AN INVESTIGATION OF THE METAMORPHISM OF THE ORIJÄRVI TYPE WITH SPECIAL REFERENCE TO THE ZINC-LEAD DEPOSITS AT MONTAUBAN-LES-MINES, P.Q.

by

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The zinc-lead deposits belonging to the Montauban mineralized zone are in the western part of Montauban Township, Portneuf County, Quebec, near the village of Montauban-les-Mines. The Montauban mineralized zone may be traced from lot 322, Seignory of Price, across lots 39 to 45, inclusive, and into Block C of Montauban Township.

The area is about 6 miles south of Montauban, formerly known as Notre Dame des Anges, which, by rail, is 52 miles from Quebec and 125 miles from Montreal. By road, Montauban-les-Mines is 78 miles from Quebec and 160 miles from Montreal.

Previous Geological Work

Low (1) and Ells (2) made reconnaissance geological surveys in the Townships of Montauban and Chavigny in 1891 and 1898, respectively, but reference was first made to the

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(1) Low, A. P. - Geo. Surv. Can., Vol. V, Pt. 1, 1890-91, pp. 45AA-46AA.

(2) Ells, R. W.- Geo. Surv. Can., Vol. XI, 1898, pp. 45J-47J.

geology in the vicinity of the ore zone by Denis (1) in the Annual Reports of the Quebec Bureau of Mines for 1912 and 1914.

Owing to the activity of prospectors in the Townships, Bancroft made a geological survey in 1915 for the Quebec Bureau of Mines (2). In his report on the district he included a rather detailed description of the zinc-lead deposits of the Montauban zone.

In 1928 the Staff of the British Metal Corporation (Canada) Ltd., (3) who were exploiting part of the ore zone at that time, gave an account of the mining and milling practice, but did not describe the geology in detail.

In 1930 Alcock (4) examined the Tétreault Mine and included a detailed description of the geology of the vicinity in his account of the zinc and lead deposits of Canada.

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(1) Denis, T. C. - Ann. Repts. on Mining Operations in the Prov. of Quebec, 1912, p. 29; 1914, p. 28

(2) Bancroft, J. A.- The Geology of Parts of the Townships of Montauban and Chavigny and of the Seignory of Grondines. Mining Operations in the Prov. of Quebec, 1913-15, pp. 103-143.

(3) Mining and Milling at the Tetreault Mine. - Bull. Can. Inst. Mining & Met., March 1928.

(4) Alcock, F. J. - Zinc and Lead Deposits of Canada; Geo. Surv. Can., Econ. Geol.; Series No. 8, 1930, pp. 79-85.

History of the Zinc-Lead Deposits

1. The Tétreault Property: Lead and zinc were first discovered in 1910, on lot 39, by Mr. Elzear Gauthier. In 1911 Mr. Pierre Tétreault acquired the mining rights to lots 322 to 327, Price, and lots 39 to 42, Montauban Township. During this year 6 to 10 men were engaged in prospecting and opening up the ore bodies. Their efforts met with such success that a concentrator with a capacity of 150 tons of ore a day was erected in 1912. This unit failed to produce a marketable concentrate, and the only production during 1913 and 1914 was a few hundred tons obtained by hand picking from rich pockets near the surface.

In 1914 the Weedon Mining Company leased the part of the property south of Mine Lake, and in 1915 the Zinc Company, Ltd., took over control of the property held by the Weedon Mining Company.

During 1915 and the four succeeding years, the high price of lead and zinc acted as an impetus to active development. A new mill, capable of treating 200 tons a day was erected in 1916. In 1917 a zinc oxide plant was constructed at Notre Dame des Anges (Montauban) but after working for several years it was destroyed by fire in 1922.

The lease of the Zinc, Company, Ltd., which expired in 1921, was not renewed and the property reverted to the Pierre Tetreault Estate.

The Mine was re-opened by the Tétreault interests in 1922, and continued operating until October, 1924, when the British Metals Corporation (Canada) Ltd., leased the property. This Company immediately started development of that part of the ore zone lying north of Mine Lake, a section of the mineralized zone that had received little attention previously. The main shaft was deepened to 500 feet, and considerable diamond drilling was done. In addition, the mill was enlarged to treat 400 to 500 tons of ore a day.

The British Metals Corporation (Canada) Ltd., continued operations until December, 1929, when the low price of zinc and lead, and diminished ore reserves, made it uneconomic to operate the property.

The Tétreault Estate then started a campaign of development, in order to block out more ore, but ore was not mined, and the mill was not re-opened until December, 1934. Production of lead and zinc concentrates continued until May, 1937, when the mine was again closed, owing to diminished ore reserves and labour troubles. Since then the mine has been idle, although it is kept unwatered to the 500-foot level.

2. The United Metals Property: During 1912, 1913 and 1914 the ore zone was traced northward on lots 43, 44, 45, and this section was known as the Thibault Prospect.

In 1914 the Montauban Mining Syndicate began operations along the zone in lots numbers 43 to 45. By 1917 this Company had sunk a vertical shaft to a depth of 50 feet, and had completed 400 feet of drifts, cross-cuts, winzes, raises, and shafts. In October, 1916, a mill building was erected, but no machinery was installed. Underground work failed to show enough ore to merit further development, and work was stopped.

The property was re-opened in 1929 by the St. Lawrence Metals Company Ltd., who did considerable diamond drilling and surface trenching. The vertical shaft (which will be referred to as the St. Lawrence Shaft) reached a depth of 100 feet, with levels at 50 and 100 feet. A winze was sunk for another 100 feet below the lower level. Results, however, were not encouraging and the property was closed in August of 1930.

The United Metals Company, Ltd., next obtained control of the property, but the only exploratory work done by this company consisted of a few surface trenches recommended by Hans Lundberg, Ltd., after the area had been geophysically surveyed.

3. The Shawinigan Property: The part of the ore zone extending into Block C, Montauban Township, was prospected by surface trenching during 1915, 1916 and 1917. Since then, the only exploration was done in 1929, by the Shawinigan Mining and Smelting Company. An inclined shaft, sunk to a depth of about 70 feet, and 1200 feet of diamond drilling, explored the ore zone at shallow depths. The property was geophysically surveyed by Hans Lundberg, Ltd., in 1937.

Production of Zinc and Lead

The total production of zinc and lead from the ore zone has come from the Tétreault Mine. Early records of the tonnage extracted from the ore bodies are not very reliable, but it is estimated (1) that about 1,100,000 tons of ore have been mined, from which about 120,000,000 lbs. of zinc and 40,000,000 lbs. of lead have been recovered.

Records of the Zinc Company, Ltd., and the British

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(1) Personal communication, F. F. Osborne.

Metals Corporation (Canada) Ltd. (1), show that the ore averaged about 9% zinc and 3% lead, with some gold and silver. Recovery during 1935, 1936, and 1937 was much lower, as shown in the following table:-

Year	% Zinc Recovered	% Lead Recovered
1935	5.0	1.6
1936	4.3	1.2
1937	3.9	1.3

Maps

The surface geology along the Montauban ore zone is shown on two sheets, plotted on a scale of 100 feet to the inch. Topographic maps, prepared by the staff of the Tétreault Mine and by F. J. Alcock, were used as a base for the southern sheet. The survey lines, cut at intervals of 200 feet across the strike of the formations by the geophysical party employed by Hans. Lundberg, Ltd., served as a base for mapping the northern sheet, which covers the United Metals and Shawinigan Properties.

Topography

The greatest elevation in the vicinity of the ore

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(1) Mining and Milling at the Tetreault Mine. Bull. Can. Inst. Mining & Met., March, 1928.

zone is about 1100 feet above sea level, and the maximum difference of elevation is about 150 feet. The ore zone lies on the western flank of a broad open valley, floored by sands and clays deposited during Pleistocene time. Across the Tétreault property the position of the ore zone is marked by a shallow depression, but north of this, it forms the backbone of a rather prominent ridge. In Block C the ridge loses altitude and exposures of bedrock are scarce because of a thick covering of sand and clay.

A small lake--Mine Lake--situated about 100 feet north of the main shaft on the Tétreault property drains into the valley to the east. The Bastiscan River, located about 1800 feet north of the Shawinigan shaft, is the only large river in the district.

Reference may be made to Bancroft's account of the geology of Montauban and Chavigny Townships for a detailed description of the topography of the region.

Acknowledgements

The writer wishes to express his indebtedness to Dr. F. F. Osborne of the Department of Geological Sciences, McGill University, who, while carrying out an examination of the Tétreault property for the Quebec Bureau of Mines, tendered the invitation that made possible the examination of the Montauban ore zone. Dr. Osborne also supplied the base maps of the area, as well as the results of many observations made on the Tetreault property. In addition, throughout the course of the investigation, he has given much valuable assistance and advice.

The writer is also indebted to Dr. J. A. L. and Mr. Georges Tétreault for hospitality extended to him during his stay at Montauban-les-Mines.

Finally, expression of appreciation must be made to Mr. Robert Milner for the use of several Rosiwal analyses made by him of various rocks from the Montauban-les-Mines area, and to Dr. R. P. D. Graham, Professor of Mineralogy at McGill University, for assistance in determining crystal forms and faces.

GENERAL GEOLOGY

The country rock surrounding the deposits of zinc and lead at Montauban-les-Mines belong to the Grenville Series, but regional metasomatism has changed large areas of the Grenville into rocks of composite character, that is, rocks consisting in part of sedimentary and in part of igneous material. Such rocks have been mapped as migmatites. In addition, metasomatism, operative at the time of mineralization, has changed other areas of the Grenville into rocks which have been mapped as metasomatic rocks.

The classification of the rocks, based on the results of field and microscopic investigations, is shown in the following table:-

Pleistocene and Recent: till, gravel, sand and clay

Metasomatic rocks

Pegmatite

Amphibolite

Granitized rocks (migmatites)

Grenville paragneisses and carbonate rocks

The Grenville Series and its Relationships

The Grenville series of metasedimentary rocks are found north, east, and west of the type locality, at Grenville, Quebec. As the series is closely folded in many areas, it is impossible to estimate the thickness with any degree of accuracy, but Osborne considers that in any restricted area in Quebec the thickness is not more than 5,000 feet.

In Grenville Township the series contains a large proportion of limestone. However, to the north and east, limestone forms only 5% of all outcrops of the series. Quartzites may occur in the same proportion as limestone, or may exceed it. Sillimanite gneisses, amphibolites, and other related rocks form the rest of the series.

Studies conducted by Osborne in the Grenville areas at Shawinigan Falls (1), Rivière à Pierre (2), and elsewhere, led him to believe that the Grenville Series is divisible into two parts; the lower part composed essentially of amphibolitic material, and the upper part consisting of quartzites, limestone, sillimanite and garnet gneisses, and related rocks. Crystalline limestone generally occurs high in the Upper Grenville. In the Shawinigan Falls area the two parts are apparently conformable, but it may not be so

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(1) Osborne, F. F. - Petrology of the Shawinigan Falls District. Bull. Geo. Soc. Amer., Vol. 47, pt. 1, 1937, pp. 198-223.

(2) Osborne, F. F. - The contrasting Plutonic Massifs of Rivière-à-Pierre. Am. Jour. Sci., 5th Series, Vol. 27, 1934, p. 418.

in other areas.

