STUDY OF A TITANIFEROUS IRON DEPOSIT AND SURROUNDING COUNTRY ROCKS IN LA LIEVRE AREA, QUEBEC

A Thesis

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Department of Geology

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Master of Science

by

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TABLE OF CONTENT

I

II

ABSTRACT

The Lyonne township anorthositic complex and related magnetite ilmenite deposit are situated in the Grenville province of the Canadian shield, twenty miles west of Roberval Lake Saint Jean, Quebec. It is the oldest intrusion of the region but is younger than the paragneiss that covers a large part of the area. The complex is locally anorthositic but most of it is noritic.

The norite is a facies of the anorthosite from which it was derived by an accumulation of ferro magnesian minerals through normal differentiation. The complex has been subjected to regional metamorphism of the granulite or high amphibolite facies. At the close of the period of metamorphism, both gabbro and ore were intruded and metamorphosed by a pink granite which is probably of the Roberval type.

The associated ore deposit contains magnetic iron ore with an unusually low percentage of TiO_2. This anomaly is believed to be the result of either metasomatism accompanied by metamorphism by the acid intrusive, or by metasomatism alone.

INTRODUCTION

Interest in the mining possibilities of the titaniferous magnetite deposits of Lyonne township was first aroused in 1956. Discovery of the deposit was followed by intensive staking of claims, and geological and ground magnetic surveys. Titaniferous magnetite deposits are almost ubiquitous in the Grenville province, wherever anorthosites occurs, but very few are of economic interest because the amount of titanium is either too low to be considered as a valuable source of titanium or too high in the same material to produce a marketable iron ore.

The ore from Lyonne township is an exception. The Quebec Department of Mines sent a geological survey party to map the region during the summer period of 1958.

The author spent that summer as a senior assistant geologist with J. G. Bray, and had the opportunity to map the ore deposit, the host, and surrounding country rock in detail.

ACKNOWLEDGMENTS

It is a pleasure to thank Professor H. D. B. Wilson whose teaching and interest in the problem under consideration was of great assistance.

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Thanks are due to Mr. René Dubeau of Roberval Mining Company, who made available the company's camp.

LOCATION AND ACCESS

The east portion of La Lièvre area, mapped during the summer of 1958 is approximately 200 square miles in extent. It lies between latitudes 48°15' and 48°30' north, and longitudes 72°30' and 72°45' west, in the electoral district of Roberval, Quebec. The centre of the area is about 21 miles west of the town of Roberval on Lake Saint Jean. The area includes the southern half of Lyonne township, the western half of Ross township, and the northwestern corner of Chabanel township. The southwestern half of the area lies in unsurveyed territory outside these townships.

The Roberval La Tuque private toll road of the Consolidated Paper Corporation crosses the area from east to west near its middle. A road of the International Paper Corporation branching off the main road 1½ miles east of the area provides access to the southeast corner of the area.

The titaniferous magnetite depostis of Lyonne township are situated 20 miles due west of the town of Roberval, but the distance by roads between these two points is 42 miles. The mining properties are accessible by numerous motor roads.

PREVIOUS WORK

One of the first geologists to study the Lake Saint Jean area was James Richardson (12) of the Geological Survey of Canada in 1857. His survey was confined mostly to the shoreline of the rivers and lakes from the mouth of the Saguenay river to Lake Mistassini. In 1870 the same author completed his work by ascending the Ashuapmuchuan River, which flows into Lake Saint Jean.

F. D. Adams (1) of the Geological Survey of Canada was first to recognise the anorthosite series of the region. His work was published in 1884.

The petrography and distribution of the various rock types and structural relationship was established by J. A. Dresser (6) 1918.

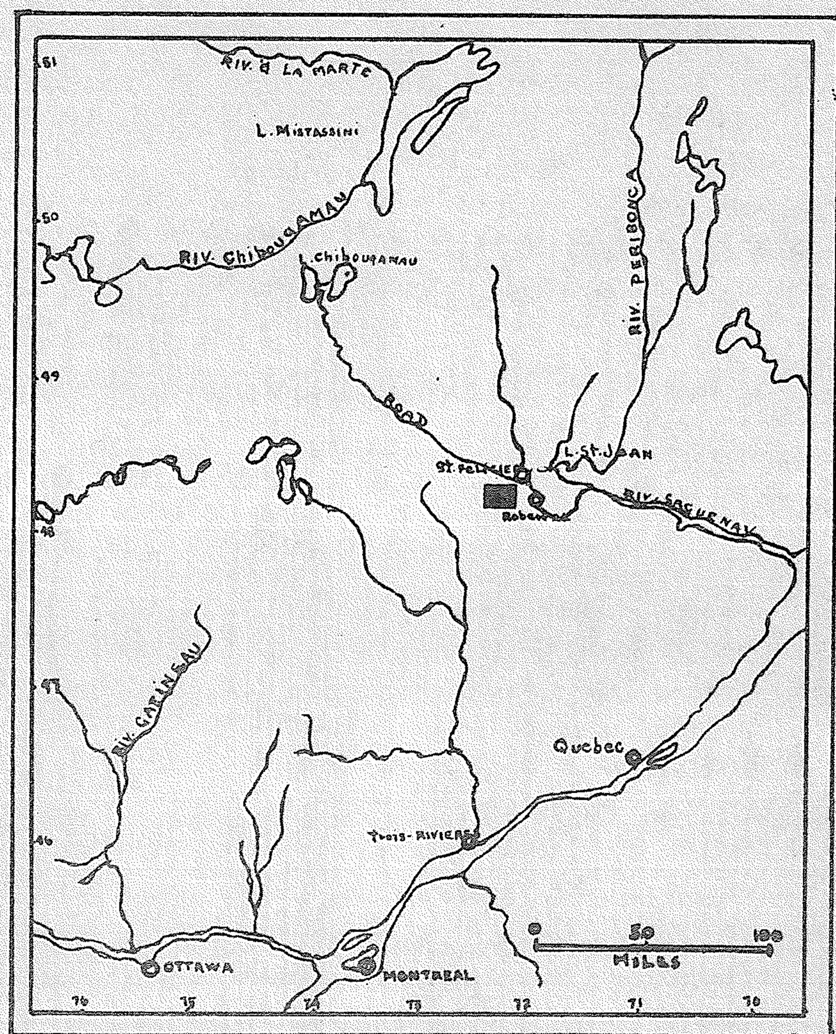
In 1933, B. T. Dennis (5) (1934) of the Quebec Department of Mines studied the northwest limits of the anorthosite series of the region and concluded:

> "Large portions of the area are underlain by rock of the same family (namely anorthosite) but in which the ferromagnesian minerals are so abundant that the rock should be termed a gabbro or a norite".

FIELD METHODS

Air photographs covering the entire region on a scale of about $\frac{1}{2}$ mile to the inch were provided for geological work. The part of Lyonne township in which a detailed survey was made had been covered by geophysical surveys and a system of cut-lines provided excellent control.

A base line was cut in a north direction generally parallel to the strike of the orebody and trend of the host rock. Lines were cut at every 400' normal to the base line. These cross lines were chained and marked at 100' intervals. The general field work was conducted by ordinary photo and compass method, and traverses were made at half mile intervals. The detailed mapping of the Lyonne township ore deposit was controlled by the cut-line system. Despite glacial drift, out-crops were numerous. However, some contacts were difficult to establish and approximations had to be made.



INDEX MAP SHOWING LOCATION OF THE AREA
(black rectangle)

Fig. 1

STATEMENT OF PROBLEM

It has been recognised and generally admitted that under no other modifying factor than its original chemical composition and the heat at which it solidified, the iron/titanium ratio of a magnetite rich magma shall follow a rather strict behaviour. This has been shown by A. F. Buddington (3) and co-workers (1955) after an extensive survey and accompanying laboratory work on titaniferous iron deposits across Canada and the United States in 1955. This ratio has proved to be consistent enough to be used as a geological thermometer for all magma having a Fe_3O_4, FeO TiO_2 system where ilmenite is present in excess as independant grains.

Numerous occurences of a gabbroic rock have been encountered recently in the Grenville of the Lake Saint Jean area; this finally led to the discovery in 1956 of an associated titaniferous magnetite deposit in Lyonne township.

Medium grained ilmenite and magnetite with minor feldspars and mafic minerals form lenses or layers alternating with small lenses or layers rich in the silicate minerals.

Both the ore and the country rock show effects that are a result of deformation and metamorphism. Various names were given to these rocks by previous workers; anorthosite, gabbro, meta-gabbro, and more recently hyperite were the most common. In some respects the rock resembles the meta-anorthosite of the Chibougamau district. However, various types of meta-gabbro are dominant and it is believed that they are correlative with the gabbro encountered in the deep drill holes northeast of lake Saint Jean.

The meta-gabbro of Lyonne township has been intruded by and has reacted with a pink granite which shows diverse facies but is probably of the Roberval type.

The deposit has several features of interest. The deposit is titaniferous but, although the magnetite contains an exceptionally low tenor of TiO_2, there is ilmenite in excess. Because the meta-gabbro is intimately involved with and is small with respect to the surrounding granite, it is believed that the meta-gabbro and associated ore tended to be brought to a new equilibrium, which was determined by the magmatic temperature and emanation from the granite.

Analyses from the occurence suggest a thermal equilibrium much below that normally found in anorthosite or gabbro and one even low for granite. It is reasonable to infer, therefore, that the enveloping granite caused an annealing temperature to be maintained for a long time so that extensive exsolution of TiO_2 took place.

The host rock shows a prominent banding which appears to be primary, although metamorphism has erased every trace of the original texture of the rock in surrounding vicinity. Lavas of the same age now are in the amphibolite facies, granites have been converted into orthogneiss, and high grade sillimanite gneisses are found in some parts of the Grenville series. Both ore and host country rock present problems of interest because both possess anomalies in their chemical as well as in their physical facies.

In order to solve these problems it will be pertinent to inquire into the areal and regional geology, the petrology and petrography of the host rock; the petrology of the enveloping acidic rock, the mineralogy of the ore. Thermometry and dynamometamorphism will have to be taken into consideration.

REGIONAL GEOLOGY

In order to place in their proper setting and understand the problems which will be the object of this thesis, it is pertinent to inquire into the general geology of the province of which La Lièvre area is a part.

The Grenville province occupies a band of 200 miles wide along the Saint Lawrence north shore from the Georgian Bay to Labrador. The Adirondacks are a part of this Grenville to which they are tied by the Frontenac axis. Geologically, it constitutes one unit of the Canadian shield differing from the remainder in rock assemblage as well as in tectonics.

The southeast limit follows a line from Georgian Bay to Brockville, then north of Ottawa and Montreal following the north shore of the Saint Lawrence River into Labrador. The northwest boundary starts at the northeast extremity of Georgian Bay, passes south of Lake Mistassini, south of the Labrador trough in the vicinity of Lake Attikonak and then to the Belle Isles strait.

Physiographically, the Grenville province is a part of the Laurentian plateau; the mountains are not the results of crustal folding, but one of an advanced state of peneplanation.

The geology of the region is complicated by deep erosion. The regional level has been lowered to such an extend that the intrusion cut into the sediments in a multitude of places so that only remnant of highly folded sedimentary formation are left. However, limestone and quartzites are easily recognised. It is difficult to classify certain areas as paragneiss or intrusion because of the high degree of granitization that took place. One of the distinctive features is the abundance of small intrusions of pegmatites and aplites.

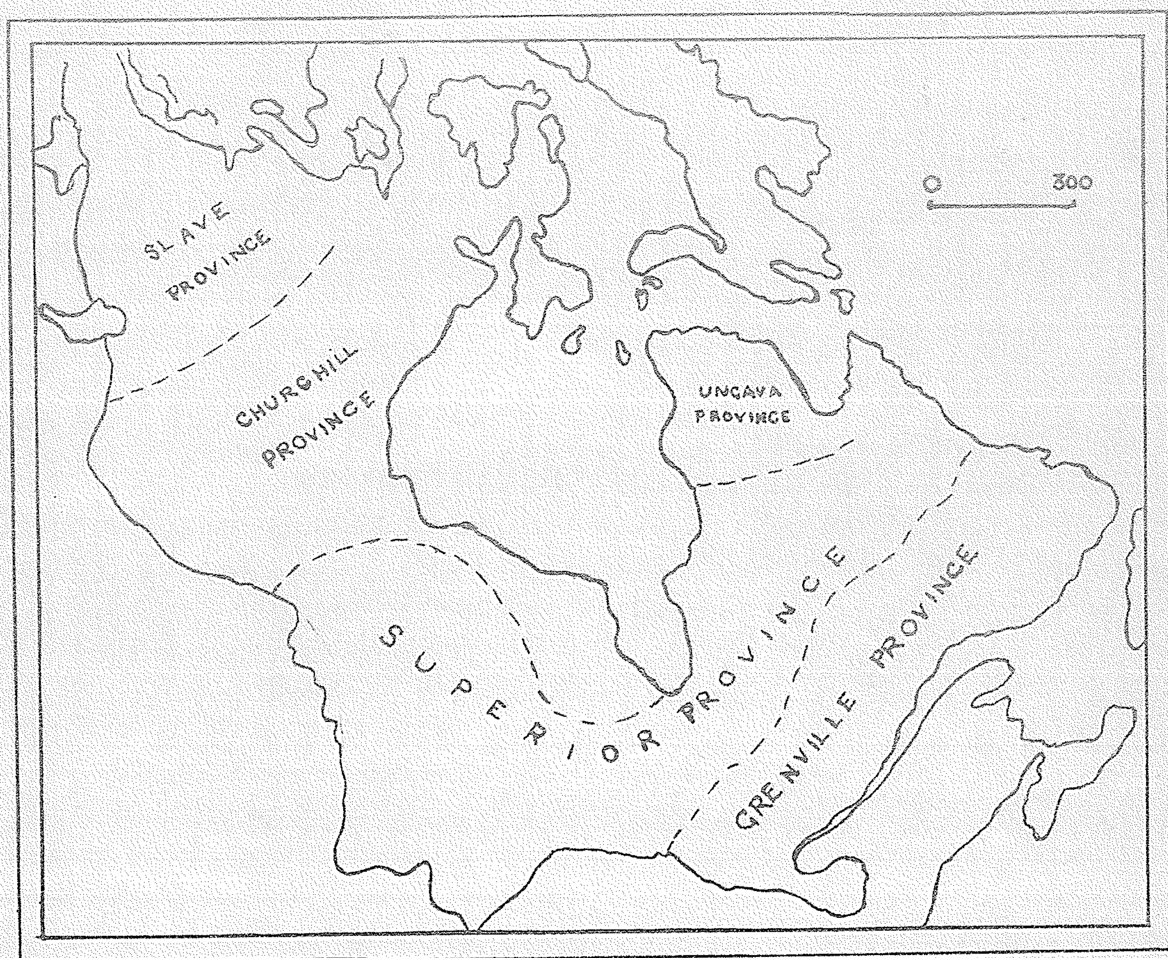
The Grenville series is intruded by numerous igneous rocks whose composition varies from granite to peridotite.

