (quoted in Vollrath, 1964), the potassium bisulphate fusion fails to extract Pb completely from silicates such as the feldspars. It also seems that results obtained when the lead content is determined in the still warm HCl solution of the bisulphate fusion, differ significantly from those obtained from a solution which has been allowed to cool and stand for several hours (Grove, 1963, personal communication). In view of these unforeseen sources of error, the analytical results for lead are not considered to be reliable, and will not be discussed.

h. Strontium

The trend of strontium in the contaminated granites is somewhat erratic. In the uncontaminated granites it decreases progressively from about 1300 ppm in the early, more mafic, varieties, to about 600 ppm in the late granites, and to less than 300 ppm in the very late stage aplite veins (fig. 6). The ion closest to $Sr^{2+}$ in size and electronegativity is $Ca^{2+}$, and consequently $Sr^{2+}$ can be expected to be concentrated in plagioclase (Wager and Mitchell, 1951; Cornwall and Rose, 1957). The $Sr^{2+}$ ion is larger than $Ca^{2+}$ and it should therefore become enriched relative to calcium in the later rocks and minerals (Osborn, 1950). Whereas this is generally so for differentiated basic sequences (Wager and Mitchell, 1951; Turekian and Kulp, 1956), it is claimed that the reverse holds true for granitic rocks (Turekian and Kulp, 1956).

Sr and Ca are covariant in the normal granites of the Opemisca Lake pluton (fig. 13). The regression line of Sr on Ca passes through or very close to the origin of the graph, indicating that the Sr/Ca ratio remains constant. (See also fig. 10).

Hornblende decreases in abundance towards the centre of the pluton (fig. 15A) and so does Ca (fig. 19). Neither the quantity of plagioclase, nor the anorthite content of plagioclase, varies significantly in the uncontaminated granite. It seems, therefore, that variation in calcium content in the Opemisca Lake pluton is essentially a reflection of variation in the abundance of hornblende. The work of Eskola (1922) and of Nockolds and Mitchell (1948), has shown that $Sr^{2+}$ does not readily substitute for $Ca^{2+}$ in calcium-bearing ferromagnesian minerals. This means that diadochy between Sr and Ca is virtually restricted to plagioclase, and that the quantity of Ca actually available for replacement by Sr remains more or less constant. Inasmuch as Sr decreases with increasing differentiation, it follows that the Sr/Ca ratio will decrease if the Ca content of hornblende is disregarded. This is in accord with the findings of Turekian and Kulp, (1956).

The reason for the decrease in the Sr/Ca ratio in granitic rocks in contrast to the increase of the ratio in mafic rocks is probably linked to the abundance of potash feldspar. Noll (1934) has shown that $Sr^{2+}$ can substitute for $K^{+}$, particularly in the feldspar lattice. On account of its higher charge and smaller size, $Sr^{2+}$, like $Ba^{2+}$, is captured by potash feldspar. If K-feldspar in the earlier granites captured much of the $Sr^{2+}$ not admitted into the plagioclase lattice, this would counteract the tendency of strontium to become enriched relative to calcium in the later fractions.

The investigations into the relations between strontium and calcium in the Opemisca Lake pluton led to the discovery of a third method permitting the distinction between contaminated and uncontaminated granites. This particular method also confirms the previously formulated law distinguishing between contaminated and normal granite on the basis of their calcium and iron contents. A graph of Ca content against Sr content clearly shows that the two different types of granites occupy two separate fields (fig. 13).

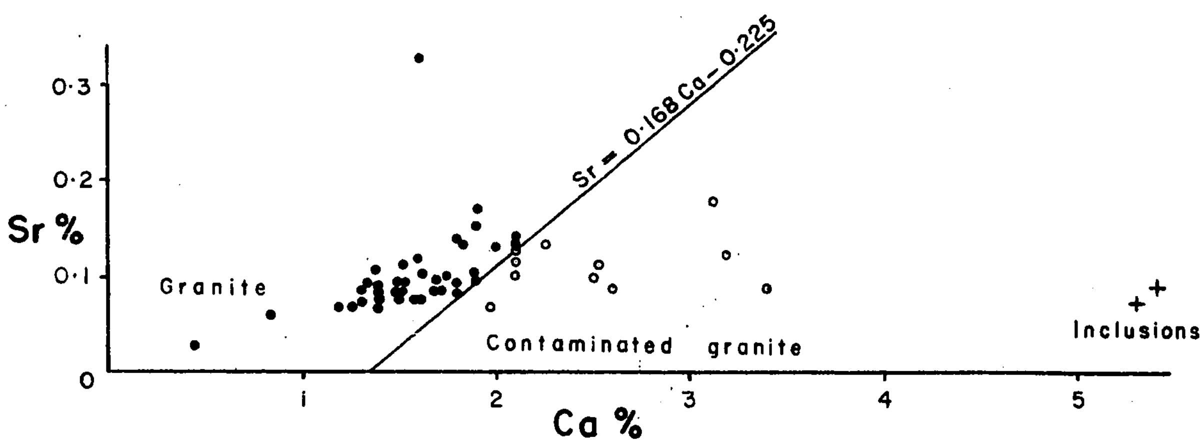



Figure 13. Variation of Sr relative to Ca in various rock types of the Opemisca Lake pluton.

A more or less arbitrary line was drawn in as the boundary between the two fields. The regression equation for this line is:

$$Sr = 0.168\ Ca - 0.225 \text{ (Ca and Sr in weight percent)}$$

It is seen in figure 13 that contaminated granites have a distinctly lower Sr/Ca ratio than normal granites with a similar Ca content. Also, Ca and Sr are covariant in the normal granite, whereas in the contaminated granite they define no particular trend other than an erratic lateral displacement in the direction of the hybridized basic inclusions. The work of Turekian and Kulp (1956) has shown that for granitic rocks the strontium content increases with an increase in calcium irrespective of regional differences, and also that the Sr/Ca ratio in granitic rocks is considerably higher than in basic rocks. The most obvious conclusion is that the discrepant relationship between Sr and Ca in the contaminated granite is due to the assimilation of high-calcium, low-strontium basic and/or ultrabasic rocks by a relatively low-calcium high-strontium granite magma.

By rearranging the equation for the boundary line so that Ca = 6Sr + 1.34, it becomes possible to define contaminated and uncontaminated granites in the Opemisca Lake pluton in terms of their Sr and Ca contents. In contaminated rocks the Ca content as calculated for a specific Sr content by means of the above formula will be less than the actual Ca content. In uncontaminated granites the reverse will be true.

It is interesting to note that sample NL-74 (4, table 5) which is a borderline case on the basis of combined Ca + Fe content is also in the same ambiguous position on the Sr-Ca diagram.

i. Vanadium

Despite the similarity in ionic radii of $V^{3+}$ and $Fe^{2+}$, and the lower electronegativity and higher charge of $V^{3+}$, the latter, according to most workers (Nockolds and Mitchell, 1948; Wager and Mitchell, 1951; Cornwall and Rose, 1957; Mason, 1966), prefers to proxy for the smaller trivalent iron ion. Magnetite and, to a lesser extent, ilmenite and the ferromagnesian minerals are the minerals in which vanadium is most likely to be concentrated.

Although the ionic radius of $V^{3+}$ is about 15 percent larger than $Fe^{3+}$, its electronegativity is so much lower as to allow $V^{3+}$ to become preferentially concentrated in early minerals of the appropriate composition (Ringwood, 1955). This leads to impoverishment of vanadium in the later minerals and rocks and a decrease in the $V/Fe^{3+}$ ratio. In the Opemisca Lake pluton the vanadium content of the contaminated as well as the normal granite diminishes gradually with increase in the differentiation index (fig. 6). During the main stage of crystallization of the normal granite the $V/Fe^{3+}$ ratio shows no tendency to decrease but remains constant (fig. 10), indicating that $V^{3+}$ and $Fe^{3+}$ were entering their lattice sites at a uniform rate. Only in the very late aplitic stage (where V is below the limit of detection of the analytical method used) does the ratio eventually decrease. The data of Nockolds and Mitchell (1948) show that $V^{3+}$ behaves in a similar manner in the Scottish Caledonian intrusives.

j. Zinc

The behaviour of zinc in the contaminated granite is extremely erratic. In the normal granite the zinc content initially remains fairly constant. As the granite becomes more differentiated, zinc increases erratically and then decreases again in the late stage aplites (fig. 6). Considering the precision of the analytical method used (see Appendix I), these variations may not necessarily reflect actual changes in the zinc content of the rock but could be largely due to sampling and analytical errors.

The most obvious element for which zinc can substitute diadochically is ferrous iron. $Zn^{2+}$ and $Fe^{2+}$ are not only identical in size and charge but also very close in electronegativity. Most workers agree that the bulk, if not all of the zinc in granitic rocks, is concentrated in the ferromagnesian minerals and, to a lesser extent, in magnetite (cf. Wedepohl, 1953; Tauson and Kravchenko, 1956; Putnam and Burnham, 1963; Azzaria, 1963 and Vollrath, 1964).

Magnetite concentrates from the Opemisca Lake granite averaged less than 100 ppm Zn (Walker, 1966). Inasmuch as the average content of the magnetite itself is less than 1 percent, not more than 1 ppm of the Zn in the bulk rock can be attributed to this source.

Ringwood (1955) claims that $Fe^{2+}$, because of its slightly lower electronegativity, will be able to compete for lattice sites more successfully than $Zn^{2+}$ and hence, the latter will become concentrated in the later fractions. In the Opemisca Lake pluton, $Fe^{2+}$ diminishes in the later granites, whereas $Zn^{2+}$ remains roughly at thé same level of concentration. It follows, therefore, that the $Zn/Fe^{2+}$ ratio will show an increase over the same range of rock types.

The non-uniform behaviour of zinc in the Opemisca Lake pluton is contrary to the findings of Wedepohl (1953) and Vollrath (1964) who observed that the Zn content decreases with increasing silica content of the host rock. However, their results deal essentially with variations among different intrusives and not within a single intrusive body and, as Putnam and Burnham (1963, p. 79) have pointed out, the geochemical behaviour of trace elements within a particular rock body can not necessarily be predicted on the basis of their behaviour in similar rocks elsewhere. Vollrath (1964, p. 95) as well as Putnam and Burnham (1963, p. 76) have noticed that biotite (or other ferromagnesian minerals) in the earlier or more basic rocks contains less zinc than biotite in the later, more differentiated varieties. This, of course, is in accordance with the trend predicted by Ringwood. However, the increased concentration of zinc in the ferromagnesian minerals of the later rocks is offset by a decrease in the ferromagnesian phase in these same rocks, and this results in a net loss of zinc in the bulk rock. It is possible that in the Opemisca Lake pluton the increase in the Zn content of the ferromagnesian minerals took place at a slightly greater rate than the decrease in the abundance of these minerals so that Zn did not diminish in the later rocks but maintained a comparatively uniform level, or even increased slightly.

About 97 percent of the zinc in the rocks of the Opemisca Lake pluton is readily leached by dilute acid (fig. 14). Tauson and Kravchenko (1956) found that leaching of the granitic rocks of the Susamyr batholith with dilute HCl removed between 67 and 94 percent of the zinc. They considered this to be evidence that the bulk of the Zn does not enter the lattice sites of the silicate minerals but is present in an "extra-silicate" form. Neuman (1949, p. 576) argued that $Zn^{2+}$, which has a co-ordination number of 4, forms rather weak covalent bonds, compared to the stronger ionic bonds of 6 co-ordinated $Fe^{2+}$ and $Mg^{2+}$. As a result, $Zn^{2+}$ would experience considerable difficulty in substituting for either of these elements. He believed that Zn had to occur largely as submicroscopic sphalerite and that this would account for its easy removal by weak acid.

Wedepohl (1953), using a fractional distillation technique, was unable to find any evidence that zinc was present in the form of sphalerite. He considered it to be structurally bound by the ferromagnesian minerals. Putnam and Burnham (1963) also caution against the assumption that the easy extraction of an element by dilute acids indicates an "extra lattice" content. They found that cold 1N $HNO_3$

readily removes Cu from biotite. On account of its low tenor of zinc, magnetite is precluded from being a significant source of easily soluble zinc in the Opemisca Lake granites, as it is in the case of copper. It is possible that the readily leachable Zn is held to or in host crystals by very weak bonds in a manner suggested by Devore (1955). Because they are not structurally bound, these elements presumably are readily removed in an acid solution.

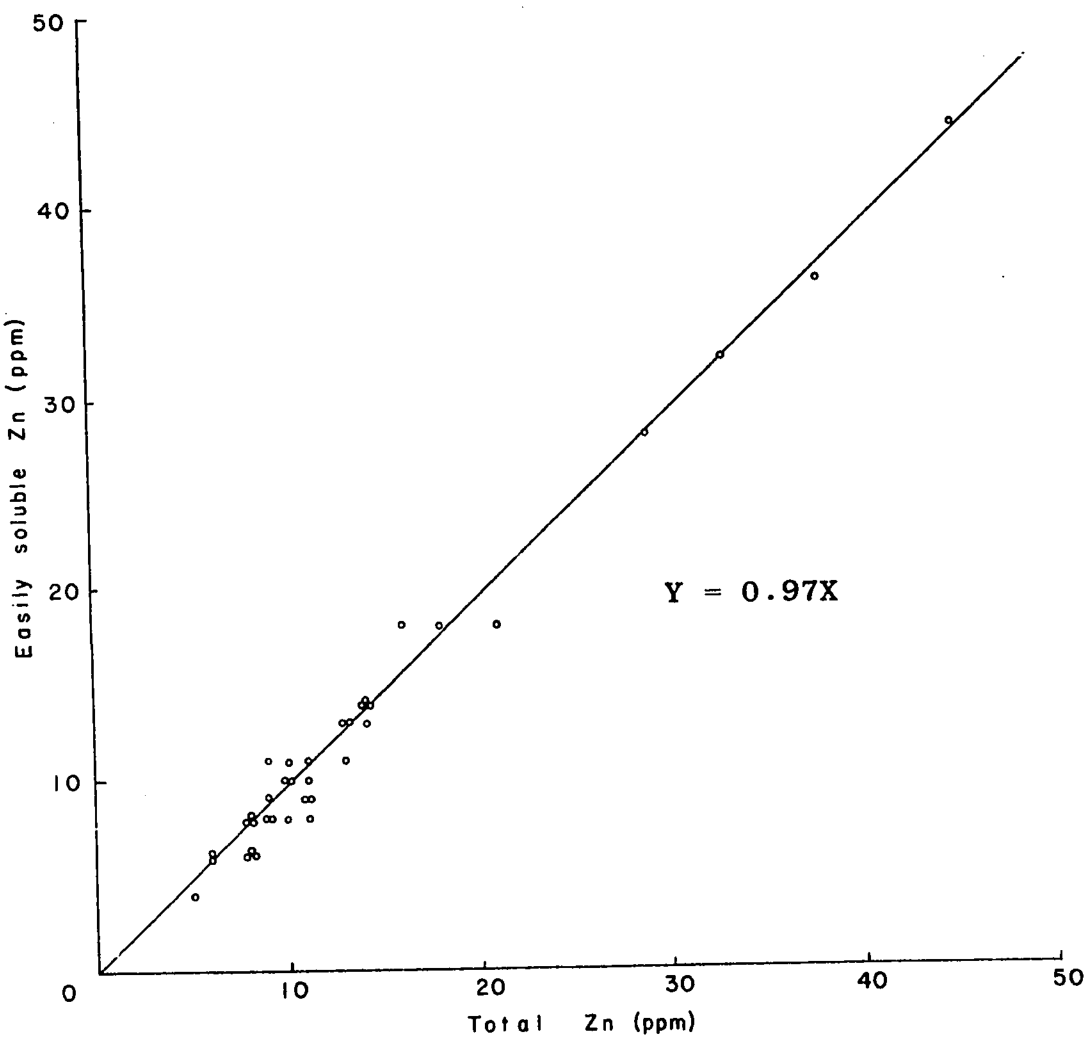



Figure 14. Ratio of easily soluble Zn to total Zn.
Regression line fitted by method of least squares.

## 5.03 Zoning

### 5.031 General Statement

Unlike layered basic intrusives in which crystal fractionation, in particular gravitational differentiation, has led to a diverse assemblage of rock types, granitic intrusives tend to be more uniform in composition. In general, the steep sides of the intrusive and the higher viscosity of acid magmas inhibit settling of heavier minerals or flotation of lighter ones. Moreover, granitic magmas represent silicate melts approaching the closing stages of magmatic crystallization and the minerals precipitating from them are usually late members of Bowen's reaction series. Consequently, unless its composition is modified by contamination, a granitic magma is incapable of generating the diversity of phases and variety of rock types which may arise from more basic magmas.

Steep-sided intrusives such as the Opemisca Lake pluton solidify from the margin inwards. If equilibrium between crystals and melt is not maintained, the magma will differentiate and the mineralogical and chemical composition of the crystallizing granite will change gradually from the margin of the pluton towards the centre. Under these circumstances the granite should become more felsic towards the core and, ideally, the progressive change in the composition of the magma should manifest itself in a series of concentric zones, each of which is characterized by a distinctive chemical and mineralogical composition. The extent to which the granite will vary from one zone to the next will be determined by the degree of equilibrium reached between crystals and melt in each of these zones. Contamination of the margins of the pluton by wallrocks and xenoliths is another factor responsible for compositional differences in the granite.

The Opemisca Lake pluton could not be sampled in a completely unbiased way by customary methods. About one third of its surface is under water, and bedrock exposure over the rest of the intrusive is scant. Furthermore, sampling of the pluton beyond the confines of northwest Levy township was carried out as an adjunct to the geologic mapping. Because of the limited time available, sample localities in the granite were largely confined to the more readily accessible shorelines of lakes. Nevertheless the sample stations are widely and fairly evenly distributed across the entire pluton (fig. 4). Such a sampling pattern is generally more favourable for studying geochemical variation in igneous rocks than one conforming to the rigid requirements of random sampling (Baird and others, 1967, p. 203).

Only raw data were used in constructing the isopleth maps. Isopleths were fitted visually and drawn by hand. The technique of trend surface analysis has come into extensive use in recent years in order to eliminate bias from maps contoured to indicate variability in areally distributed data (Dawson and Whitten, 1962; Sinclair, 1967), to assess regional variation of measurable properties in quantitative terms (Whitten, 1960, 1961), and to separate regional trends from localized effects (Grant, 1957; Whitten, 1961; Dawson and Whitten, 1962; Baird and others, 1967; Nackowski and others, 1967). The use of trend surface analysis and interpretation of data derived therefrom, has not gone unchallenged. Chayes and Suzuki (1963) have raised serious objections to many of the assumptions and inferences made by Whitten (1960, 1961).

The decision not to use trend surface analysis in this work is based on the following reasons:

a) It is an advanced statistical tool. Interpretation of results derived by this method require a very considerable background in statistics theory, which the writer does not have.

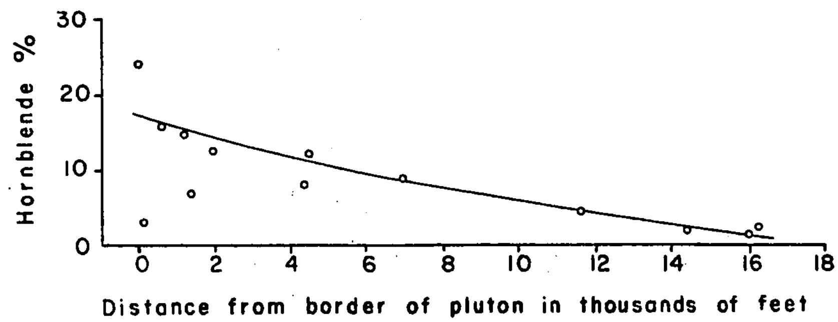
b) The distribution pattern and trends of most elements in the Opemisca Lake pluton are simple and self-evident and do not require statistical verification.

c) Although the fitting of trend surfaces to quantitative data will eliminate bias, it is not certain whether this is desirable under all circumstances. When contouring data based upon field and laboratory work, it is often necessary to be deliberately subjective because of knowledge of conditions in the field, which are not reflected in the laboratory results. To eliminate bias under these circumstances is to eliminate knowledge gained in the field.

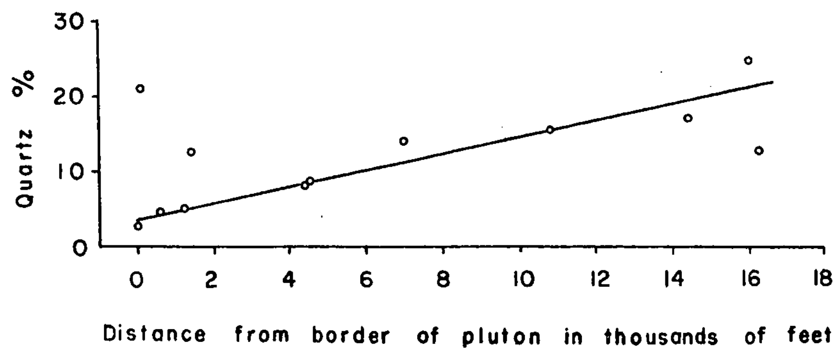
It is more than likely that the seemingly non-uniform distribution of magnetite, $Na_2O$, Co, Cu, Mo and Zn may be elucidated by trend surface analyses. However, none of these components, with the exception of $Na_2O$, are important constituents of the granite, and a change in their distribution patterns will in no way affect the conclusions that have been drawn.

5.032 Mineralogical Zoning

The number of samples subjected to modal analysis were insufficient to outline any distinct zonal pattern in the distribution of the essential minerals and only a general trend has been established. The mineralogical changes appear to be relatively small. The most significant changes are the decrease in the abundance of ferromagnesian minerals (essentially hornblende) from the margin of the intrusive towards the centre (fig. 15A), and the concomitant increase in the quartz content (fig. 15B). Except for a sharp decrease in the marginal zones, owing to the incoming of abundant hornblende, the content and composition of plagioclase very relatively little across the batholith. The amount of potash feldspar present is somewhat erratic and does not specifically increase or decrease in relation to its distance from the margin of the pluton .




A. Hornblende




B. Quartz

Figure 15. Variation in abundance of quartz and hornblende in Opemisca Lake pluton.

In some of the granites near the border of the intrusive, the plagioclase contains a considerable quantity of saussurite which doubtlessly signifies an initially more calcic composition. In contrast, the plagioclase grains from other granites, also in the border zone, are virtually unaltered and contain only a slight sprinkling of saussurite. Nonetheless, their composition, which may range from sodic oligoclase ($An_{15}$) to albite, is essentially similar to that of plagioclase from granites in or near the centre of the intrusive. Allen (1966, p. 293) noticed a similar homogeneity in plagioclase composition in a granodiorite stock in Wyoming. The work of Nockolds on the effects of contamination of granitic magmas offers a possible explanation for the relative lack of variation in the composition and content of plagioclase and the behaviour of potash feldspar. He observed (1933, p. 578) that the introduction of excess lime into a granitic magma could give rise to a variety of reactions depending on the relative scarcity or abundance of alumina. If the available alumina content is high, a basic plagioclase will form and the excess alumina will combine with FeO, MgO and $K_2O$ in the magma to form biotite at the expense of potash feldspar. If the available alumina is low, a less basic plagioclase will form and excess lime will combine with FeO and MgO to form hornblende. Impoverishment of the magma in FeO and MgO forestalls the formation of biotite and the $K_2O$ which is present enters into potash feldspar.

Many of the rocks bordering the Opemisca Lake pluton at its present level of exposure are pyroxenitic and amphibolitic varieties. It is therefore reasonable to assume that substantial quantities of these rocks were incorporated in the granite as xenoliths. In order to have converted these low-alumina pyroxenes and actinolite to the common aluminous hornblende with which the granite was in equilibrium would have entailed the transfer of significant quantities of alumina from the magma to the xenolith during hybridization. It is conceivable that a reduction in the supply of alumina in the magma might have inhibited the formation of the more aluminous calcic plagioclase and facilitated crystallization of the less aluminous alkali feldspars. The exceptionally high Na/Ca ratio might have been a further factor in enhancing the crystallization of sodic plagioclase rather than the more calcic varieties.