The origin of the amphibolites offers a problem which has not been definitely solved. Their general resemblance to one another makes it impossible to assign to them a precise mode of origin, unless cross-cutting relationships are determined in the field, in which case the rock has probably originated from a dyke. Osborne (1) has pointed out that volcanic material is present in the Lower Grenville, and believes that many of the amphibolitic bodies of the Lower Grenville have been formed from basic tuffs or flows.

It is difficult to assign the Grenville rocks in the vicinity of the Montauban ore zone to a specific part of the Grenville series, not only because of the small areas mapped by Alcock and the writer, but also because Bancroft's general geological map of the Montauban-Chavigny area indicates all Grenville rocks, except quartzites and limestone, in one color. However, the absence of older amphibolitic material and large bodies of limestone, and the presence of quartzite, sillimanite and garnetiferous and related gneisses suggest that the Grenville rocks in the Montauban ore zone area belong to the lower part of the Upper Grenville.

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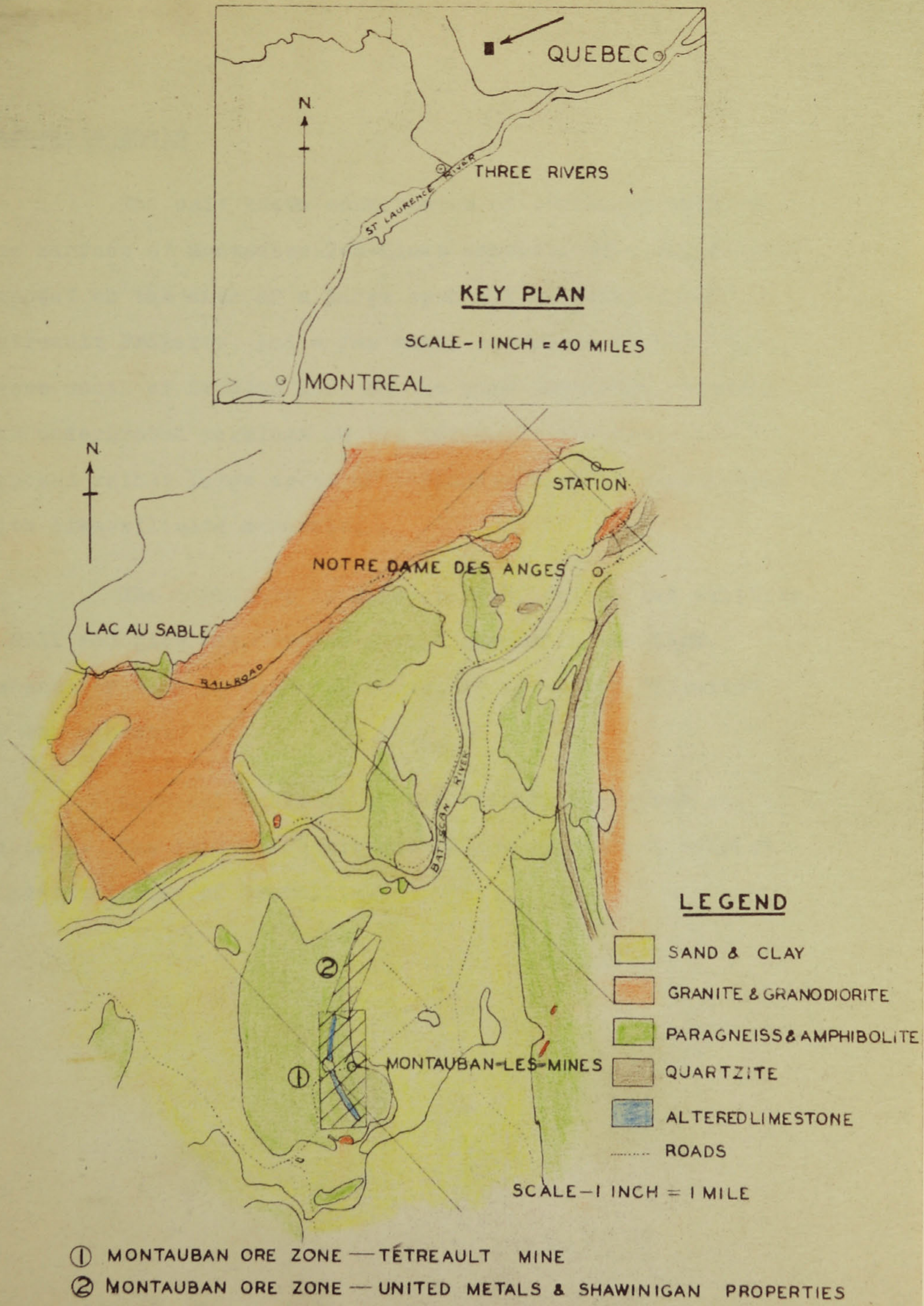
(1) Osborne, F. F. - Labelle-l'Annonciaton Map Area. Que. Bur. Mines, Ann. Rept., 1934.



GEOLOGY OF AREA NEAR MONTAUBAN-LES-MINES
(AFTER BANCROFT)

Carbonate Rocks

The only known occurrences of carbonate rock on the surface at Montauban-les-Mines consists of a minor band exposed on the side of a large open cut at Section 10N, Tétreault Property, and a few small exposures a short distance south of Section 10S, on the same property. However, the underground workings on the Tétreault property have exposed rather large areas of carbonate rock in association with lime-silicate minerals.

The carbonate is fine-grained, white, and exhibits a dull red glow when struck with a hammer in the dark. Because of this peculiar property, it is called "fireite" by the miners.

Chemical analyses of the fireite are given in Table I. The impurities present in analysis No. 1 consist almost entirely of tremolite.

TABLE I

Analyses of Carbonate Rock

	I	II
$CaCO_3$	56.60	43.80
$MgCO_3$	37.87	35.80
Fe_2O_3 } Al_2O_3 }	---	1.00
Insoluble	5.00	17.50
Total	99.47	98.10

	III
SiO_2	4.52
Al_2O_3	1.40
Fe_2O_3	0.62
CaO	40.51
MgO	11.83
CO_2	39.62
H_2O	0.74
Total	99.24

No. I - Analysis of fireite. Kindly supplied by Dr. J. S. Brown.

No. II - Analysis of fireite. M. F. Goudge. Limestones of Canada, Part III, Mines Branch Pub. No. 755, 1935, p. 149.

No. III - Analyses of fireite. M. F. Goudge. op. cit.

The carbonate rock is of great importance economically, for the only workable ore bodies along the zone occur in close association with it.

Paragneisses

It has been indicated that in their normal development the paragneisses of the Grenville series are of considerable thickness, but that in the ore zone area, two processes, regional and local metasomatism, have combined to alter most of the paragneisses to migmatites and metasomatic rocks. Of the two processes, that of regional metasomatism has played the more important role as regards the areal extent of the alteration. This process has affected the paragneisses to such a degree that now only "islands" of paragneiss remain of the once extensive series.

Reference to the maps will show the areal distribution of the paragneisses which have escaped migmatization. The most important of these areas forms a band which runs across the Tétreault and United Metals properties and extends into Block C. Northward, beyond the limits shown on the map, a heavy covering of clay and sand makes mapping impossible, but a few scattered outcrops in this area show that it continues for at least another 1,000 feet beyond the Shawinigan Shaft.

The central part of the band has been extensively altered by the metasomatism accompanying the mineralization, so actually, the band is divided in two parts, and the whole is enclosed in the migmatites.

The paragneisses are fairly regular in width across the southern portion of the Tétreault Property, but owing to folding in the vicinity of Section 16N, the bands widen considerably. North of this Section they gradually diminish in width until near the Shawinigan Shaft they are only 125 feet in width. It may be noted that contacts between the paragneisses and metasomatic rocks are gradational, and separation of the types is in most cases a matter of personal judgment. In addition, the scarcity of exposures in certain areas makes accurate mapping difficult.

Close examination of the paragneisses shows the presence of bedding planes, but these are never conspicuous. Schistosity, defined by biotite or sericite, is apparently invariably parallel to the bedding planes. This relationship between bedding planes and schistosity holds good even where the paragneisses have been crumpled and contorted.

The bedding planes and schistosity have a general north-south strike; over most of the exposed area dips are to the east, but in the vicinity of the boundary between the

Tétreault and United Metals properties dips may be vertical, horizontal, or to the west. The significance of these dips will be discussed in connection with the structure of the orebody.

Petrography of the Paragneisses

During the field work two main varieties of paragneisses were mapped: (1), nodular sillimanite gneiss, (2), paragneiss. The mineral proportions in the latter variety are very variable; light and dark coloured bands, garnetiferous-and garnet-free bands, and many other types alternate with each other in such an extremely intricate manner that no attempt was made in the field to differentiate between them. They are fine-grained, rusty weathering equigranular rocks, in which quartz, biotite, oligoclase, and garnet, in very diverse proportions, are the predominating minerals. Microscopic examinations show that in addition, sillimanite, microline, apatite, zircon, iron ore minerals, sericite, and chlorite may be present. Those near the metasomatic rocks may have a small amount of cordierite in them, but rocks of this type are considered to belong to the metasomatic rocks, rather than to the paragneisses. Microscopic examination of the paragneisses shows that they may be divided into the four groups shown below. A fifth group, characterized by microcline, is included, but since this type of rock is represented by only two specimens, (obtained from a bore hole), it is uncertain if it is an altered dyke, a migmatite, or a paragneiss.

The varieties are subdivided as follows for discussion:

1. Quartz-garnet-biotite paragneisses
2. Quartz-garnet-biotite-sillimanite paragneisses
3. Quartz-biotite-sillimanite paragneisses
4. Quartz-biotite paragneisses
5. Microcline-sillimanite paragneisses

The above types by no means represent all the possible combinations of minerals in the paragneisses of the area. A more extended classification would entail detailed mapping and petrographical investigation, but the results of such a study would not add much data bearing on the solution of the problem under consideration.

Rosiwal analyses of various types of paragneisses, the figures of which are in volume percent, are shown in Table II.

TABLE II

Composition of Paragneisses (Volume Percent)

	I	II	III	IV
Quartz	41.8	44.0	52.5	69.3
Plagioclase	31.8	26.0	19.5	18.7
Microcline	-	-	-	-
Biotite	22.9	22.0	7.5	10.9
Garnet	0.7	1.5	-	-
Sillimanite	-	4.0	18.0	-
Iron Ore Minerals	0.4	0.2	2.3	-
Sericite	2.3	2.0	0.2	1.0
Chlorite	0.1	0.3	-	0.1
Total	100.0	100.0	100.0	100.0

No. I. Quartz-garnet-biotite paragneiss

No. II. Quartz-garnet-biotite-sillimanite paragneiss

No. III. Quartz-biotite-sillimanite paragneiss

No. IV. Quartz-biotite-paragneiss

In the various types of paragneisses quartz may be from 35% to 70% of the rock; it occurs in disks, plates, or porphyroblasts intergrown along sutured edges with neighboring quartz or plagioclase. Strain shadows are rare, and in most places where they are developed, they are confined to the vicinity of garnets. Some granulation of quartz may be observed. In some thin sections examined the quartz is elongated with the larger dimensions in the plane of the bedding. Trains of a black, sub-microscopic mineral running across the crystals of quartz, are common in some sections. The quartz includes small crystals of apatite, zircon, and biotite.