In his papers on the Adirondacks A. F. Buddington (2) describes four series in which the composition ranges from gabbro to granite:

1. Older series of gabbro and anorthosite.
2. Series of pyroxene diorite, to biotite quartz diorite.
3. Series of granite and syenite. (quartz syenite to hornblende and biotite granite).
4. Series of granite (hornblende or biotite granite, more recent).

In general, intrusions of the Grenville-Adirondack province can be classified only by their general facies.

Felsic facies	Granite and granitic pegmatite Syenite and pegmatitic syenite
Intermediate facies	Quartz monzonite Granodiorite Quartz diorite Diorite
Mafic facies	Gabbro Anorthosite Pyroxenite Peridotite



Geologic Provinces of Canada (Gill, 1949)

Fig. 2

PHYSIOGRAPHY

The La Lièvre area is from 1,150 to 1,850 feet above sea level, with an average of about 1,500 feet. Local relief is up to 400 feet. Continental glaciation has left extensive glacial and fluvioglacial deposits. These are found chiefly in areas of gneiss and gabbro which tend to have low or moderate relief and rounded hills; the later intrusive rocks forms comparatively rugged highlands, with little drift. A few large eskers over 40 feet high and numerous smaller ones trend southwards; several glacial or post glacial lake and stream terraces are present in the south of the area. A number of deep valleys occupied by rivers and lakes and apparently controlled by foliation or jointing, are thought to be pre-glacial.

The drainage has been glacially deranged: lakes and rapids are common. The northeastern third of the area drains into Lake Saint Jean, either directly or via the Ashuapmuchuan River; the rest drains southwards into the Saint Maurice River system.

The northeastern half of the area is thickly wooded with spruce, jack pine, birch and poplar; low, marshy ground carries alders. In the southwest, some areas are bared of trees and others are covered with a dense second growth vegetation as a result of extensive and repeated bush fires.

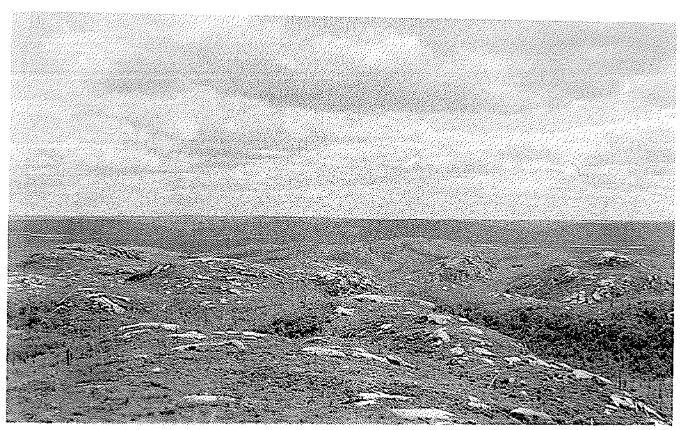


Fig. 3 The Grenville "plateau"

AREAL GEOLOGY

All the consolidated rocks of the area are Precambrian. Grenville type gneisses underlie most of the area; their general strike is west-northwest to north. Large plutons intrude these older rocks in the north and south. They consist chiefly of pyroxene quartz monzonites and hornblende biotite granite; the associated hornblende biotite granite is thought to be younger but genetically related to the quartz monzonites. The margins of the plutons usually are gradational. The Lyonne township titaniferous magnetite orebody is associated with an intrusion of gabbro or meta-norite of the anorthositic type; this meta-gabbro intruded the gneiss and in turn has been cut by the granite and monzonites. The anorthositic gabbro forms but a small part of the area of intrusions and its position as a unit of restricted dimension in the near center of a batholith of acidic composition explains the degree of metamorphism and metasomatism that characterise it.

TABLE I

TABLE OF FORMATIONS

Cenozoic	Recent	Sand, gravel
	Pleistocene	Till and glacial outwash
Unconformity		
Precambrian	Archaean	Gneissic hornblende biotite granite, aplite and pegmatite dykes, and hybrids
		Indefinite contact
		Pyroxene Quartz Monzonite Aplitic Sills
		Intrusive contact
		Meta-Anorthosite, Gabbroic Anorthosite, Meta-norite Granitized Equivalents, Ore
		Intrusive contact
		Granitized gneiss Pegmatites Amphibolite Quartzite Limestone, Metasomatic equivalents Pyroxenite

The Mixed Gneiss

Typical gneiss may contain 40 to 50 per cent grey to buff plagioclase (oligoclase to andesine), 20 to 25 per cent quartz, 15 to 20 per cent pinkish orthoclase, and 10 to 20 per cent ferromagnesian minerals. Differences in composition are marked principally by variations in ferromagnesian mineral content and in the proportions of hornblende and biotite. On this basis, three main types of gneiss can be distinguished: hornblende gneiss; hornblende-biotite gneiss; and biotite gneiss. These three types comprise most of the gneiss of the area. These rocks are variably grey, medium/or coarse grained and always show strong gneissic structure; Foliation of the gneiss generally strikes northwest. Near the margins of large intrusive bodies, the strike swings towards the west or north, giving the concordant structure typical of the area. With few exception dips are to the northeast and fairly steep.

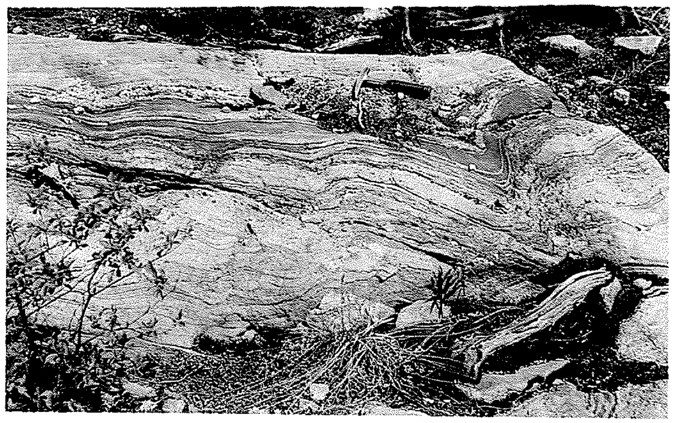


Fig. 4 Grenville "Paragneiss"

Fig. 5 Interbanded paragneiss with amphibolite layers.

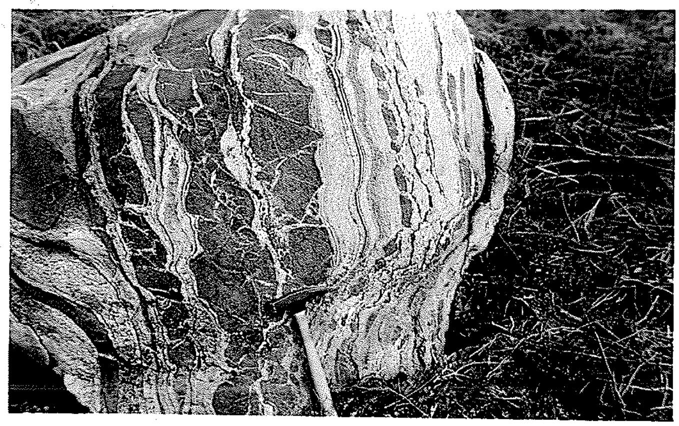


Fig. 6 Layers or amphibolites
in paragneiss.

Fig. 7 Boudinage in amphibolites.
A common structural feature
in the region.

The Host Rock

The host rock of the titaniferous magnetite ore presents many facies. In some part of the area the texture, colour and content of plagioclase feldspar definitely characterise the rock as an anorthosite; however, the outcropping part of this unit is restricted and most of the exposures are of gabbroic or noritic type; the content of dark mineral is much higher than in the anorthosite and the main dark mineral is orthopyroxene showing well developped shiller structure. This group, or complex, outcrops in the northwest part of La Lièvre area, covering an average of fifteen to twenty square miles; they intrude the older gneiss and are intruded by the much younger granite.

Buddington (2) classifies the rocks of the anorthosite gabbro type by their tenor of mafic minerals in the following manner:

Anorthosite	0 - 10 %
Gabbroic, noritic or dioritic anorthosite	10 - 22.5%
Anorthositic or feldspatic gabbro or norite	22.5 - 35 %
Gabbro or norite	35 - 65 %
Mafic gabbro or mafic norite	65 - 77.5%

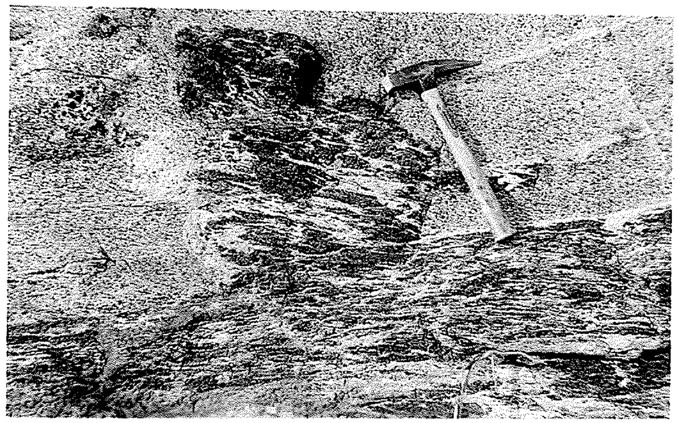


Fig. 8 Meta gabbroic anorthosite in a fine grain groundmass of a gabbroic composition.

Almost all of these related facies can be found in the Lyonne township complex and a tentative distinction of each type is given here under the title "Petrography of the host rock".

Generally, the rock is medium/to coarse grained, showing a strong lineation of elongated mafic minerals varying from dark for the anorthositic type to grey and buff for the more gabbroic or noritic one. The green or grey and mauve plagioclase range from 30 to 80 per cent. Orthopyroxene with strong shiller texture is the dominant ferromagnesian mineral though it becomes the least important one in the facies most affected by metamorphism and metasomatism, where it is replaced by hornblende and biotite.

The intrusion trends generally northward and dips range from 80 degrees west to vertical. Joints are highly irregular and complicated by numerous dykes, tongues and veinlets of granitic material that cut across or fill them.

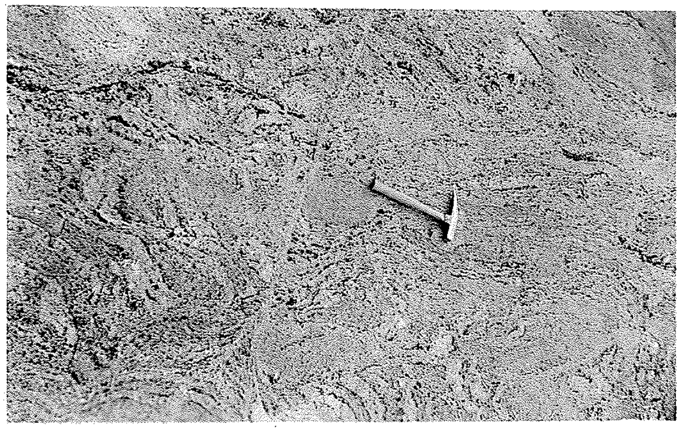


Fig. 9 Micro folding in meta-norite.

Fig. 10 Typical meta-norite.

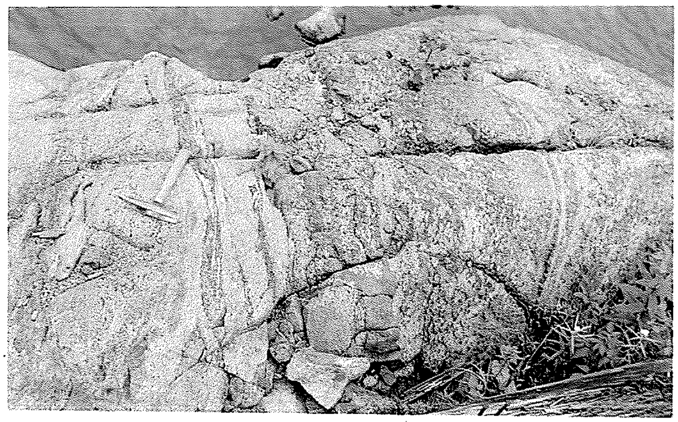


Fig. 11 Layered anorthositic norite.