Magnetite is the only mineral for which the distribution pattern is known in considerable detail. In his study of the trace element content of magnetite in the Opemisca Lake pluton, Walker (1966) investigated magnetic concentrates from more than 220 samples - a sampling frequency four times more dense than that of the writer. The sample locations and distribution pattern of magnetite are shown in figure 16.

The bulk of the normal granite has a magnetite content ranging from 0.5 to 1.0 percent. The tenor of magnetite increases rapidly towards the margin and reaches its peak along the northern, southwestern and southeastern contacts of the intrusive. The high magnetite content along the borders of the intrusive is readily attributable

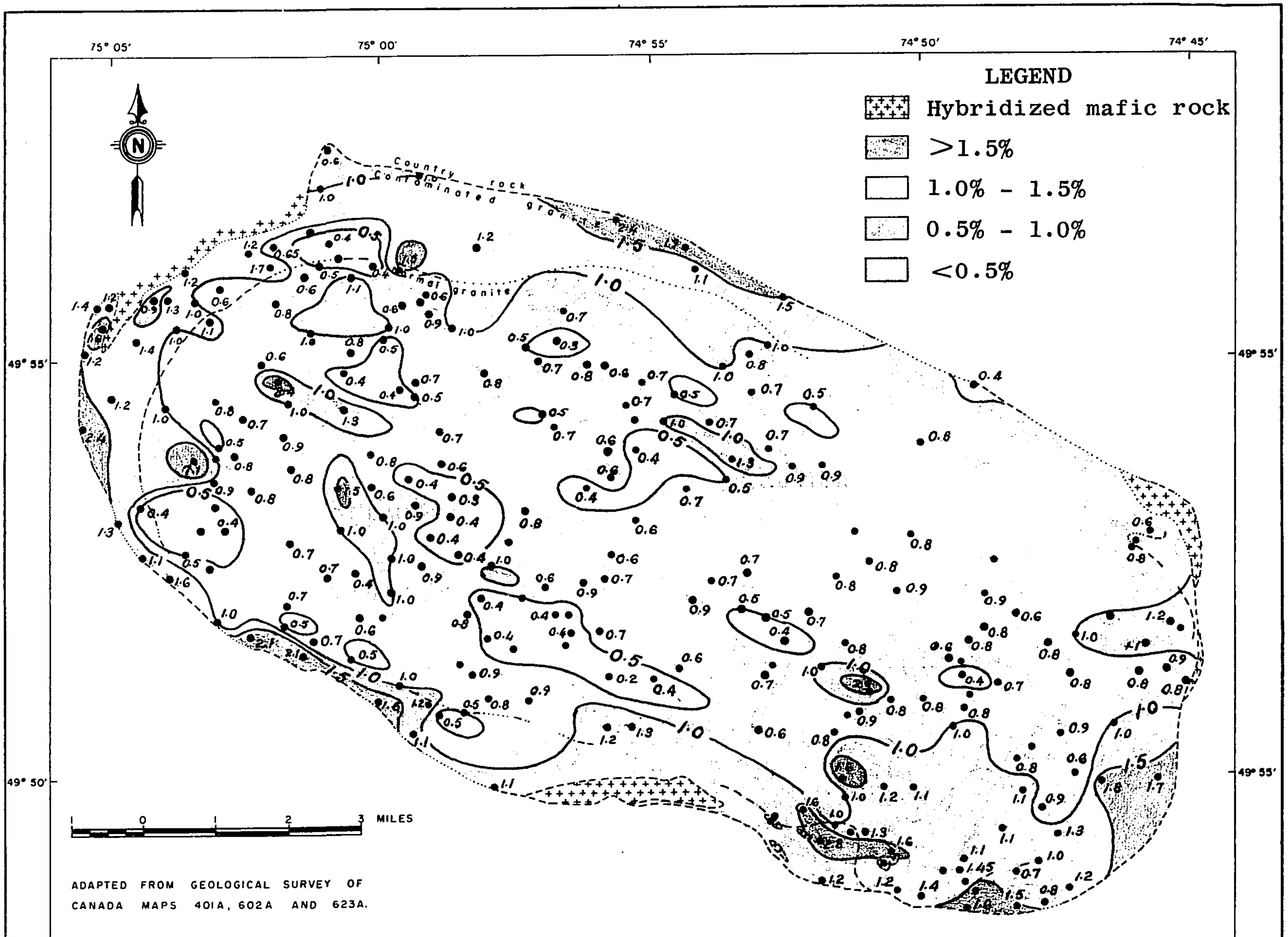



Figure 16. Isopleth map showing distribution pattern of magnetite.

to contamination of the granite by mafic country rocks, inasmuch as the areas of more than 1.0 percent magnetite coincide very largely with the contaminated granites.

Numerous small "pockets" of higher or lower magnetite content are enclosed within the 1.0 percent isopleth line - an area underlain almost wholly by uncontaminated granite (fig. 16). It is noteworthy that the "pockets" of lower than average magnetite content (less than 0.5 percent) are almost invariably closely associated with or flanked by areas of higher than average magnetite content (more than 1.0 percent). This association strongly suggests a transfer of iron from the low magnetite to the high magnetite "pockets". This transfer probably took place during crystallization of the magma when magnetite, for one reason or another, started precipitating earlier or more rapidly in some localities than in others. The irregular rate of removal of iron from the magma resulted in the magma becoming relatively impoverished in iron in the areas where magnetite precipitated in greater abundance. This in turn led to a concentration gradient being set up which brought about the influx of additional iron into the impoverished areas from the surrounding magma. It is evident that if the crystallization of magnetite proceeded along the lines portrayed above, then the close association of areas of high and low magnetite is readily explained. It is also clear that the transfer of iron could only have taken place by diffusion, which, in some localities, involved migration over distances well in excess of a thousand feet. This ready transfer of material by diffusion during the crystallization of the granite is a concept which will be dealt with more fully in the discussions which are to follow.

### 5.032 Chemical Zoning

The majority of the elements or oxides which have been determined in the Opemisca Lake pluton define very clearly the concentric structure within the intrusive. For the most part, this chemical variation appears to be related to variation in the content of quartz and the ferromagnesian minerals. Some elements (or oxides) vary systematically from the core of the intrusion to the margin, whereas the distribution of others has been influenced and modified locally by other factors.

In general, where the effects of contamination are complementary to those produced by differentiation, the variation within the granite will tend to be systematic. On the other hand, where the effects of contamination oppose those produced by differentiation, the distribution pattern of a particular element may be considerably less regular, especially in the marginal zones of the intrusive.

The relative effects of contamination and differentiation have been discussed in a previous section

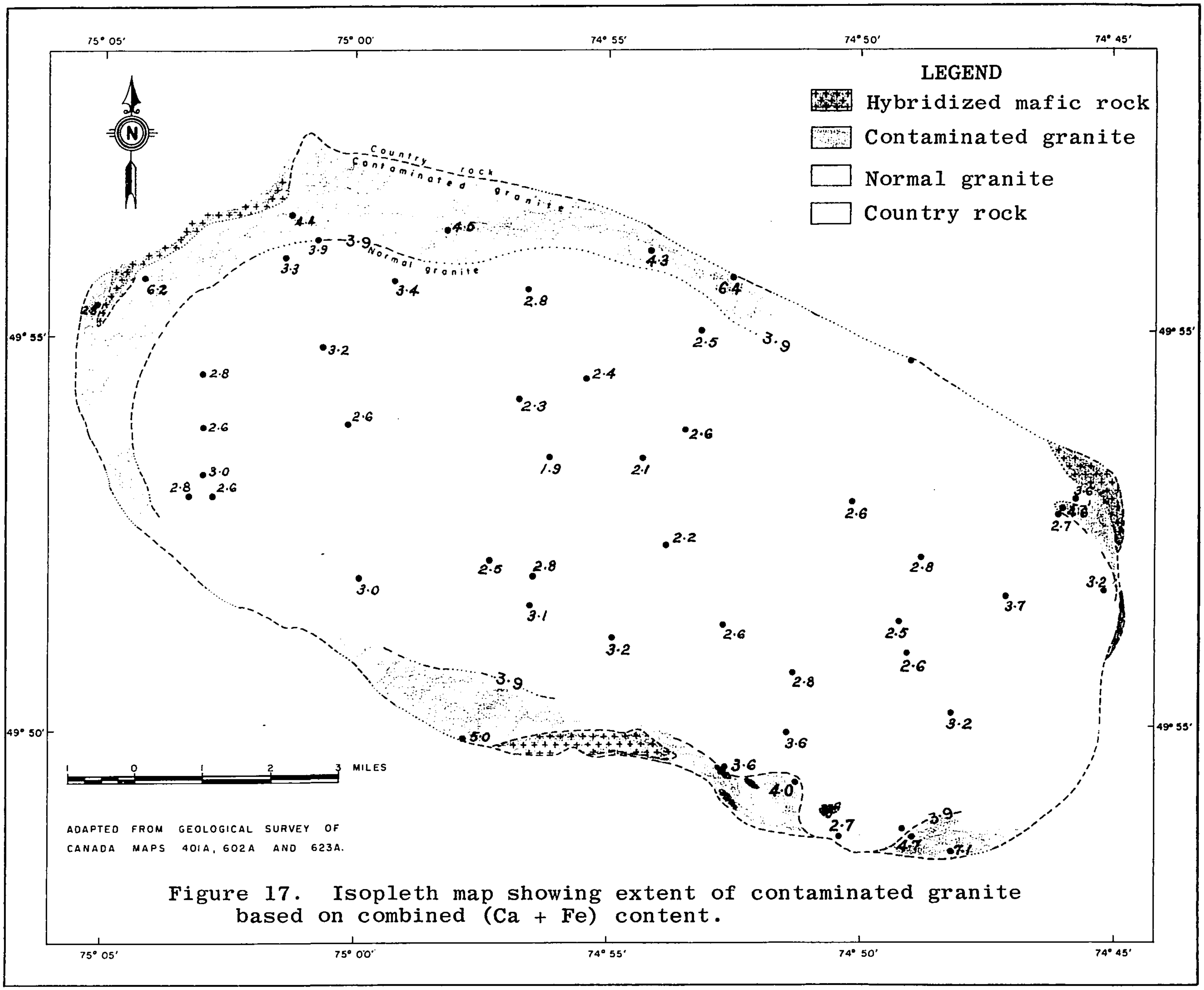



Figure 17. Isopleth map showing extent of contaminated granite based on combined (Ca + Fe) content.

and methods have been outlined whereby it is possible to distinguish between contaminated and uncontaminated granites. In particular, the combined total of calcium and iron has proved to be a sensitive indicator of the extent of contamination of the granite. (See p. 69). On a map depicting the distribution pattern for the combined total of these two elements the isopleth line for (Ca + Fe) = 3.9 will define the approximate boundary between contaminated and uncontaminated granite (fig. 17).

The trend surfaces of the major elements are shown in figures 18 to 25. The relative simplicity of the distribution patterns for $SiO_2$, $Al_2O_3$ and MgO may be largely due to the rather small number of analyses for these oxides.

As a result of differentiation in the uncontaminated granite, $SiO_2$ decreases from the core outwards. This trend is maintained in the contaminated granite which has been modified by reaction with essentially basic and ultrabasic wallrocks, in which the silica content is considerably lower than in the granite. The reverse is true for Ca, Fe, Mg and Ti which increase progressively from the core of the pluton towards its walls. The trend surfaces for each of these elements shows a distinct concentrically zoned distribution.

Silicon (fig. 18, p. 103)

The silica content decreases gradually from more than 70 percent in the interior of the pluton to about

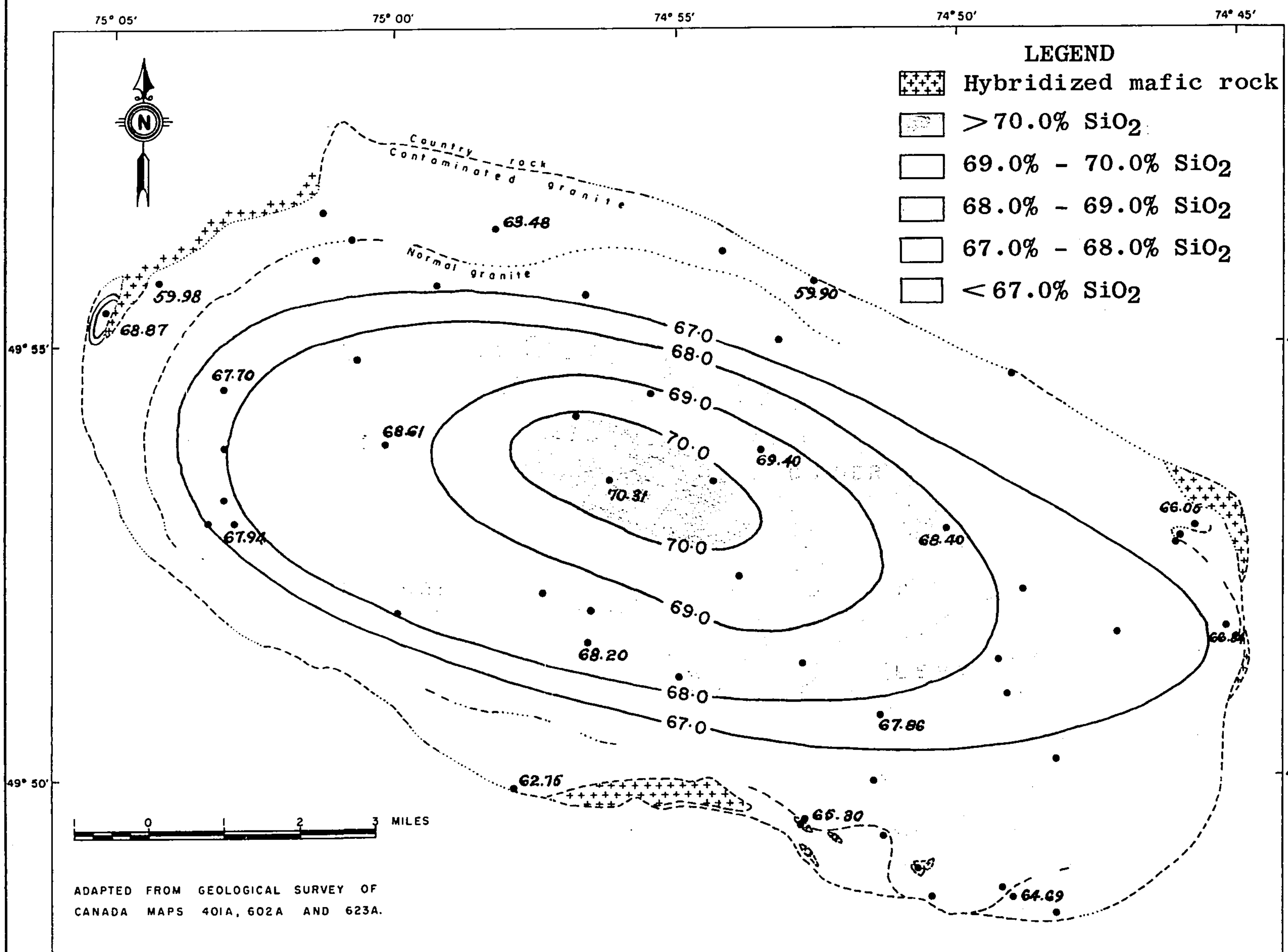



Figure 18. Isopleth map showing distribution pattern of $SiO_2$.

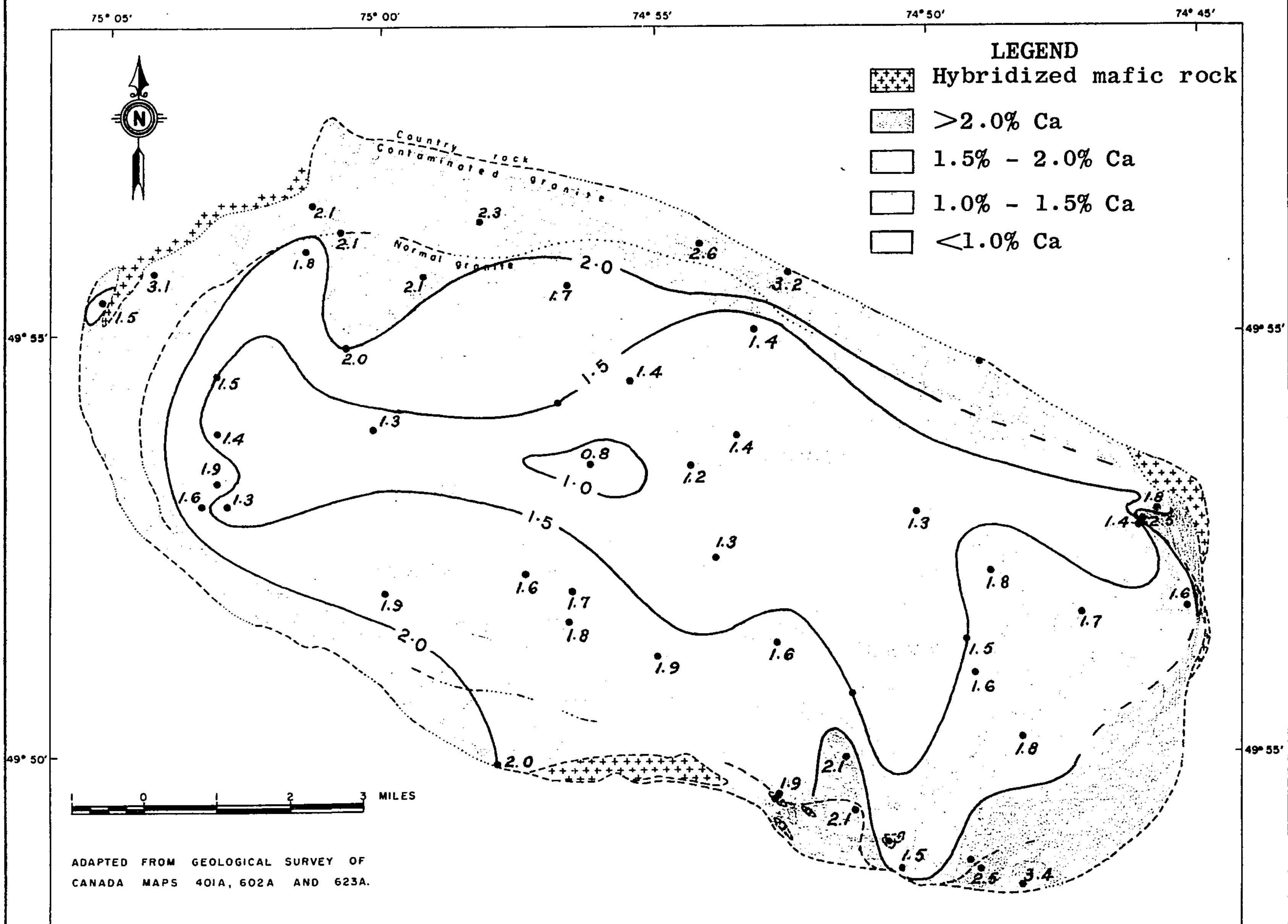



Figure 19. Isopleth map showing distribution pattern of Ca.

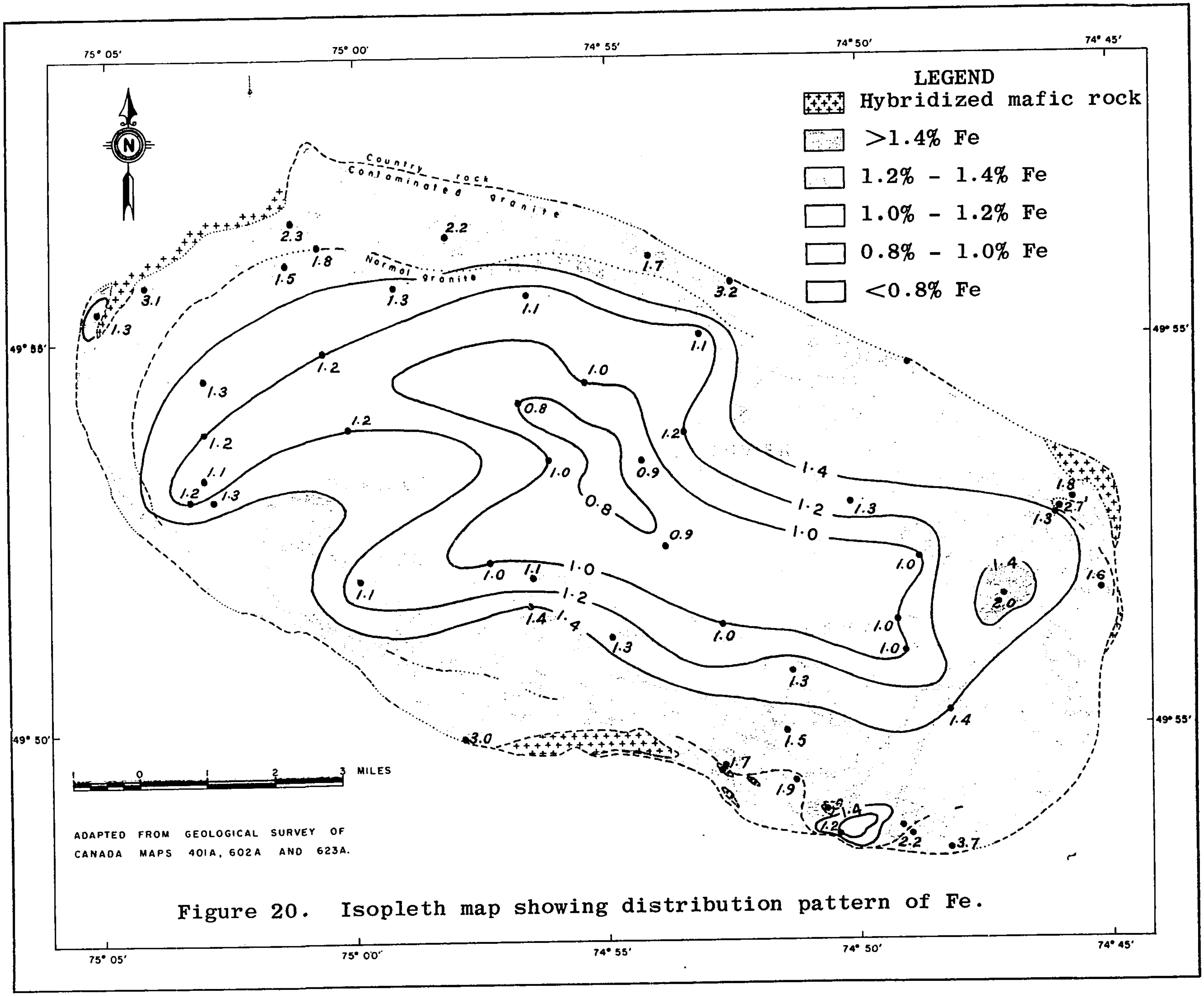



Figure 20. Isopleth map showing distribution pattern of Fe.

66 percent along the outer limits of the uncontaminated granite. In the contaminated granite, silica continues to decrease to 60 percent or less in some of the melasyenitic contact rocks. The average silica content of the uncontaminated granite is 67.88 percent and of the contaminated granite 62.16 percent.

Calcium (fig. 19, p.104)

Calcium ranges from as low as 0.8 percent in the centre of the pluton to about 2.1 percent along the marginal phase of the uncontaminated granite. The contaminated granite generally contains more than 2.1 percent calcium,and in some of the border rocks this figure may be as high as 3.4 percent. The most calcic rocks are located in the northern, northwestern and southern parts of the pluton. These are the areas where contamination has been most intense. The average calcium content of the uncontaminated granite is 1.60 percent and of the contaminated granite 2.53 percent.