Plagioclase is, with quartz, the most persistent mineral in the paragneisses, but it is not so abundant as quartz. It occurs as disks or porphyroblasts, and interlocks with the quartz along intricate sutured lines. Twinning after the albite law is common in some of the rocks but is lacking in others. The plagioclase is of diverse composition in the several rocks; it may be as sodic as An_{10} or as calcic as An_{40}, but it averages about An_{30} (oligoclase). Zoning is over narrow limits, and it is not commonly developed. Inverse zoning (the core more sodic than the margins) was noticed in a crystal of plagioclase in one thin section.

Microcline is not present in most of the paragneisses, and has been found in only two specimens. Unfortunately, both these specimens came from a bore hole on the Tetreault property, and although they have the appearance of paragneisses, it may be that they are paragneisses that have been partly granitized. As will be shown later, microcline is a common, and abundant, mineral in the migmatites, where it has apparently formed as the result of the introduction of potassia into the paragneisses. Although these two specimens have been provisionally grouped with the paragneisses, available data indicate that potash feldspar is never present in the paragneisses, and no doubt the specimens represent a transition zone between paragneiss and migmatite.

TABLE III

Composition of Microline-sillimanite Paragneiss

(Volume Percent)

Quartz	35.7
Plagioclase	28.0
Microcline	21.2
Biotite	11.7
Garnet	1.7
Sillimanite	1.0
Iron Ore Minerals	0.1
Sericite	0.6
Total	100.0

One specimen is characterized by the presence of light blue eyes in a white, fine-grained groundmass; the other is similar in appearance to the groundmass of the first. The eyes consist of quartz, and the groundmass consists of intergrown quartz, oligoclase, and large and small plates of microcline, which have the typical cross-hatchured twinning. Microcline in both specimens forms about 20% of the rock. Biotite is rare, and sericite is particularly abundant along schistosity planes. Sillimanite is distributed through the rocks, included in quartz and plagioclase in small needles. It forms only 1 or 2% of the rock.

Biotite is found in all the paragneisses studied. It occurs in large or small plates which lie in the plane of the bedding. Inclusions of quartz in biotite are fairly common, but it in turn is included by quartz. Dark brown pleochroic haloes, developed around small crystals of zircon, are rather abundant in some places. The mineral is optically negative, and the optic axial angle appears to be near 0°. The pleochroic formula is as follows:-

X = colorless,

Y = Z = light brown to red brown,

but in some cases Y and Z may be dark brown. A colorless chlorite is found in places around its edges, but alteration has never affected the biotite to any great extent. The laminae of biotite rarely show evidence of deformation.

The proportion of garnet present in different bands is very variable; some bands are free of it, but in others it may form 30% of the rock. As a general rule, if garnet is abundant, then biotite is also abundant, but the converse is not necessarily true.

The mineral occurs in small forms which average about 1/8 inch in diameter; garnets larger than ¼ inch are rarely observed. It is pink and always highly fractured. Under the microscope certain areas of the garnets, particularly near the margins, are anisotropic. Inclusions of quartz, plagioclase, and biotite are common, and in some places 40% of the volume of the garnet consists of quartz or plagioclase. Refractive index, and specific gravity, 3.94 and 1.78 $\pm$ 0.005, respectively, indicate that these garnets are approximately 56 mol percent pyrope, 35 mol percent almandite and 9 mol percent andradite. Many of the garnets are sharply bounded by crystal faces, but others are xenoblastic. As a rule, the xenoblastic forms are more highly poikilitic than the idioblastic forms.

Sillimanite occurs in small prisms in paragneisses of appropriate composition, either in isolated needles or in sheaves, which tend to lie parallel to the schistosity defined by biotite. The prisms are idioblastic on (010) and cross-fractures parallel to (001) are commonly developed. The sheaves of sillimanite are light brown, but single crystals are colorless. Owing to the small size of the crystals, it was found impractical to obtain all the optical properties.

The mineral is included in quartz, oligoclase, and biotite, but not in garnet.

Small prisms of apatite and zircon are distributed throughout the paragneisses, but are not abundant. Both minerals are associated with biotite. Sericite is invariably present in minor quantities, and in some types of paragneisses it may form 15% of the rock. In this type, which is probably an altered feldspathic quartzite, the sericite occurs in plates sharply bounded by (001). The optic-axial-angle is about 30° and the sign is negative. Chlorite occurs as a fringe around biotite; pseudomorphs of chlorite after biotite are rare.

Nodular Sillimanite Gneiss

This rock occurs as two narrow bands, about 30 feet wide, on either side of the diopside-tremolite zone exposed south of Mine Lake, but north of the lake, where metasomatism has been intense, it outcrops only for about 100 feet on the west side of the diopside-tremolite zone. Near Section 16N, however, where erosion has truncated the folded structure of the paragneisses, it again appears in two bands, one of which (the western) broadens towards the north; near the boundary of the Tétreault and United Metals properties it is about 200 feet wide. Beyond this it gradually diminishes in width, and north of the St. Laurence Shaft it is only 2 to 3 feet wide. The eastern band continues for only a few hundred feet north of Section 16N, where it grades into the metasomatic rocks. The southern extensions of both bands pass into migmatites.

The nodular sillimanite paragneiss is distinguished from the other gneisses of the area by abundant light-coloured nodules elongated parallel to the schistosity as defined by biotite. The largest nodules are about an inch long, and ¼ inch wide, but the average is about ½ inch long. On weathered surfaces they stand in relief, or in places lie loose upon the surface.

In the hand specimen the nodules are fine grained and have a silk-like lustre. In thin section, they are seen to consist of sheaves of sillimanite, held together by a mosaic of quartz crystals which, in turn, contain numerous needles of sillimanite. In some sections, sillimanite forms as much as 60% of the rock, but the average thin section does not contain over 40% of this mineral.

The groundmass of the rock is made up of a mosaic of quartz and plagioclase; biotite is sporadic in occurrence; zircon and apatite are distributed through the rock in small crystals. The plagioclase (An_{30}), is untwinned and unzoned. Plates of biotite are approximately parallel to the elongation of the nodules, but the schistosity is impaired in places by the tendency of the biotite to wrap itself around the nodules. Needles of sillimanite are also distributed throughout the groundmass.

Except for a higher quantity of sillimanite, and less biotite, these rocks are mineralogically similar to the quartz-biotite-sillimanite paragneisses.

Granitized Rocks (Migmatites)

The view that sedimentary rocks may by drastic alteration be converted to rocks resembling igneous rocks in all respects has been stated inferrentially or explicitly by many geologists. Unfortunately, regions in which such an alteration has been operative are not well-described, and until recently these rocks have not received much attention. The philosophical discussion of the changes has yielded such terms as syntexis, anatexis, rheomorphism, ultrametamorphism, palingenesis, which have appeared in many papers, but convincing and satisfactory descriptions of the process and rock types are not numerous. This is, in part, because of the loose use of terms.

Of the many theories advanced to account for the complete disposal of rocks that occupied the space now taken by intrusives, only two have been seriously considered in recent years. The piece-meal stoping hypothesis of Daly was much in vogue amongst geologists until investigation of the physical-chemistry of silicate melts demonstrated that granitic magmas in all probability do not have sufficient superheat to fuse rocks on the necessary scale.

An older theory, which has received renewed attention in recent literature, was advanced by the French school of petrologists, led by Lacroix, Duparc, Michèl-Levy, Barrois, and others. The aureole of metamorphic rocks around intrusives, and the common occurrence of lit-par-lit and injection gneisses about granitic masses, led them to believe that emanations from the invading magma permeated the older rocks and caused recrystallization and replacement. Since, in schists, foliation planes served as channelways for the solutions, the resulting rock in many places consists of alternating bands of granite and schist, to which Michèl-Levy gave the name lit-par-lit gneisses. They also seriously considered the possibility of a more advanced stage in the process, whereby the emanations converted the older rocks to rocks not dissimilar to the invading rock.

Sederholm (1) concluded that older rocks were remelted by the heat and gases from an underlying magma, giving rise to granitic magmas formed in-situ. He termed the process anatexis, which differs from the similar term, syntexis, (proposed by Loewinson-Lessing (2)), in that the former term is used in connection with refusion of a portion of the crust consisting mainly of one type of rock, such as granite, whereas the latter term is applied to the processes giving rise to magmas by the remelting or assimilation of portions of the lithosphere which consist of diverse rocks.

Sederholm believed that injection gneisses and lit-par-lit gneisses, which have "two elements of different genetic value", were rocks that had undergone a high degree of regional metamorphism, and that they had not been subjected to the intense metamorphism required for anatexis. For such rocks, characterized by the "re-solution of material like the first or by an injection from without" Sederholm proposed the term migmatite.

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(1) Sederholm, J.J. - Om granit och gneis. Bull. Comm. Geol. Finlande, No. 23, 1907, p. 102.

(2) Lowewinson-Lessing, F. - Geol. Mag., 1911, p. 297.

In later papers, however, Sederholm (1) considered that brecciation of overlying rocks by an advancing magma, followed by their partial or complete digestion by the magma, was the dominant process in anatexis. He extended the meaning of the term migmatite to cover rocks such as eruptive breccias and granitized rocks, and for this reason its use in later literature has resulted in confusion. For instance, Grout (2) considers migmatite applicable to an altered zenolith, Quirke (3) applies the term to feldspathized quartzites, and Miller (4) objects to its usage unless there has been brecciation.

Since Sederholm's original work on migmatitic and anatectic rocks, the importance of the role of metasomatism in the conversion of sedimentary rocks to rocks with an igneous

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(1) Sederholm, J.J. - Migmatites and Associated PreCambrian Rocks. Bull. Comm. Geol. Finlande, Part I, No. 58, 1923; Part II, No. 77, 1926.

Ultrametamorphism and Anatexis. Pan. Amer. Geol., Vol. 61, p. 241-250.

(2) Grout, F.F. - Criteria of Origin of Inclusions in Plutonic Rocks. Bull. Geol. Soc. Amer., Vol. 48, Pt. 4, 1937, p. 1521.

(3) Quirke, T.T. - Killarney Gneisses and Migmatites. Bull. Geol. Soc. Amer., Vol. 38, 1930, p. 753.

(4) Miller, W.J. - PreCambrian and Associated Rocks near Twenty-Nine Palms, Cal. Bull. Geol. Soc. Amer., Vol. 49, 1938, p. 427.

appearance has been stressed by many authors. Berkey and Rice (1) in accounting for the variations in the crystalline rocks of the West Point Quadrangle, New York, considered materials from the magma capable of impregnating and replacing the country rock. Quirke (2) believes the Killarney quartzite in the Killarney district of Ontario has been altered to granite by the introduction of potash and soda, and Quirke and Collins (3) have described a similar occurrence in the French River district of Ontario. Metasomatism is believed by these authors to have been the dominant process in the formation of such rocks.

During recent years many papers have appeared describing granitized sediments, references to which have been compiled by Holmes (4). Most of these papers stress the importance of metasomatism in the formation of such rocks, and recently Barth (5) has suggested that syntectic

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(1) Berkey, C.P. & Rice, M. - Geology of West Point Quadrangle. Bull. N.Y. State Mus., Nos. 225-226, 1919, pp. 40-42.