Fig. 12 Gabbroic anorthosite: Weathering or interstitial minerals accentuate the texture of the rock.

The Meta-diabase Dykes

Narrow dykes of the same composition as the meta-norite are scattered throughout the complex. They are grey on the weathered surface and range from fine grained in their outer part to porphyritic in the core. They become almost evenly porphyritic when intruded or transected by granitic material. Large porphyroblasts are mainly recrystallized acid andesine or labradorite up to an inch in length. Hyperthene is the dominant ferromagnesian mineral. Accessory minerals are magnetite, ilmenite and apatite. Secondary minerals are hornblende after hypersthene and biotite after magnetite-ilmenite.

The amount of movement or flowage that took place during regional metamorphism is well examplified by the attitude of these dykes. Most are broken and folded along their strike and compression has resulted in much variation in width. In thin section they show a high degree of mylonization and recrystallization.

Fig. 13 Folded meta-diabase dykes
in meta-norite.

The Enveloping Acidic Rock

The acidic magma intruding the gabbroic complex and associated ore is a pink, medium/to coarse grained rock, usually massive but sometimes crudely foliated. It appears as a rim or partial rim to the quartz monzonite which forms intrusions of batholitic dimension in the area. Its position and the presence of a pseudo uniaxial hornblende mineral in each type suggests a genetic relationship. The fact that the granite tends to occur near the margins and as small plugs in the pluton suggests that it is the younger rock.

Like most other igneous rocks in the area, the foliation of the granite is oriented northward but varies near contacts with other rocks.

A variety of partly digested and metasomatized hybrid rocks occur in the marginal granite zone. Norite xenoliths in granite usually have gradational margins and other rocks of the gneiss group were highly digested. The crude gneissic texture and mineralogy of the granite are characteristic of a much lower grade of metamorphism than that affecting the other rocks of the area. These features and its similarity to the granite of the Roberval type, outcropping in the vicinity of La Lièvre area, and classified as "Post Kinematic" are all proofs that the granite was intruded after or in the later stages of the regional orogeny.

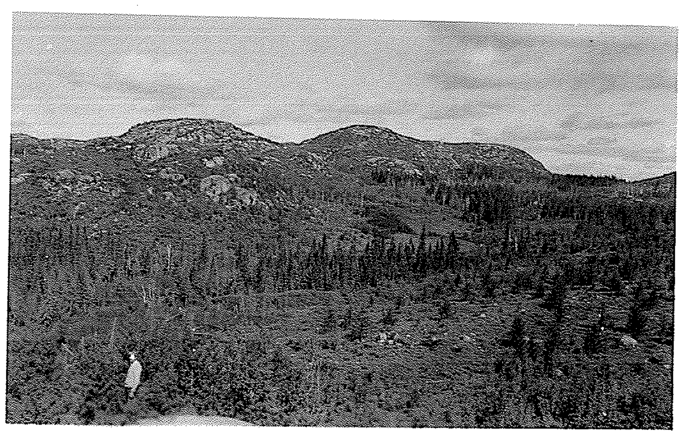


Fig. 14 Quartz monzonite and granite intrusions. These acid rocks form massifs of batholithic dimension in the La Lièvre area.

GEOLOGY OF THE DEPOSIT

F. F. Osborne (8) divides magmatic iron ore intrusions into two categories: the concordant and the discordant bodies. The first group is characterized by the following:

a) The bodies are sill like.

b) Minerals composing them are late crystallization in country rock.

c) They are in sharp contact with the anorthosite (or gabbros).

d) The texture shows that these rocks crystallized under static conditions.

e) When feldspars are present the amount of iron ore increases with the amount of pyroxenes.

The Lyonne township titaniferous magnetite deposit belongs to this first group and complies with every characteristic listed by Osborne. The deposit occurs as a marginal late injection in the outer part of the complex, striking northward parallel to the complex and generally dipping west at the same steep, nearly vertical, angle. The ore body is divided into two main zones very similar to each other; they are about six hundred feet wide and average 1,000 to 1,600 feet in length. These zones are known and referred to as zone A and B, and are separated from each other by blocks of gabbroic rock and dykes and tongues of granitic composition. There is no doubt that the ore is genetically related to the gabbroic intrusion because its geographical location at the offset of the complex and its similar petrographic character and mineralogy are proof of the relationship. The following table indicates the succession of formations in the vicinity of the ore:

TABLE II

Aplites, Granite, Pegmatites

Intrusive contact

Granite intrusion

Intrusive contact

Titaniferous magnetite deposit

Intrusive contact

Meta-diabase Dykes

Intrusive contact

Anorthosite, Meta-norites

The relation of silicates to ore (Fe_2O_3 + $FeOTiO_2$) provides a threefold classification of the ore: a) the layered, medium rich type, where ore lenses alternate with silicate lenses; b) the non-layered iron disseminated type; c) and finally the non-layered rich zones, composed of solid ore.

a) The greatest part of the deposit consists of the layered type. In these, the intercalation of silicates with the ore is very irregular; layers of buff-colored silicates range from a few inches to a foot in width and a few inches to several yards in length. Late injection of some ore has broken these silicate lenses along their length into many individual pods resulting in a boudinage-like structure. Differential weathering of less resistant silicates have formed accentuated pitting.

b) The non-layered silicate rich-type is classified as ore because of its occurence in the ore zone and its sharp contact with the host rock; the percentage of silicate minerals would otherwise classify it as a magnetite-rich gabbro.

Weathering of the silicates and the ore gives the rock a buff rusty colour. Some concentrations of magnetite in schlieren-like lenticles stand out in relief; these concentrations being very irregular but invariably elongated parallel to the strike of the layered type ore. In this non-layered type, silicate minerals compose about 75 per cent of the rock in aggregate with the magnetite and ilmenite.

c) The third type is referred to as the solid or non-banded type though it also contain a fair amount of silicate minerals. Its pitch black colour and regular surface gives the impression that it is composed of pure magnetite and ilmenite but close observation reveals only 40 to 50 per cent of these minerals. In contrast with the silicate-rich type, weathering has given the solid ore a smooth and rounded surface.

The various ore types are related by an intrusive sequence. The silicate-rich non-banded type is intruded by the layered one and this in turn, by the solid ore.

Fig. 15 Late injection of ore breaking silicate lenses of layered ore.

Fig. 16 Infiltration of granite (center) in solid ore (upper and lower).

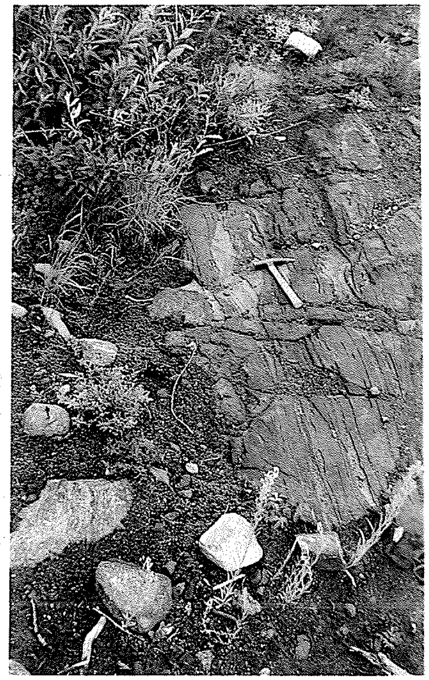


Fig. 17 Layered ore. Lenses rich in silicate minerals alternating with lenses or ore.

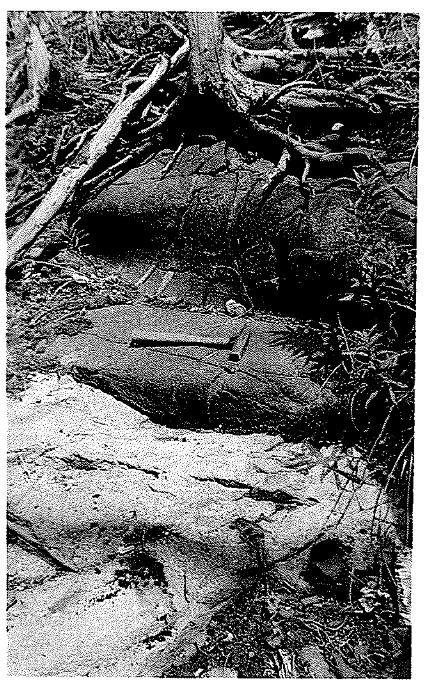


Fig. 18 Solid ore resting on apophysis of granite.

MORPHOLOGY AND STRUCTURAL RELATIONSHIP

The erosive action of weathering and glaciation has resulted in lowering the surface level of the ore. The more resistant gabbro and granite stand up in relief above the fairly level surface of the deposit. The general aspect of the deposit is that of a rectilinear sill-like body, striking northward and dipping steeply west at a near vertical angle. Its width and length are regular and diamond drilling indicates that it is also regular down to a depth of two hundred feet. Mechanical action of the acid intrusion has resulted in a fold/and fault like pattern, but horizontal movement was not extensive, ranging from a few inches to a maximum of twenty-five feet. All horizontal movement was directed westward, from the granite toward the gabbro. Vertical movement, however must have been of considerable amplitude.

Fig. 19 Silicate rich ore (right),
intruded by solid ore (left)

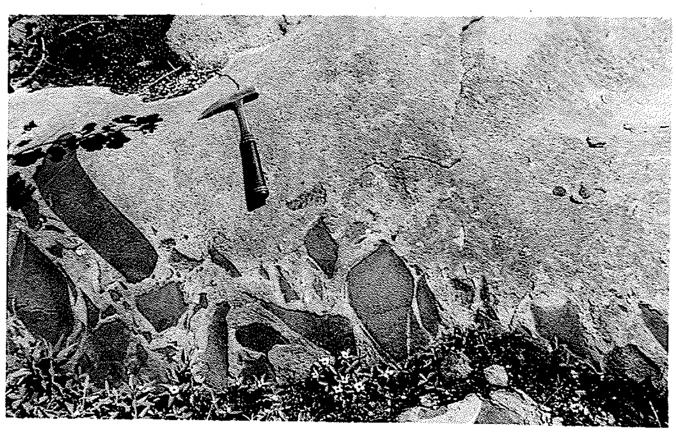
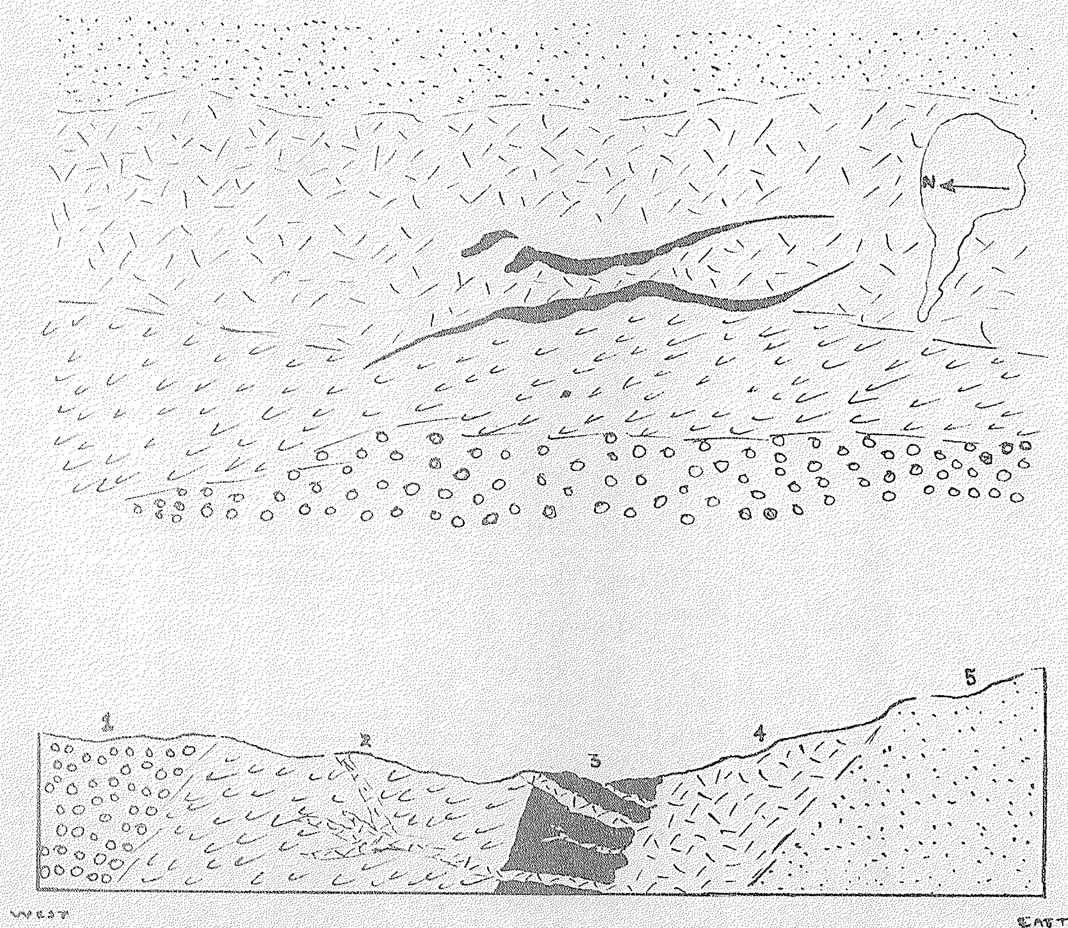


Fig. 20 Intrusive Breccia:
Angular blocks of ore in granite.