Iron (fig. 20, p.105)

The average iron content of the normal granite is 1.24 percent. The range is from 0.8 percent or less in the interior of the pluton to about 1.9 percent at the limits of the uncontaminated granite. In the contaminated granite, iron increases to as much as 3.7 percent in the more melanocratic varieties. The areas of highest iron content

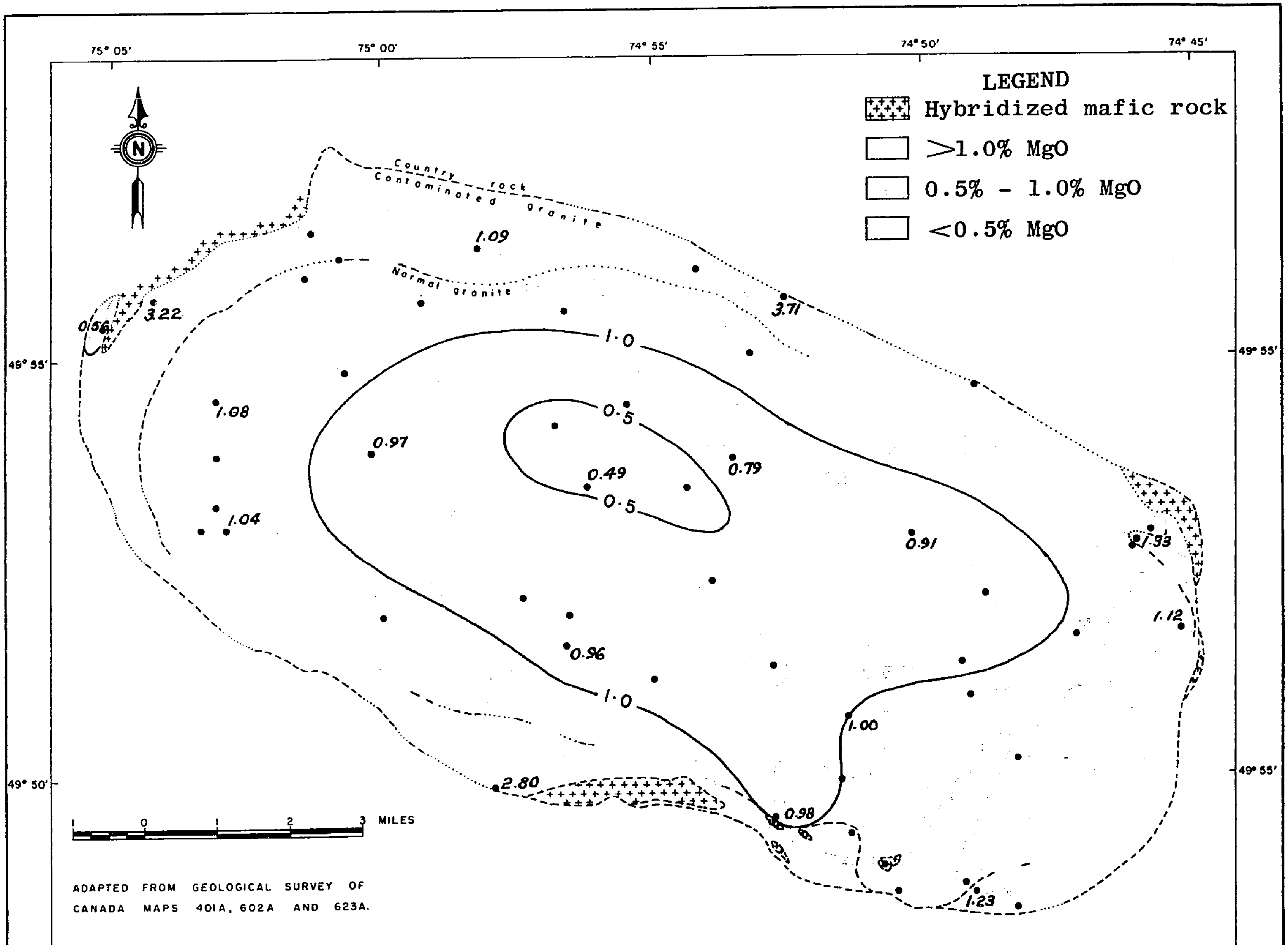



Figure 21. Isopleth map showing distribution pattern of MgO.

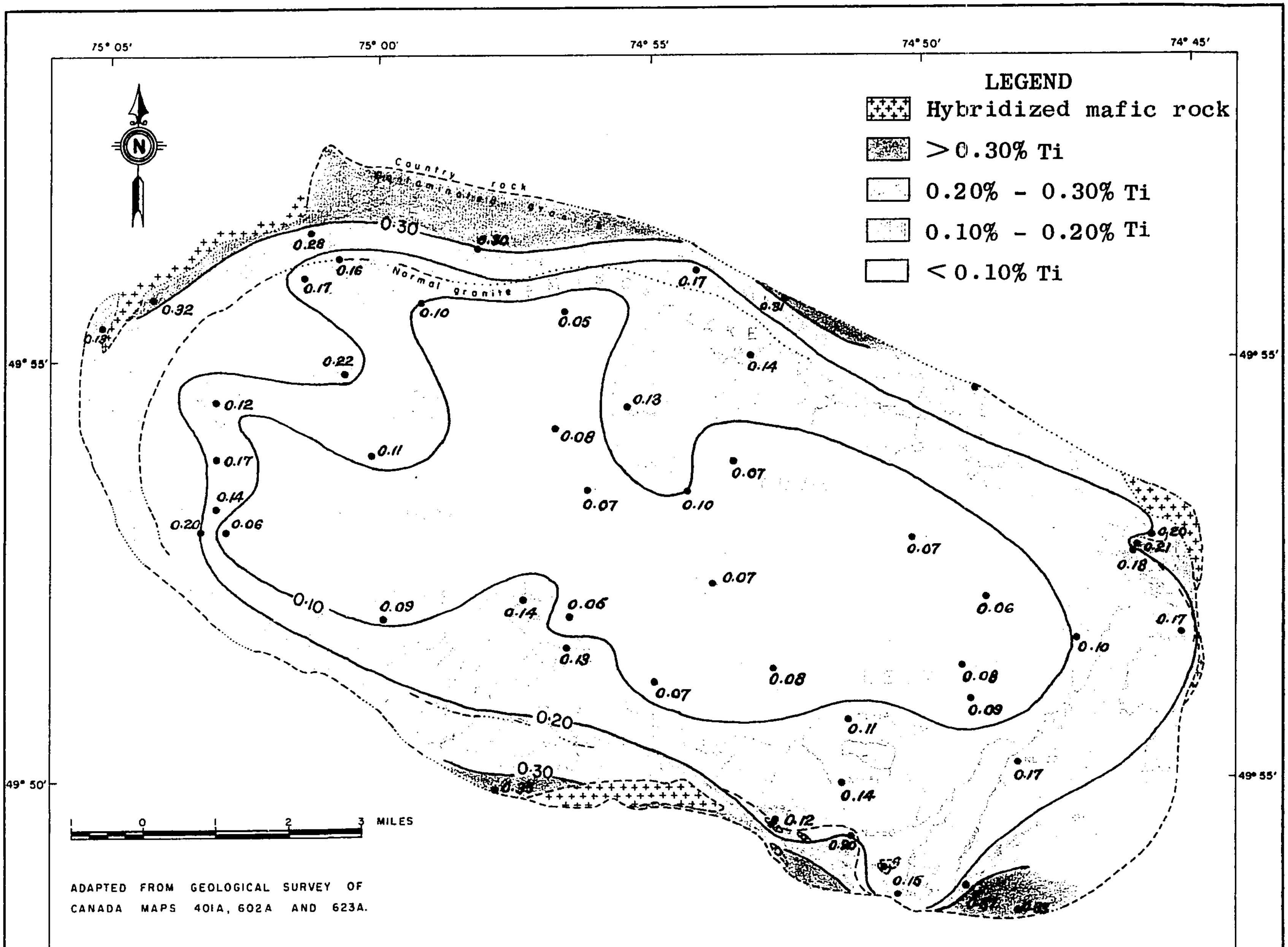



Figure 22. Isopleth map showing distribution pattern of Ti.

coincide with those of highest calcium content. The contaminated granite averages 2.48 percent iron.

Magnesium (fig. 21, p.107)

Magnesia increases from less than 0.5 percent at the core of the intrusive to approximately 1.1 percent at the outer limits of the normal granite. The average magnesia content of the normal granite is 1.00 percent. In the contaminated granite, magnesia averages 2.41 percent, ranging from 1.1 percent to as much as 3.7 percent in the border phases. The areas of highest magnesia content are again coincident with those of highest iron and calcium.

Titanium (fig. 22, p.108)

The distribution of titanium is characterized by a large core of normal granite containing less than 0.10 percent Ti. This is followed by a zone in which the Ti content ranges from 0.11 to 0.20 percent - the 0.20 percent isopleth coinciding for the most part with the boundary of the normal granite. The contaminated granite is generally characterized by a Ti content in excess of 0.20 percent. Areas in which the Ti content exceeds 0.30 percent again coincide largely with the areas of high Ca, Fe and Mg. Average titanium content of the normal and contaminated granites is 0.12 and 0.27 percent respectively.

Potassium (fig. 23, p.110)

The average potash content of the uncontaminated

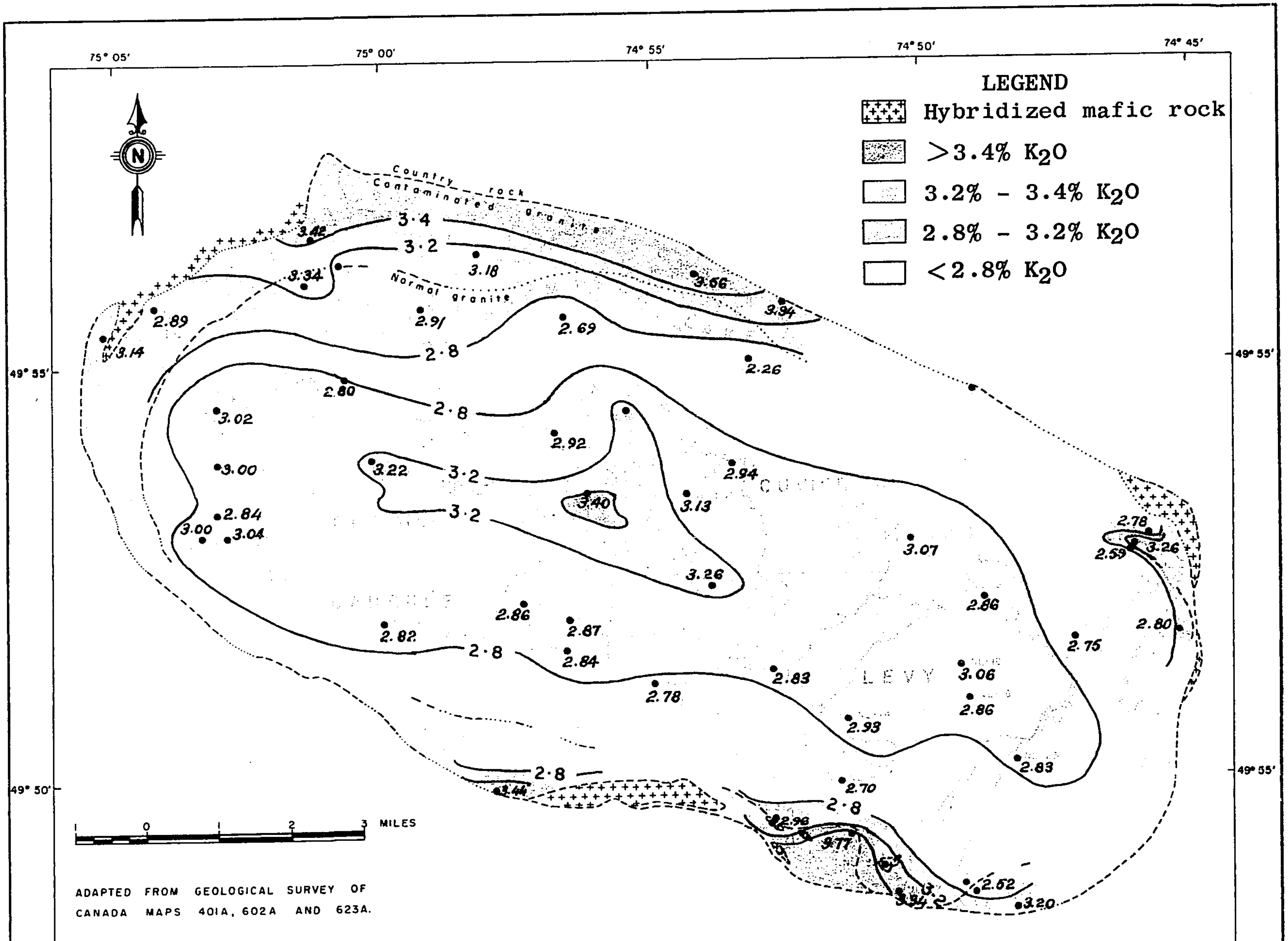



Figure 23. Isopleth map showing distribution pattern of $K_2O$.

granite is 2.93 percent. Potash decreases initially from 3.4 percent or more at the centre of the intrusive to less than 2.8 percent in the outer half of the normal granite. Thereafter, the potash content gradually starts to build up again, particularly in the south central, southeast, north central and northeast sectors of the pluton, attaining concentrations as high as 3.3 percent where the normal granite merges into the contaminated granite. Potash continues to increase in the contaminated granite and reaches its highest concentrations (as much as 3.77 percent) along the borders of the pluton in the four areas mentioned above.

These areas of high potash content generally coincide with those of high Ca, Fe, Mg and Ti content. There can be no doubt that the enrichment in these last four elements resulted from contamination of the granite by the wallrocks. This would suggest that potash was enriched by the same process except for the fact that all of the presently exposed wallrocks, even the rhyolites, are notably poor in potash. The most obvious potassic minerals are potash feldspar and biotite, which is probably the reason why the high potash areas also coincide with areas of high alumina content.

The potash content of the contaminated granites and syenites averages 3.25 percent and is significantly higher than that of normal granites. The behaviour of potash in the contaminated granite runs contrary to expectations.

Possible reasons for this seemingly anomalous situation are as follows:

a) The granite was contaminated at depth by potash-rich rocks not presently exposed in the wallrocks. This is an unsatisfactory explanation for several reasons. Firstly, nowhere in the entire map-area are potash-rich pre-granitic rocks exposed, neither do they occur in any of the immediately adjacent map-areas. Secondly, the abundance of Ca, Mg, Fe and Ti in the contaminated rock clearly indicate that basic rocks, usually characterized by very low potash contents, were the contaminants.

b) Differential melting of basic and intermediate greenstone wallrocks and xenoliths. Minerals low in the reaction series such as muscovite (sericite), potash feldspar (if present), albite and quartz would go into solution provided the magma was still undersaturated with respect to these minerals (Bowen, 1928, p. 221). The composition of such an early melt would be in the vicinity of the ternary minimum on the Quartz-Orthoclase-Albite diagram (fig. 35, p.143 ). It would be considerably more potassic than the granite magma and hence should lead to enrichment of the granite in potash. Removal of the early melting minerals would bring about a disintegration of the greenstone xenoliths, leaving behind the more mafic remnants. This could be the reason why the contaminated granites and syenites in the high potash areas are generally thickly strewn with tiny granular mafic aggregates.

c) Chemical and mineralogical data indicate that potassium has been introduced into many of the xenoliths and fixed as either potash feldspar or biotite, or both. This hybridization may have been responsible for an influx of potassium from the inner portions of the pluton to the margins where contamination was most extensive. The process visualized is as follows: potassium transfuses readily into magnesium-rich xenoliths (Nockolds, 1933, p. 570). This may bring about impoverishment in K in the areas where the magma has been much contaminated. Impoverishment results in a concentration gradient being set up, which in turn leads to an influx of potassium by diffusion from the inner portions of the intrusive where potassium is still abundant in the magma. A serious objection to this theory is the supposed slow rate of diffusion in viscous silicate melts. However, as Bateman and his co-workers (1963) have pointed out, diffusion, even at the rate of a few centimeters per year, could attain major significance

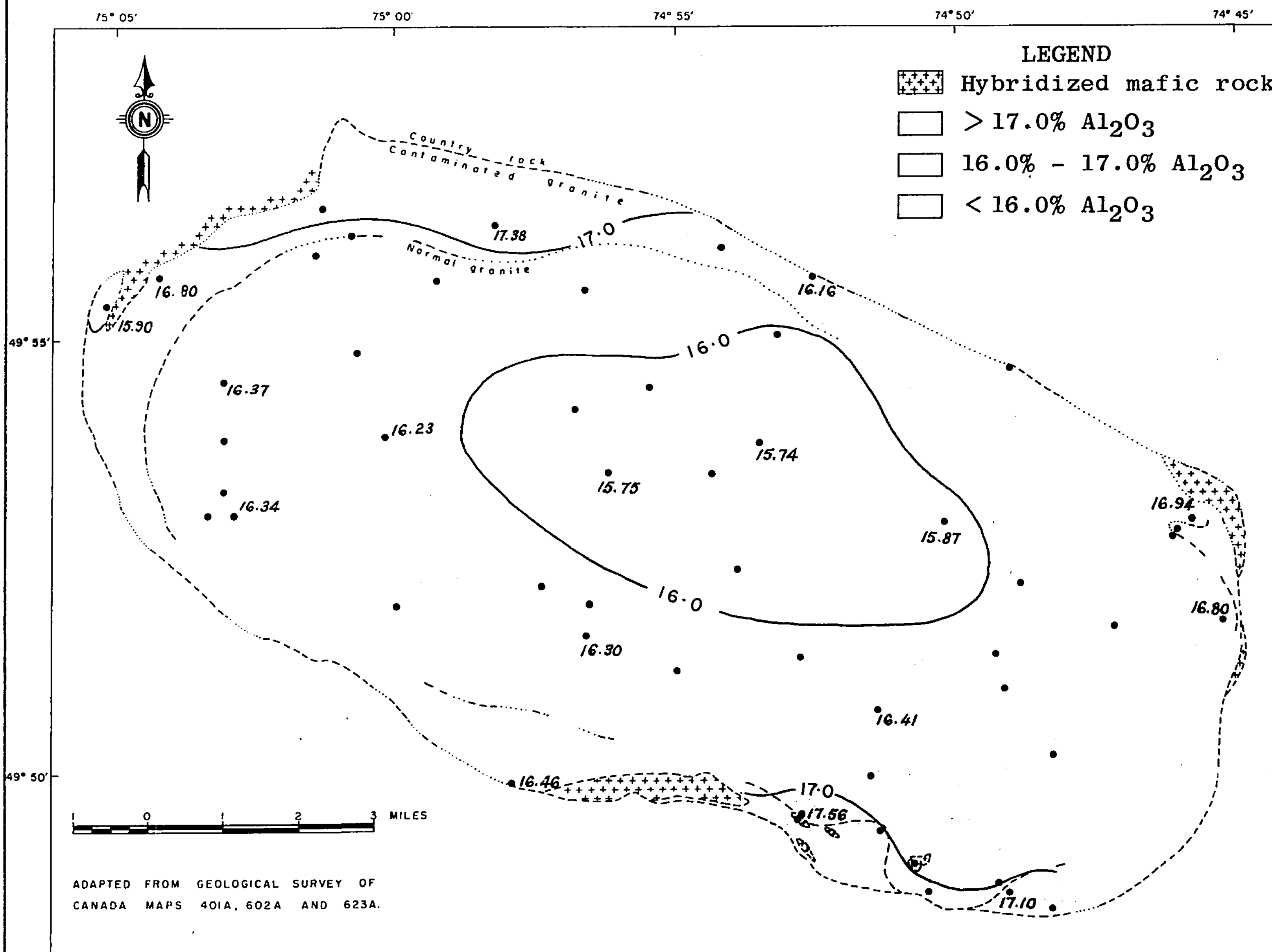



Figure 24. Isopleth map showing distribution pattern of $Al_2O_3$.

over the period of crystallization of a pluton, which may extend over hundreds of thousands of years[1]. Moreover, it has already been pointed out (see pp. 99-100 ) that the peculiar distribution pattern of magnetite must have involved the diffusion of iron over distances of as much as a thousand feet or more. There is no reason why potassium which is not removed from the magma at such an early stage as the iron and which is therefore "active" over a longer period of time, should not be capable of similar action. The general abundance of potassium in large basic xenoliths in the granite, as compared to other elements introduced from the granite, testifies to its ability to migrate freely by diffusion.

Aluminum (fig. 24, p.114)

The uncontaminated granite contains an average of 16.44 percent alumina, and the contaminated granite 16.78 percent. The central portion of the pluton is characterized by an extensive area in which the alumina content is less than 16.0 percent. From here, alumina increases gradually outwards and most of the rocks in the pluton, normal as well as contaminated granites, contain between 16.0 and 17.0 percent $Al_2O_3$. In two areas, along the northwestern and

[1]Lovering (1955) has calculated that the Sierra Nevada batholith probably took more than one million years to solidify.

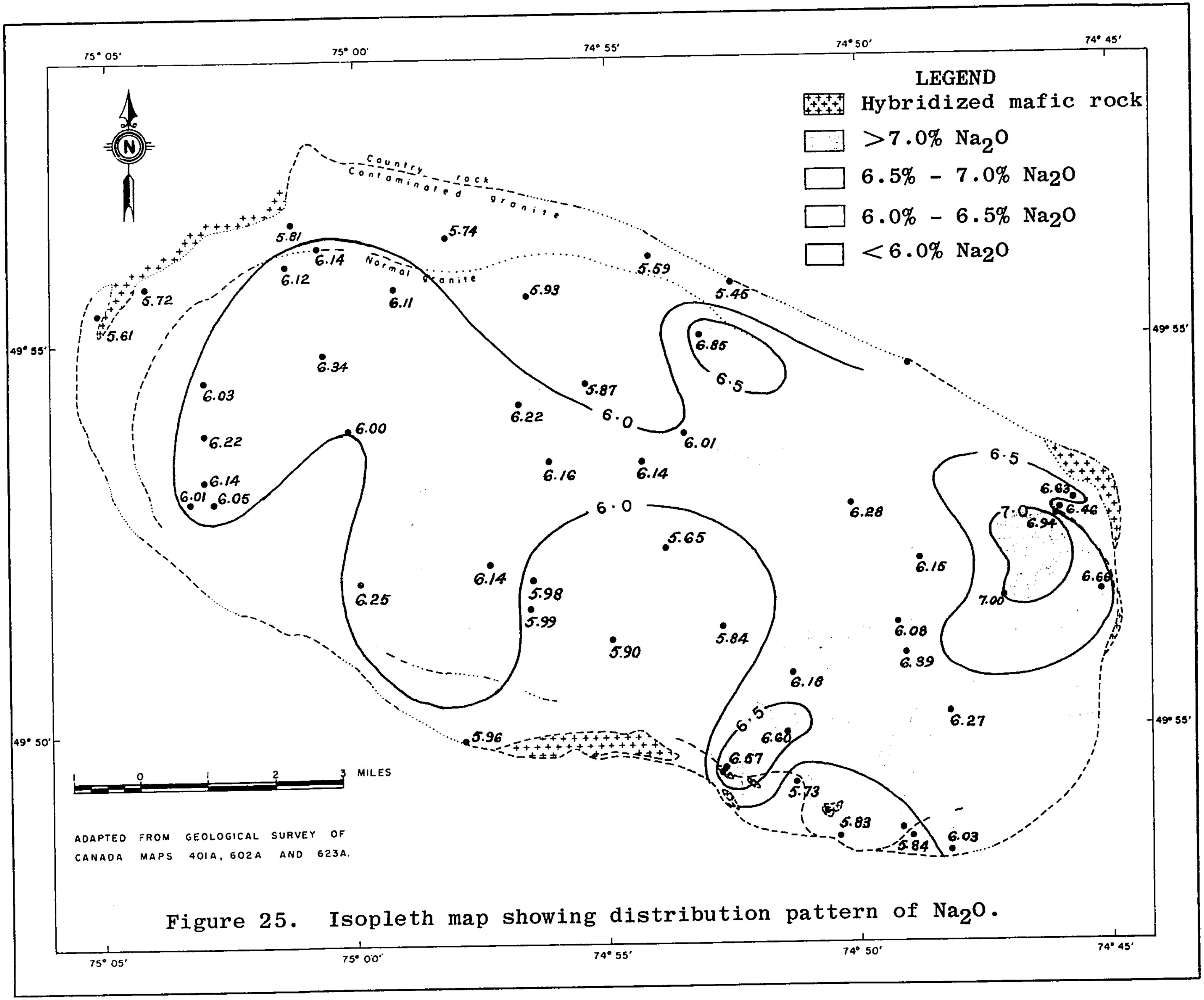



Figure 25. Isopleth map showing distribution pattern of $Na_2O$.

southeastern borders of the pluton, the alumina content exceeds 17 percent. These areas coincide to a considerable degree with those characterized by high Ca, Fe, Mg, Ti and K.