(2) Quirke, T.T. - op. cit.

(3) Quirke, T.T. & Collins: - The Disappearance of the Huronian, Can. Dept. Mines, Geol. Surv. Mem. 160, 1930.

(4) Holmes, A. - The Origin of Primary Lead Ores. Paper II, Econ. Geol., Vol. 33, 1938, p. 836.

(5) Barth, T.F.W. - Structural and Petrologic Studies in Dutchess County, N.Y., Part II, Bull. Geol. Soc. Amer., Vol. 47, 1936, pp. 775-850.

rocks (defined by Barth as rocks formed by the stewing of pre-existing rock material in liquids of magmatic and/or palingenic origin) should form a separate division in a revised classification of rocks. Barth considers migmatites to be syntectic rocks in which the ratio of solid fragments to magmatic material is rather large; they are equivalent to injection gneisses. Syntectic rocks, according to Barth, differ from metasomatic rocks only in that the latter are formed by stewing solid rocks in low-temperature liquids. Barth has attempted to distinguish between metasomatic processes and processes generally considered to be metamorphic; however, in many places the effects of metasomatism overlap and may destroy the effects of metamorphism so that differentiation of the two types is not always possible.

The problem of granitization, or migmatization, is not fully understood. It is known that pre-existing rocks are transformed into rocks not dissimilar to an igneous rock, and that all gradations between these two extremes may be found. It is also generally accepted that in processes involving such alterations, metasomatism has played an active part, but to date there has been no general acceptance of the many terms advanced in philosophical discussions of the problem. For want of more suitable, or more precisely defined terms, the author prefers to call the regionally metasomatized rocks in the vicinity of Montauban-les-Mines "migmatites" or granitized paragneisses in the sense in which the term migmatite was originally used by Sederholm.

<u>Migmatites at Montauban-les-Mines</u>

The migmatites at Montauban-les-Mines are biotite gneisses, which, on the whole, are lighter in colour, and somewhat coarser in grain than the paragneisses. East of the Tétreault ore body they are homogeneous in appearance. At many places on the United Metals and Shawinigan properties, however, the biotitic gneisses are associated with sill, and, to less extent, with dyke-like masses of granitic aspect. The "sills" are 4 to 6 inches thick, and are separated from one another by 2 to 3 inches of biotitic gneiss. The biotitic gneisses are also well developed in the southern and western parts of the Tétreault property, but in these areas a few small masses of rusty weathering paragneiss have escaped migmatization, and occur as "islands" in the migmatites. In addition, the paragneisses near the ore zone have also escaped regional metasomatism, and grade into the migmatites by a gradual decrease in mafic minerals, and the development of structural features of the migmatites.

The major distinction between paragneisses and migmatites does not depend so much on mineralogy as it does on structure. In the paragneisses, foliation follows the bedding planes, which, in turn, follow the folded and contorted structure, whereas the schistosity of the migmatites, faintly defined by biotite, always dips to the east, and no contortion or crumpling is evident. In addition, in the western and southern part of the Tétreault property, and on the United Metals property, the foliation of the paragneisses has not in all places been destroyed by granitization, and the schistosity of the migmatites has been superimposed on it. Exposures in which the two structures are present are relatively rare, for, as a rule, migmatization has been so intense that earlier features of the paragneisses have been obliterated.

The relationship of the schistosity of the migmatites to the schistosity in the paragneisses is extremely important, for it is only by tracing the attitude of the relic Grenville foliation across the area that it is possible to interpret the structure of the paragneisses.

The schistosity surfaces of the migmatites have a general north-south strike and dip consistently to the east. They intersect the relic foliation of the paragneisses at appreciable angles; on the United Metals property the angle of intersection is only 10 to 15 degrees, but in the southern part of the Tétreault property angles up to 40 degrees are not uncommon. In most of the small masses of paragneiss which have escaped migmatization, the foliation is approximately horizontal, whereas the foliation of the surrounding migmatites shows the usual eastward dip. Similar significant relationships exist in those exposures where both structures are present, although the earlier foliation is not necessarily horizontal, as it follows the folded structures now almost obliterated by migmatization.

In addition to schistosity, the migmatites also have a well-defined linear structure or rodding, which is rather plainly shown megascopically. The b-directions have a general north-south trend, usually deviating only a few degrees from the strike of the schistosity, and flat, or low pitches, which indicate the general trend of cross-folds. Although traces of the earlier b-direction of the paragneisses are almost destroyed by migmatization, the fragmentary evidence available indicates that lineation in the folded structure of the paragneisses had about the same trend as the corresponding structure in the migmatites, but that pitches of the earlier b-directions were probably steeper.

The "sills" of granite lie in the plane of the schistosity of the migmatites and are lenticular. The granitic rocks are only slightly schistose, and must have taken on this structural feature before the decline of the regional stress. Their lens-like character is also indicative of emplacement under stress. The granites are closely related to the metasomatism, but there is no evidence to indicate whether they were injected during granitization, or later.

Tension joints are present in the migmatites, the paragneisses, and the metasomatic rocks. Since they are normal to the b-directions, they are almost vertical. They formed at the time of the decline of the regional stress. In places within the ore zone they are filled with sphalerite and galena. They must have formed, therefore, after the alteration of the paragneisses, but before deposition of the sulphide minerals.

Petrography of the Migmatites

The migmatites consist of quartz, oligoclase, microcline, hornblende, and biotite, with small quantities of carbonate, epidote, zoisite, sphene, zircon, sericite, chlorite, and sillimanite. Quartz and plagioclase are invariably present, but the other minerals may or may not be present. If hornblende is present, it is accompanied by carbonate, zoisite and epidote, and if microcline is present, hornblende is absent. In most of the thin sections examined the minerals were distributed according to this rule, but in some thin sections all the minerals are present.

For purposes of discussion, the migmatites are petrographically classified into two main types, (a) a hornblende bearing type, and (b) a microcline bearing type. The mineralogical composition of the two types are shown by Rosiwal analyses in Table IV.

TABLE IV

Composition of Migmatites (Volume Percent)

	I	II
Quartz	49.7	43.5
Plagioclase	30.4	28.7
Potassic feldspar	-	20.7
Biotite	0.5	5.9
Hornblende	16.2	-
Carbonate	0.6	-
Zoisite and epidote	0.6	-
Sericite	1.6	0.9
Chlorite	0.2	0.1
Iron Ore Minerals	0.2	0.2
Total	100.0	100.0

No. I - Hornblende migmatite. (Averages of several specimens).

No. II - Microcline migmatite. (Averages of several specimens).

The quartz, plagioclase, and microcline are intergrown, to form an equigranular groundmass containing prisms and irregular anhedra (larger than the euhedral forms) of hornblende. The plagioclase is commonly twinned after the albite law, and although it is invariably zoned, the range is short. In some specimens it is as sodic as An_{17}, and in others it is An_{40}; the average, however, is about An_{30}. In places the plagioclase is altered along cleavage planes, or in irregular patches to a fine, fibrous aggregate which has the optical properties of sericite.

The hornblende is negative, and the optic-axial-angle is large. The maximum extinction angle in the zone parallel to (010) is 21°. It is pleochroic in shades of green, as follows:

X = greenish yellow

Y = yellowish green

Z = green

Dark brown pleochroic haloes, developed around small crystals of zircon, are rather common.

Epidote and zoisite are in small crystals, and are accompanied by carbonate. The epidote, which is more abundant than the zoisite, has a large optic-axial-angle and a negative sign; the optic-axial-plane is transverse to the elongation. Zoisite is easily distinguished from epidote by its ultra-blue interference colours. It is positive, and $2V = 60^{\circ}$. The optic-axial-plane, which is normal to the elongation shows that it is a ferriferous (β variety) zoisite.

The carbonate occurs in rather large, irregular, anhedra scattered throughout the rock. Sphene is in lozenge-shaped crystals, and iron ore minerals occur in small rounded grains.

Biotite is relatively rare in the hornblende-bearing rocks, and occurs as small scales partly altered to chlorite or in small ragged flakes included within the hornblende. It is more abundant in the microcline-bearing migmatites where it is developed in small plates. It is apparently uniaxial, and negative. The pleochroism is as follows:-

X = light yellow to colourless

$Y = Z$ = dark brown

β, determined by immersion in oils, is 1.625 ± 0.003.

Sillimanite is of rare, though significant, occurrence. It was observed in only two thin sections, in small needle-like forms with the characteristic fracture parallel to {001}.

Since it is widespread in distribution throughout the paragneisses, regional metasomatism must have destroyed most of it. The specimens containing sillimanite probably represent a stage in the granitization of the paragneisses. It has already been noted that two other specimens containing microcline and sillimanite were provisionally classed as paragneisses, owing to their megascopic appearance, but it is probable that they too represent a stage intermediate between paragneisses and migmatites.

Granitic Rocks

The granitic rocks are somewhat coarser in grain, and more leucocratic than the metasomatized paragneisses. They consist of an equigranular groundmass of quartz, plagioclase (An_{17}), and microcline, with a few small ragged flakes of biotite (X = colourless, Y = Z = dark brown) and a small quantity of epidote. Small, dark red garnets are sporadic in occurrence. The plagioclase is twinned after the albite law, and a platey mineral is developed within it along cleavage planes and in irregular patches.

Origin of the Granitized Rocks

Although previous workers in the area mapped the migmatites at Montauban-les-Mines as Grenville gneisses, there is sufficient evidence available to show that the once extensive series of paragneisses have been drastically altered to rocks differing not only in mineralogy, but also in structure, from the older rocks.

It is believed that prior to granitization, the paragneisses along the syncline took up the regional stress by yielding along bedding planes, but away from this zone the paragneisses were unable to yield in this fashion, and eastward dipping schistosity planes developed at an angle to the bedding and foliation of the paragneisses. While the regional stress remained fairly constant, emanations from a magmatic source advanced upwards, and entered the paragneisses wherever inclined schistosity planes had developed. The emanations permeated the paragneisses and the equilibrium existing prior to the entrance of the emanations being destroyed, the new equilibrium formed between minerals of the older rocks and the liquids with which they were in contact caused some of the older minerals to be destroyed and new ones to be deposited in their place. This process was accompanied by, or perhaps followed by, the injection of granitic magma, which also advanced along the inclined schistosity planes. Most of the magma was emplaced as sill-like bodies and the rest formed small, irregularly-shaped bodies.

Although there was recrystallization of the paragneisses, chemical changes indicate that it was accompanied by replacement on a wide scale. Lacking chemical analyses of the paragneisses and the migmatites, it is difficult to postulate the exact chemical changes required for the paragneisses to give rocks of the composition of the migmatites, but the presence of considerable amounts of microcline and hornblende, and small amounts of carbonate in the migmatites indicate that potash and probably lime were introduced by the emanations. While the importance of lime in the metasomatism is unknown, the large amount of potassic feldspar indicates that considerable potash was introduced, for potassia is not abundant in the paragneisses.

The addition of potash to the paragneisses must have been by replacement, as no field evidence has been found indicative of increase in volume or in density of the mixed rocks. It is known that sillimanite, which is normally rather abundant in the paragneisses is rare in the migmatites, so that it must have been replaced. Its alumina and silica probably united with introduced potash to give microcline. It is improbable that the small amounts of sillimanite in the migmatites was formed at the time of granitization, for sillimanite is considered by most petrologists to be foreign to igneous rocks, and therefore, rocks bearing both sillimanite and microcline have not been as intensely granitized as those with no sillimanite.