Invasion of large apophyses of granite at depth has broken loose huge blocks of ore which are now more or less resting or "floating" on granitic material. It is difficult to establish the degree of movement that took place along these vertical planes but outcropping granite tongues and dykes responsible for that movement vary from 5 to more than 75 feet thick. The general contact of ore and granite is saw-toothed and highly irregular; hundreds of veinlets of granitic composition more or less contaminated by gabbroic rock fragments transect the deposit.

The contact between ore and host rock is very sharp and no visible chill zone occurs. In one place, however, a large block of gabbro eight feet wide and about thirty feet long is situated inside the ore zone. This anomalous emplacement is difficult to explain but it is possible that the block was torn away from the wall of the host rock during the intrusion of the ore.



1 Anorthosite
2 Meta Norite
3 Ore
4 Granite
5 Monzonite

Plan and Cross Section of Magnetite Deposit

Fig. 21

PETROGRAPHY OF HOST ROCK

Geographically the Lyonne township meta-gabbro is close to the well known Lake Saint Jean anorthosite and the gabbro intrusions recently discovered in the eastern portion to the same area. If this meta-gabbro presented only one facies it probably would be possible to ascertain their genetic association to one or other member of the areal intrusions. Actually such is not the case; the rock presents a series of facies grading from a pegmatic one of the anorthosite family through a suite of intermediate types, passing in a discontinuous fashion into a meta-gabbroic anorthosite, a meta-norite, a transitional facies of coronites and finally at the other extreme into what could be called a biotite diorite.

The anorthositic part provides a possible correlation and genetic connection with the many areal anorthositic intrusives but it accounts for such a minor part of the whole complex that it would certainly not be representative. However, the notable absence of olivine is suggestive of a possible relation.

Principal primary minerals were plagioclases, orthopyroxenes, augite, apatite, biotite, and opaque minerals, mainly magnetite, ilmenite and a little pyrite.

Most of these minerals have undergone chemical alteration and recrystallization. Some of the plagioclases are completely recrystallized, pyroxenes were converted to hornblende which in its turn was altered to biotite. Calcite is visible in the most altered facies, magnetite is surrounded by rims of sphene and leucoxene. Plagioclase becomes more sodic in the later phases and some albite is present; the percentage of silica was also augmented considerably.

There is considerable variation in texture and in mineral and chemical composition from one point to another inside any part of the intrusion; the gabbroic facies turns suddenly into an anorthositic one while the anorthositic type gives place to layers or bands of gabbroic character.

Structurally the complex is more regular. Regional movement has produced slight folding and faulting and these features may be found in any unit of the complex.

Even if it is impossible to correlate the different facies in the field, the complex is made up of many rock types related by a mineralogical evolution strikingly revealed by thin section investigation. This evolution is in part due to normal differentiation, regional and local metamorphism and alteration by granitic injection.

Accepting for the moment that we are dealing with a differentiated mass having the original character of an anorthositic rock, we would have the following succession:

a) Meta-anorthosite

b) Meta-gabbroic anorthosite

c) Meta-norite

d) Transition facies (coronites)

e) Biotite diorite (granitized meta-norite)

A) Meta-Anorthosite

The only location where a rather homogeneous body of anorthositic type could be found is in the vicinity of Cariboo Lake, approximately two miles from the main part of the complex. There it outcrops along the shoreline as a layered irregular pegmatitic mass that is dark to pale grey and shows a very strong rugosity due to differential weathering of its minerals. Interstitial minerals are less resistant to erosion than the plagioclases and form pits which accentuate the texture of the rock.

The feldspar is andesine to labradorite and mafic constituents do not amount to more than 15 per cent of the total composition. More than 75 per cent of the rock is composed of plagioclases, often curved and broken. The rest is composed of orthopyroxene, augite, hornblende, magnetite, ilmenite and minor apatite with biotite grouped mainly around the other ferromagnesian minerals.

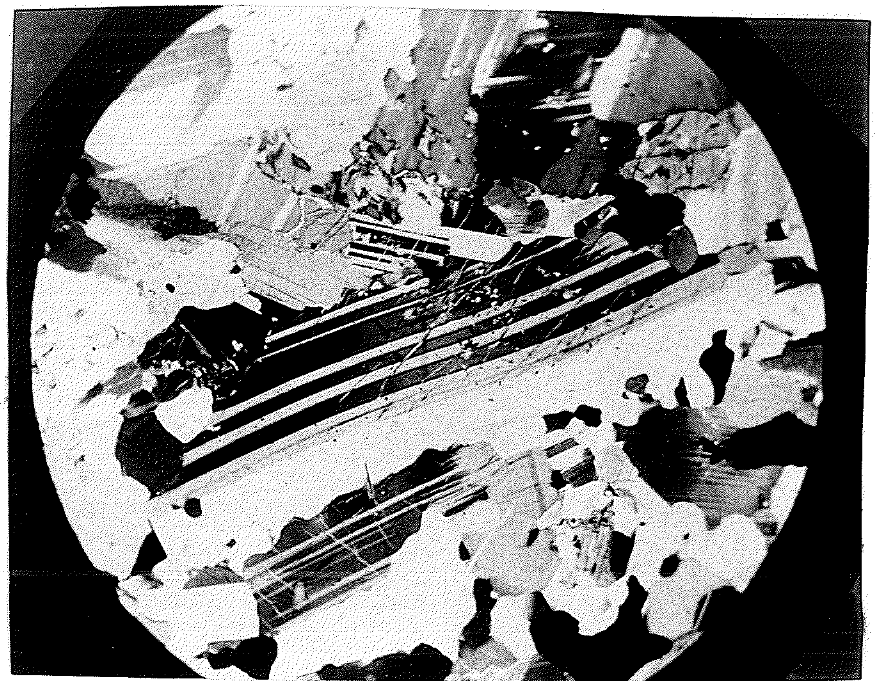


Fig. 22 Plagioclase porphyroblasts in anorthosite.

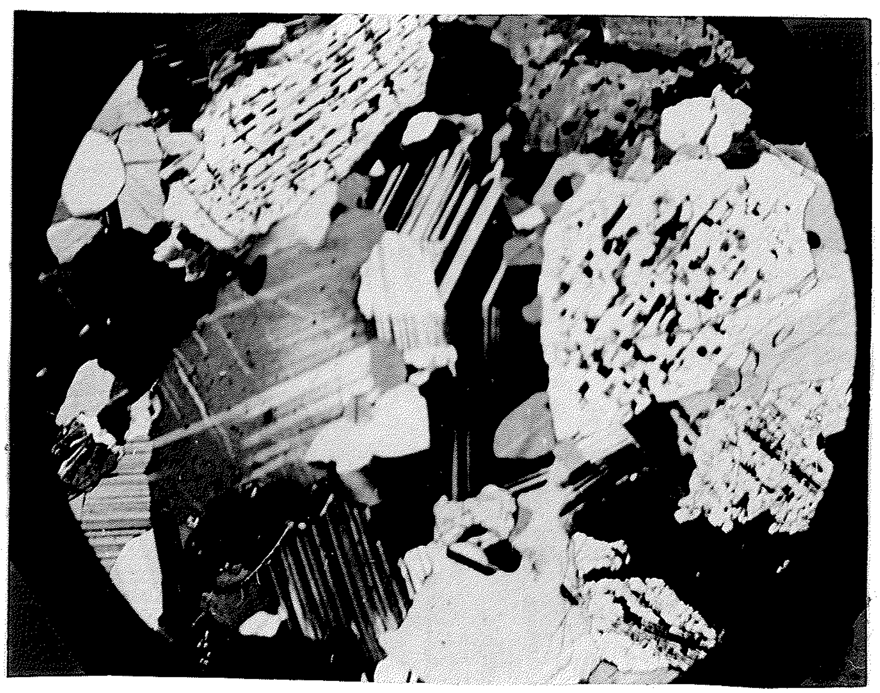


Fig. 23 Gabbroic anorthosite. Plagioclase, hypersthene, hornblende.

TABLE III

MODAL ANALYSES OF META-ANORTHOSITE

Plagioclase	82.3	76.3	81.5
Hypersthene	7.2	8.2	6.7
Augite	2.7	4.1	3.1
Hornblende	0.1	3.0	0.3
Biotite	-	1.4	0.7
Opaque	0.4	2.1	2.2
Apatite	1.4	0.7	1.3
Quartz	2.7	2.2	3.0
Garnet	2.1	0.4	0.5

B) Meta-Gabbroic Anorthosite

This member of the complex does not appear in any particular zone of geographical position relative to the other members. It outcrops usually in the paragneiss and the meta-norite. It appears in the latter as irregular and disconnected blocks of pegmatitic texture in a fine groundmass of gabbroic character from which it differs in mineral composition and texture.

Its mineralogical features are similar to the meta-anorthosite already described and from which it is certainly derived, although the percentage of the composing minerals is different. Ferromagnesian minerals increase to about 20 per cent with a corresponding decrease in the feldspars. The texture is very coarse and consists mainly of broken and curved feldspars dusted with inclusions of unidentified minerals. Augite and hypersthene are the predominant ferro-magnesian minerals. Some hornblende secondary after pyroxene is present. One remarkable feature is an intergrowth of ilmenite and magnetite.

Only one lamella of magnetite shows this phenomenon, but it provides a clue to the mode of origin of this member as a slowly cooling mass, probably protected from metamorphism by the shielding effect of the paragneiss. On cooling, unmixing of the solid solution of ilmenite and magnetite occured because of decreased solubility: the ilmenite separating from the magnetite parallel to the face of the octahedron.

The fact that the gabbroic anorthosite is pegmatitic is consistent with the appearance of that feature known as the Widmanstetten structure. The volatiles which were necessary to produce the pegmatitic character have also restrained the rate of cooling of the ore minerals.

Where intruding the regional paragneiss, the meta-gabbroic anorthosites do not show the same well-defined structures that they have when intruding the norite. The gneiss reacted strongly and was mostly digested. The resulting rock is mostly composed of altered feldspar and biotite; sphene and apatite are present as accessories.

C) The Meta-Norite

This is the part of the whole intrusive sequence which is preponderant in both its geographical extension and its geologic regularity. It occupies an area of about forty square miles outcropping irregularly, striking in a general northward orientation, but locally modified by small folds and faults.

The surface varies from dark to pale grey or buff in the more weathered zones. Its superficial aspect is very different from the anorthosite which has a mottled surface. The norite on the contrary is smooth and very regular. A strong lineation of the elongated ferromagnesian minerals gives the rock a gneissic appearance. This gneissosity is amplified by the presence of shlieren consisting of an accumulation of dark minerals. The origin of these shlieren is enigmatic but the high content of biotite suggests that they were originally blocks or "lambeaux" of paragneiss enfulfed and almost totally digested by the norite.

The meta-norites are mineralogically composed of 30 to 50 per cent of grey and mauve plagioclases. Altered plagioclases are restricted, most have recrystallized into clear, fresh, less calcic varieties. The recrystallized types are well twinned whereas the altered plagioclases are cloudy with inclusions and have lost all their crystallographic structure.

Orthopyroxene with strong schiller structure is the dominant ferromagnesian mineral but its ratio to secondary hornblende formed at its expense is much lower than in the previous facies. In some thin sections the percentage of secondary hornblende is equal to that of pyroxene. Hornblende is ofter clouded with secondary magnetite probably released during the transformation of an iron rich pyroxene (hypersthene) to an iron poor amphibole (hornblende). Although secondary magnetite appears very fresh, primary grains of titaniferrous magnetite are highly altered and leucoxenized.

Saussuritized feldspars, usually found in similar Grenville rock are lacking here. It can be explained by the fact that the amount of water available was required for the conversion of hypersthene to hornblende, preventing the formation of zoisite or/and epidote. The process could also have been one of uralitization and the lower percentage of anorthite in the plagioclase due to the original differentiation.

The calcium released by uralitization of hypersthene combined with silica and the titanium of ilmenite to produce sphene and leucoxene; the rest remained as free calcite and is present in that form in variable amount.

TABLE IV

MODAL ANALYSES OF THE META-NORITES

Plagioclases	48.2	54.8	61.4
Hypersthene	25.1	22.1	18.3
Hornblende	16.3	14.3	14.1
Biotite	0.8	0.5	0.2
Opaque	2.4	1.9	1.3
Apatite	0.9	0.8	1.0
Quartz	2.3	3.2	1.6
Garnet	1.2	1.8	0.9
Sphene, Leucoxene	0.7	1.0	0.2
Calcite	0.3	0.1	-

D) The Coronites

Pseudomorphism of some of the pyroxenes by amphiboles is characteristic of the meta-norite; a more advanced stage of replacement is given by the coronites in which most primary minerals such as hypersthene, magnetite, and feldspars can now be considered as relics. Most of these minerals are now surrounded by more or less well developed reaction rims. These rims occur at the contact of plagioclase and mafic minerals, encircling mafic minerals and in extreme cases as separate rounded grains, where the original minerals have been completly replaced.