The explanation of the high alumina content, like that of the high potash content in these marginal contaminated rocks, is problematical. Chemical analyses of samples collected by the writer show that with the exception of certain rare meta-andesitic rocks and the greywackes, none of the country rocks in the region have alumina in excess of 17 percent. Therefore, the high level of $Al_2O_3$ in the contaminated granite is not due simply to the assimilation of xenolithic material. Rather, the close association of potash- and alumina-rich contaminated rocks suggest that biotite and potash feldspar contribute substantially to the alumina content of the contaminated rock. The alumina required for the formation of biotite and K-feldspar may have been introduced along with and in the same way as the potassium.

Sodium (fig. 25, p.116)

The unusually high soda content (average 6.20 percent) of the normal granite is one of its most distinctive features. The average soda content of the contaminated granite decreases to 5.86 percent, but there is no distinct dividing line between the two types of granite on the basis of their soda contents. The trend surface for $Na_2O$ shows that most of the pluton is underlain by normal as well as contaminated granites containing in excess of 6.0 percent $Na_2O$. This area of high soda content is deeply embayed in the northern, southwestern and south central parts of the pluton by granites containing less than 6.0 percent $Na_2O$. Several patches of above average soda content occur in the eastern half of the pluton, and in the easternmost of these areas, the granite contains as much as 7.0 percent (or more) $Na_2O$.

The reason for the irregular distribution of sodium is not known and will probably require a more detailed study of the wallrocks to see whether changes in the composition of the granite along the borders of the intrusive can be related to changes in the nature and geochemistry of the adjacent wallrocks.

The trend surfaces of the trace elements are shown in figures 26 to 34. It is quite possible that contouring of the points for the various elements by other individuals could give rise to configurations differing from those shown in this work. This is particularly true for those elements which are less systematically distributed, such as Co, Cu, Mo and Zn. It was pointed out in a preceding section (p. 94) that the data for these elements might benefit from a trend surface analysis. With the exception of Zn, it is these same elements which are present, for the most part, in concentrations at or near the lower limit of sensitivity of the analytical methods used. The results are

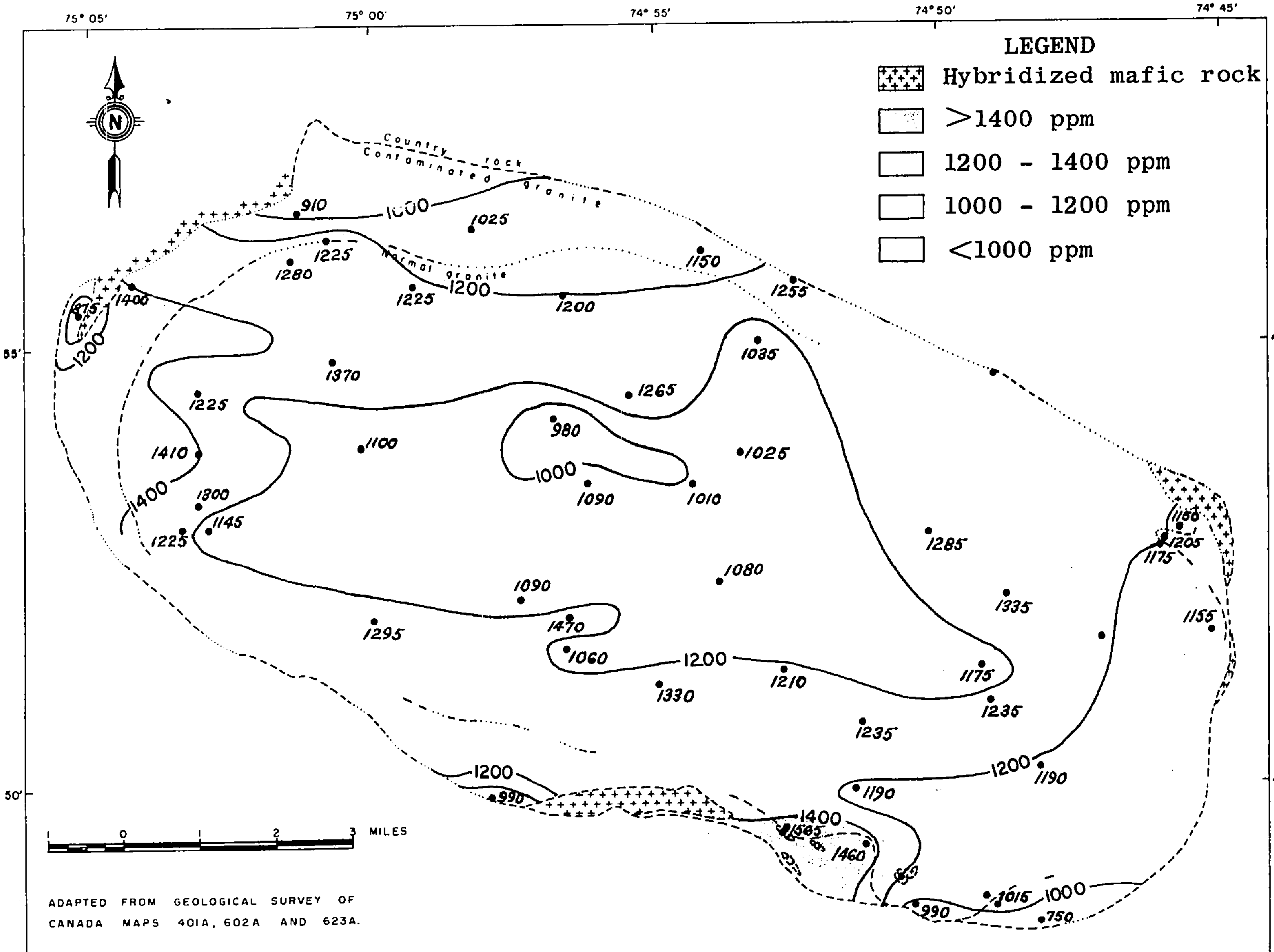



Figure 26. Isopleth map showing distribution pattern of Ba.

therefore more susceptible to error than those of the other trace elements.

Barium (fig. 26, p. 119)

Barium and strontium are the two elements which illustrate most clearly how the distribution of an element is affected when contamination and differentiation of the granite give rise to opposing trends.

As a result of its tendency to be captured by early potassium-bearing minerals during magmatic crystallization, Ba should have become impoverished in the core of the pluton where the final crystallization took place. This is so and it is found that Ba increases from less than 1000 ppm in the centre of the intrusive to as high as 1565 ppm along the outer margins of the normal granite. However, the trend of the isopleth lines is independent of the contact between the normal and uncontaminated granites, so that the concentration of Ba in this particular region varies considerably. Generally it is less than 1300 ppm.

The increase of Ba from the core outwards is counteracted by contamination of the granite in the border zones by mafic and ultramafic country rocks with a low barium content. Consequently, the initial increase is followed by a decrease, and in the areas where contamination was most extensive, particularly along the northwest, southeast and south central contacts of the pluton, the Ba content has diminished to less than 1000 ppm.

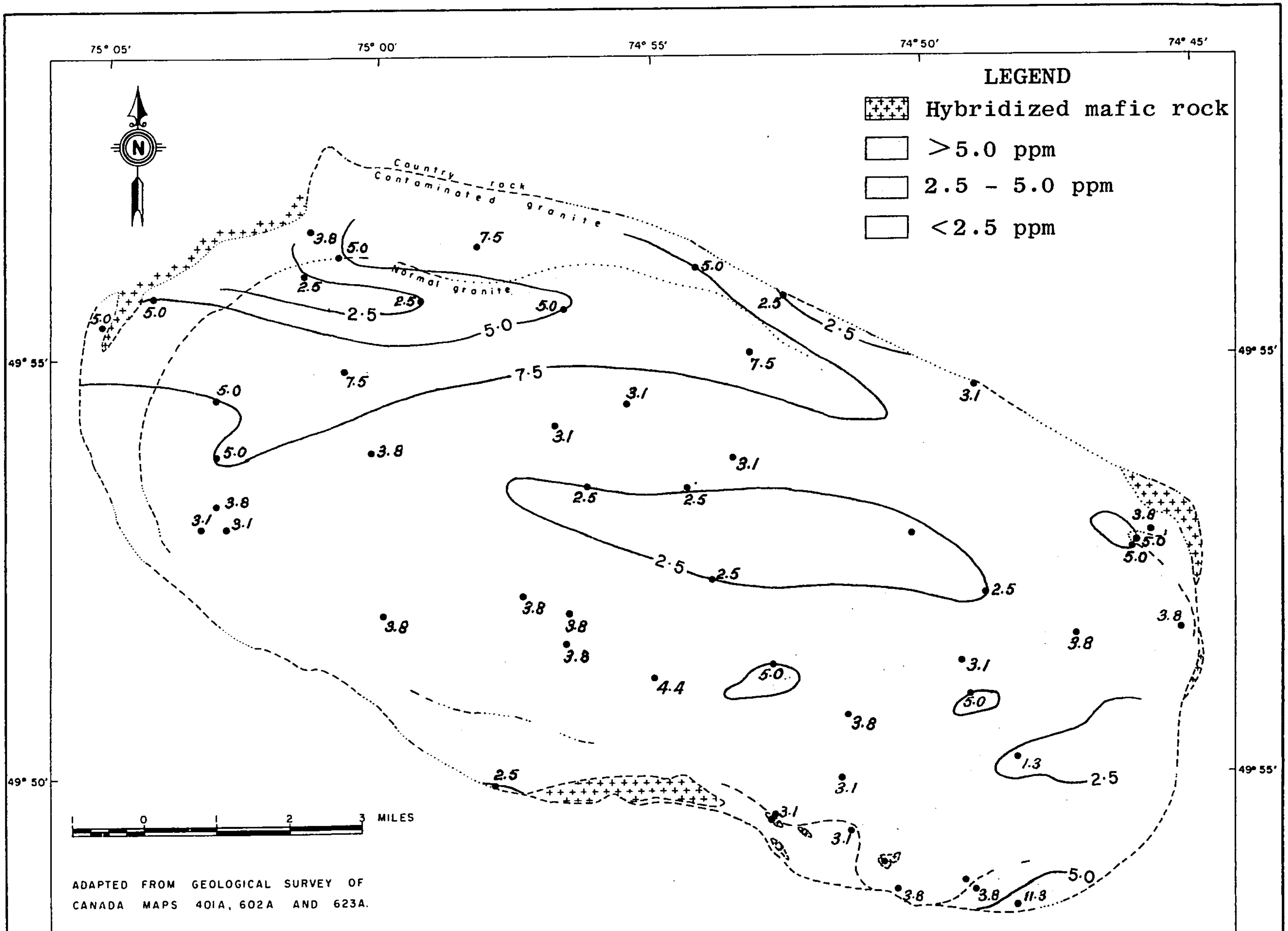



Figure 27. Isopleth map showing distribution pattern of Co.

The average Ba content of the normal (uncontaminated) granite is 1205 ppm and of the contaminated granite 1130 ppm.

Cobalt (fig. 27, p. 121)

Cobalt distribution in the Opemisca Lake pluton is characterized by an elongated area of low cobalt content (2.5 ppm or less) in the centre of the intrusive, surrounded by a zone of granite containing between 2.5 and 5.0 ppm cobalt which covers most of the pluton. The north-western part of the pluton is underlain by an irregular elongated strip of normal and contaminated granite containing more than 5.0 ppm cobalt. In the interior of this strip, the cobalt content decreases again to 2.5 ppm or less. Other small patches of granite carrying 5 ppm or more of cobalt are sparsely scattered across the eastern half of the intrusive.

With the exception of the core of low cobalt content which coincides with the more highly differentiated granite in the centre of the pluton, the distribution pattern for cobalt does not tie in well with the distribution pattern of the other elements, nor can it be related to the effects of differentiation and contamination in the way most of the other elements can.

The average cobalt content of the normal granite is 3.8 ppm, which is very close to the theoretical figure of 3.9 ppm predicted by the Co-Mg curve of Carr and Turekian (1961, fig. 11). The contaminated granite has an average

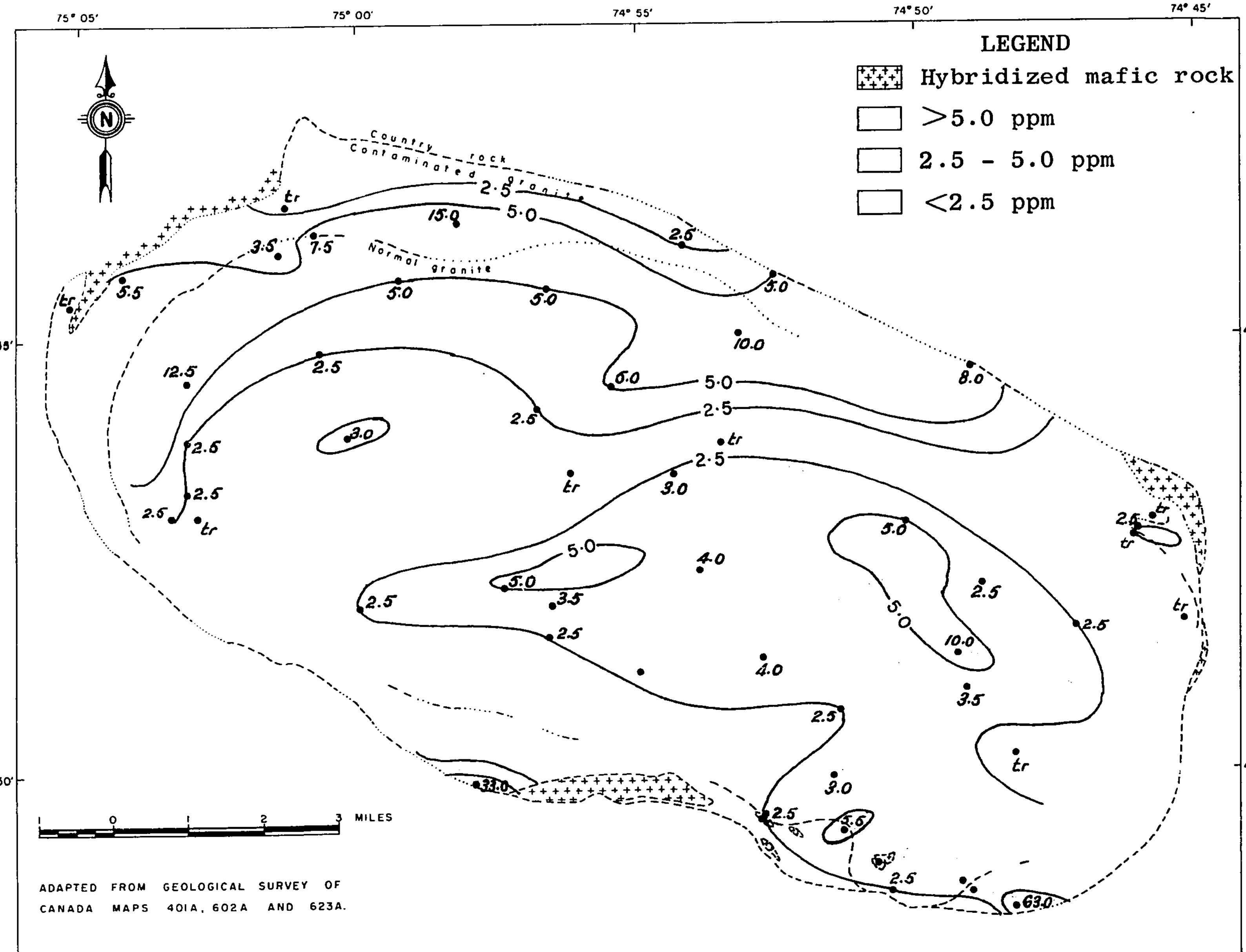



Figure 28. Isopleth map showing distribution pattern of Cu.

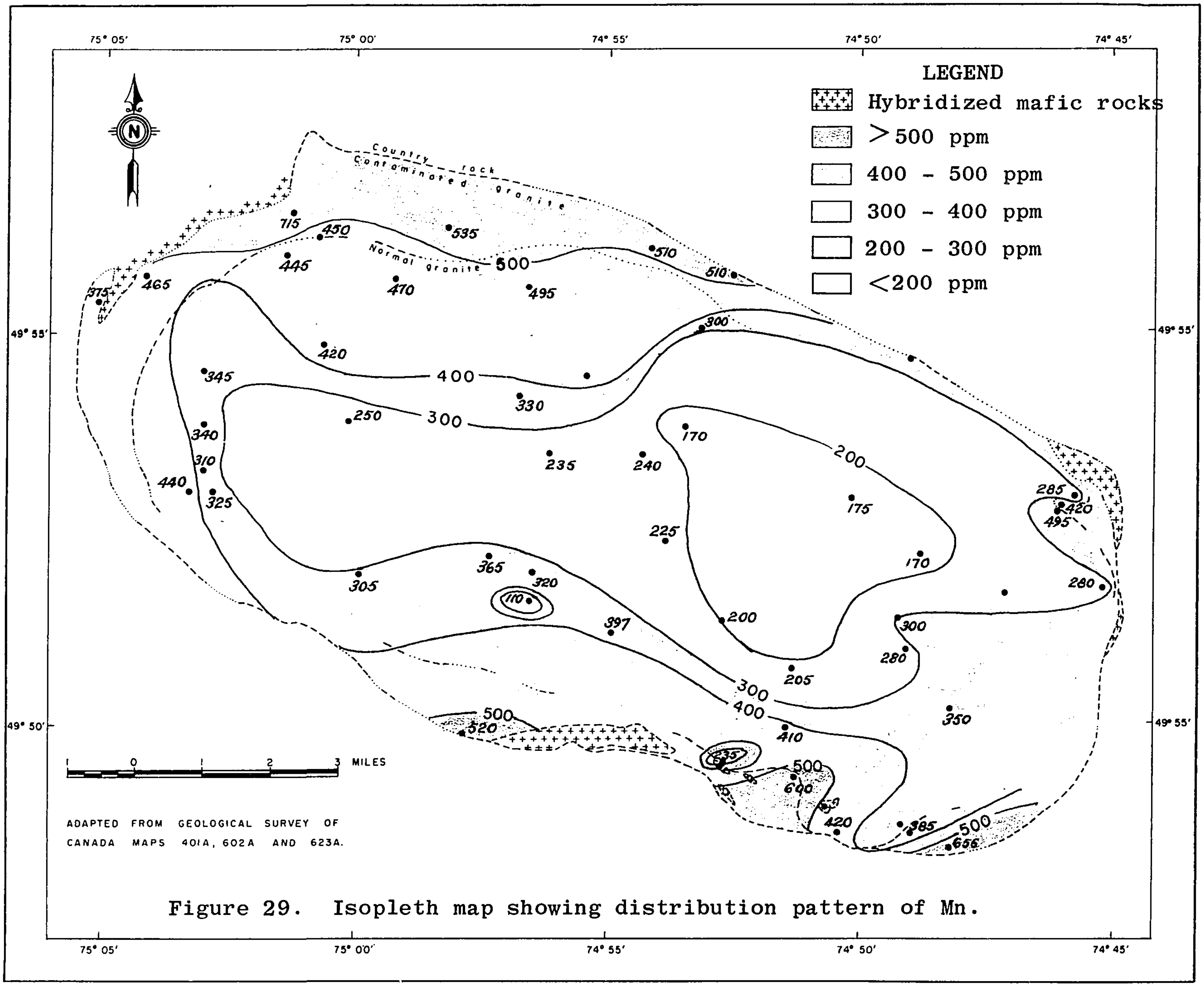



Figure 29. Isopleth map showing distribution pattern of Mn.

cobalt content of 5.0 ppm.

Copper (fig. 28, p. 123)

The average copper content of the normal granite lies between 3.3 and 3.8 ppm, depending on the actual quantity of Cu present in those samples in which it was too low for quantitative measurement. Although some of the contaminated granites have a high copper content (ranging from 10 to almost 20 times as high as in the normal granite), their average content is only 12.9 ppm Cu. Apart from these isolated manifestations of contamination of the granite by mafic or ultramafic country rocks with a comparatively high copper content, the distribution pattern for copper is unsystematic. Possible reasons for this have been discussed in the section dealing with the chemical trends of elements within the pluton.

Manganese (fig. 29, p. 124)

Manganese shows an excellent concentrically zoned pattern. It increases progressively from a core of less than 200 ppm Mn to as much as 715 ppm in some of the highly contaminated granites along the border of the intrusive. Although the areas of highest manganese content coincide with those of highest Ca, Fe, Mg and Ti, the core of low manganese content is noticeably offset to the southeast of the area at the centre of the intrusive where most other elements reach their highest or lowest concentrations.

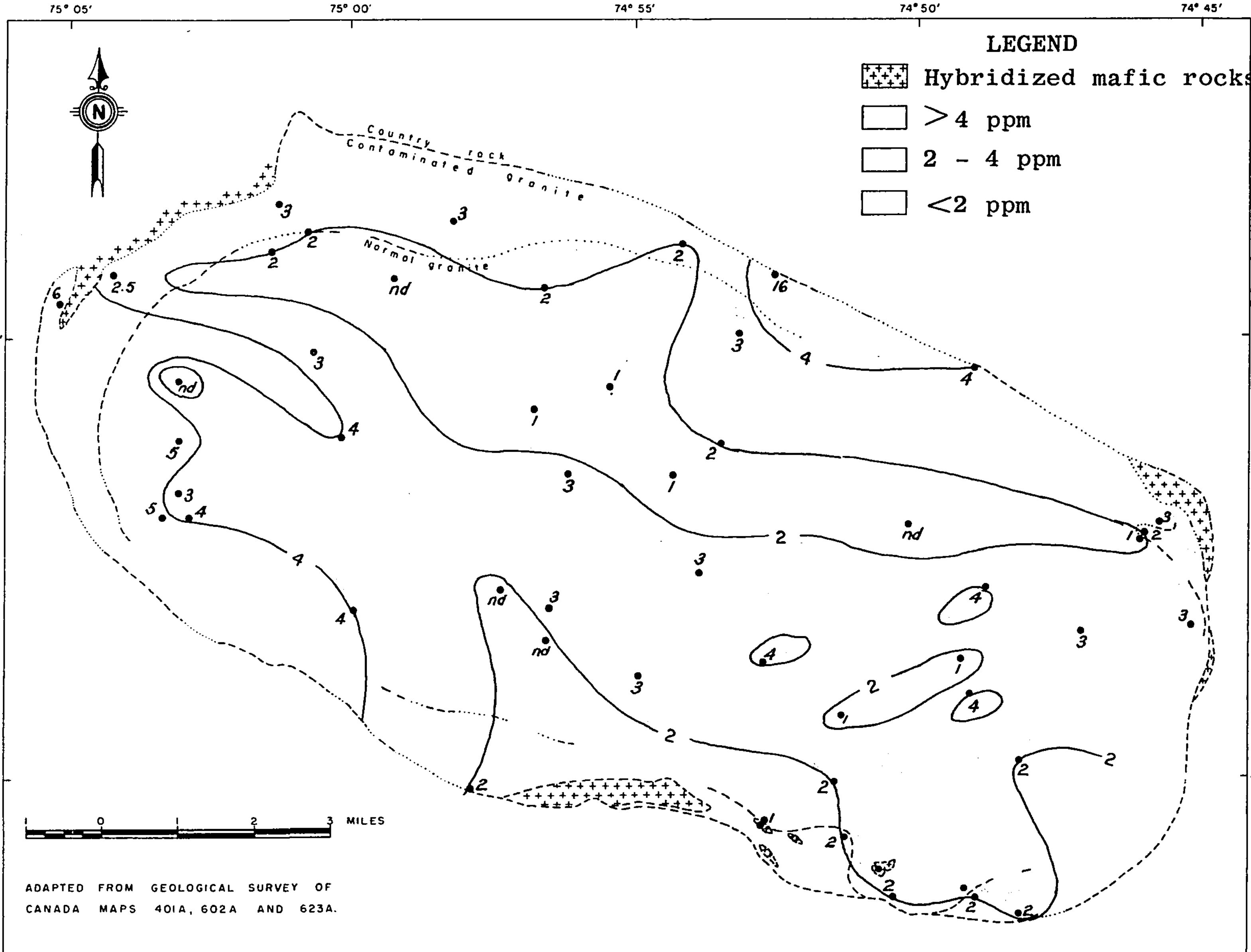



Figure 30. Isopleth map showing distribution pattern of Mo.