Replacement of the older minerals by potash was probably not direct, but complex reactions occurred, which, unfortunately, cannot be traced, as micro-structures, such as myrmekite, perthite, mottled intergrowths, chess-board structure, etc., which are often useful in determining the relationships of various minerals to one another, were not developed.

At first thought, it might be considered possible to trace the various changes from paragneiss to migmatite by studying the gradational contact zones. However, in a study of this kind many difficulties are encountered. The most important complicating factor is variations in the composition of the paragneisses. Changes of composition within the migmatites, and in the gradational zones may be due not only to the intensity of replacement processes, owing to the susceptibility of certain bands to replacement, but also because of initial changes in the composition of the paragneisses.

The part played by structure in the formation of the migmatites cannot be over-estimated. Examples of the resistance offered to granitization or migmatization by limestone have been described from many parts of the world.

Eskola (1), in describing a limestone bed in an area of migmatites at Orijärvi, says -

"Even in the midst of a migmatite area, where all silicious rocks have been thoroughly mixed or assimilated with the granitic magma, the limestones are generally quite free from granitic injections.... Moreover, the limestone seems to have protected the adjoining wall rock.... By reason of this preserving action, limestone masses surrounded by narrow layers of leptite or gneiss are common in many of the areas of granite or granitic migmatites". He goes on to state that similar occurrences are common throughout Southwestern Finland.

There is no doubt but that the ability of the carbonate pod in the paragneisses at Montauban to yield to early stress has, in some measure, protected the surrounding rocks from migmatization. However, carbonate rocks are confined to the south end of the ore zone, and it is apparent that the main part of the paragneisses have escaped migmatization, because, occurring as they do along the axis of a syncline, they were easily deformed during the folding, and

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(1) Eskola, P. - Petrology of the Orijärvi District. Bull. Comm. Geol. Finlande, No. 40, 1914, p. 36.

inclined schistosity surfaces were unable to form in them; hence they were not permeated by the potash solutions, nor penetrated by magmatic material. Near the boundaries of the infolded paragneisses a few schistosity planes developed, and at greater distances from the infolded paragneisses still more developed, so that contacts between migmatites and paragneisses are gradational.

The foliation and bedding of the paragneisses preserved in the syncline have not a constant attitude, and most of the "islands" of paragneiss show a horizontal foliation. On the other hand, the inclined schistosity planes of the migmatites dip consistently to the east. It is well known that rocks with bedding planes that dip into an intrusive at a high angle are more liable to alteration than those in which the bedding planes are horizontal or dip away from the intrusive; the inclined schistosity planes were the controlling structural feature in the formation of the migmatites away from the syncline, but the paragneisses occupying the core of the syncline (which have steeper dips than the inclined schistosity planes) were protected from migmatization by their ability to yield to stress.

While most migmatites have been considered to have formed by the actual injection of magmatic material along planes of weakness in the older rocks, there is no evidence that much magma has been injected into the granitized rocks at Montauban. The homogeneous appearance of the migmatites, particularly those east of the Tetreault shaft, suggests that metasomatism was more important than injection.

The source of the potash-rich solutions offers a problem not easily solved. Eskola (1) points out that in the zone of anatexis, unfused portions of the rock become impoverished in the granite compounds, and the percentage of potash diminishes. Because the fused, potash-rich portion is lighter, it tends to rise, and, entering the rocks of the zone above, changes them by a potash metasomatism. Accepting this possibility, it must be assumed that the rocks in the zone of anatexis at Montauban were rich in potash, and that they were not Grenville paragneisses of the composition of those occurring around the Montauban ore zone, which are poor in potash. A simpler explanation is that the potash solutions were derived directly from granitic magma.

Examples of regional metasomatism characterized

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(1) Eskola Pentti - On the Differential Anatexis of Rocks. Bull. Comm. Geol. Finlande; No. 103, 1933, p. 24.

by the introduction of potash have been described from many parts of the world. They are so common that Eskola (1) regards them as characteristic of a zone lying between an upper zone in which there are no injections of granitic material and a lower zone (the zone of anatexis) where granitic rocks are able to form <u>in-situ</u> by fusion. Migmatites are, according to Eskola, confined to either the zone of potash metasomatism, or to the zone of differential anatexis.

In summary, available evidence indicates that the Grenville paragneisses were altered to migmatites by the introduction of potash, and probably other oxides, by emanations, which advanced from below along inclined schistosity surface, and, disrupting the previous equilibrium in the paragneisses, caused simultaneous solution and reprecipitation, giving rise to new minerals. The metasomatism was controlled by schistosity planes dipping to the east, which not only gave entry to the emanations, but also to the magmatic material emplaced as sills and irregularly-shaped bodies.

Amphibolites

In their memoir on the Haliburton and Bancroft areas

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(1) Eskola, Pentti - op. cit.

of Ontario, Adams and Barlow (1) described numerous occurrences of amphibolites in the Grenville series, and showed that such rocks may have formed by the metamorphism of gabbro, basic dykes and flows, or limestone. Owing to the general lithological similarities, it is often extremely difficult to assign a definite origin to a given exposure, unless field relationships are clearly shown. Amphibolites derived from limestone are rather rare in Quebec, but Bancroft (2) believes that some amphibolites at Lac-au-Sable, 3½ miles from Montauban, are derived from limestone. Bodies of amphibolite at Shawinigan Falls (32 miles west of the Ore Zone) and Rivière à Pierre (15 miles east) are believed by Osborne (3) to have originated from basic volcanic rocks.

Amphibolites derived from basic dykes or sills have been described by many authors in Canada and Fennoscandia. Intrusive relationships of such bodies are in most places easily seen in the field, and doubt as to their

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(1) Adams, F.D. & Barlow, A.E. - Geology of the Haliburton and Bancroft Areas. Geol. Surv. Can. Mem. 6, 1910.

(2) Bancroft, J.A. - The Geology of Parts of the Township of Montauban, and Chavigny and of the Seignory of Grondines. Mining Operations Prov. Que., 1913-15, pp. 117-118.

(3) Osborne, F.F. - Petrology of the Shawinigan Falls District. Bull. Geol. Soc. Amer., Vol. 47, Pt. 1, 1937, p. 203.

origin is removed. The amphibolitic bodies of Montauban-les-Mines are derived from sills.

Amphibolites at Montauban-les-Mines

The amphibolites at Montauban-les-Mines occur in the migmatites near the band of paragneisses, into which they extend. They are sills, with a maximum thickness of 60 feet, and in most places conform to the schistosity surfaces in the migmatites, but they intersect the beds and schistosity surfaces in the paragneisses at an angle. Although one amphibolitic body, from Section 12N. to Section 30N., Tétreault property, lies within the paragneisses and metasomatic rocks, underground examination has shown that where the sills enter the paragneisses, they tend to feather out or form a rounded edge against the paragneisses. The crosscutting relationships between paragneisses and amphibolites and the relatively plastic character of the paragneisses probably combined to prevent the amphibolites penetrating the latter rocks.

In addition to the crosscutting relationships indicated above, the intrusive character of the amphibolites is indicated by small local off-shoots, which cut across the structure, and by a small inclusion of paragneiss in an amphibolitic body near Section 16N.

An interesting amphibolite sill near Section 14S follows the bedding of the paragneisses and swings around the Ore Zone in a sharp curve. The structural significance of this will be discussed later.

All the amphibolites have the same general "salt and pepper" appearance. Schistosity, commonly so slight it is difficult to recognize, lies parallel to that of the migmatites, and dips to the east. This textural feature indicates that the regional stress, operative at the time of the formation of the migmatites, did not decline until after the intrusion of the igneous bodies which gave rise to the amphibolites.

Thin sections show the amphibolites consist of a green amphibole and plagioclase, with subordinate quartz and biotite, and occasional grains of ilmenite, sphene, zoisite, epidote, apatite, and zircon. The proportions of minerals in different sections is surprisingly constant, and the average Rosiwal analyses, in volume percent, of several amphibolites is shown in Table V.

TABLE V

Composition of Amphibolite (Volume Percent)

	I	II
Hornblende	37.2	54.9
Plagioclase	52.2	22.7
Biotite	3.9	-
Quartz	4.9	4.2
Garnet	-	16.2
Ilmenite	0.4	1.5
Sphene	0.2	-
Zoisite and Epidote	0.2	-
Apatite	1.0	0.5
Total	100.0	100.0

No. I. Average Rosiwal analyses of amphibolite.

No. II. Average Rosiwal analyses of garnetiferous margins of amphibolite.

Calculations of the composition of the rock from the mineral composition show that it is a trifle richer in lime but otherwise resembles the average for andesites of Daly.

The hornblende is black in the hand specimen, but in thin section it is pleochroic in shades of green, as follows:-

X = yellowish green

Y = greenish yellow

Z = green

The optic-axial-angle is about 80° and $Z \wedge c = 20°$. It occurs in small sub-idioblastic, commonly short prismatic forms, and in fairly large xenoblasts intergrown with plagioclase. A few small dark brown haloes are developed around a mineral which is probably zircon.

The plagioclase occurs interstitially to the hornblende. It shows a considerable range of zoning in which the cores average about An_{55} and the margins are about An_{45}. It is commonly twinned according to the albite law; pericline twinning is far less abundant.

Quartz is in small rounded grains or in rather large xenoblasts intergrown with plagioclase. Small plates of biotite occur at the interstices of, and included in, the plagioclase. The biotite is negative in sign and apparently uniaxial; the index of refraction of β is 1.630 ± 0.003, and X = light brown, Y = Z = red brown. In places a bleached biotite forms small ragged margins to the hornblende. Some of the biotite is altered to a colorless chlorite. Epidote and zoisite are in small crystals and include plagioclase and quartz. Epidote, which is more abundant than zoisite, is negative, the optic-axial-angle is about 85°, and $Z \wedge 001$ cleavage = 29° (or $X \wedge c$ = 4°). Zoisite shows very weak birefringence and in places very strong dispersion, with 2V about 40°, a positive sign, and the optic-axial-plane normal to the elongation, which indicate that the mineral is ferriferous. A few small prisms of apatite are included within feldspar and hornblende. Sphene is in small rounded grains, and in places a shell of leucoxene is developed about ilmenite. It is quite possible that all the sphene is of secondary origin.

Sills of amphibolite within the metasomatic zone have a selvage as much as 3 feet wide, characterized by porphyroblasts of dark red garnet set in a black, fine-grained groundmass. By a decrease in the amount of garnet, and an increase in the size of the grain, the marginal garnetiferous zone grades into the normal amphibolite. Alcock (1) reports the existence of garnet margins on both sides of such amphibolites, but insofar as the writer is aware, they are confined to one side of the amphibolite.

Microscopic examination of the selvages shows the

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(1) Alcock, F.J. - Zinc and Lead Deposits of Canada. Geol. Surv. Can. Ec. Geol. Ser. No. 8, 1930, p. 81.

groundmass consists of small prisms of hornblende, similar in optical properties to that of the normal amphibolite, with interstitial plagioclase, garnets, quartz, and biotite. The plagioclase is more sodic than that in the central parts of the amphibolite, and is zoned from An_{28} and An_{38}. Biotite in small amounts forms ragged flakes near garnet. A small amount of iron ore mineral, probably magnetite, is associated with the hornblende.