All degrees of replacement occur in a single thin section; for example, sphene or leucoxene coronae may have an average volume to ilmenite of 1:5 whereas in other places a barely visible grain of ilmenite is left in the center of the newly developed mineral. Hornblende after pyroxene shows all degrees of replacement from one grain to another. This secondary hornblende shows two different modes of development from the primary pyroxenes; in one case the hornblende takes the form of tiny little rods growing outward, and in the other case the hornblende seems to grow inward without any definite pattern. Partly replaced pyroxenes yielded secondary quartz and magnetite as the result of their transformation.

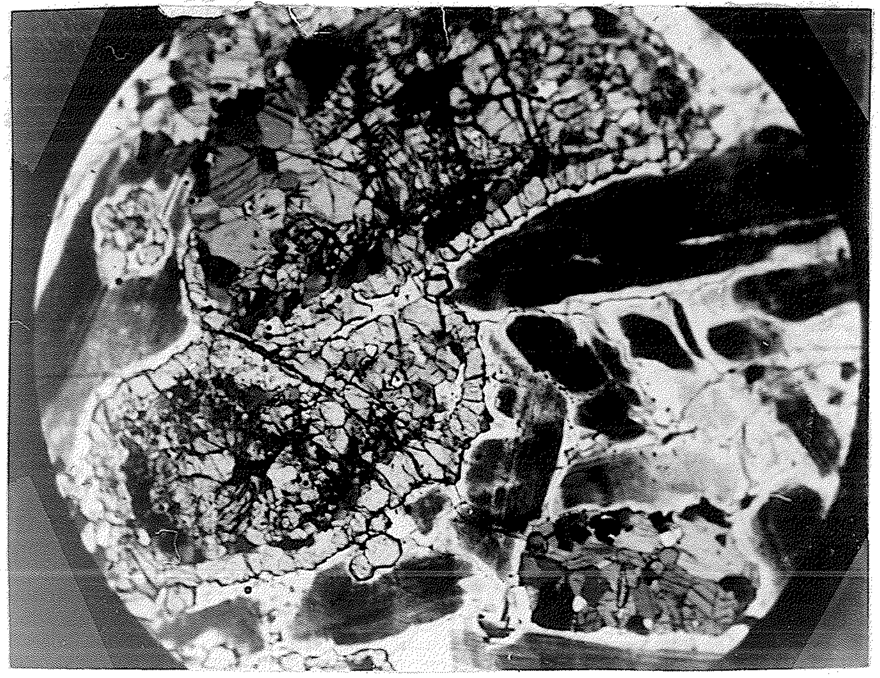


Fig. 24 Corona of garnet formed at contact between plagioclase and hypersthene.

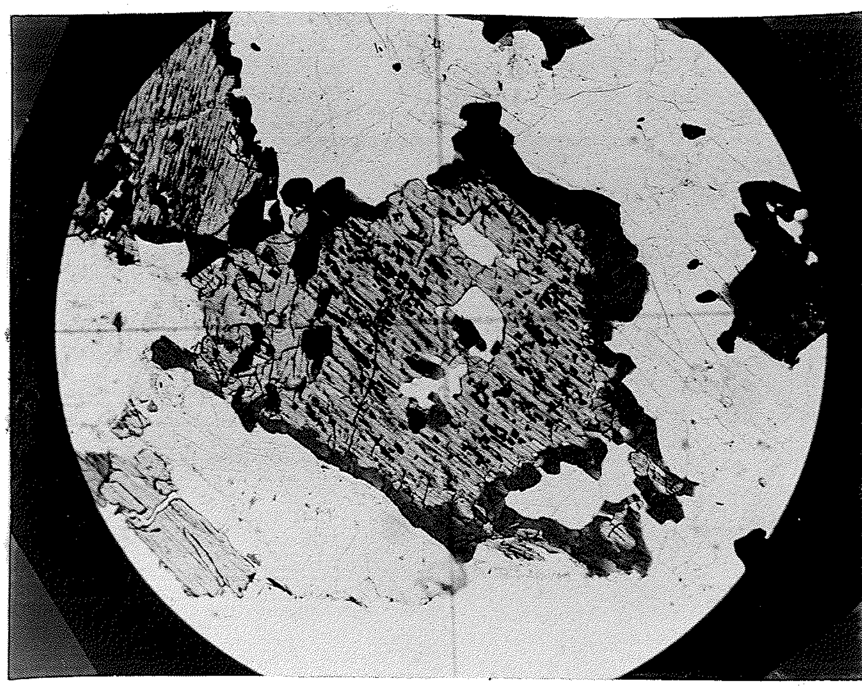


Fig. 25 Detail of a corona of hornblende around hypersthene showing secondary magnetite and quartz in the ocre of the latter.

TABLE V

MODAL ANALYSES OF THE CORONITES

Plagioclases	43.8	44.2
Hypersthene	12.1	13.1
Hornblende	28.4	24.8
Biotite	3.1	2.7
Opaque	2.4	4.3
Quartz	4.0	3.2
Garnet	3.9	5.1
Sphene, Leucoxene	2.1	1.4

Garnet (see Fig. 24) are found in euhedral independent grains or as blebs between feldspar and mafic mineral. Successive zones around an original mineral, as described by many authors are not found in Lyonne meta-gabbro, except perhaps for the presence of biotite from secondary hornblende.

Most feldspars are recrystallized to clear plagioclases ranging from andesine to calcic oligoclase, but grains or primary labradorite are deformed and full of inclusions.

One persisting mineral that shows no evidence of metamorphism or alteration is apatite. It still appears in groups of euhedral grains usually where magnetite is concentrated.

Except for a slight schistosity, megascopic characteristics do not delimit the zone where the coronites occur in the gabbroic complex. For this reason it is difficult to ascertain whether their origin is a result of a late deuteric alteration or thermal solutions from the invading granitic magma.

E) The Biotite Diorites

The origin of the biotite diorite as an altered facies of the norite caused by the granitic invasion is much more easily established than the origin of the coronites.

Megascopically in the field, and microscopically in thin section, the diorite can be readily seen to be the result of mechanical and chemical action from the invading acidim magma. This facies forms only a small part of the total gabbroic intrusion but it is outstanding in its regularity as a reaction band following closely the numerous tongues, apophyses, and dykes of injection granite.

The diorite is a pale grey to buff-coloured rock with a fine grained texture and a more or less well-developed schistosity parallel to the contact. Mineralogically it is composed of feldspars, hornblende, and biotite with a variable amount of recrystallized pyroxenes (augite). The plagioclases range from andesine to oligoclase. They are usually clear but some are granulated. In places the amount of secondary biotite exceeds that of hornblende. In one thin section, a Rosiwall analysis revealed up to 35 per cent biotite with a corresponding decrease of the hornblende. Quartz is both primary and from injection. Secondary minerals are sphene, apatite, and magnetite. Garnet is present locally.

TABLE VI

MODAL ANALYSIS OF THE BIOTITE DIORITES

Plagioclase	47.6	44.2
Hornblende	22.2	14.6
Biotite	12.7	25.1
Augite	7.1	4.1
Opaque	1.1	2.3
Quartz	6.2	5.0
Apatite	1.3	—
Garnet	0.2	3.1
Sphene, Leucoxene	1.6	1.2

PETROGRAPHY OF ENVELOPING ACIDIC ROCK

The rock intruding the meta-gabbro and ore is a pink medium grained granite containing 50 to 60 per cent orthoclase and microcline microperthite, with a little sodic plagioclase and a total of about 10 per cent hornblende and biotite. As much as 25 per cent quartz may be present. Dykes and apophyses of the same composition radiate from the main granitic plugs and intrude all other types of rock in the area, thus dating the granite as the youngest intrusive body. In contrast with the other igneous intrusions of the region, the granite shows a very fresh texture: the presence of microperthite in place of the usual microcline and albite found as separated feldspars in metamorphosed zones and the non-undulatory extintion of quartz suggest that the rock is younger than the period of tectonic activity that affected the region.

TABLE VII

MODAL ANALYSIS

	1	2
Microperthite	38.2	32.1
Orthoclase albite	32.1	33.5
Quartz	23.0	24.2
Hornblende	4.3	7.1
Biotite	.1	1.3
Accessory mineral	1.0	.7

COMPARATIVE MODAL ANALYSIS OF THE ROBERVAL TYPE GRANITE.

Orthoclase	35.50
Albite	30.30
Anorthite	6.39
Quartz	22.50
Ilmenite	0.61
Magnetite	1.16
Diopside	1.67
Hypersthene	1.36

(In the eastern part of the district the Roberval granite contains less quartz, the feldspar becomes largely microperthite and the rock approaches syenite. J. A. Dresser (6))

METAMORPHISM

The study of metamorphism of the Lyonne gabbroic intrusion is complicated by the degree of variation in mineral composition that takes place from one point to another. Beside normal differentiation of a gabbroic mass of anorthositic origin, the complex was subjected to regional and local metamorphism and metasomatism. Each member has reacted according to its original composition and geographical situation, and now shows features resulting to some extent from these primary characters.

The mafic minerals of the meta-norites, the most important part of the complex, are mainly hornblende and hypersthene with minor recrystallized augite. The plagioclases are either dusty labradorite or clear recrystallized acid andesine. In some instance garnet is present as a reaction between dusty plagioclases and mafic minerals, and its position as corona is nicely displayed. These coronites contain invariably clouded plagioclases.

The following conditions for clouding of plagioclases are suggested by Poldervaart and Gilkey (9). These conditions are:

1) The existence of an adequately high temperature for a sufficient length of time.

2) The presence of an aqueous pore liquid.

3) The presence of iron-bearing minerals in the original rock.

Shand (14) believes that coronites are the result of thermal metamorphism and MacGregor (7) suggested a similar origin for clouded feldspars.

When feldspars are recrystallized, garnets appear as free knots and are found as separated grains. There is a complete transition in pseudomorphism. In some places, hornblende has almost completely replaced hypersthene whereas in others it forms more or less well-developed coronas around it. Where replacement is partial, secondary quartz and magnetite occur in the core of pyroxenes. Primary ilmeno-magnetite is usually surrounded by a rim of sphene or leucoxene. Biotite is often developed either from secondary hornblende or primary magnetite. Apatite is not affected either by metamorphism or metasomatism. This mineral, rather abundant in the anorthositic facies, becomes scarce in normal meta-norite but re-appears in the more mafic zones of the same rock. In magnetite rich meta norite, the non-recrystallized pyroxenes are highly pleochroic from yellow to deep blue, thus suggesting the presence of titanium in their composition. The presence of brown hornblende tends to corroborate that suggestion. Inclusions in pyroxenes are too small to be identified but their needle shape terminated by pyramids suggests rutile.

The general texture ranges from ophitic in the least affected portion, to granulitic where pyroxene and hornblende are in crushed aggregate with plagioclases, and granoblastic where recrystallization has taken place. Such variation raises difficulty in interpreting the exact degree of metamorphism.

The andesine labradorite anorthosites and associated gabbros of Precambrian terranes are sometimes classified as member of the granulite facies, but this is a very broad classification and often erroneous when applied to a particular area. Buddington (2) mapped a series of three metamorphic zones in the Adirondacks (Grenville) based on mineral assemblage of rocks of anorthositic and gabbroic composition. They cover a progression from the almandine amphibolite facies (zone I) through the hornblende granulite (zone II) into the pyroxene granulite subfacies (zone III). The prevailing characters of each zone are given below.

Zone I Green hornblende facies (almandine amphibolite).

a) The pyroxene shows partial to complete alteration to hornblende.

b) The rocks have a microtexture varying from essentially massive rock with a primary ophitic to subophitic texture of magmatic crystallization through mortar gneiss to mylonite.

c) The secondary mineral is predominantly green hornblende.

Zone II Hornblende, hypersthene, augite facies (hornblende granulite).

a) Mafic minerals are predominantly hornblende and hypersthene with more or less augite and usually a little biotite.

b) In large part, the augite forms fresh recrystallized grains.

c) Most of the labradorite is in clear recrystallized grains.

Zone III Garnetiferous facies (pyroxene granulite)

a) Garnet is present, in addition to other mafic minerals and is diagnostic for the facies.

b) In more metamorphosed facies, much of the meta-gabbro is strongly garnetiferous so that hornblende is subordinate or absent and pyroxenes and garnets are the major mafic minerals.

c) The plagioclase ranges from labradorite to oligoclase in the more advanced facies.

The mafic mineral composition and recrystallization of some of the pyroxenes and plagioclases in the Lyonne complex is similar to the facies of zone II of Buddington's classification. Garnet, a diagnostic mineral of zone III is also present but it does not appear in sufficient amount to displace hornblende and/or pyroxene as the dominant ferromagnesian mineral.

The conclusion is that the anorthositic gabbro of the Lyonne township belongs to the granulite or at least to the high amphibolite facies.

REACTION ZONE AND CONTACT PHENOMENA

The penetration of the meta-norite and titaniferous magnetite by the acid intrusion has resulted in a variable mineral assemblage in places quite different from the original one.

A zone of modified gabbroic rock situated near the contact has already been described as a biotite diorite. The characteristics of that zone were mainly the high percentage of biotite, the presence of a more sodic plagioclase and the amount of introduced silica. In addition to this general alteration however, a whole set of phenomena worthy of description is visible in thin section from rocks situated at the immediate contact with the granite. They are as follows, in no definite order:

a) Formation of myrmekite structure.

b) Micrographic and vermicular intergrowth of plagioclase and alkali feldspar.

c) Formation of antiperthite.

d) Chloritization of hornblende and biotite.

e) Introduction or concentration of some radioactive minerals.

f) Synneusis texture of mafic minerals.