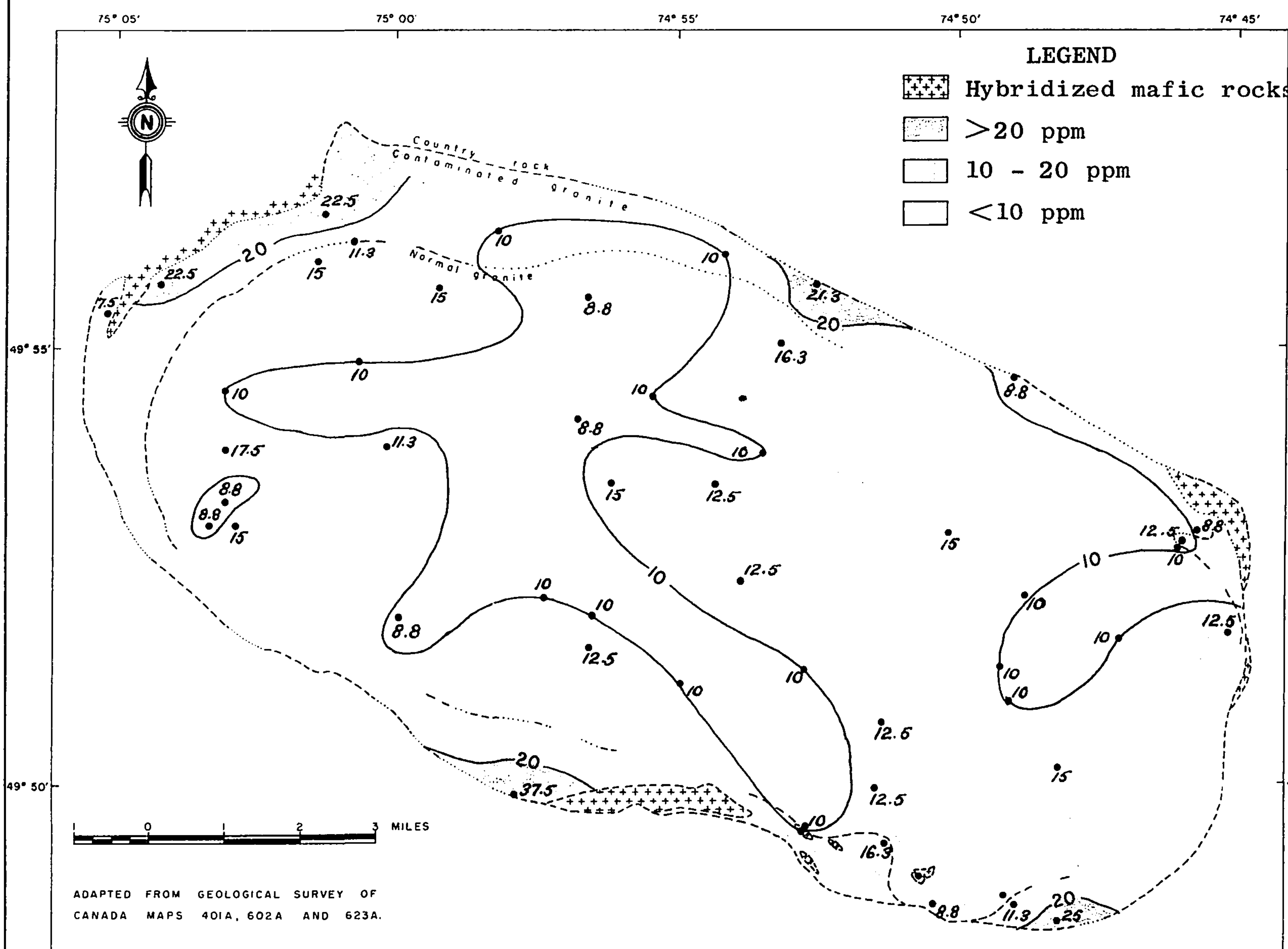



Figure 31. Isopleth map showing distribution pattern of Ni.

The average manganese content of the uncontaminated granite is 317 ppm, and of the contaminated granite 524 ppm.

Molybdenum (fig. 30, p. 126)

Most of the Opemisca Lake pluton is underlain by rocks having a molybdenum content between 2 and 4 ppm. An elongated area containing less than 2 ppm Mo lies to the northeast of, and parallel to, the longest axis of the pluton. There is a tendency for the molybdenum content to increase somewhat erratically outward from this low area, but this trend is disrupted in the southeast of the pluton where the Mo content again diminishes to less than 2 ppm. These trends do not coincide with those of any of the other elements.

The average molybdenum content of the uncontaminated granite is 2.3 ppm and of the contaminated granite 3.5 ppm. The higher figure for the contaminated granite is essentially due to one analysis which yielded 16 ppm Mo. If the result of this analysis is considered as possibly being a gross error, the average for the contaminated granite decreases to 2.4 ppm - virtually identical to that of the normal granite.

Nickel (fig. 31, p. 127)

The lowest nickel contents (less than 10 ppm) in the Opemisca Lake pluton are confined largely to a highly irregular area, offset slightly to the northwest of the centre of the intrusive. A somewhat erratic increase of Ni takes place from the core outward and although several small patches of granite containing less than 10 ppm Ni occur elsewhere, the bulk of the exposed rocks of the pluton carry between 10 and 20 ppm Ni.

Nickel in excess of 20 ppm is found only in a few localities along the borders of the intrusive where contamination of the granite has been most pronounced.

Although the distribution of nickel conforms more or less to the expected pattern, several anomalous situations do exist. Most important, the area of low nickel content does not coincide well with the most highly differentiated rocks in the centre of the intrusive, and in some areas along the borders of the pluton the nickel content is unexpectedly low, despite contamination of the granite by basic and ultrabasic wallrocks which carry notable quantities of nickel. The reasons for this are not understood.

The average nickel content of the normal granite is 11.4 ppm and of the contaminated granite 17.4 ppm.

<u>Lead</u>

Inasmuch as the analytical results for lead are suspected of being in error, the distribution pattern for this element has not been plotted.

<u>Strontium</u> (fig. 32, p.130 )

Strontium, which becomes impoverished in the late crystallizing fractions of granitic rocks, shows much the same trend as barium. From the core of the intrusive where

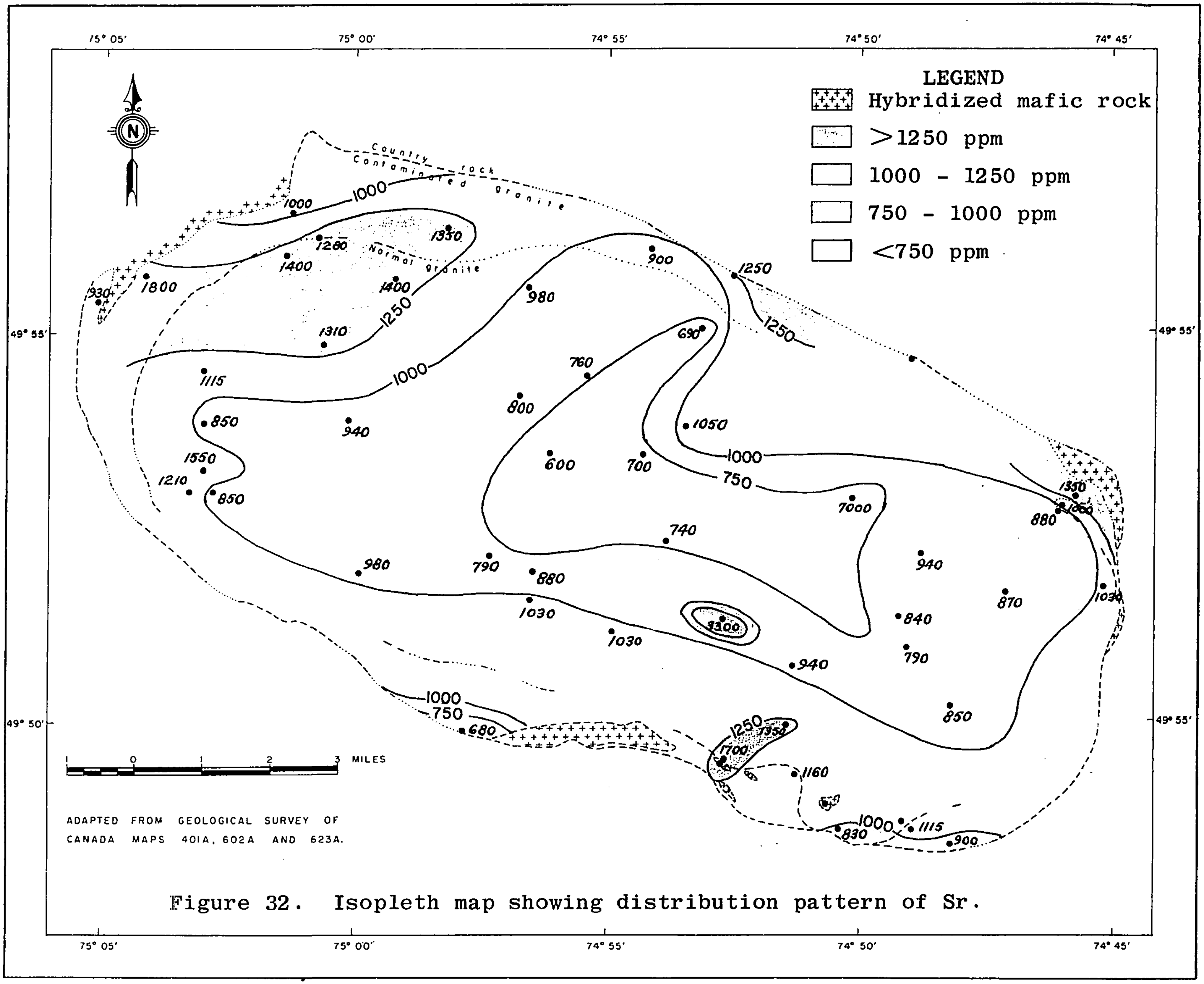



Figure 32. Isopleth map showing distribution pattern of Sr.

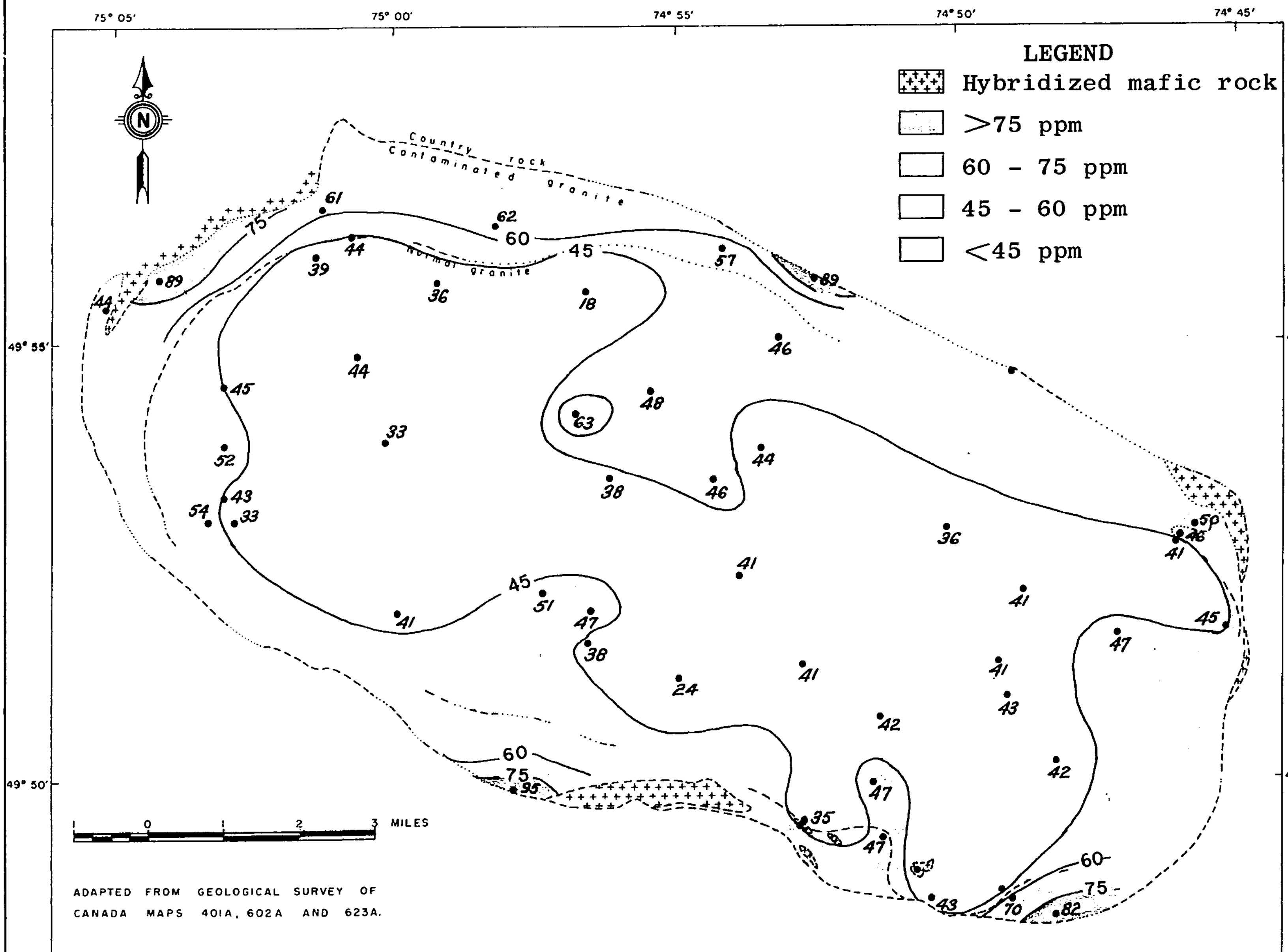



Figure 33. Isopleth map showing distribution pattern of V.

the concentration is less than 750 ppm, it increases initially to as much as 1800 ppm[1] near the borders of the pluton. Thereafter, the strontium content diminishes rapidly in several localities where the granite has been markedly contaminated by low strontium wallrocks.

The average strontium content of the contaminated and normal granites is 1130 ppm and 990 ppm respectively.

<u>Vanadium</u> (fig. 33, p. 131)

The greater part of the normal granite is underlain by an irregular area in which the rocks do not contain more than 45 ppm vanadium. The vanadium content increases towards the margins of the intrusive and, as is to be expected, is particularly abundant in the areas where contamination has been most pronounced.

Not only do areas of high vanadium content tend to coincide with those of high magnetite content, but 8 of the 10 samples carrying less than 40 ppm V are drawn from within or very close to areas of less than 0.6 percent magnetite content, thus confirming the preferential association of $V^{3+}$ and $Fe^{3+}$.

The average vanadium content of the normal granite is 42 ppm and that of the contaminated granite significantly higher at 67 ppm.

[1]Analysis of sample NL-9 (9, table 3) yielded 3300 ppm Ba. This appears to be a gross error, as it is nearly double the next highest concentration in the remaining samples. This particular analysis was omitted for purposes of calculating the average.

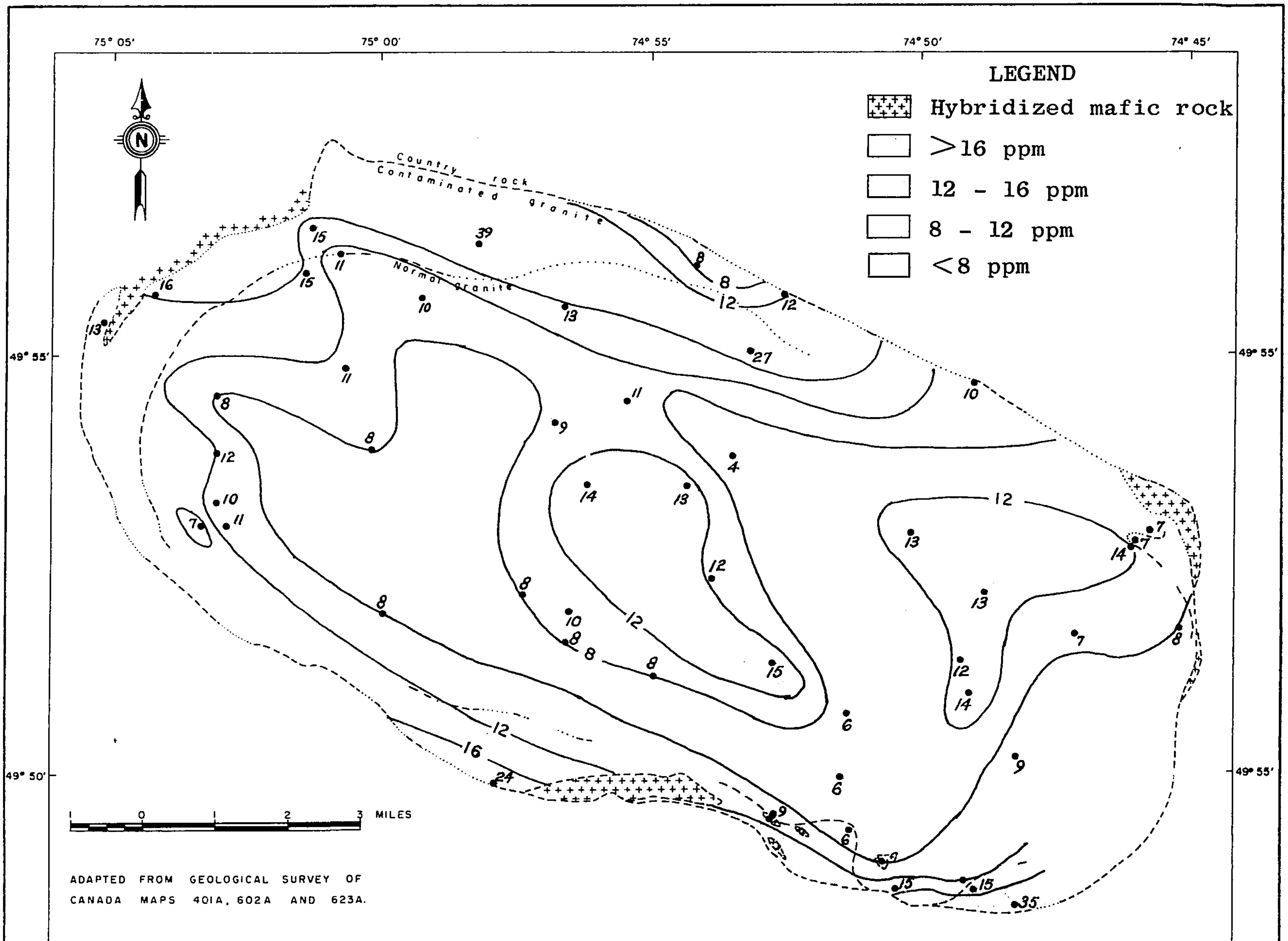



Figure 34. Isopleth map showing distribution pattern of Zn.

Zinc (fig. 34, p. 133)

The surface trend map for zinc shows an area more or less at the centre of the intrusive, which has a zinc content slightly in excess of 12 ppm. Successive zones around this core show an initial decline in the zinc concentration, but this trend is soon reversed as zinc starts building up to higher levels towards the margins. Except for a few sporadic low values along the northern and northeastern contacts of the pluton, the marginal zone of the intrusive has a higher zinc content than the core. The mafic wallrocks and xenoliths no doubt have contributed substantially to the zinc content of the granite in the vicinity.

The normal granite contains on the average 10.7 ppm zinc and the contaminated granite 18.0 ppm.

## 5.04 Comparison of chemical composition with that of other granitoid rocks.

The mean compositions of the normal and contaminated Opemisca Lake granites and various other granitic suites are shown in tables 8 and 9.

Comparison of the major element content of the normal Opemisca Lake granite with Nockolds' (1954) averages for the various members of the granitic clan show the striking dissimilarity in chemical composition of the common alkali and calc-alkali granites on the one hand, and the Opemisca Lake rocks on the other. Apart from its exceptionally high soda content, the Opemisca Lake granite is deficient in silica, ferrous iron and potash, and enriched in alumina, ferric iron, magnesia and lime relative to the alkali and calc-alkali granites.

Despite significant differences in the content of some components, the Opemisca Lake granite is chemically more closely related to the adamellite and granodiorite families than to the granites proper. Silica, ferric iron, magnesia and lime contents in the Opemisca Lake rocks are either very close to the average compositions of the adamellites and granodiorites, or else within the compositional limits suggested by Nockolds (1954, p. 1014). Alumina and soda are higher, whereas ferrous iron is lower than in the granodiorites and adamellites. Potash content of the Opemisca Lake granite is considerably lower than in the adamellites, but close to the average of the granodiorite family. Except that it is higher in potash and lower in lime, the Opemisca Lake pluton is also very similar in composition to the trondhjemites (11, table 8).