The garnets occur in porphyroblasts, most of which are about $\frac{1}{4}$ inch in diameter, but there are some garnets which may be as much as 2 inches across. Most of the garnets are rounded, and show no crystal faces. They have many inclusions of plagioclase, biotite, and quartz, and in places are slightly anisotropic. The specific gravity is 1.780; the refractive index is greater than 1.80. Because of the inclusions and the strong absorption, the refractive index could not be determined in a prism.

For comparison with the unaltered amphibolite, the average of Rosiwal analyses of the marginal garnetiferous zone is given in Table V.

Pegmatites

Pegmatites are relatively scarce in the area near the Ore Zone and have not been studied in detail. Two rather large, flat-lying bodies occur a few hundred feet southwest of the main shaft on the Tétreault property. They consist of a coarse-grained aggregate of quartz, microcline and albite, with subordinate biotite and tourmaline. Small, pink garnets are scattered throughout the rock.

The optical properties of the tourmaline, $\omega = 1.660$, (dark green), $\epsilon = 1.630$ (light violet brown) suggest it contains about 45% of the schorl molecule.

One of these pegmatite dykes extends a short distance into the paragneisses and at the contact an alteration zone, 3 to 4 feet in width, has developed. The alteration zone is white, fine grained, and consists essentially of basic plagioclase, (An_{76}).

Other occurrences of pegmatite within the area are small and unimportant. Since pegmatites intrude amphibolite, and, on the other hand, have in places been affected by the metasomatism giving rise to the gangue minerals, they must be younger than the amphibolites, but older than the metasomatic rocks.

The only specimen of pegmatite examined under the microscope came from a small dyke on the south shore of the Batiscan River. It consists of plagioclase (An_{10} - An_{18}), subordinate orthoclase, and opaque minerals. The plagioclase is much altered, and epidote, zoisite, calcite, and chlorite, are developed in the altered zones.

STRUCTURE OF THE AREA AROUND THE ORE ZONE

Because of inadequate information given on the map of the region prepared by Bancroft, interpretation of the structure at Montauban-les-Mines is necessarily drawn from observations restricted to the relatively small area investigated; it may be found that a better understanding of the regional structure may make necessary some revisions of the interpretation of the structure given below.

Folding

The paragneisses in the area under discussion show certain structural features similar to those in many other areas of Grenville rocks in Quebec; this is particularly true of the development of schistosity parallel to bedding planes. The composite gneisses developed in other areas of the Grenville sub-province are commonly of the lit-par-lit injection type, but the granitic injections in the Montauban area are in no way related to the schistosity or bedding planes of the paragneisses. For this reason the structure is more complicated than that ordinarily found in the Grenville region, and since lithology plays an important part in the ultimate interpretation, it is advisable at this stage to re-describe the general structural relationships between paragneisses and migmatites.

The migmatites have been formed from the paragneisses by metasomatism and injection of igneous material along schistosity planes developed in the paragneisses prior to granitization. All gradations from completely granitized rocks to those in which meta-sedimentary material is dominant over igneous material may be observed in the field. In places, especially where migmatization has not been intense, the schistosity formed prior to granitization may be seen inclined to the schistosity and bedding planes of the paragneisses. The interpretation of the structure of the paragneisses is, therefore, largely dependent on observations of the attitudes of the older schistosity preserved in the less intensely migmatized areas.

On the United Metals and Shawinigan properties the strike of the relic schistosity is from north-south to N.20°E. Small remnants of paragneiss in the migmatites forming the hills west of the Tétreault Mine strike north-south and dip about 30° east, but southwest of the shaft the strike changes to N.45°W. and the dip is to the northeast. In the southern part of the Tétreault property the strike is almost east-west and dips are to the north. The direction of the older schistosity cannot be observed in the highly granitized rocks east of the Tétreault Shaft, but its change of strike in the western part of the area from approximately north-south to east-west suggests a syncline with the eastern arm obliterated by migmatization.

The distribution of nodular sillimanite gneiss along both sides of the diopside-tremolite zone and the fact that diamond drilling shows the migmatites to underlie the paragneisses, is additional evidence that the migmatites surround a synclinal mass of paragneiss cored with limestone. Further evidence supporting such an interpretation of the structure is afforded by petrologic data, particularly the attitude of the amphibolite intrusives and the relationships between the various metasomatic minerals and the paragneisses.

Shearing

Diamond drilling has shown that a short distance below the lowest level of the Tétreault Mine (the 600-foot level) the migmatites underlie the syncline of paragneiss. From an examination of the cores of these holes, F.F. Osborne has concluded that s shear zone, about 7 feet wide, extends downwards through the migmatites. Within the shear zone cordierite, anthophyllite, and mica are developed, but these minerals do not occur in the migmatites bordering the sheared zone. Since, as will be shown later, the solutions which carried the necessary elements into the paragneisses for them to give rise to cordierite-anthophyllite rocks must have advanced from below, it is believed that the shear zone tapped their source at depth, and served as a means of access to the overlying carbonate and paragneiss beds.

Faulting

During the field work no faults were observed on the surface but there is evidence suggesting that the paragneisses have been faulted along the strike. Smooth faces in some of the workings on the Tétreault Mine indicate a certain amount of adjustment, which may be the reflection of movement along the shear zone. In addition, about 400 feet north of the St. Lawrence shaft there is a break in the continuity of the band of nodular simmomanite gneiss, but, unfortunately, owing to a scarcity of exposures in this particular area, it is unknown if the discontinuity is the result of cross-faulting or folding.

Structure of the Migmatites

Schistosity surfaces defined by mica flakes are easily observed in the migmatites. In general, they strike about north-south, and dip east. Across the United Metals and Shawinigan properties the dip is 20°-40°E., except in the southwestern corner of this area where dips as steep as 80° prevail. Steep dips are also common in the northern part of the Tétreault property, but in the vicinity of, and south of the Tétreault shaft, the dip of the schistosity of the migmatites is 25°-40°E.

In some places a rather well-defined linear structure or rodding gives some indication of the general trend of cross-folds. From Section 14S to Section 6N, Tétreault property, the megascopic b-direction of the migmatites have a normal pitch of 10°-15° north, although in places flat or low pitches to the south indicate minor cross-folds superimposed on the major pitch to the north. North of Section 6N the b-directions pitch to both the south and north, with the south pitching planes (5°-10°S) probably more abundant. The corresponding structures in areas of paragneiss not intensely granitized have about the same trends as those in the migmatites, but the pitches are apparently steeper.

Structure of the Ore Zone and Paragneisses

From the distribution of the nodular sillimanite gneiss, it is apparent that the diopside-tremolite band lies along the axis of the syncline. In the vicinity of Section 14S, Tétreault property, the syncline comes to the surface and on account of its pitch dies out to the south along the strike. The peculiar manner in which the amphibolites intrusives wrap themselves around the nose of the syncline is further indicative of such a structure, and amphibolite intrusive bodies have been emplaced along planes whose attitudes have been largely controlled by the relative plascicity of the infolded band of paragneisses.

To the north of the diopside-tremolite zone the band of paragneisses widens considerably,and a rather open anticline, followed to the west by a syncline, replaces the more simple structure to the south. However, the closed structure is known to extend almost as far north as this locality, so it is probable that the complex folding described above has taken the place of the simple syncline. The complex folding gradually dies out to the north and disappears entirely about 700 feet north of the Tétreault-United Metals boundary; its extent to the south is unknown, since migmatization at Section 16N has obliterated all traces of it.

Along the diopside-tremolite zone on the Tétreault property it is known that a pod of carbonate rock, which forms only small outcrops at the surface, lies with its long axis about 200 feet below the surface. The paragneisses tend to wrap around the bottom part and to overfold the upper part of the pod. Extensive mining operations in this area show that the axial plane of the syncline dips to the east at a steeper angle than the foliation surface of the migmatites surrounding the carbonate pod.

In summary, available data indicate that the paragneisses were folded to give a syncline, which plunges to the north in the southern part of the Tetreault property. North of the main shaft on the Tetreault property, evidence is conflicting, but it is believed that in the northern part of the Tetreault property, and on the United Metals and Shawinigan properties, the syncline has a tendency to plunge to the south. Minor folds take the place of the syncline in the vicinity of the northern boundary of the Tetreault property. Schistosity of the Grenville beds, preserved in the migmatites west of the ore body on the Tetreault property, indicates that away from the syncline the paragneisses, prior to granitization, were in places horizontal.

Structure of the Amphibolites

One amphibolite body only is known to occur on the United Metals and Shawinigan properties on the surface, but amphibolite with garnet-bearing margins is found on the dump at the St. Laurence shaft, so it may be presumed that others occur. The amphibolite exposed on the surface lies in the migmatites.

Most of the amphibolite on the Tétreault property is confined to granitized paragneisses in the vicinity of the Ore Zone. It is in lenticular bodies, which follow the inclined schistosity planes. As a rule, the sills of amphibolite feather out or end bluntly against the paragneisses, because of the lack of continuity of the S-planes through the paragneisses. The placticity of the paragneisses acted as a brake on the advance of the magma.

A body of amphibolite, in the vicinity of Section 14S, follows the bedding of the paragneisses, and passes around the nose of the syncline. At Section 9S, diamond drilling and surface mapping indicate that this amphibolitic sill may pass beneath the syncline, so that the syncline apparently plunges to the north.

The amphibolites in the migmatites are slightly schistose, and conform in structure to the rocks which contain them. The igneous material must have been injected after granitization, for it was emplaced along the inclined schistosity planes, but became solid and was altered to amphibolite before the decline of the regional stress.

THE MONTAUBAN ORE ZONE

Rocks, characterized by metasomatic minerals and mineral associations, are confined to the syncline extending across the Tétreault, United Metals, and Shawinigan properties. The metasomatic minerals are of great interest, not only because of their petrologic peculiarities, but also because of their close association with sulphides of lead, zinc and iron sulphides. The mineral associations were determined by the factors temperature, pressure, and concentration, and, although the metasomatic minerals were deposited before the sulphides, the ore minerals developed at any one place along the zone have a significant relationship to the type of mineral association accompanying them. For this reason, silication is discussed prior to metallization.

Silication

It has been indicated that the metasomatic mineral associations were formed from paragneisses by local metasomatism. There can be no doubt as to this, since all gradations between paragneiss and completely metasomatized paragneiss can be observed in the field. The fact that several mineral associations have developed along the zone indicates that temperature, pressure, and concentration, have played important parts in their formation. It is not intended to discuss the genesis of the associations at this place, but a brief consideration of the physical and chemical conditions under which the gangue minerals were formed may assist in understanding their relationships. Although temperature and pressure at any one time were probably uniform throughout the whole zone, the concentration, governed largely by the composition and character of the paragneisses and carbonate rocks, varied greatly from one part of the ore zone to another, and this factor was probably largely instrumental in determining the character of the gangue mineral associations. It is to be understood, however, that the solutions forming the associations were active for considerable time, and that minerals or mineral associations which reached equilibrium in one physico-chemical environment were changed (replaced) as temperature, pressure, and concentration changed. In addition, in some places equilibrium was not attained, and consequently, certain associations are represented by minerals which were normally unstable in the physico-chemical environment.