All the features mentioned above were found in rocks so highly contaminated that they are superficially much closer to granite than gabbro, whereas for no apparent reason, some gabbro close to the granite contact has been left almost intact.

This selectivity in alteration must have been controlled by irregular sets of fissures and cracks or by the now obscure but still visible banding of the rock.

a) Myrmekite:

In the myrmekite the feldspar enclosing the quartz stringers is usually a plagioclase of andesine oligoclase composition.

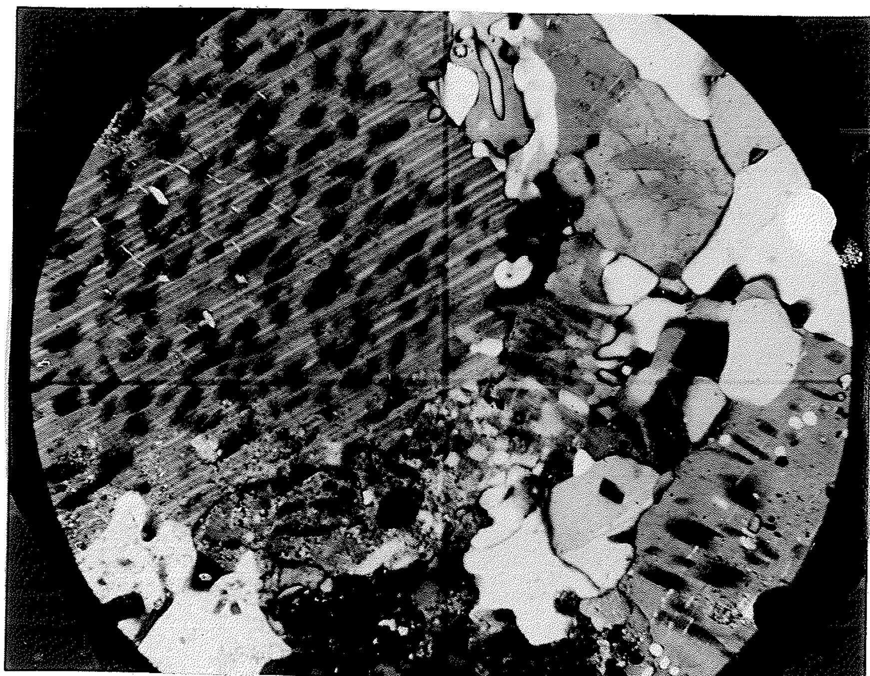


Fig. 26 Patch perthite and myrmekite.

Because oligoclase is limited to the hybrid zone and is definitely the result of the introduction of alkali, it is concluded that this introduction took place before or at least simultaneously to that of quartz.

c) <u>Formation of perthites and antiperthites:</u>

It is generally admitted that perthite and antiperthite can be produced by exsolution as well as by replacement. Some criteria may be used to determine which of these process is probably responsible in a particular case. Regular blebs, stringers threads and well oriented rods suggest the slow and quiescent process of unmixing. On the other hand, replacement usually results in large irregular unoriented blebs. Both features can be seen in the invaded gabbro of Lyonne complex. Replacement is shown by the presence of braided antiperthite.

It would be hazardous to explain the braided antiperthite of the plagioclases as a result of the exsolution of its original content of alkali; one more probable explanation is that some alkali was introduced when the granite was still molten and later on exsolved upon gradual cooling.

d) Chloritization of hornblende and biotite:

Chrysotile-like veinlets were formed by the penetration of alkaline solutions and subsequent chloritization of the mafic minerals of the gabbro. The orientation and ramification of these veinlets suggest that the solutions were travelling along channels. Magnetite, probably secondary, is always concentrated on the border on these channels.

The mineral was not positively identified and one could hardly expect chrysotile from the alteration of aluminous rich mafic minerals. However, the mineral does not correspond to the characteristics of chlorite and its fibrous aspect suggest chrysotile.

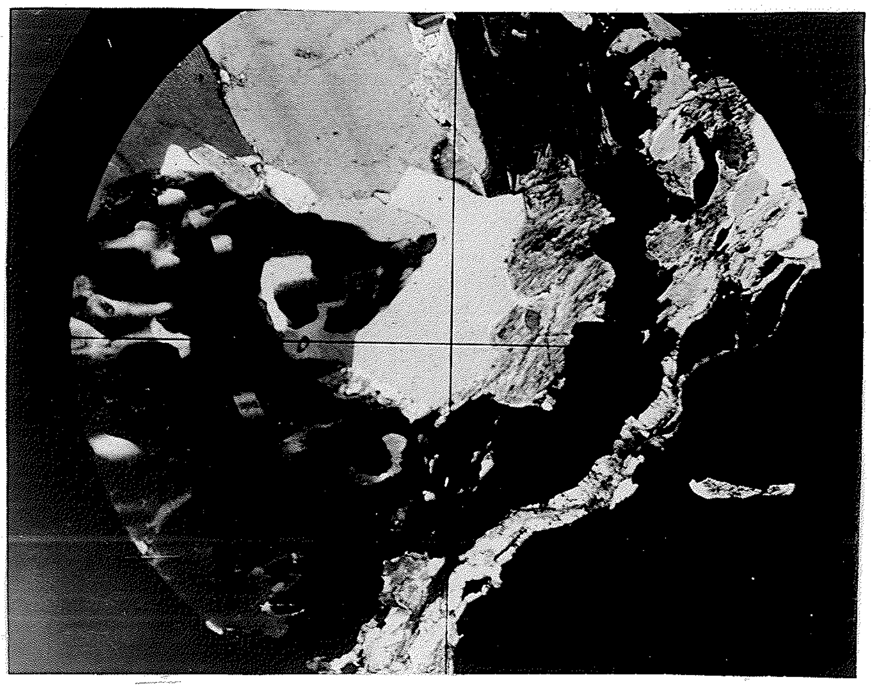


Fig. 27 Chrysotile like veinlets formed during chloritization of mafic minerals.

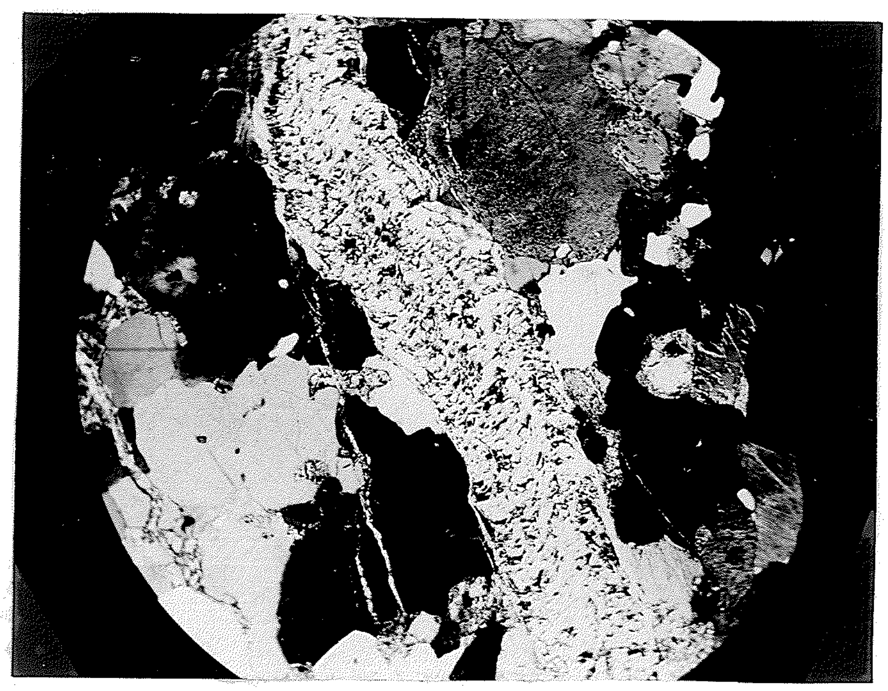


Fig. 28 Greater magnification showing details of veinlets.

e) Introduction or Concentration of Radioactive Minerals.

A relatively small amount of radioactive mineral is found in the ore and gabbroic rock. It is impossible to tell whether these minerals were already present in the original gabbro but their concentration near the contact suggest that they were introduced with the granitic material.

One of these minerals has been identified as allanite. Minerals in the vicinity of allanite show a high degree of metamictization probably due to radioactive bombardment; high relief is also a characteristic. Radioactive sphene is slighly recrystallized.

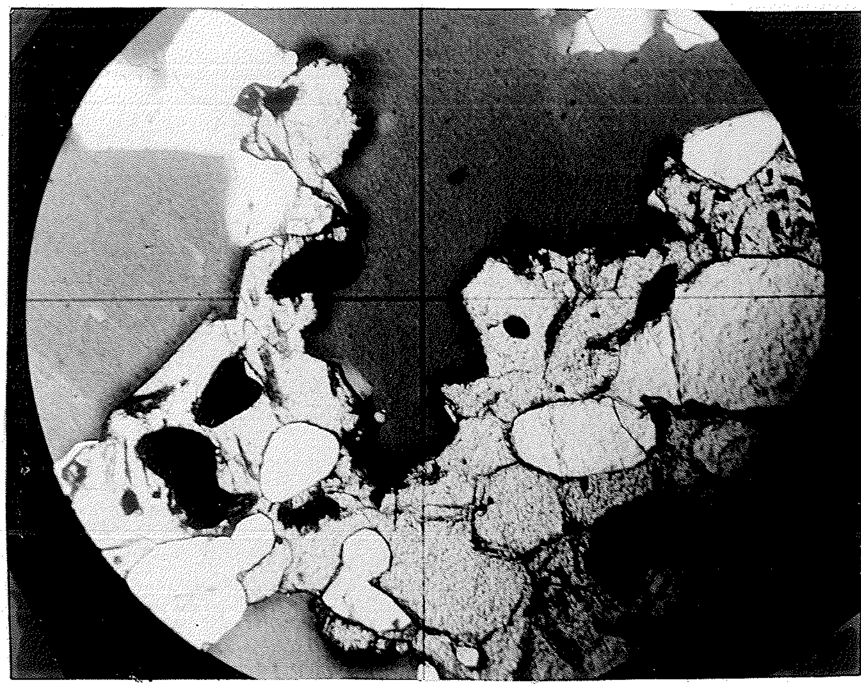


Fig. 29 Radioactive minerals in the gabbro near the contact with granite.

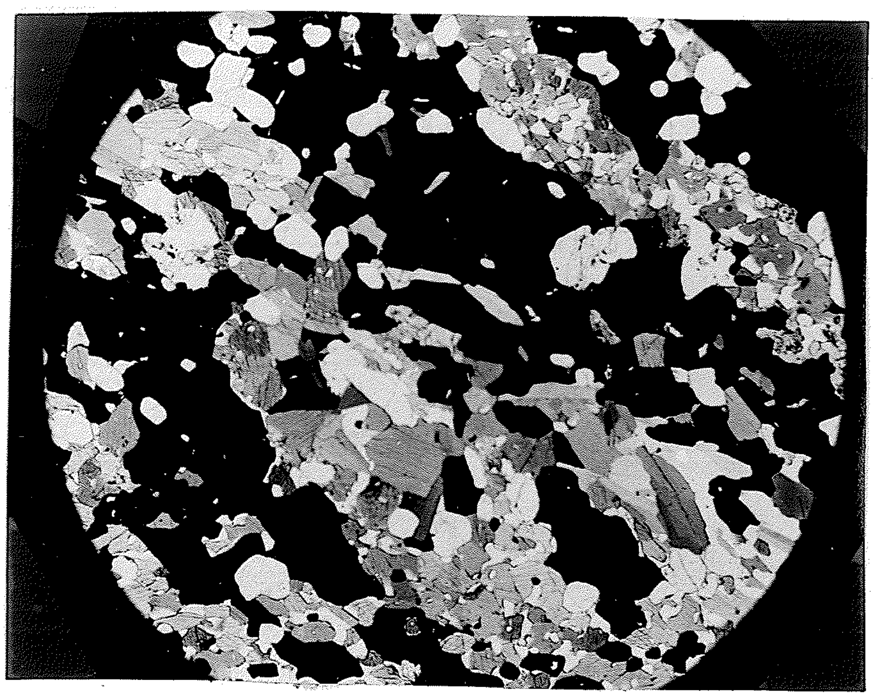


Fig. 30 Segregation of mafic from felsic minerals (synneusis texture).

f) Synneusis texture:

The segregation of mafic from felsic constituents of the injected gabbro can readily be seen in the field along dykes of pegmatitic material. It resulted in two separated bands: the first, close to the dykes, mainly composed of fine-grained mafic minerals and the outer one composed of large porphyroblasts of recrystallized plagioclase. The total width along which segregation has occured is about one foot.

In this section, the segregation of magnetite and biotite from feldspars has resulted in a micro-shistose or synneusis-like texture.