The great abundance of albite in the Opemisca Lake granite would account for the unusually high concentrations of soda and alumina. It is interesting to note that the addition of 25 percent albite to Nockolds' average biotite granodiorite (1, table 8) would yield a rock (2, table 8) not unlike the Opemisca Lake granite in composition. It is not suggested that this is the way the

TABLE 8. MEAN CHEMICAL COMPOSITIONS OF GRANITOID ROCKS FROM THE OPEMISCA LAKE PLUTON AND ELSEWHERE

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$........ | 67.88 | 62.16 | 68.97 | 68.92 | 67.01 | 67.05 | 70.36 | 70.00 | 71.6 | 72.9 | 69.30 |
| $TiO_2$........ | 0.19 | 0.45 | 0.45 | 0.36 | 0.50 | 0.31 | 0.45 | 0.20 | 0.26 | 0.17 | 0.23 |
| $Al_2O_3$...... | 16.60 | 16.78 | 15.47 | 16.28 | 15.40 | 15.84 | 15.66 | 16.00 | 15.7 | 15.4 | 16.81 |
| $Fe_2O_3$...... | 1.23 | 1.88 | 1.12 | 0.90 | 1.37 | 1.12 | 0.84 | 1.28 | 2.0 | 1.4 | 0.28 |
| FeO......... | 0.69 | 1.84 | 2.05 | 1.64 | 2.40 | 2.22 | 0.71 | 0.51 | --- | --- | 1.26 |
| MnO......... | 0.04 | 0.07 | 0.06 | 0.05 | 0.06 | 0.06 | tr | 0.08 | 0.03 | 0.03 | tr |
| MgO......... | 1.00 | 2.41 | 1.15 | 0.92 | 1.60 | 2.05 | 0.64 | 0.50 | 0.66 | 0.49 | 1.08 |
| CaO......... | 2.24 | 3.54 | 2.99 | 2.39 | 3.84 | 3.30 | 2.64 | 2.30 | 2.3 | 1.9 | 3.34 |
| $Na_2O$........ | 6.20 | 5.86 | 3.69 | 5.31 | 4.79 | 4.79 | 5.45 | 5.34 | 5.2 | 5.0 | 6.00 |
| $K_2O$......... | 2.93 | 3.25 | 3.16 | 2.53 | 1.89 | 2.91 | 2.24 | 2.99 | 2.5 | 3.2 | 1.39 |
| $H_2O+$........ | 0.46 | 0.69 | 0.70 | 0.56 | 0.50 | -- | 0.60 | 0.52 | --- | --- | 0.50 |
| $P_2O_5$........ | -- | -- | 0.19 | 0.16 | 0.12 | 0.14 | 0.25 | 0.05 | --- | --- | 0.03 |
| TOTAL... | 99.44 | 98.93 | 100.00 | 100.02 | 99.48 | 99.79 | 99.84 | 99.77 | 100.25 | 100.49 | 100.22 |

Explanation of table 8

1. Normal granite, Opemisca Lake pluton (average of 13 complete and 25 partial analyses)
2. Contaminated granite, Opemisca Lake pluton, (average of 5 complete and 6 partial analyses.
3. Biotite granodiorite (average of analyses; Nockolds, 1954, p. 1014).
4. Preceding analysis with 25 percent albite added.
5. Presqu' Île batholith, S.W. Levy township, Quebec (1 analysis).
6. Granodiorite, Preissac-Lacorne batholith (average of 76 analyses; Dawson, 1966, p.41)
7. Quartz albitite, Cadillac township, Quebec (Gunning and Ambrose, 1937, 9. 22).
8. Sill rock, Rainy lake, Ontario (Lawson, 1913, p. 59).
9. Granodiorite, northwestern Ontario (average of 308 analyses; Vollrath, 1964, p. 52).
10. Granodiorite, northwestern Ontario (average of 30 analyses; Vollrath, 1964, p.52).
11. Trondhjemite, Trondhjem, Norway (Goldschmidt, 1916, 9. 75).

granite originated. However, granodioritic magmas are readily capable of assimilating albite by solution. Unless such a magma is superheated, this process would necessitate precipitation of minerals with which the magma is saturated, but at the same time it would also hasten the cooling of the magma (Bowen, 1928, p. 191).

As a result of low grade regional metamorphism albite is one of the most common minerals in the pre-granitic rocks and there is no problem as to its availability. A significant number of rocks, notably the rhyolites, sediments and Ventures gabbro are also unusually sodic in composition. It seems that high soda content is an inherent feature of many of the magmas in this region.

It is interesting to observe that granitic rocks from other parts of the southern Canadian Precambrian Shield have much in common with the Opemisca Lake granite (see table 8). The biotite granite of the Presqu'Île batholith, about 5 miles south of Opemisca lake, some of the granitic rocks from the Preissac-Lacorne batholith about 180 miles to the southwest (Dawson, 1966), and the rocks from two of the four plutons in northwestern Ontario investigated by Vollrath (1964), are all characterized by high soda and alumina and low potash concentrations. So are the albitite from Cadillac township, Quebec (Gunning and Ambrose, 1937) and the sill rock from Rainy lake, Ontario (Lawson, 1913).

The mean composition of the granodiorite from the

Preissac-Lacorne batholith, in table 8, is a weighted average of analyses of all rock types occurring in the batholith. It does not truly portray the remarkable similarity between many of these rocks and the normal granite of the Opemisca Lake pluton. Except for $Fe_2O_3$ which is slightly lower, and FeO which is somewhat higher than in the Opemisca Lake granite[1], those rocks of the Preissac-Lacorne batholith which have differentiation indices between 10 and 13 (the range spanned by the normal Opemisca Lake granite) are virtually identical in composition to the uncontaminated granite of the Opemisca Lake pluton.

Soda granites are also known to occur extensively in the Bachelor Lake area (Gilbert, 1947), about 50 miles southwest of Opemisca lake.

The average composition of the contaminated granite clearly shows the effects of assimilation of largely basic and ultrabasic wallrocks and xenoliths upon the granite. $SiO_2$ and $Na_2O$ have decreased, whereas the remaining components have all increased to produce a rock notably more basic in composition than the original granitic magma.

The mean trace element content of the Opemisca Lake granites and granitoid rocks from other areas are shown in table 9.

[1]These differences appear to be largely due to analytical techniques rather than actual differences in composition. See appendix I.

TABLE 9. MEAN TRACE ELEMENT CONTENT OF OPEMISCA LAKE GRANITE COMPARED WITH PUBLISHED DATA

| | WORLD-WIDE GRANITIC ROCKS | | | CANADIAN PRECAMBRIAN SHIELD | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Vinogradov (1962) | Turekian and Wedepohl (1961) | | Opemisca Lake pluton, Que. | | Preissac-Lacorne (Dawson, 1966) | | Lake St. Joseph map area, N.W. Ont. (Vollrath, 1964) | | | |
| | Felsic rocks | High Ca granite | Low Ca granite | Normal granite | Contam. granite | Granodiorite | Leuco-adamel. | Quartz diorite | Granodiorite | Granodiorite | Adamellite |
| Ba | 830 | 420 | 840 | 1205 | 1130 | 1070 | 326 | -- | -- | -- | -- |
| Co | 5 | 7 | 1 | 3.8 | 5.0 | 17 | -- | 6 | 4 | 3 | 3 |
| Cu | 20 | 30 | 10 | 3.5 | 12.9 | 16 | 8 | 8 | 5 | 4 | 4 |
| Mn | 600 | 540 | 390 | 317 | 524 | 672 | 497 | -- | -- | -- | -- |
| Mo | 1.0 | 1.0 | 1.3 | 2.3 | 2.4 | -- | 6 | 1 | 1 | 1 | 1 |
| Ni | 8 | 15 | 4.5 | 11.4 | 17.4 | 23 | 17 | 14 | 7 | 9 | 6 |
| Pb | 20 | 15 | 19 | 10 | 12 | 13 | 13 | 7 | 13 | 8 | 10 |
| Sr | 300 | 440 | 100 | 990 | 1130 | 1649 | 194 | -- | -- | -- | -- |
| V | 40 | 88 | 44 | 42 | 67 | 60 | 51 | -- | -- | -- | -- |
| W | 1.5 | 2.2 | 1.3 | nd | 1 | -- | -- | 1 | 1 | 1 | 1 |
| Zn | 60 | 60 | 39 | 10.7 | 18.0 | -- | -- | 32 | 31 | 21 | 19 |

Compared to the crustal abundances of trace elements in rocks of approximately equivalent composition (Turekian and Wedepohl, 1961; Vinogradov, 1962), only Co, Ni, V and, to some extent, Pb and W of the trace elements determined in the Opemisca Lake granite, occur in concentrations of about the same order of magnitude. Sr, Ba and Mo are substantially higher in the Opemisca Lake granite, whereas Cu, Mn and Zn are lower. On the whole, there is a far greater degree of similarity between the results of the present study and those of Vollrath (1964) and Dawson (1966). This is not surprising inasmuch as all these investigations involve Precambrian granitic intrusives in the Canadian Shield. The average levels of concentration of Co, Cu, Ni, Pb and W in the normal Opemisca Lake granite are in reasonably good agreement with the mean concentrations of these same elements in four plutons in northwestern Ontario (Vollrath, 1964). Mean Ba, Pb, Sr and V contents compare favourably with Dawson's (1966) data on the Preissac-Lacorne batholith. Mo is higher in the Opemisca Lake intrusive than in any of the four Ontario plutons, but it is lower than in the leucoadamellite of the Preissac-Lacorne batholith. The Mn content of the normal Opemisca Lake granite is substantially lower than in any of the other areas.

From the foregoing discussion it would appear that at least some of the Precambrian granitic intrusives in the Canadian Shield form a distinct geochemical group which differs notably from granitic rocks in the crust as a whole. The most characteristic features of these particular Precambrian granitic rocks, as compared to the average crustal granite or granodiorite are: high soda and alumina contents and a low potash:soda ratio.

# CHAPTER VI

## PETROGENESIS

While it is impossible to treat the behaviour of natural granitic melts quantitatively in terms of relatively simple two-, three- or four-component systems, the large volume of experimental work to date does permit the crystallization pattern of a granitic magma to be predicted with reasonable confidence. The crystallization of simple granitic melts can be approximated by the determination of phase equilibria in the various binary and ternary combinations of the system $SiO_2$ (Q) - $KAlSi_3O_8$ (Or) - $NaAlSi_3O_8$ (Ab) - $CaAl_2Si_2O_8$ (An). Verification of the pronounced fluxing effect of water vapour under pressure on certain of these systems, particularly Q - Or - Ab (Tuttle and Bowen, 1958) and Or - Ab - An (Yoder, Stewart and Smith, 1957), is of further assistance in narrowing the gap between simple laboratory melts and the more formidable natural magmas.

Projections of the norms of the uncontaminated granitic rocks of the Opemisca Lake pluton are shown in figure 35 which represents the liquidus relations in the system Q - Or - Ab - An at 5000 bars water-vapour pressure. The figure has been constructed by Bateman and his co-workers (1963) from data by Bowen (1937, 1954), Franco and Schairer (1951), Yoder, Stewart and Smith (1957), Yoder (1950) and

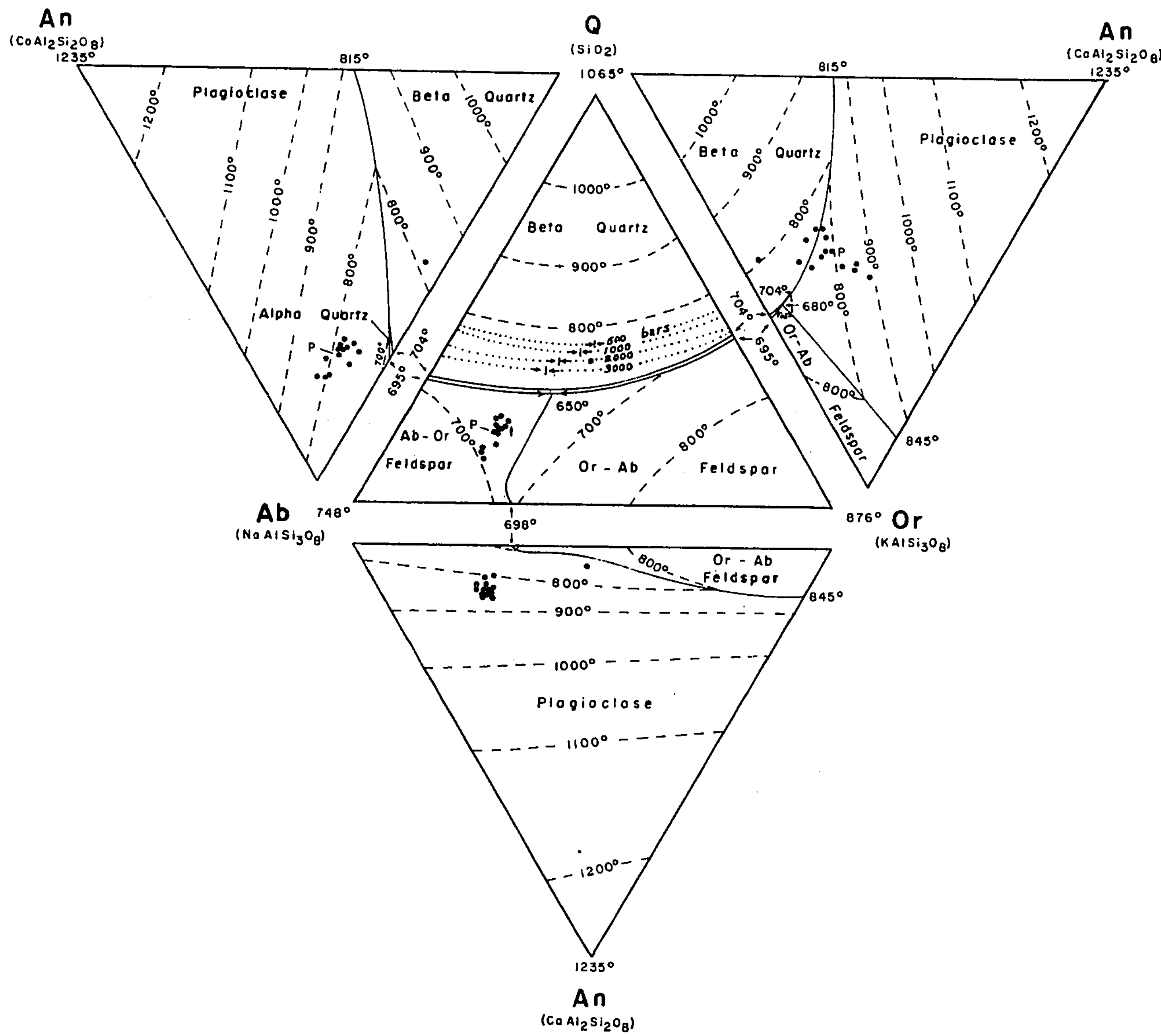



Figure 35. Tetrahedron showing the liquidus relations in the system Or ($KAlSi_3O_8$) - Ab ($NaAlSi_3O_8$) - An ($CaAl_2Si_2O_8$) - Q ($SiO_2$) - $H_2O$ at 5000 bars water vapour pressure (after Bateman and others, 1963, p. 34). Field boundaries are shown by solid lines, and isotherms by dashed lines. Dotted lines indicate the quartz - feldspar boundary at various pressures. The small cross-bar on each of the dotted lines is the ternary (temperature) minimum for that particular water pressure. Solid circles are projections of the norms of uncontaminated granites from the Opemisca Lake pluton. P represents the average composition of this granite.

Stewart (1958), and from a few unpublished sources.

The normative composition of the original magma would plot near the centre of each of the groups of points in figure 35, if it be assumed that the average composition of the uncontaminated granite (P in fig. 35) approximates the composition of the original liquid. Had equilibrium been attained at all stages during the crystallization of the granite, the bulk composition of the final rock would have been the same as the initial liquid, and theoretically would have been represented by a single point on the diagram. The spread in the projections of the norms in figure 35 indicates that equilibrium was not maintained and that a certain amount of fractionation did take place, thereby giving rise to chemically and mineralogically diverse rock types. The rocks closest to the margin of the pluton, presumably the first to crystallize, are also closest to the Ab and An corners of the tetrahedron, whereas those nearest the core plot at the other extremity of the point groups, closer to the Q ($SiO_2$) corner. This is in accordance with the generally accepted principles of magmatic differentiation.

Figure 35 indicates that sodic plagioclase was the first salic mineral to crystallize. As a result, the composition of the residual liquid was pushed in the general direction of the alkali (Or - Ab) feldspar-plagioclase and the quartz-feldspar field boundaries. Which of these surfaces was the first to be intersected by the changing liquid would have depended to a considerable extent on the prevailing water vapour pressure in the system, which effects a very sensitive control on the position of the quartz-feldspar field boundary. There are several reasons to believe that during much of its cooling history the Opemisca Lake pluton crystallized under considerably lower water-vapour pressures than shown in the diagram. Under these circumstances, the quartz-feldspar boundary curve would have shifted much closer to the Q corner, and potash feldspar would presumably have crystallized before quartz. This is borne out by the petrographic studies of the granite. While plagioclase and K-feldspar were precipitating, the liquid changed its composition along the Or - Ab feldspar-plagioclase field boundary until it intersected the quartz boundary surface. At this point quartz commenced crystallizing as well until the remaining liquid was used up.

Compared to the spread in the projections of norms of other granites, the Opemisca Lake rocks occupy a rather restricted space within the Q - Or - Ab - An tetrahedron. Only one analysis, that of an aplite, does not plot within the relatively small cluster representing the uncontaminated granitic rocks. The reason for this seems to be that although fractionation did take place in the cooling magma, it was never the dominant process, and most of the time liquid and crystals attained a state of near-equilibrium.

Close examination of the point group in figure 35 reveals several significant features. The analysis of sample NL-14 (11, table 4) is virtually identical to the average analysis of the uncontaminated granites and for practical purposes may be assumed to represent the average uncontaminated granite. It is indicated by point P in figure 35. Four of the analyses always lie closer to the feldspar sideline than P, and tend to form a small subgroup somewhat removed from the remaining points. Each of these four analyses, which are marginal phases of the granite, is located within 2000 feet of the contact of the intrusion. The remaining points form a rather tight cluster with P lying on the least siliceous side. If P can be assumed to represent the approximate composition of the original magma, then the arrangement of the remaining points becomes clear. The marginal phases of the intrusive cooled relatively quickly, thereby hampering the maintenance of equilibrium between the early-formed crystals and the liquid. Being therefore effectively barred from further reaction, the marginal granite is in effect akin to a "cumulative phase" and hence lies on the more basic side of P. The residual liquid, now somewhat more siliceous than originally and presumably with a higher volatile content, cooled at a much slower rate which permitted equilibrium or near-equilibrium to be maintained until virtually the entire intrusive mass had solidified. Very little fractionation took place. As a result, the projections of the norms on each side of the faces of the

Q - Or - Ab - An tetrahedron form a small tight cluster[1], with P located at the low-silica end of the cluster.

The slow cooling and ample opportunity for reaction between crystals and liquid is confirmed by the generally small variation in anorthite content from core to rim in zoned plagioclase crystals, the extremely vague and diffuse nature of the zoning in most plagioclase grains, and also by the relative mineralogical homogeneity of the uncontaminated granite. Only in the very latest stages of crystallization was a small residuum of highly siliceous and alkaline liquid abstracted from the nearly solid crystalline aggregate, probably by filter pressing. This liquid was injected into fractures in the granite where it crystallized as aplite dykes. The removal of residual liquid at such a late stage explains the considerable gap between the point pattern of the granites and the aplite which plots near the ternary minimum at 1000 bars water-vapour pressure.

It was mentioned earlier that the Opemisca Lake pluton probably crystallized at lower water-vapor pressure

[1]The seemingly open pattern of the normative values on the Q - An - Or face is deceptive and is due to the method of construction. The projection of each point on a particular face can be visualized as the intersection of that face with an imaginary line drawn from the opposite corner through the position of the specific point within the tetrahedron. A small group of points located relatively close to a corner, projected onto the opposite face will therefore result in a much inflated pattern. The point groups on the remaining three faces are fairly close to their true size because of the proximity of each of these faces to the cluster of points within the tetrahedron.

than that represented in figure 35. The reasons leading to this conclusion are as follows: Tuttle and Bowen (1958, p. 139) have suggested that unmixing of potash-feldspar to the perthite or cryptoperthite stage takes place in a relatively "dry" magma from which the volatile materials have escaped, or in which they may have been used up in the formation of hydrous phases. Perthitic microcline is, of course, the common potash feldspar in the Opemisca Lake pluton, which would seem to indicate that the magma crystallized under conditions of rather low water vapour pressure. Assimilation of mafic wallrock or xenoliths may have been a major factor in reducing the water-vapour pressure in the magma. Reaction between the magma and the mafic material would have resulted in the introduction of considerable Ca, Fe and Mg into the granite. The consequent crystallization of abundant hydrous ferro-magnesian minerals such as hornblende and biotite probably led to a considerable reduction in the water content of the magma. Moreover, anhydrous minerals in the xenoliths, such as pyroxene, would also have required water if they were to be converted to amphibole. The almost total lack of contact metamorphism and metasomatism in the wallrock is another cogent argument in favour of a relatively dry magma and a lack of water in excess of that taken up by the hydrous minerals (Hunt and others, 1953, p. 165; Tuttle and Bowen, 1958, p. 93).

In the final stages of crystallization, water pressure had probably built up to a more substantial level, and the residual liquid which gave rise to the aplites appears to have crystallized somewhere between 500 and 2000 bars water-vapour pressure.

# CHAPTER VII

# ORIGIN AND EMPLACEMENT OF THE PLUTON

## 7.01 Evidence of Magma

One of the fundamental problems, and a recurring theme in the voluminous literature dealing with granitic rocks, is the so-called "space problem". It is in answer to this, and other questions related to the genesis and emplacement of granites, that the concept of granitization, the formation of large bodies of granite by metasomatic processes, was formulated.

In the preceding sections it was tacitly assumed that the Opemisca Lake pluton originated at depth and that it was injected into the country rocks as a magma. In this chapter, the evidence leading to this assumption is critically examined and a proposed mode of emplacement is suggested.

Firstly, was the Opemisca Lake pluton emplaced as a magma, or could it have originated in place as the result of metasomatic replacement (granitization) of the pre-existing rocks? The following criteria are cited as evidence that the pluton was originally a magma and that the bulk of the rocks within it crystallized from this magma as it cooled. This evidence is incompatible with a process of large scale granitization in place.

1) Contacts of the pluton with the wallrocks, wherever they were seen, are knife sharp.

2) Small cylindrical satellitic stocks of granite or quartz-syenite porphyry pierce the ultrabasic complex about 1½ miles south of the pluton. Chemically and mineralogically they are identical to the granite in the pluton, and there can be little doubt as to their relationship. The only difference is in the texture of the porphyry, which indicates that the stocks were intruded as a partly crystalline magma which was rapidly chilled.

3) Small dykes (apophyses) emanate from the main body of granite and cut sharply across the bedding or layering of the enveloping rocks. In a few places, the walls of some of these apophyses match, indicating that the openings for the dykes were formed by dilation. In one dyke a slab of rock matches the wall immediately adjacent from which it had been pried loose. Apparently the intruding magma was very viscous at that stage, for the slab remained suspended in place.

4) The presence of high soda, low potash rhyolite flows in the pregranitic sequence testifies to the existence of magmas which share the peculiar compositional pattern of the granite.

5) Wherever extensive alteration of xenoliths has taken place, and in the one outcrop in which metasomatic replacement of the wallrock alongside granitic veinlets is indisputable,

the resulting rocks have textures strikingly different from that of the granite.

6) Foliation in the marginal zones of the granite is independent of foliation in the adjoining wallrocks.

7) Variations in the chemistry and mineralogy of the granite, which can be predicted as a result of the study of simple granitic melts in the laboratory, are confirmed by chemical and petrographical evidence.

8) The distribution pattern of major and trace elements in the pluton are in accord with a process of consolidation from the margin of the intrusive inwards. Disturbance of the pattern in the border zones can be explained in terms of contamination of an acid magma by a heterogeneous but largely mafic assemblage of wallrocks.

9) To convert any of the known wallrocks of the pluton, with the exception of rhyolite, to granite by a process of metasomatic replacement, would require that an enormous amount of material be transferred away from the pluton. Nowhere in the country rocks is there evidence of any such influx of material.

### 7.02 Origin of the Magma

Assuming that the pluton was indeed emplaced as a magma, the next problem is the origin of this magma.

Current theories favour two modes of origin (Turner and Verhoogen, 1960, p. 383):

1. Differentiation of a basic magma;

2. Differential fusion of crustal rocks at depth.

At present, the concensus of opinion seems to be in favour of the second of the two alternatives. Although there can be no reasonable doubt that fractional crystallization of basic rocks leads to a granitic residuum, the vast quantity of basic rocks required to generate granitic plutons and batholiths of regional extent, create an even bigger room problem than the granite itself. Moreover, with the possible exception of the Skye granite (Bott and Smithson, 1967, p. 871), the evidence to show that large bodies of granite can originate in this way has not yet been demonstrated in the field by a continuous sequence of rock types (Heimlich, 1965).