Seven main types of mineral association have been recognized, and perhaps a more detailed investigation would disclose others. They are as follows:

1. Bytownite-anthophyllite)
   Bytownite-diopside)
   Anorthite-sphene)
2. Diopside-tremolite
3. Actinolite-carbonate-quartz
4. Cordierite-anthophyllite
5. Cordierite-staurolite-spinel
6. Cordierite-corundum
7. Hedenbergite-garnet

These associations are roughly divisible into two groups: those relatively high in lime, and those characterized by a rather high content of magnesia in comparison to the lime. Except for a few small exposures of only local importance, the lime-rich group (Nos. 1, 2, 3, and 7) are confined to the Tétreault property. The diopside-tremolite zone, extending from Section 13S to Section 13N, crops out as an irregular band with a maximum width of 200 feet at Section 10N. It grades into the bytownite-diopside association at its southern end and into the bytownite-anthophyllite type at its northern end. In addition, the bytownite-anthophyllite association occurs beside and beneath the diopside-tremolite zone, so a shell of calcic plagioclase-bearing rocks encloses the diopside-tremolite zone. The actinolite-carbonate-quartz association forms small veins in tension cracks in the diopside-tremolite zone, and is nowhere abundant.

The cordierite-anthophyllite association extends from about Section 13N northward across the United Metals and Shawinigan properties. This association also occurs underneath and around the diopside-tremolite rocks, from which it is separated by the bytownite-bearing zone. The associations characterized by staurolite, spinel, and corundum, are confined to a few small bands in the cordierite-anthophyllite zone on the United Metals property.

The hedenbergite-garnet type of rock occurs in the lowest part of the Tétreault Mine. It apparently lies within the outer shell of cordierite-anthophyllite rocks, and probably between the shell of bytownite-anthophyllite rocks surrounding the diopside-tremolite zone, but its extent, and an exact determination of its relationship to the other zones could not be determined because the lowest level of the mine is flooded with water.

1. Bytownite-anthophyllite, bytownite-diopside, and anorthite-sphene associations

The bytownite-anthophyllite, bytownite-diopside and anorthite-sphene associations are rather coarse grained, light-coloured rocks, which, under the microscope are characterized by large plates of bytownite with a small amount of interstitial quartz. The plagioclase is not zoned, and although its composition is different in different specimens, it falls between An_{70} and An_{76}. It is characteristically twinned after the pericline law. The bytownite-anthophyllite rocks contain 20 to 30 percent plagioclase, but the bytownite-diopside rocks contain 90 or 95 percent plagioclase. Most of the bytownite is fresh in appearance, but in places it is altered to a mass of finely fibrous or lamellar minerals.

Anthophyllite occurs in short, or much elongated prisms. Cordierite, though present, is rare, and is not found with lime-rich feldspar. Biotite is in small foils or scales, and wollastonite was observed in one thin section only. Zircon, sphene, and apatite form only a small part of the rock.

The bytownite-diopside rock differs from the bytownite-anthophyllite rock in that diopside takes the place of anthophyllite. Diopside, however, is in far smaller quantities than anthophyllite in the corresponding rock types. The coarse-grained, light-green, diopside-bytownite rocks are rusty-weathering on account of the oxidation of pyrrhotite. Under the microscope the rock is seen to consist essentially of large anhedra of plagioclase (An_{76}), with characteristic pericline twinning. Minor amounts of chlorite, biotite, apatite, and one or two grains of zoisite are scattered throughout it. Diopside is relatively rare. Pyrrhotite appears to be in thin films separating grains of plagioclase.

The most interesting rock of this group is a fine-grained white rock, appearing on the surface near the western margin of the diopside-tremolite zone at Section 5N. It contains wedge-shaped crystals of black sphene up to ½ an inch long. Microscopic examination shows that except for the sphene, it consists solely of untwinned, and unzoned, anorthite (An_{97}). In places it is altered to a purplish-coloured mineral, which has been called "wilsonite".

Although wilsonite is fairly widely distributed on the dumps at the Tétreault Mine, it is not a common mineral in the diopside-tremolite zone. In the underground workings it is in fringes along the border of the diopside-tremolite zone, and apparently bears a significant relationship to the bytownite-bearing rocks.

Wilsonite was first described by T. Sterry Hunt (1), who considered it a new mineral species. Later, however, it was shown (2) that it is actually an alteration product of scapolite.

There is no doubt that the wilsonite in the anorthite rock described above has formed from the anorthite. Although evidence as to its origin in other sections of the area are not so conclusive, several factors suggest that all of it has formed either from anorthite or other calcic plagioclases. First, it occurs as a fringe around the diopside-tremolite zone. Second, wilsonite is usually accompanied by sphene crystals, which suggests it originated from anorthite-sphene rocks, and third, crystals consisting of wilsonite were found to have the form of anorthite. The crystals are about 2 inches long and 1 inch wide, and determined faces were (110), (100), (130), (010), (207), (001), (111), and (021).

Under the microscope, wilsonite shows aggregate polarization, and its refractive index is near 1.575. Most of the wilsonite apparently consists of fine, scaly mica, accompanied by a small amount of calcite.

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(1) Hunt, T. Sterry - Geology of Canada, 1853, 1863
Amer. Jour. Sci., Vol. 19, p. 428

(2) Chapman, E. S. - Amer. Jour. Sci., Vol. 20, p. 269

2. Diopside-tremolite Association

Where exposed on the surface this zone consists of a coarse-grained aggregate of acicular and fibrous crystals of colourless, or more rarely, light green or grey tremolite, with some diopside, carbonate, and scapolite. On first thought, it is natural to assume that the tremolite has formed by metasomatism from the re-crystallized sedimentary carbonate, fireite. However, there is very little fireite exposed on the surface, and mining operations have shown that the upper part of the main body of fireite is some distance below the surface. The tremolite rocks grade into the surrounding paragneisses, and "islands" and "horses" of paragneiss in the tremolite zone are not uncommon. It is apparent, therefore, that most of the tremolite on the surface has formed by replacement of the paragneisses. It may also be pointed out that the distribution of nodular sillimanite gneiss bears a significant relationship to the width of the tremolite zone, for where the tremolite zone is fairly narrow, the nodular gneiss is on both sides of the tremolite zone, but where the tremolite widens out the nodular sillimanite disappears, indicating that it has been replaced by the tremolite.

The tremolitized paragneisses contain only a small amount of sulphide minerals. There is some disseminated mineralization, but most of the sulphides are in tension cracks and fractures, which, in places, have yielded small tonnages of high-grade ore. The quantity of sulphide minerals increases with depth, and below the 200-foot level the largest ore bodies were encountered. Most of the ore has been stoped out, but a study of the pillars, although probably not representative of the part removed, shows that the gangue minerals were diopside, tremolite, fireite, and other carbonates.

Diopside obtained from pillars and dumps is colourless (some is transparent), grey, or light green and in many places it forms nearly symmetrical 8-sided prisms with glistening faces which reach a length of 2 feet, and a diameter of 6 inches. More rarely it occurs with granular or fibrous habit. Microscopic examination of the crystalline varieties shows a parting due to twinning parallel to (001). The diopside has an optic-axial-angle of 60°, a positive sign, and a maximum extinction in the zone parallel to (010) of 39°. The refractive indices are as follows:-

$$\alpha = 1.665$$
$$\beta = 1.672$$
$$\gamma = 1.695$$
$$\gamma - \alpha = 0.030$$

Correlating optical properties and refractive indices, Winchell's tables show that the mineral contains little, if any, of the hedenbergite molecule.

Tremolite is apparently younger than diopside, as it replaces the latter mineral along cleavages and fractures. Where associated with diopside, the tremolite is commonly developed in acicular or fibrous aggregates, in crystalline masses in which cleavage faces are prominent and crystal faces rare, and in blade-like crystals up to 2 inches long. Its optical properties are given below.

$\alpha = 1.602$	$Z \wedge C = 18^{\circ}$
$\beta = 1.619$	$2V =$ large
$\gamma = 1.633$	Sign: negative
$\gamma - \alpha = 0.031$	

Two kinds of carbonate accompany the diopside and tremolite. Fireite, the recrystallized sedimentary carbonate which glows red when struck with a hammer, occurs in irregular masses. A coarsely-crystalline white carbonate (some of which is translucent), with rhombohedral cleavage planes, fills interstices between diopside and tremolite crystals, or occurs in small veins along cleavage planes or fractures in these minerals, and is undoubtedly later than the tremolite. The coarse-grained carbonate is probably fairly pure calcite, as tests with log-wood dye did not indicate dolomite.

Biotite is not found in the central parts of the zone, but dark brown to black biotite occurs in flakes or as fringes alongside amphibolitic intrusives that extend for short distances into the diopside-tremolite rocks. Biotite also forms a fringe along the inner side of the bytownite-anorthite zone. In a few places it is mineralized with sphalerite.

There are several varieties of minerals in the diopside-tremolite zone, which, although they do not form large bodies, are nevertheless of mineralogical interest.

Leuchtenbergite

Some of the tension cracks within the tremolitized paragneisses are filled with booklets of colourless, or amber-coloured, transparent chlorite, which enclose small, elongated prisms of tremolite. The laminae are brittle. The mineral is optically positive, the optic-axial-angle is 15° to 20°, and $\beta = 1.570$. Although the composition of the chlorite cannot be definitely determined from its optical properties, it is believed that it is a variety of the magnesian-rich chlorite, leuchtenbergite.

This mineral also occurs in fine scales in calcite, and as a fringe around dravite in a pegmatite cutting the diopside-tremolite rocks on the first level.

Penninite

This chlorite is not abundantly developed in the tremolitized paragneisses, but it must have been a rather common mineral in certain parts of the stopes, for it is widely distributed on the dumps. It occurs in scales along cleavage planes in massive tremolite, and in some specimens is more abundant than tremolite. It also forms fine-grained, light green, crystalline schists. It is negative in sign, the optic-axial-angle is about 10°, and $\beta = 1.575$ to 1.585. Its colour is from dark green to bluish green to light green.

Antigorite

Antigorite occasionally occurs in small masses in tremolite, from which it has apparently formed. It is light green and shows aggregate polarization.

Tourmaline

The only known occurrence of this mineral on the surface is in a trench about 300 feet north of the Tétreault shaft. It is light brown in colour, occurring in small aggregates made up of numerous small stubby crystals. It is surrounded by coarsely fibrous tremolite. The refractive indices are: ω = 1.635 (colorless), ϵ = 1.612 (brown). Specimens from underground show massive tourmaline, with no definite crystal faces, which occurs with wilsonite, and small needles with a radiating habit in coarsely crystalline galena.

The massive tourmaline has ω = 1.635 (light brownish violet), ϵ = 1.615 (dark green), and the tourmaline with a radiating habit has somewhat higher indices, being ω = 1.645 (pale yellow), ϵ = 1.622 (yellowish brown).

The optical properties of tourmaline in the diopside-tremolite zone shows them all to be dravite.

Brucite

Considerable amounts of this mineral occur on a dump 600 feet north of the Tetreault shaft. It forms white, fine-grained masses, which include numerous small prisms of white tremolite. It is uniaxial, positive, and ω = 1.570, ϵ = 1.585. It also forms talc-like aggregates in the ore body.