MINERALOGY AND MINERALOGRAPHY OF THE ORE

The ore is composed of variable proportion of silicate minerals, mainly hornblende, hypersthene biotite sphene and recrystallized plagioclase, in addition to magnetite, ilmenite and hematite. The composition and proportion between the silicates is similar to that of the granitized zone of gabbro. Hornblende is pseudomorphic after hypersthene which it may rim or almost completely replace; biotite is secondary after either hornblende or magnetite, and the plagioclase is recrystallized to a less calcic variety than in the normal gabbro. Sphene is mostly confined to zones where granitic material is in direct contact with ore. The pleochroism of recrystallized augite suggests that it is titaniferous. Euhedral crystals of apatite are grouped in clusters.

Magnetite and ilmenite fill the interstices between the various silicates although it is visible in the matrix of a few non-recrystallized dusty plagioclases.

The relation of ore minerals to hypersthene, augite, hornblende, is more indefinite. Magnetite is present in the core of incompletely replaced hypersthene but it could be secondary. If not, the crystallization sequence of the different minerals is plagioclase first, then hypersthene, followed or contemporaneous with ilmenite and magnetite. It might be pertinent at this point to indicate the strong similarity between the order in which the constituent minerals of the ore crystallized and the order in which differentiation of the host rock took place, that is, anorthosite (plagioclase) first followed by norite (hypersthene) and finally the ore itself (magnetite-ilmenite).

This is consistent with the origin of ilmenite-magnetite deposits as a filter pressed differentiate when pure ore represents a final product derived after most to the pyroxene and plagioclases had separated as suggested by F. F. Osborne (8).

As expected from the result of ore analysis, magnetite and ilmenite are not found in the usual solid solution but mostly in recrystallized euhedral and subhedral independent or interlocking grains. The small remaining portion of ilmenite not completely exsolved from its host is best seen in grains of slightly hematitized magnetite where it appears as broad parallel or sub parallel and forked tongues. This arrangement is known as seriate or oleander texture. The migration movement of the ilmenite lenticles to form independent grains can be estimated by the attitude of these tongues. When such tongues reach the host crystal boundary, they loose their rod like structure, get much wider and form amorphous but almost independent pods.

The size of the magnetite and ilmenite grains is highly variable, but in general form almost independent pods.

The size of the magnetite and ilmenite grains is highly variable, but the general range is from 0.3 to a maximum of 10 millimeter in length and width. The parallel rods of ilmenite enclosed in magnetite have a width of 0.01 to 0.1 millimeter. Some grains of pyrite and pyrrhotite are disseminated through the ore minerals.

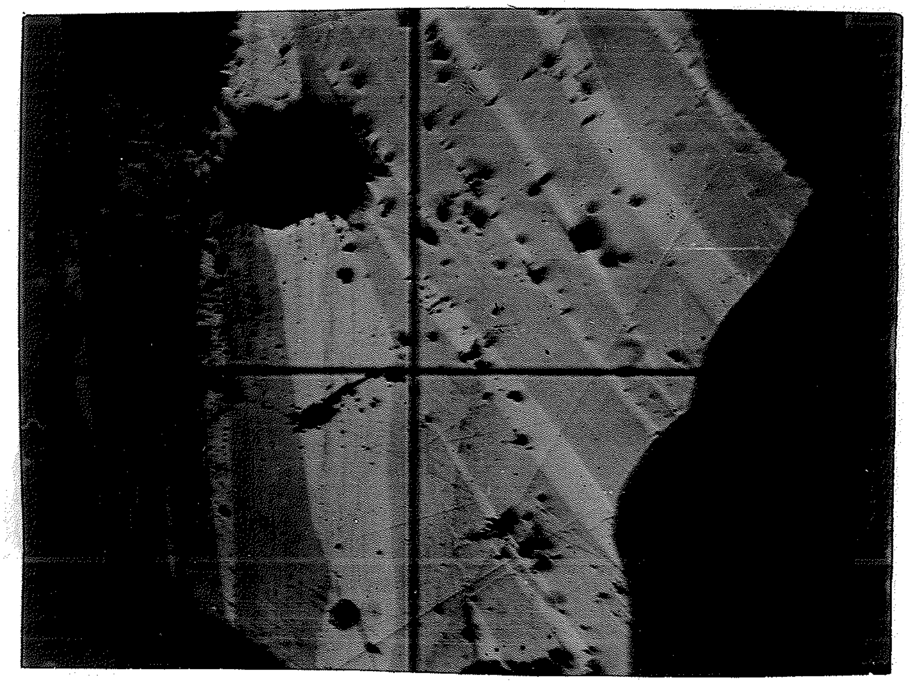


Fig. 31 Ilmenite exsolution bodies on a base of hematite (seriate arrangement).

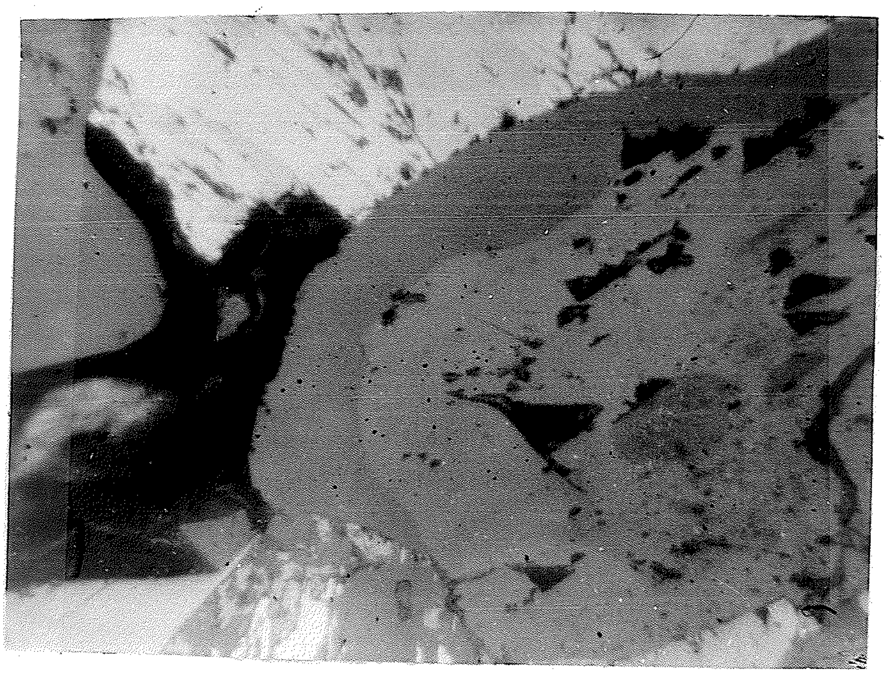


Fig. 32 Concentration of ilmenite on the border of magnetite.

ANOMALY OF THE ORE

The number of analyses of the Lyonne township titaniferous magnetite deposit is sufficient to show that there is little variation in the proportion of the various ore constituents from one point to another. The total content of titanium oxide (12.5 to 18.1 per cent) is also similar to that of other orebodies where the host rock is of gabbroic character. However, the titanium content of the magnetite is not similar to that of other deposits. The usual content of titanium in the magnetite of titaniferous ore is from 12 to 24 per cent. In this deposit it is only 1 to 1.5 per cent with an average of 1.15 per cent. A rough calculation based on these figures shows that the content of titanium oxide in magnetite is about 90 per cent lower than usual.

The titanium oxide content of accessory magnetite in each facies of the host rock is also lower (1.4 to 5.8 per cent) than in similar facies of the same type of rock of other regions (4 to 11 per cent) but the disproportion is somewhat less than in the ore. Titanium is a plentiful element in the composition of both silicate and ore magma so the lack of this element is definitly not the cause of this anomaly, and to explain it, we must look for external phenomena whose effects were a regional or local magnetude.

TABLE VIII

VARIATION IN PERCENT OF TiO_2 IN TITANIFEROUS MAGNETITE OF LYONNE TOWNSHIP LA LIEVRE AREA

A In orebody (sampled lenghtwise)

B As accessories in the diverse facies of host rock

A

	Non magnetic portion		Magnetic portion	
% Magnetite	Fe	TiO_2	Fe	TiO_2
58.25	14.32	13.04	70.02	1.11
35.50	16.25	11.84	70.13	1.18
36.40	15.70	11.97	71.10	1.14
36.70	16.22	11.86	70.12	1.19
43.70	16.93	11.51	71.32	1.21
45.90	16.72	11.82	70.45	1.23
42.10	18.14	12.00	76.70	1.09
46.40	17.47	12.02	79.80	1.14

B

Facies	% Magnetite	% TiO_2 in Magnetite
Anorthosite	0.33	4.10
Anorthositic Norite	0.12	5.23
Norite	0.70	3.81
Mafic facies in Norite	0.78	5.82
Granitized Norite	0.61	1.13

TABLE IX

VARIATION IN PERCENT OF TiO_2 IN TITANIFEROUS MAGNETITE FROM OTHER REGIONS

A Magnetite Ilmenite rich segregations or orebodies

B Magnetite Ilmenite as accessories

(For comparative Purposes)

A

Associated rock	Locality	% TiO_2 in Magnetite
Olivine Anorthosite	Quebec	20.2
Gabbro of Anorthosite	St. Charles, Que.	13.8
Gabbro	Bad Vermilion Lake, Que.	23.0 - 24.4
Gabbro	Riviere des Rapides, Que.	19.8
Gabbro	Desgrosbois, Que	11.9 - 12.6
Gabbro	Minnesota	15.0 - 20.8

B

Associated rock	Locality	% TiO_2 in Magnetite
Olivine Pyroxenite Anorthosite	Lake St. Jean, Que.	7.2
Gabbro	Minnesota	4.0 - 11.1

GEOCHEMISTRY OF THE MAGNETITE-ILMENITE-HEMATITE SYSTEM

(Exposé of Buddington's theory)

It is known experimentally (Pouillard (10)) that FeO, Fe_2O_3, and TiO_2 form a polycomponent system at high temperature with the development of the compounds; Magnetite (FeO, Fe_2O_3) Ilmenite (FeO, TiO_2) Ulvöspinel (2FeO, TiO_2) and a tetragonal titanate ($2Fe_2$, TiO_2). These minerals can coexist in a single phase solid solution with each other, or in a more or less pronounced stage of exsolution. The following varieties are among those included; titanmagnetite (a single phase solid solution of TiO_2 compounds in magnetite); ilmenomagnetite (a micro-intergrowth of ilmenite in magnetite); and mogensenite (a micro-intergrowth of ulvöspinel in magnetite). The ilmenite intergrowth in the magnetite may occur as a very fine film or a thin plate-like grid oriented parallel to the octahedral planes of the magnetite, as coarse blade parallel to a single plane, or as granules in or on the border of the magnetite grains depending on the amount and degree of migration of the exsolved material.

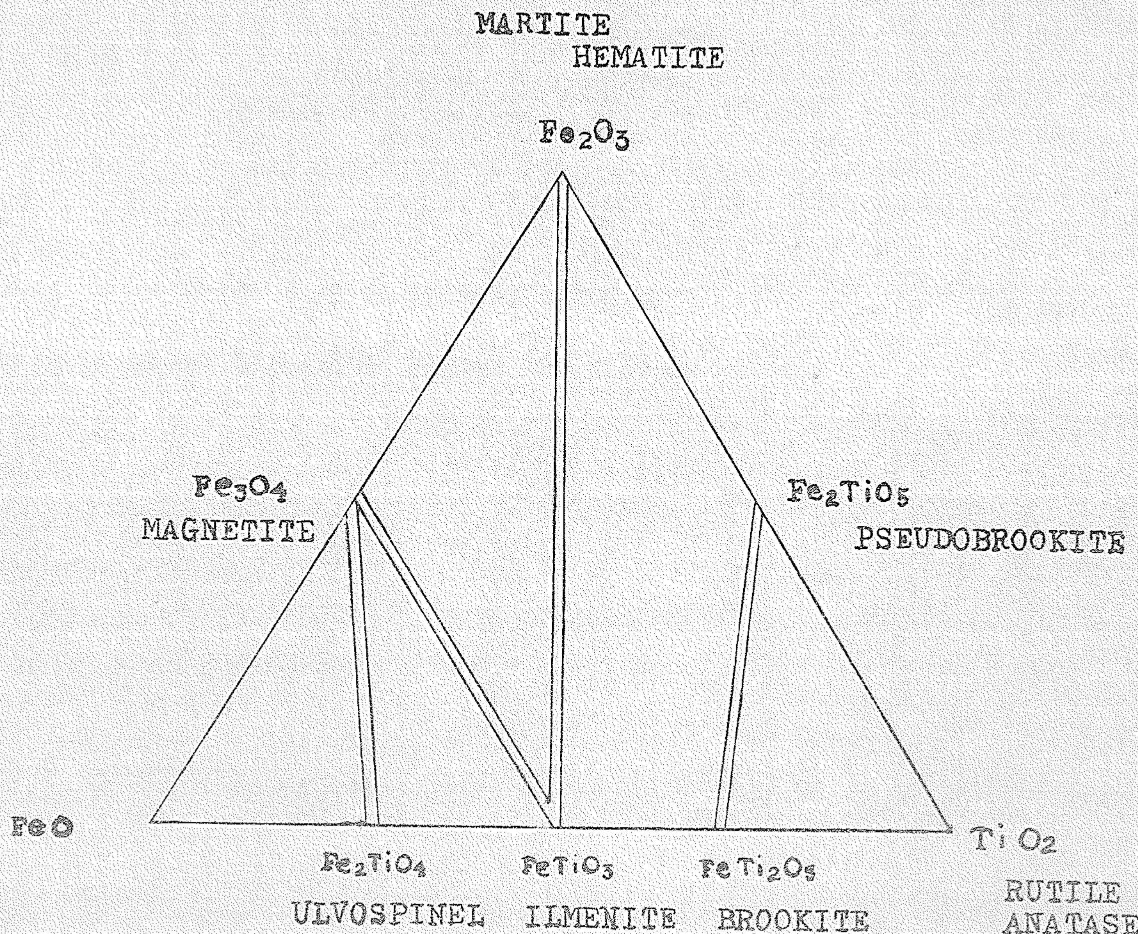


Diagram for the relationship of FeO, Fe2O_3, TiO_2 system
(After Pouillard)

(Doubled line indicate solid solution of the)
(phases joined)

Fig. 33

Little solution of magnetite and ilmenite would be expected because they crystallize in two differemt systems and it has been suggested that the solid solution was of magnetite and ulvöspinel where the ulvöspinel had broken down to ilmenite. However, Chevalier and Girard (4) have synthetized a solid solution for $FeTiO_3$ and Fe_3O_4, using molten borax as a solvent. A cubic solid solution containing as much as 37 per cent $FeTiO_3$ was formed, and the conclusion is that there is a cubic phase (γ $FeTiO_3$ which on exsolution or cooling inverts to β $FeTiO_3$ (ilmenite)).