The concept of fusion of crustal rocks at depth was first propounded by Sederholm (1967) during the early part of the twentieth century, in his classic accounts of the geology of the Precambrian terrains of Finland. More recently, experimental verification of the theory (Tuttle and Bowen, 1958; Kranck and Oja, 1960) has given it new impetus. Fusion is considered to be prevalent in orogenic regions, where downbuckling has depressed crustal rocks to levels of high pressure and temperature (Hess, 1938; Griggs, 1939; Kennedy, 1948). Strontium isotope ratios in granitic rocks preclude the possibility that these rocks are melted <u>wholly</u> from either crustal rocks, or from mantle rock (Hamilton and Myers, 1967, p. 17). The isotopic data also indicate that granitic magmas are melted from rocks existing at much greater depths than those exposed in basement complexes. In brief, Hamilton and Myers (1967, pp. 20-21) visualize the following sequence of events in the generation of a granitic magma: the peculiar melting behaviour of basalt above the eclogite - gabbro transition zone in the upper mantle or lower crust, will lead to the formation of a highly feldspathic magma. The buoyant magma breaks away from the zone of melting, and rises. Subject to the pressure gradient, volatiles continue to rise to the top of the magma column where melting temperatures are lowered in consequence. Roof rocks are melted and incorporated into the magma, which becomes progressively enriched in the lowest melting fractions of both initial magma and the intruded rocks. The magma will continue to rise until crystallization terminates further movement or until it erupts at surface.

This concept of zone melting in a rising magma column (Dickson, 1958) does offer an explanation as to how the Opemisca Lake pluton could have become enriched in soda. If albite were freely available in the wallrocks, the continued influx of volatiles into the roof zone of the rising pluton might have depressed the freezing point of the magma to such an extent that it was able to dissolve substantial quantities of albite before consolidating. The ultimate source of soda, however, is still not known.

## 7.03 Emplacement of the Pluton

Problems pertaining to the emplacement of the pluton are concerned essentially with the mechanism whereby the pluton was able to create room for itself. It is suggested that emplacement of the magma was accomplished by the following means:

1) Stoping and foundering of stoped blocks:

The large mafic xenoliths within the pluton certainly indicate that this process was operative during the emplacement of the magma, but its relative importance is difficult to evaluate quantitatively. There is no way of knowing how many of the blocks have sunk out of sight.

2) Assimilation of wallrock:

At its present level of exposure, the bulk of the rocks surrounding the pluton are mafic and ultramafic varieties. It has been inferred from textural evidence in the satellitic stocks that the magma arrived at its present position in a partly crystalline state. It is, therefore, unlikely that the magma would have been capable of assimilating significant quantities of mafic wallrock before crystallization was complete. This is confirmed by the rather narrow margin of contaminated granite.

3) Forceful intrusion:

The bulk of the evidence available at present suggests forceful intrusion of the pluton as being the single most significant mechanism of emplacement. The nature of this evidence is as follows: Apophyses emanating from the pluton, and the satellitic stocks in particular, indicate that the magma was injected into the enveloping rocks under considerable pressure. Protoclastic texture in the margin of the pluton signifies crushing and recrystallization in the crystalline or partly crystalline outer shell of the granite during intrusion. An alternative interpretation of the protoclastic texture is that the granite intruded at a stage when regional folding was waning, and that the crushing and recrystallization reflect mild regional deformation.

The most compelling evidence in favour of forceful emplacement is a deformation pattern in the wallrocks which appears to be closely related, spatially and genetically, to the intrusion of the pluton rather than to regional deformation. Regional folds axes trend east-southeast and are, with rare exceptions, more or less horizontal. In contrast, a significant number of steeply plunging folds occur in the immediate vicinity of the pluton. These folds appear to have formed in the wallrocks in response to a strong outwardly directed pressure exerted by the magma.

The area shown in figure 36 offers some of the most convincing evidence favouring forceful intrusion of the pluton. The right-angled deflection of the strike of the volcanic rocks to the north of Springer mountain implies

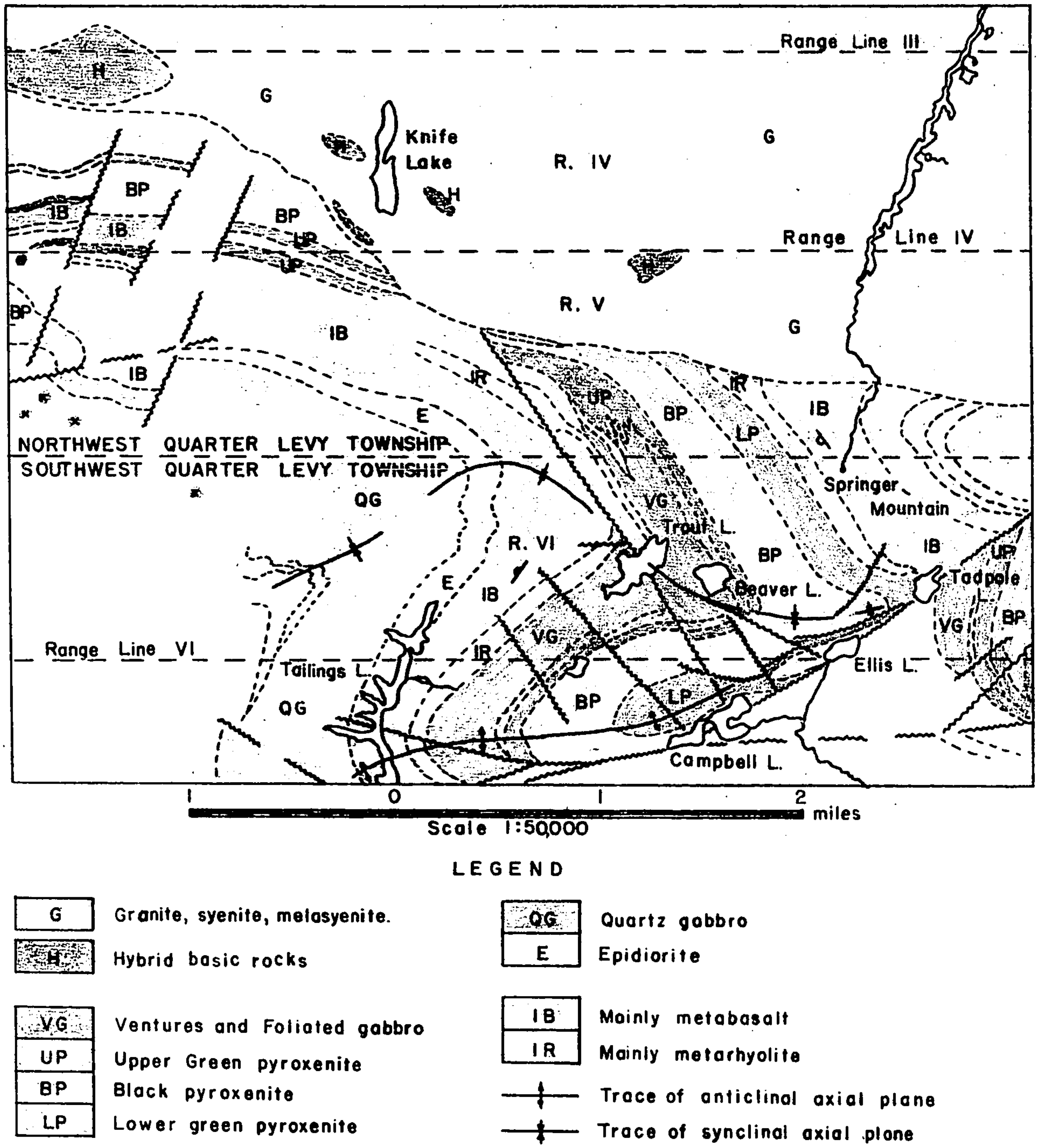



Figure 36. Structure in country rocks along the southeastern border of the Opemisca Lake pluton.

wedging apart and bending of the layered wallrocks.

The most obvious explanation for the gradual change in the trend of the axial planes of the Beaver Lake - Trout Lake syncline from northeast to southeast and east, and of the Ellis Lake anticline from east-northeast to east, is that the granite forcibly shouldered aside its walls. The northwesterly trending faults in this particular area also seem to be intimately related to this phase of deformation.

If this interpretation is correct, it also offers an explanation for the extreme thinning and virtual elimination of the Lower Green pyroxenite in the limbs of the Ellis Lake anticline, in the area between Campbell and Ellis lakes. The intense compression induced in the wallrocks by the intruding pluton gradually forced the hinge of the Beaver Lake-Trout Lake syncline around to the south. This resulted in the limbs of the Ellis Lake anticline being pinched into a tight isocline. The closing of the limbs prevented the beds from being pushed outward any farther. The only way the tightly compressed Lower Green pyroxenite could yield under the continuing pressure was by being squeezed out of the limbs of the fold either by plastic flow or along shear zones parallel to the limbs.

It is interesting to note that the fault pattern in the area around the western extremity of the pluton (fig. 3) is identical to the fracture pattern produced by forceful intrusion of rhyolite into schists at the Homestake Mine in South Dakota (Noble, 1952, p.36, and fig. 37A below).

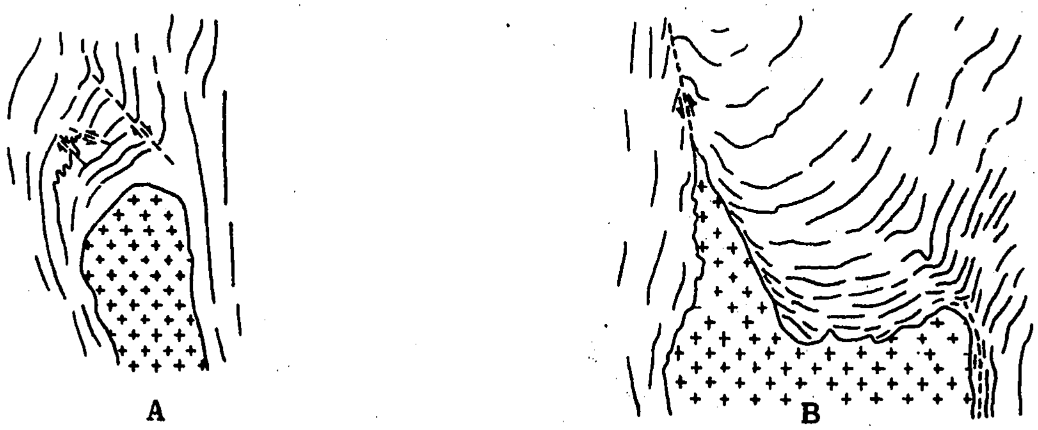



Figure 37. Deformation of schist at the end of two dykes in the Homestake Mine, South Dakota. The schists have been thrust aside and ahead of the advancing magma and have been displaced along small faults. In B the magma subsequently advanced along one of these faults. The dyke in A is about 15 inches wide, that in B about 7 feet wide. A is a plan, B a vertical section (after Noble, 1952).

The localization of the Opemisca Lake pluton and other intrusives in the core of a regional anticline is of considerable significance in assessing a probable mechanism of emplacement. To the east of the pluton, a heterogeneous assemblage of intrusive rocks is exposed continuously in the core of the anticline as far as Lake Chibougamau, and from there northeastwards for an undetermined distance (fig. 2). Over most of this section, the axis of the anticline probably does not deviate much from the horizontal, for the rocks flanking the fold remain essentially the same. To the west of the Opemisca Lake pluton, the fold axis plunges westward, and the north and south limbs close rather abruptly. The two belts of volcanic rocks which fringe the intrusive, nose out at Lac des deux Orignaux, about 9 miles west of the pluton.

The close spatial and structural relationship of a series of intrusives studded along the axial part of a fold raises the possibility that they may also be genetically related. It is interesting to speculate that the plutons may be upward protuberances of a much greater composite batholithic mass at depth.

What mechanism could have controlled and guided a series of diverse intrusives to the same structural site? Two alternatives suggest themselves:

1) An area of lower confining pressure was created in the core of the anticline as the crest was being lifted. This low pressure area served as a focal point for rising bodies of magma. This hypothesis presupposes intrusion and folding to be contemporaneous. However, as will be pointed out in a later section, there is little evidence supporting this viewpoint.

2) The tight isoclinal folding of the pregranitic sequence gave rise to a system of transverse and longitudinal shear zones in the crest of the anticline. The type of pattern visualized is exemplified by the fault pattern in the Kettleman Hills dome in California (Woodring and others, 1940, plate 51) which is illustrated in figure 38.

Available maps do not show any longitudinal (axial plane) faults in the nose of the fold to the west of the pluton, but this by no means precludes their presence. Faults of this type are extremely difficult to detect in isoclinally folded volcanic sequences in which there is a notable lack of marker beds, because they tend to parallel the layering and rarely show evidence of displacement or discordant structure. Moreover, detailed mapping in the area to the south of the Opemisca Lake pluton has revealed an abundance of shear zones parallel to the regional trend (Wolhuter, 1962, p. 13). Most significant of these is the massive axial plane shear zone in the hinge of the complementary syncline to the south of the Opemisca Lake anticline. Displacement along this shear zone has eliminated much of the upper part of the south limb of the syncline (Norman, 1948, p. 827; Wolhuter, 1962, p. 13).

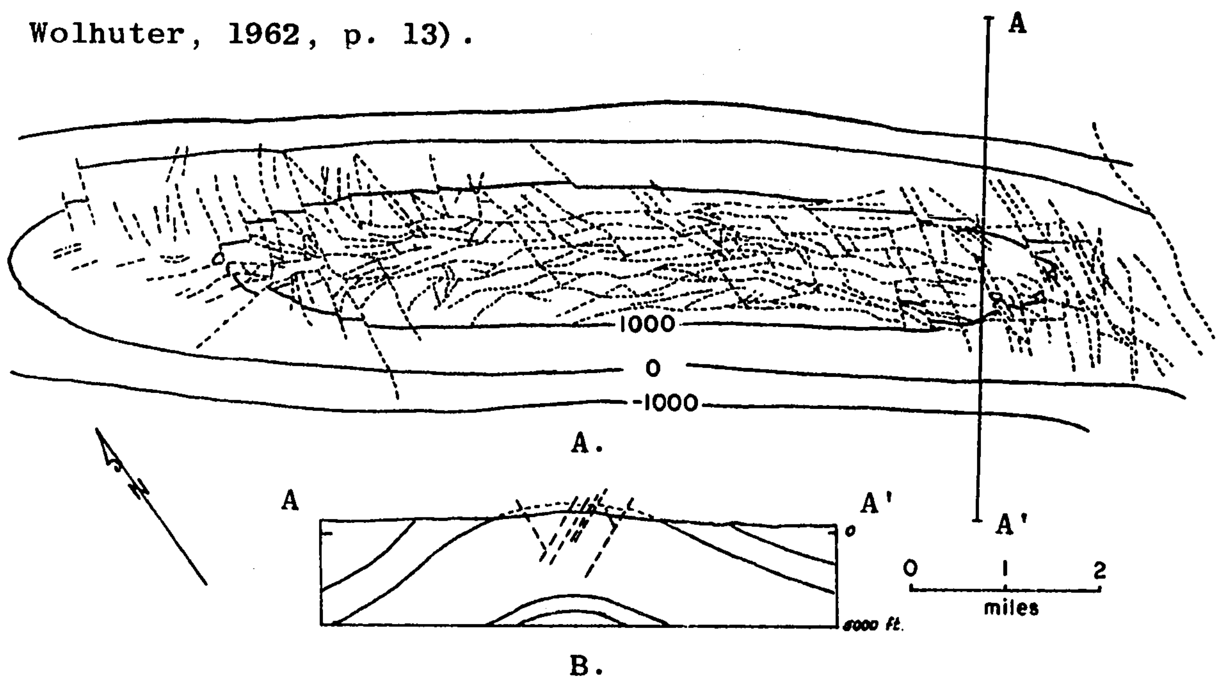



Figure 38. Longitudinal and transverse fault pattern, north dome, Kettleman Hills, California. A is a plan, B a vertical section. (After Woodring and others, 1940, pl. 51). Note similarity between transverse faults and fault pattern around borders of Opemisca Lake pluton. Solid lines are structure contours, dotted lines are faults.

Now, if such a system of axial plane and transverse shear zones were present in the crest of the Opemisca Lake anticline, and they penetrated to fairly deep levels, they could have provided a convenient channelway for ascending bodies of magma. The magma could rise by wedging its way in along fault planes, but the most likely means of creating space would simply be to displace the numerous fault blocks and slices resulting from the anastomosing pattern of longitudinal and transverse faults, upwards along existing fault planes. Obviously the rather narrow conduit provided by a fault zone would be incapable of accommodating the enormous volume of magma rising from below. This is especially true if the upward flow of magma were to be impeded, say by a crystalline plug forming at the head of the magma column, where loss of heat and volatiles would be greatest. Unless stoping and foundering assumed a role of major importance, room to accommodate the pluton under these conditions could hardly have been obtained other than by structural adjustment in the wallrocks. The bowing out and dislocation of the wallrock around the swelling pluton may have been facilitated by movement along the transverse faults.

In summary, forceful intrusion appears to have been the most important mechanism leading to the emplacement of the Opemisca Lake pluton. The same tectonic stresses that led to regional folding may have guided the magma to the axial region of a major anticline. However, intrusion was essentially post-kinematic and it seems that a system of deeply penetrating faults in the crest of the anticline facilitated the ascent of the magma. Initially, the magma created room by raising the faulted roof rocks along existing fault planes. Later, it also spread laterally and thrust the wallrocks aside.

The amount of space accounted for by stoping and foundering is impossible to evaluate and it cannot be assumed that this process was of little consequence in creating room for the pluton. Assimilation of the stoped blocks (xenoliths) and wallrocks was only of minor importance, judging by the rather narrow rim of contaminated granite in the pluton. Emplacement by granitization was negligible.

## 7.04 Timing of the Intrusion

The setting of the Opemisca Lake pluton and its shape indicate that the structure of the country rocks exerted considerable control over its emplacement. The close association of the pluton with a major fold raises the question whether intrusion was contemporaneous with folding (synkinematic) or whether it post-dated folding (post-kinematic).

Available evidence, although meagre, is in favour of post-kinematic or very late synkinematic intrusion. The following evidence is cited in support of this statement.

The texture of the granite in the satellitic stocks indicates that the intruding magma consisted of a suspension of crystals in a melt. The magma that solidified at the present level of exposure of the pluton, may have contained as much as forty percent or more liquid. If intrusion took place during the major phase of tectonic deformation, then crystallization of the remaining liquid would have taken place under directed stress and the fabric of the pluton as a whole should bear the imprint of this stress. This is not so. Only a narrow marginal phase of the granite shows any sign of a preferred mineral orientation, and this orientation is attributed to magmatic flow rather than regional deformation. The remainder of the pluton is characterized by a megascopically isotropic fabric.

The characteristic mineral assemblage of the greenstones surrounding the pluton is: actinolite and/or chlorite, albite and epidote. Post-magmatic alteration of rocks within the pluton is typified by chloritization of biotite and saussuritization of albite-oligoclase. It is difficult to decide, therefore, whether the alteration in the pluton was the result of deuteric processes or of low grade regional metamorphism, as both would lead to more or less similar mineral assemblages. Theoretically, the hornblende in the granite should have been converted to actinolite and/or chlorite under conditions of low grade regional metamorphism (Hutton, 1940, p. 31). However, a petrographic investigation by the writer, of the metamorphosed basic and ultrabasic rocks to the south of the pluton, revealed that hornblende of magmatic origin in these rocks is capable of persisting without any alteration in typical greenschist mineral assemblages. Non-alteration of the hornblende in rocks within the pluton does not, therefore, preclude the possibility of regional metamorphism post-dating intrusion.

The common sequence of alteration in the granite is:

$$\text{hornblende} \xrightarrow[\text{magmatic}]{} \text{biotite} \xrightarrow[\text{deuteric (?)}]{} \text{chlorite}$$

Where pyroxene is present, as in some inclusions, the sequence is:

$$\text{pyroxene} \xrightarrow[\text{magmatic}]{} \text{hornblende} \xrightarrow[\text{magmatic}]{} \text{biotite} \xrightarrow[\text{deuteric (?)}]{} \text{chlorite}$$

The alteration of pyroxene to biotite may proceed with little, if any, prior alteration to hornblende.

The comparable reaction involving amphibole in the greenstones is

$$\text{actinolite} \xrightarrow[\text{metamorphic}]{} \text{chlorite}$$

The large xenolith straddling the Levy-Daubrée boundary line shows the following pattern of alteration:

$$\text{actinolite} \longrightarrow \text{biotite} \longrightarrow \text{chlorite}$$

The alteration of actinolite to biotite is the result of reaction between the inclusion and the granite magma and clearly implies that actinolite was present in the wall rocks from which the inclusion was derived. The presence of a few grains of actinolite, partly altered to hornblende, in contaminated granite from the southeastern border of the pluton, further substantiates this argument. In other words, the enveloping rocks had already been metamorphosed at the time of intrusion of the granite. Regional metamorphism must therefore have preceded emplacement of the pluton. Mineralogical reconstitution and development of a conspicuously schistose texture in the weaker layers of the country rocks can be clearly identified with regional folding. Therefore, it may be concluded that regional folding pre-dates the intrusion of the pluton.

# CHAPTER VIII

## SUMMARY AND CONCLUSIONS

The Opemisca Lake pluton intruded into the core of an anticlinally folded sequence of metamorphosed volcanic, intrusive and sedimentary rocks. The wallrocks form part of the easterly-trending Waswanipi-Chibougamau greenstone belt.

On a regional scale the pluton is concordant with the surrounding rocks, but in detail the contacts show considerable discordance. The rocks immediately adjacent to the pluton dip vertically or steeply inward. Contacts between pluton and wallrocks are typically sharp. The latter show no evidence of contact metamorphism. Foliation in the margin of the pluton is interpreted as a flow phenomenon, indicating that the intrusive rose as a unit past its wallrocks. Inclusions are common in the marginal zone of the pluton, but rare in the interior.

A few small satellitic stocks, as much as 120 feet in diameter, pierce the country rocks about 1½ miles south of the pluton. The stocks are chemically and mineralogically similar to the normal granite in the pluton, but they differ in texture.

The pluton is composed chiefly of a soda granite. The essential minerals of the granite are albite (or highly sodic oligoclase), potash feldspar, quartz and hornblende. Quartz increases in abundance from the margin to the centre of the intrusive, whereas the reverse is true for hornblende. However, the compositional changes in the interior of the pluton are so gradual that they impart to it an appearance of monotonous uniformity. Only in the marginal granite is there a pronounced increase in the content of mafic minerals (essentially hornblende) and in the inhomogeneity of the granite. The abundance of hornblende and the lack of homogeneity in the peripheral zone is largely due to contamination of the granite by a heterogeneous assemblage of mafic and ultramafic wallrocks and inclusions.

Textures in the rocks of the pluton and some of its satellitic stocks indicate that hornblende and highly sodic oligoclase, or calcic albite, were the first of the essential minerals to crystallize. They were followed soon afterwards by potash feldspar, and lastly by quartz. The potash feldspar crystals generally grew to a large size and engulfed many of the earlier minerals. The microscopic evidence is in complete agreement with the crystallization trend inferred from published experimental studies on silicate melts. The experimental data also suggest that during most of its cooling history the granite crystallized from a relatively dry magma. This is confirmed by exsolution features in the potash feldspar and the lack of contact metamorphism in the wallrocks.

Geochemical studies of the pluton indicate that it is possible to distinguish between contaminated and uncontaminated granites by means of variation diagrams. The contaminated granites are characterized by: a) a differentiation index less than 10, b) a combined calcium and iron content in excess of 3.9 percent, provided calcium exceeds 1.95 percent, c) for a specific Sr content, a calcium content higher than that which is calculated by means of the formula Ca = 6Sr + 1.34. The inclination of the trend lines of the various elements in the range of differentiation indices above 10 is in agreement with the commonly accepted principles of differentiation during magmatic crystallization.