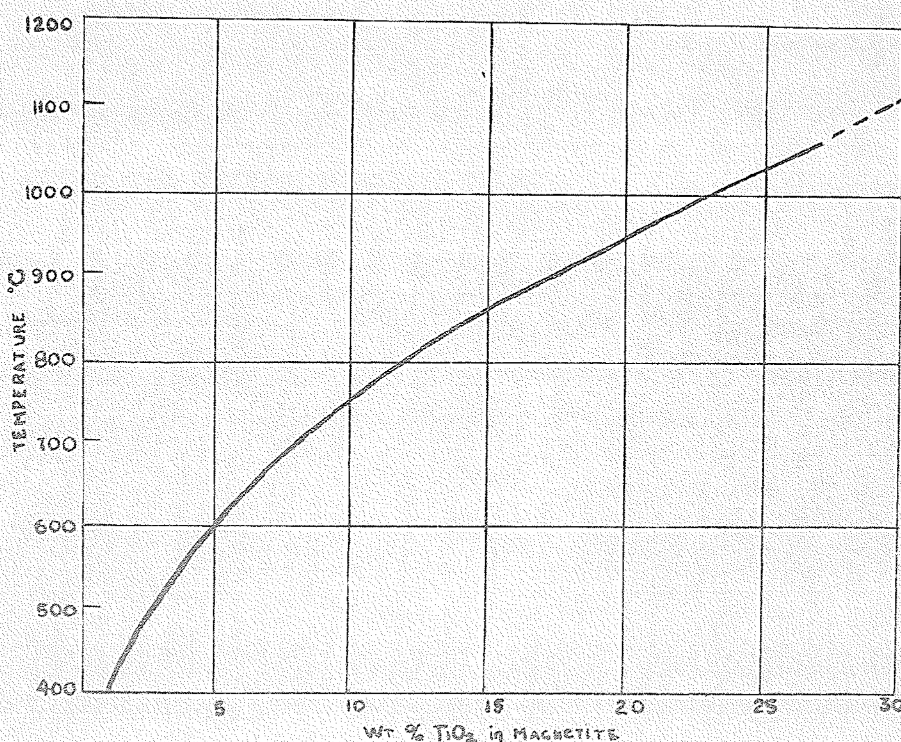
It is also known (Ramdohr (11) that ilmenite and hematite form a continuous solid solution at temperatures above 600°C. On cooling unmixing occurs and results in the production of two different solid solutions, one a ferriferous ilmenite, the other a titaniferous hematite (titanhamatite).

The ex-solution bodies of titanhematite are usually distributed on a base of ilmenite with their long axes parallel to one another.

It is generally admitted that the degree of unmixing of these minerals is a direct effect to temperature, that is, the amount of TiO_2 in magnetite, in whatever form, seems to be directly proportional to the temperature at which a magma crystallized or was subjected after its consolidation period. However, the chemical system inherent in a specific magma could also have an effect, mainly by the possible production of sphene or leucoxene at the expense of the TiO_2 contained in the magnetite.

Taking all these date into consideration, Buddington et al. (3) set up a survey using over 200 analyses of rocks sampled from the Japanese volcanic regions to the Adirondack anorthosite and granite.

A curve built on the inferred temperatures of formation of these rocks proved to be consistent with the TiO_2 content of their magnetite. In the metamorphic and metasomatic rocks representing facies reconstituted in different temperature ranges in solid state, there is also a diminution in the TiO_2 content in magnetite with decrease of temperature.



Inferred relationships for percent of TiO_2 in magnetite for different temperatures

(Buddington, 1955)

Fig. 34

MODE OF LOWERING OF THE TiO_2 CONTENT IN MAGNETITE OF THE MAGNETITE-ILMENITE DEPOSIT OF LYONNE TOWNSHIP

The high points in the geological history of Lyonne township gabbroic intrusion and associated ore can be listed as follows: a) The intrusion of the silicate magma followed and terminated by the injection of the ore at the offset of the host rock with probable slow cooling. b) Regional metamorphism affecting both gabbro and ore. c) Invasion of the ore and the gabbros in the vicinity of the ore by a granitic melt at the close of the period of metamorphism.

a) Most geologists recognize that ilmenite magnetite ore deposits related to gabbro and anorthosite are injected or differentiated at magmatic temperature and that this temperature is in the range of 1000° to 1500°C. At this temperature most TiO_2 is in solid solution with magnetite and analyses from chill zones of such injections consistently reveal a percentage varying from 12 to 25 per cent TiO_2 in the magnetite.

The deposit of Lyonne township was probably not an exception and it is believed that most if not all TiO_2 (15 20 per cent) was in the magnetite at the time of the crystal formation. Further cooling to lower temperature could have resulted in some exsolution.

b) The metamorphic facies of the noritic intrusion is of the granulite or high amphibolite grade. Rosengvist (13) estimates the temperature range for metamorphism in the granulite facies as $500^{o} - 900^{o}C$ for depths of about 6 and 11 miles respectively. Buddington (2) states that the Adirondack (Grenville) granulite rocks were at depths greater than 5 miles at the time of reconstitution and that their temperature range may be estimated as between $500^{o} - 700^{o}C$. At this temperature the amount of TiO_2 in the magnetite is approximately 4 to 5 per cent. This is consistent with the actual percentage of TiO_2 in the accessory magnetite of the non-granitized norite of the area (3.8 - 5.8 per cent). It is probable that a proportional lowering of the TiO_2 content of the magnetite of the associated deposit took place but there is no means available to prove this assumption.

c) The final phase in relation with the low content of TiO_2 in the magnetite of the deposit and probably also the most important one from an economic point of view is the invasion and complete reworking of the orebody and nearby norites by an acidic melt and its pegmatittic residuum.

The temperature of injected granite pegmatite is estimated at 500° to 700°C with variations according to the percentage of hyperfusibles and mineralizers in the melt. The acid rock itself has been described as a biotite hornblende orthoclase or microcline microperthite granite is from 675° to 850°C but the presence of biotite is indicative of lower temperature. The presence of the two feldspars, microcline and albite, in the granite penetrating the ore and border facies of the same intrusion is also indicative of lower temperature than the granite of central parts where the feldspar is mainly of perthitic texture.

At this point, three alternatives have to be considered: either the ore was heated to the same temperature as the invading permatites and then the temperature of the melt was pretty low (400° to 500°C); or the injection took place at higher temperature (500° to 700°C) but the orebody was heated to a fraction of that temperature; or it was heated to the same temperature but cooling was very slow.

The first alternative does not seem probable but must be rejected with care. Buddington et al. (3) describes acid pegmatites with the same composition as the one criss-crossing the ore (allanite pegmatites, New Jersey) whose magnetite reveals 1.7 per cent TiO_2.

The second and third alternatives, however, are more probable. One would not expect contact metamorphism to take place at the same temperature as the magma that provokes it; slow cooling is no less probable; it was mentioned earlier that the granite and associated quartz monzonite were intrusions of batholithic dimensions. If the rate of cooling of a particular magma is proportional to its size, a long period of time must have been involved before all reactions stopped between intruding and intruded rocks.

In addition to remobilization at low temperatures, chloritization of the silicate minerals (biotite-hornblende) contained in the ore has resulted in secondary titanium-free magnetite that dilutes the general content of TiO_2. Production of sphene is another similar factor.

The lowering effect on the TiO_2 content of magnetite by the acid intrusion is best illustrated by comparing the composition of magnetite of the non-granitized gabbros (3.8 - 5.8 per cent TiO_2) with that of the granitized facies (1.43 per cent).

SUMMARY OF EVENTS AND DISCUSSION

The first major development in the history of Lyonne township complex is the emplacement of the intrusion into a series of metamorphic rocks. This emplacement did not consist of a single phase intrusion but of a compound type starting with the anorthosite, followed by the norites, and terminated by the injection of the ore; each of these magmas represent a more advanced stage of differentiation that took place in the magmatic chamber. This process went further and became delicate enough to produce a further differentiation in an already differentiated mass. This is shown clearly by the three types of ore described, each richer in magnetite-ilmenite and in intrusive contact relation with its predecessor.

It is generally admitted that these types of ore are injected at magmatic temperature but as a more or less crystallized mush. Although intrusive contacts are seen, deposits of this kind do not show any evidence of forceful intrusion. Their mode of origin and emplacement are, on the contrary, suggestive of a very quiescent process. This led some authors to explain their origin as a result of differentiation in the solid state but this cannot explain the very high temperature at which they are known to be injected. It is not impossible that exothermic heat due to partial crystallization at depth by producing a sufficient pressure is the original driving force. In such case, the ascending differentiate would act as a thermostat or pressure control valve maintening the chamber pressure at a non explosive level.

The composition of the magnetite suggests an equilibrium below normal for a deposit associated with gabbro. This was explained by the metasomatic action of an invading granite melt, but the same equilibrium is even below normal for granite. It was mentioned earlier that these granites form aureoles or rims around their mineralogically related quartz monzonite; it was also mentioned that these granites were emplaced at the close of the period of metamorphism. These three factors, low temperature, relation with monzonite, and emplacement at the end of metamorphic period could be more than a coincidence and one explanation offered is that these granites are differentiated in the solid state from the monzonite.

SUMMARY OF CONCLUSIONS

The conclusions resulting from this study can be listed as follows:

1. The host rock is a norite of an anorthositic series.

2. The norite has a composition of a biotite diorite near the contact with granite.

3. The degree of metamorphism that affected the complex is of the high amphibolite or granulite grade.

4. The associated deposit of magnetite ilmenite is the concordant type.

5. The composition suggests a late residual accumulation of mafic minerals filter pressed from the magmatic chamber.

6. The total content of titanium is normal.

7. The titanium content of magnetite is lower than normal and believed to be due to a revived exsolution process due to re-heating the titaniferous magnetite by granite intrusions.

8. By lowering the titanium content of the magnetite through concentration of the titanium into separate grains of ilmenite of sufficient size to be separated from the magnetite by a milling process to produce a magnetite concentrate, a merchandable iron ore deposit was formed out of a non-valuable one.

BIBLIOGRAPHY

1. ADAMS, F. D., Preliminary reports to Director of the Geological Survey of Canada on Anorthosite of Saguenay and Morin areas: Rep. of the Geol. Surv. of Canada, 1884.

2. BUDDINGTON, A. F., Adirondack igneous rocks and their metamorphism: Geol. Soc. America Mem. 7, 1939.

3. BUDDINGTON, A. F., FAHEY, J., and VLISIDIS, A., Thermometric and petrogenetic significance of titaniferous magnetite: Am. J. of Sc., Vol. 253, 1955.

4. CHEVALIER, R., and GIRARD, J., Synthèse de titano-magnetites: Soc. Chim. France Bull., 5th Ser., Vol. 17, 1950.

5. DENNIS, B. T., La partie nord ouest de la région du Lac Saint Jean: Pub. Ministère des Mines, Québec, 1934.

6. DRESSER, J. A., Etude d'une partie de la région du Lac Saint Jean: Com. Géol. du Canada, Mem. 92, 1918.

7. MacGREGOR, A. G., Clouded feldspar and thermal metamorphism: Mineralog. Mag., Vol. 22, 1931.

8. OSBORNE, F. F., Certain magnetite titaniferous iron ores and their origin: Econ. Geol., Vol. 23, 1928.

9. POLDERVAART, A., and GILKEY, A. K., On clouded plagioclase: Am. Mineralogist, Vol. 39, 1954.

10. POUILLARD, E., Sur le comportement de l'alumine et l'oxide de titane vis-à-vis des oxides de fer: Annales de Chimie, Vol. 5, 1950.

11. RAMDOHR, P., Beobachtungen an Magnetit, Ilmenit Eisenglanz und Ueberlegungen ueber das System FeO Fe_2O_3 TiO_2: Nues Jahrb. Min. Geol. Pal. 54, Beil. Bd., Abt. A., 1926.

12. RICHARDSON, J. The Geology of the vicinity of Lake Saint Jean: Rep. of the Geol. Surv. of Canada, 1857.

13. ROSENGVIST, I. T., The metamorphic facies and the feldspar minerals: Univ. Bergen Arbok. 1952.

14. SHAND, S. J., Coronas and coronites: Geol. Soc. America Bull., Vol. 56, 1945.