Isopleth maps were constructed to outline the extent of the contaminated granite and the distribution patterns of the various elements in the pluton. Most of the elements depicted show a pronounced concentric, or rudely concentric, zonal arrangement. For certain elements the regularity of the pattern is noticeably disrupted by contamination towards the margins of the pluton.

The uncommonly high soda content, the abundance of alumina, and the low potash to soda ratio of the Opemisca Lake pluton is characteristic of several other large granitic intrusives in the Superior province of the Canadian Precambrian Shield.

The Opemisca Lake pluton may have been localized in the core of a regional anticline by crestal faults penetrating deeply into the crust. Space to accommodate the pluton was apparently obtained by the forcible injection of the magma. In the initial stages, the magma presumably created room by lifting its roof along the fault planes. Later the limbs of the anticline were buckled outward to make more room. The forceful shoving aside of the walls was accompanied by considerable disruption and deformation in the country rocks. Magmatic stoping may have been important during the upward advance of the magma, but the general absence of xenoliths away from the marginal zones does not support the idea that this was a dominant process of emplacement.

The origin of the magma is obscure, but it may have resulted from partial melting of basalt (gabbro) in the upper mantle or lower crust (Hamilton and Myers, 1967) or from the melting of downbuckled sedimentary or volcanic rocks. Gravitational differences between the newly generated magma and the surrounding more basic rocks may have caused the more buoyant magma to rise, but it could also have been set into motion by tectonic stresses.

The composition of the magma could have been modified continually during its upward journey through the crust, so long as an adequate supply of volatiles was available to lower melting temperatures at the head of the column. This enabled the magma to become enriched in the low melting fractions of the wallrocks. The high soda content of the granite may be attributable to incorporation of substantial quantities of albite during this stage. By the time the magma arrived at its final site in the upper reaches of the crust, its composition had undergone profound modification.

In the early stages of its ascent, the magma at the head of the column was probably sufficiently fluid to permit the sinking of unfused remnants of country rock before extensive reaction took place. Later, as the supply of volatiles dwindled and heat was lost more rapidly to the cooler country rock in the upper reaches of the crust, viscosity in the margins of the pluton increased greatly. Xenoliths torn from the walls no longer were able to sink freely. Smaller ones may even have been carried upward by the viscous mass. Now reciprocal reaction between the acid magma on the one hand, and the mainly basic and ultrabasic xenoliths and wallrocks on the other, became effective. The magma became enriched in Ca, Fe, Mg and Ti while at the same time Si and alkalis were transferred to the xenoliths. The higher viscosity of the marginal magma, which was reacting with xenoliths and wallrocks, would inhibit mixing and homogenization of the resulting contaminated magmas. In consequence, the composition of these contaminated magmas varied considerably from place to place, depending on the nature, quantity and composition of the contaminating rock type.

The increased rate of crystallization in the contaminated granite soon resulted in the margins of the pluton becoming an essentially solid crystalline mass. This in turn effectively removed the xenoliths and wallrock from further reaction with the magma, and allowed the processes of magmatic differentiation to proceed unaffected by extraneous factors.

It is during this period of crystallization that the well defined concentric zoning of the pluton was established. As the magma cooled and solidified from the shell of contaminated granite inward, earlier as well as more recently formed crystals adhered to the walls or became trapped in the layer of highly viscous liquid there. If, due to the increasing viscosity of the outermost layer of magma, reaction between crystals and melt was inhibited and equilibrium not established, the liquid would gradually change its composition according to the commonly accepted principles of differentiation. Successive zones would reflect this change and would be characterized by mineralogical differences as well as differences in major and minor element content. It is also possible that thermo-diffusion (Soret effect) may have contributed to the zoning in the pluton. This mechanism has been invoked by Bateman and his co-workers (1963) as a possible contributing process to zoning in various plutons in the Sierra Nevada batholith.

During the gradual cooling and crystallization of the Opemisca Lake pluton, fractionation was never of great magnitude and a fairly high degree of equilibrium was maintained between crystals and melt. This is borne out by petrographical investigation as well as petrological considerations based on published experimental data. Only in the very final stages of crystallization was a small highly siliceous and alkaline residuum left over. This remnant liquid was extracted and injected into fractures in the surrounding granite where it crystallized to form aplitic dykes.

A pervasive deuteric alteration, following the final consolidation of the magma, is manifested in the chloritization of biotite and saussuritization of plagioclase.

# CHAPTER IX

## CONTRIBUTION TO KNOWLEDGE

The author claims this study presents new information on the petrology, geochemistry and manner of emplacement of the Opemisca Lake pluton. The following items in particular are considered to contribute significantly to the understanding of granitic intrusives:

1. The facts of occurrence and internal variations in composition have been determined by mapping, petrographic studies and chemical analyses.
2. Seventeen new complete rock analyses and 33 new partial analyses have been studied and the first geochemical surface trend maps of the pluton have been constructed.
3. The information gathered is used to prove beyond reasonable doubt that the pluton crystallized from an injected magma and that the variations in composition agree with crystallization trends inferred from published experimental studies on silicate melts.
4. Variation diagrams show a clear distinction between contaminated and uncontaminated granites and a map is provided showing the extent of the contamination. Contaminated granites are defined positively on the basis of their differentiation indices, their combined Ca and Fe contents, and the relationship between Sr and Ca.

5. The surface trend maps show a definite concentric zoning in the pluton, which is accounted for by the combined effects of reaction with the wallrocks and differentiation during cooling.
6. Smaller satellitic stocks are shown to be chemically and mineralogically closely similar to the Opemisca Lake pluton, and their distinctive textures are used as evidence in interpreting the changes that occurred in the main pluton during crystallization.
7. The pluton is shown to be post-kinematic and its mode of emplacement is discussed. Forceful injection is indicated, but magmatic stoping may have been important during the upward advance.

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# APPENDIX I

## SAMPLING AND ANALYTICAL TECHNIQUES

### A1.01 Selection of Samples

Fifty-two samples were collected for chemical analysis. Forty-eight of these were chosen as representative granitic rocks. The remaining four samples were selected specifically because they showed uncommon features or mineralogical composition. The number of samples was decided upon after discussions with Dr. R.H.C. Holman of the Geological Survey of Canada, in the spring of 1962. During the preceding years, the Geological Survey had undertaken an extensive programme of geochemical investigation of rocks in the Canadian Shield in northwestern Ontario. Holman (1962, personal communication) had found that 30 to 50 rock specimens provided a satisfactory sampling of a body the size of the Opemisca Lake pluton. A sample size smaller than this would be rather inadequate for geochemical purposes. On the other hand, for a sample size exceeding 50 specimens, the amount of additional information gained was not commensurate with the increase in time and expense.

The area underlain by the intrusive was divided into 16 parts, all approximately equal in size. From each of these subdivisions, 3 samples of granitic rock were collected for analysis - a density of approximately one sample for every two square miles. The location of each sample was determined largely by the availability and/or accessibility of outcrop. For statistical purposes, such a sampling pattern is biased, but it is favourable for studying geochemical variation in the pluton. Seventeen of the samples were drawn from that part of the pluton lying inside the northwest quarter of Levy township, the area which was also mapped in detail.

Two (1, 2, table 6)[1] of the four extra samples are from the xenoliths along the southern margin of the pluton and were selected so that there would be some basis for evaluating the changes taking place when inclusions and granite magma interact to produce hybrid rocks and contaminated granite. The remaining two samples include an unusual greyish-pink porphyritic syenite (3, table 4) from the southeastern part of the intrusive and one of the rare aplite dykes (18, table 4).

A rock specimen weighing 2 to 3 lbs. was collected from each outcrop sampled. Care was taken to sample only fresh rock unaffected by surface weathering.

## A1.02 Sample Preparation

The rock samples selected in the field were broken into smaller fragments, approximately 1 inch in diameter, with a hydraulic splitter. One fragment from each sample was

[1]References to tables or figures preceded by the letter A are in the appendix. All others are in the text.

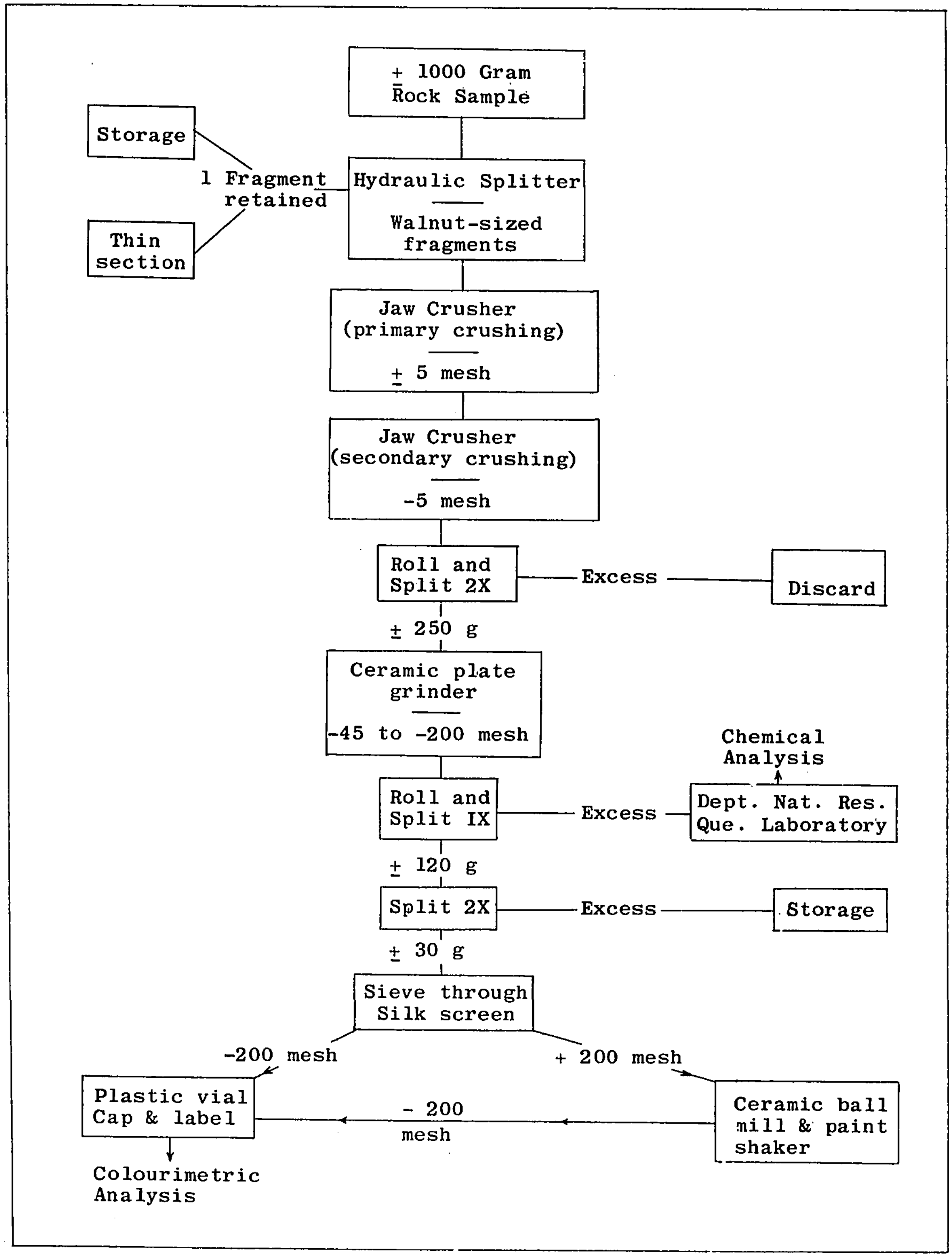


Figure A-1. Sample preparation flow diagram retained for reference and for thin sections where required. The remaining fragments were crushed in a jaw crusher, initially to approximately 5 mesh size, and then a second time to -5 mesh size.

The crushed rock was rolled on a large sheet of kraft paper to ensure thorough mixing, and then split twice to reduce the sample to about one quarter the original size. The excess was discarded. Next, the remainder was passed through a ceramic plate grinder and ground to a powder ranging from -45 mesh to -200 mesh in grain size.

This powder was then mixed by rolling on kraft paper and split once. Half was sent to the laboratories of the Department of Natural Resources, Quebec, for chemical analysis. The remainder was split two more times to reduce the sample size to about 30 grams. The excess powder was bagged in plastic pouches and stored.

The retained powder was sieved through 200 mesh silk bolting cloth. The -200 mesh fraction was kept in a plastic vial. The + 200 mesh fraction was placed in a ceramic ball mill and shaken for 30 minutes on a paint shaker, by which time all the powder was reduced to -200 mesh. This was added to the portion already in the plastic vial. The vial was then capped, labelled and held for chemical analyses.

A flow diagram of the sample preparation is shown in figure A-1.

## A1.03 Chemical Analyses

All chemical analyses were made in the laboratories of the Department of Natural Resources, Quebec, except for Co, Cu, Ni, Pb, W and Zn, which were determined by the writer.

Analyses for the major elements were by classical wet chemical methods (Groves, 1951). For trace elements, colourimetric and spectrographic techniques were used.

To analyse for Co, Cu, Mo, Ni, Pb, W and Zn, the writer used well-known colourimetric methods. The techniques for Cu, Pb and Zn are essentially those described by Gilbert (1959), and use dithizone as a colour indicator. Ni was determined according to the $\alpha$-furildioxime method described by Stanton and Coope (1958). Colourimetric analysis for Co utilizes 2-nitroso-1-naphthol as colour indicator (Almond, 1953). Analytical techniques for molybdenum and tungsten are described by North (1956).

## A1.04 Precision and accuracy of chemical analyses

The precision and accuracy of analyses by the laboratory of the Department of Natural Resources, Quebec, are not known. It should be pointed out that in the method used to determine ferrous iron (Groves, 1951), the ferrous oxide is extremely susceptible to oxidation. This could result in too high a value for $Fe_2O_3$ and too low a value for FeO, and should be borne in mind when evaluating the analyses in table 4.

Possible sources of error in the determination of Pb have been discussed on page 81 of the text. W was detected in only 4 samples and the accuracy and precision of the method are not considered here. The analytical technique for Mo is said to be accurate to "± 40 percent" (North, 1956); precision is not known.

The precision of the analytical techniques used to determine Cu, Ni, Zn and Co was measured by replicate analyses of a number of samples. Accuracy of the determinations for Cu and Ni was measured by analyses of the standard granite W-1 and the standard diabase W-1. Results are summarized in tables A-1 to A-4.

TABLE A-1. PRECISION AND ACCURACY OF COPPER ANALYSES

| Sample number | Replicate analyses | | | Mean | Variance | Std. Dev. | Coeff. of var. |
|---|---|---|---|---|---|---|---|
| | $x_1$ | $x_2$ | $x_3$ | $\bar{x}$ | $s^2$ | s | c% |
| NL-77 | 5 | 4 | 7.5 | 5.5 | 3.25 | 1.80 | 32.8 |
| GR-5 | 35 | 35 | 29 | 33 | 12.00 | 3.46 | 10.5 |
| NL-39 | 2.5 | 2.5 | 2.5 | 2.5 | 0.00 | 0.00 | 0.0 |
| GR-1 | tr | 2.5 | tr | 2.5 | - | - | - |
| NL-66 | 2.5 | 2.5 | 4.0 | 3.0 | 0.75 | 0.87 | 29.0 |
| NL-65 | 5.5 | 4.0 | 5.5 | 5.0 | 0.75 | 0.87 | 17.4 |
| G-1 | 14.0 | 12.6 | - | 13.3 | 0.98 | 0.99 | 7.4 |
| W-1 | 105 | 99 | - | 102 | 18.00 | 4.24 | 4.2 |

The coefficient of variation $C = \frac{s}{\bar{x}} \times 100\%$ is a measure of the relative dispersion, i.e. precision, of replicate analyses. For Cu (table A-1) it ranges from zero to 32.8 percent. Duplicate analyses of the two standard samples G-1 and W-1 have low coefficients of variation. The mean copper contents determined for G-1 and W-1 are 13.3 and 102 ppm respectively, and are very close to the recommended averages of 13 and 110 ppm (Fleischer and Stevens, 1962). Neither of the duplicate analyses for G-1 or W-1 differed by more than 10 percent from the recommended values.

TABLE A-2. PRECISION AND ACCURACY OF NICKEL ANALYSES

| Sample number | Replicate analyses | | | Mean | Variance | Std. Dev. | Coeff. of var. |
|---|---|---|---|---|---|---|---|
| | $x_1$ | $x_2$ | $x_3$ | $\bar{x}$ | $s^2$ | s | c% |
| GR-1 | 11.5 | 15.0 | 11.0 | 12.5 | 4.25 | 2.06 | 16.4 |
| NL-2 | 25 | 27 | 23 | 25 | 4.00 | 2.00 | 8.0 |
| NL-12 | 10.0 | 17.5 | 10.0 | 12.5 | 18.75 | 4.33 | 34.6 |
| NL-18 | 11.0 | 11.0 | 8.0 | 10.0 | 3.00 | 1.73 | 17.3 |
| NL-64 | 11.3 | 9.0 | 6.0 | 8.8 | 7.07 | 2.66 | 30.2 |
| G-1 | 4.2 | 4.2 | - | 4.2 | 0.00 | 0.00 | 0.0 |
| W-1 | - | - | - | - | - | - | - |

The coefficient of variation for Ni analyses (table A-2) ranges from zero for the two duplicate analyses of G-1, to 34.6 percent for sample NL-12. The lowest coefficient of variation for any of the triplicate analyses is 8.0 percent for sample NL-2. The mean Ni content determined for G-1 is 4.2 ppm, which is more than double the recommended value of 1 to 2 ppm (Fleischer and Stevens, 1962). The large difference between the recommended and determined abundances of Ni in G-1 can be attributed to the low Ni content of the standard granite. In the analytical method used, Ni can be determined reasonably precisely to as low as 6.25 ppm. Below that level, matching standards have to be estimated. The estimates are subject to considerable error because of the extremely small colour variations in this range.

The Ni content in W-1 could not be determined owing to interference of some other element (probably Fe) which gave rise to a yellowish hue in the indicator of the test solution which differed from that in the standards.

TABLE A-3. PRECISION OF COBALT ANALYSES

| Sample number | Replicate analyses | | | Mean | Variance | Std. Dev. | Coeff. of var. |
|---|---|---|---|---|---|---|---|
| | $x_1$ | $x_2$ | $x_3$ | $\overline{x}$ | $s^2$ | s | c% |
| NL-71 | 2.5 | 5.0 | 7.5 | 5.0 | 6.25 | 2.50 | 50.0 |
| NL-81 | 4.8 | 5.5 | 4.8 | 5.0 | 0.17 | 0.41 | 8.2 |
| NL-14 | 4.8 | 3.5 | 3.0 | 3.8 | 0.87 | 0.93 | 24.5 |
| NL-40 | 22.5 | 22.5 | 18.8 | 21.3 | 4.55 | 2.13 | 10.0 |
| NL-68 | 2.5 | 3.5 | 3.3 | 3.1 | 0.28 | 0.53 | 17.1 |

The coefficient of variation for Co analyses ranges from 8.2 percent to 50.0 percent (table A-3). With the exception of the one unexpectedly high value of 50 percent, all other coefficients of variation are less than 25 percent. The accuracy of the analytical method was not determined.

The coefficient of variation for Zn analyses ranges from zero to 16.7 percent (table A-4). The generally low level of the coefficient of variation suggests that the analytical method for zinc was more precise than those for Cu, Ni and Co. However, there is reason to believe that the zinc contents as determined are lower than the actual zinc contents of the rocks. Holman (quoted in Vollrath, 1964) found that the bisulphate fusion method failed to yield as much zinc as a hydrofluoric acid extraction.

TABLE A-4. PRECISION AND ACCURACY OF ZINC ANALYSES

| Sample number | Replicate analyses | | | Mean | Variance | Std. Dev. | Coeff. of var. |
|---|---|---|---|---|---|---|---|
| | $x_1$ | $x_2$ | $x_3$ | $\bar{x}$ | $s^2$ | s | c% |
| NL-80 | 12.0 | 13.0 | 12.5 | 12.5 | 0.25 | 0.5 | 4.0 |
| NL-69 | 6.3 | 6.3 | 6.3 | 6.3 | 0.00 | 0.0 | 0.0 |
| NL-9 | 12.0 | 16.5 | 16.5 | 15.0 | 6.25 | 2.50 | 16.7 |
| NL-70 | 13.5 | 11.0 | 11.5 | 12.0 | 1.75 | 1.32 | 11.0 |
| NL-67 | 11.0 | 12.0 | 13.0 | 12.0 | 1.00 | 1.00 | 8.3 |

A1.04 Petrographic methods

Optic axial angles, anorthite content and twin laws of plagioclase were determined by means of a universal stage, using the techniques and migration curves of Reinhard (1931) and modified Reinhard migration curves (Barber, 1936).

The undulatory extinction and vague zoning of plagioclase grains in the Opemisca Lake pluton are not conducive to accuracy or precision on the universal stage, and consequently this method was abandoned. Instead, refractive indices of 001 and 010 cleavage flakes were measured, and the anorthite content determined by referring the results to a modified version (Morse, 1961) of the familiar Tsuboi-Smith curves (Tsuboi, 1923; Smith, 1956).

Modal analyses of thin sections were made by means of a Swift point counter with automatic stage. The horizontal intercept distance and traverse interval were changed for each thin section so that about 1,000 points would blanket as closely as possible the entire area of the thin section.

A1.05 Precision of petrographic methods

To check the precision of the point counting, thin section NL-11 was counted in its entirety at traverse intervals of 1 mm and a horizontal intercept distance of 1/6 mm. A total of 3,443 points were counted over 450 $mm^2$. The traverse intervals and intercept distances were then spaced more widely and only 1,060 points were needed to cover the area of the thin section. The thin section was then rotated in its holder and a third count, using the same settings as for the second count, but this time limited to 1,000 points, was made. The results of these various counts are shown in table A-5. It is clear that, for practical purposes, the count of 1,060 points is as precise as the one involving 3,443 points. The third count, after rotation, shows that a high degree of precision can also be expected irrespective of the direction of traverse across the section.

TABLE A-5. PRECISION OF POINT COUNTING

ENTIRE AREA OF THIN SECTION NL-11

| | Number of points counted | | |
|---|---|---|---|
| | 3443 | 1060 | 1000 |
| Plagioclase[1] | 55.6 | 55.6 | 56.1 |
| K-feldspar | 26.9 | 26.4 | 27.4 |
| Quartz | 13.0 | 12.3 | 12.2 |
| Hornblende | 2.9 | 3.0 | 3.4 |
| Accessories and holes | 1.6 | 2.7 | 0.9 |
| TOTAL | 100.0 | 100.0 | 100.0 |

[1]Includes myrmekite

In contrast, if the entire thin section is not covered by the count, spurious results are obtained. Table A-6 shows the modal composition as obtained at various stages during the initial counting of the 3,443 points in section NL-11.

TABLE A-6. PRECISION OF POINT COUNTING ONLY PART OF THIN SECTION NL-11

| | Number of points counted | | | | |
|---|---|---|---|---|---|
| | 250 | 500 | 800 | 1000 | 3443 |
| Plagioclase[1] | 62.4 | 60.6 | 62.5 | 60.5 | 55.6 |
| K-feldspar | 24.8 | 27.2 | 25.8 | 21.8 | 26.9 |
| Quartz | 11.6 | 9.2 | 8.6 | 13.9 | 13.0 |
| Hornblende | 1.2 | 1.2 | 1.1 | 1.9 | 2.9 |
| Accessories and holes | 0.0 | 1.8 | 2.0 | 1.9 | 1.6 |
| TOTAL | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

[1]Includes myrmekite

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