Breunnerite

This magnesian-iron carbonate is sporadically distributed in small amounts throughout the ore zone, and it is generally accompanied by tremolite. It is rather coarsely crystalline, with perfect rhombohedral cleavages, and is translucent. Because it is rusty weathering it is easily identified in the field. It is uniaxial negative, o = 1.705, e = 1.520.

Scapolite

Specimens of scapolite were obtained from the mine workings. It is generally in small, compact masses surrounding calcite and accompanied by andesine, from which it has probably been derived. Scapolite also occurs on the surface in the diopside-tremolite zone near Section 11S.

It is uniaxial, negative, and o = 1.567, e = 1.548, so that it consists of approximately 40% meionite ($Ca_3Al_6Si_6O_{24}.CaCO_3$) and 60% marialite ($Na_9Al_3Si_9O_{24}.NaCl$).

Apatite

Apatite occurs in dark green or bluish-green crystals up to 2 inches across. It is most abundant in diopside-tremolite rocks on a dump 500 feet north of the Têtreault shaft, and most of it occurs in the vicinity of sphalerite and galena.

The crystals are short prismatic, and the common crystal forms are (100), (010) and (001).

Hisingerite

This mineral, $Fe_2O_3.2SiO_2.nH_2O$, occurs sparingly in fibrous tremolite, or with calcite, diopside, and chlorite. It forms small dark brown or black clots, seldom more than 1/10 of an inch across, which have a vitreous lustre. In powder, it is golden yellow and isotropic. The refractive index is from 1.515 to 1.545.

Barite

No specimens of barite were obtained, but it has been reported that while milling, small quantities of a heavy white mineral were observed on Wilfley tables, and it is probable that this mineral was barite.

3. Actinolite-carbonate-quartz Association

These minerals form small, though rather coarse-grained, veins in tension cracks in the tremolitized paragneisses. Actinolite is in long-laded light to dark green transparent crystals, in places 2 to 3 inches long, which are enclosed in coarsely crystalline calcite. The quartz is colourless, and prisms terminated by rhomobohedral faces are common. In places, the veins have coarsely-crystalline sphalerite and galena.

The optical properties of the actinolite are as follows:-

$\alpha = 1.612$	$Z \wedge C = 17$	
$\beta = 1.625$	$2V =$ large	
$\gamma = 1.637$	Sign: negative.	
$\gamma - \alpha = 0.025$		

This association is definitely younger than diopside or tremolite gangue, as it occupies tension cracks formed after the decline of the regional stress, which did not take place until after tremolitization of the paragneisses.

4. Cordierite-anthophyllite Association

The variable proportions of the constituent minerals of these rocks makes it difficult to give a general description of them. Since the paragneisses vary greatly in composition, it is to be expected that the metasomatic rocks formed from them would also vary greatly, and as a result all stages between rocks carrying small amounts of cordierite and anthophyllite to those consisting entirely of one, or both, of these minerals is to be found. Those in which replacement has not been extensive consist of quartz, plagioclase (An_{30}) biotite, garnet, zircon, apatite, a little sillimanite, cordierite, with subordinate anthophyllite. Except for the presence of the latter two minerals, most of these rocks resemble paragneisses, not only in general appearance but also in the manner in which proportions of garnet, quartz, biotite, and plagioclase vary from band to band. Although in such rocks it is difficult to distinguish cordierite from quartz, weathered surfaces are commonly pitted because of the relative ease with which cordierite succumbs to epigenetic processes, and as a consequence, the identification of cordierite-bearing rocks is made relatively easy.

Paragneisses which have been more intensely altered are easily identified in the hand specimen. Such rocks have a glassy lustre and a blue colour, owing to cordierite, and are generally coarser in grain than the paragneisses. The cordierite occurs in rather large, rounded masses, and is accompanied by garnet and biotite. Finally, a more advanced stage in the metasomatism destroys all the characteristics of the paragneisses, and the resulting rock consists essentially of cordierite and anthophyllite. Such rocks are common on the dump at the St. Laurence shaft. The anthophyllite forms rosettes, sheaves, or large prisms, set in a groundmass of cordierite. In many specimens the two minerals are present in about equal proportions, but a few specimens, some of them of several pounds weight, consist solely of cordierite.

The cordierite shows considerable diversity in colour in the same specimen, colourless, light or dark shades of blue predominating. It is altered, particularly near sulphides, to a "robin's egg" blue coloured aggregate of pinite, but as a rule, it is fresh. The massive cordierite forms large plates intergrown with one another, but in rocks not intensely altered, and which still resemble paragneisses, it occurs in porphyroblasts up to $\frac{1}{4}$ of an inch in diameter, and may form 60% of the rock.

In thin section the cordierite is colourless, but here and there, however, are yellow pleochroic haloes around microscopic crystals of zircon. In places the haloes are in swarms, and as many as 20 haloes may be observed within the field of a medium-powered lens.

Many plates of cordierite are relatively free of inclusions, but other crystals have considerable amounts of anthophyllite, quartz, plagioclase, and small quantities of zircon and apatite in them. Twinning is rather rare.

The optical properties of the cordierite are not constant in even one specimen, a feature which is fairly common in the cordierite of other occurrences. As a rule, the mineral is negative, but one part of a crystal may be negative, and another part positive. The optic-axial-angle, like the sign, varies considerably, but is never less than 80°.

Optically positive cordierite is not mentioned in many textbooks, but it has been described within the past few years by Chacko (1), Krishman (2), Rutherford (3),(4), Conant (5), Pehrman (6), and others.

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(1) Chacko, I.C. - Optically Positive Cordierite. Geol. Mag., Vol. 3, 1916, pp; 462-464.

(2) Krishman, M.S.- Note on Cordierite in a Cordierite-gneiss from Madura District, Madras, India. Min. Mag., Vol. 20, pp. 248-251.

The determination of the refractive indices of the cordierite by immersing fragments in oils, shows that there is no apparent relationship between colour, optical properties, and indices. Pehrman (1), Shibata (2), and Winchell (3), have drawn diagrams from available information correlating optic properties and compositions, but their data are of little use when the optical properties vary so much in the same crystal.

Refractive indices of fragments of cordierite are shown below:-

	Glassy Cordierite	Smokey blue Cordierite	Dark blue Cordierite
α	= 1.539	1.534	1.545
β	= 1.545	1.538	1.549
γ	= 1.550	1.543	1.555
$\gamma - \alpha$	= 0.011	0.009	0.010
2V	= large	large	large

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(3) Rutherford, R.L. - Optically Positive Cordierite from the Northwest Territories, Canada. Amer. Min., Vol. 18, 1933, p. 216.

(4) Rutherford, R.L. - Optically Positive Cordierite from the Kisseynew gneiss, at Sherridon, Man. Amer. Min., Vol. 21, 1936, pp. 386-388.

(5) Conant, L.C. - Optically Positive Cordierite from New Hampshire. Amer. Min., Vol. 20, 1935, pp. 310-311.

(6) Pehrman, Gunnar - Uber Optisch Positiven Cordierit. Acta Acad. Aboensis Math. et Phys., Vol. 6, No. 11, 1932, p. 12.

(1) Pehrman, Gunnar - Op. cit.

(2) Shibata, H. - Jap. Jour. Geol. Geogr., Vol. 13, 1936, p. 205.

(3) Winchell, A.N. - Cordierite. Amer. Min., Vol. 22, 1937, pp. 1175-1179.

Cordierite is a relatively rare mineral, not only in Canada, but throughout the world. Adams and Barlow (1) have described it in association with gedrite in Harcourt Township, Ontario. It is also known to occur at the Amulet Mine, P. Q. (2), near Halifax City, N.S. (3), in Baffin Land (4), at Sherridon, Man. (5), Lake Athabaska (6), Sask., and near Coquihalla, B.C. (7).

The anthophyllite at Montauban occurs in radiating aggregates and sheaves of prismatic crystals measuring up to 4 inches in length, and in places it is so abundant that cordierite appears to fill interstices between radiating aggregates of anthophyllite. Most of it is pale brown or mauve, but the anthophyllite in biotite-rich bands is darker

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(1) Adams, F.D. & Barlow, A.E. - Geology of the Haliburton & Bancroft Areas, Ont. Geol. Surv. Can., Mem. No. 6, 1910, pp. 157-172.

(2) Walker, T.L. - Univ. Toronto Studies, Geo. Ser. No. 29, Univ. Toronto Press, 1930.

(3) Johnson, R.A.A. - A List of Canadian Mineral Occurrences. Geol. Surv. Can., Mem. 74, p. 132.

(4) Walker, T.L. - Minerals from Baffin Land. The Ottawa Naturalist, Aug.-Sept., 1915, p. 65.

(5) Rutherford, R.L. - op. cit.

(6) Rutherford, R.L. - op. cit.

(7) Cairnes, C.E. - Coquihalla Area, British Columbia. Can. Geol. Surv. Mem. No. 139, p. 74.

in colour than that elsewhere. In both varieties, however, the optical properties (2V close to 90°, positive, z $\parallel$ c, optic-axial-plane parallel to the elongation) are the same, but the darker-brown anthophyllite has higher refractive indices, indicating a higher iron content. Applying the optical data to the curves correlating variations in composition and optical properties of orthorhombic amphiboles as given by Winchell, the lighter brown varieties contain about 8 mol percent and the darker varieties about 22 mol percent of the ferranthophyllite molecule.

Light brown anthophyllite		Dark brown anthophyllite	
α	= 1.608	α	= 1.622
β	= 1.618	β	= 1.633
γ	= 1.630	γ	= 1.645
$\gamma-\alpha$	= 0.022	$\gamma-\alpha$	= 0.023

Since the dark brown variety is accompanied by black biotite (β = 1.580) it must be inferred that the amount of iron available in such rocks was enough to cause the formation of a more ferriferous variety of amphibole than was ordinarily developed.

Microscopic examination shows the anthophyllite is normally sharply bounded by (100), cleavage parallel to the elongation is common, and in places an ill-defined cleavage parallel to (001) may be observed. Alteration of anthophyllite along cleavages to a light green mineral (antigorite?) with aggregate polarization was observed, but it is rare. The anthophyllite replaces the biotite of the paragneisses along cleavage planes; its relationship to cordierite, a mineral of relatively low crystallizing strength, cannot be determined in thin sections, but the general appearance of hand specimens suggests it also replaces cordierite.

The cordierite-anthophyllite rocks contain small quantities of mica, most of which is in foils 1 or 2 inches across, but is also in small flakes distributed throughout the cordierite. Nowhere, however, is it very abundant. It is invariably light brown in colour, and has the optical properties of biotite. It is negative, the optic-axial-angle is 10° or less, and $\beta = 1.577$. The pleochroism is

$$X = \text{colourless}$$
$$Y = Z = \text{brown.}$$

It is developed along cleavage planes in cordierite, and was apparently formed at a later time than the silicate minerals with which it is associated.

Although sillimanite is very abundant in the neighboring paragneisses, it is rare in the interior of the metasomatized zone, and only appears in association with cordierite near the contacts. It may be noted that in such places anthophyllite is absent. Evidence obtained from the cordierite-staurolite-spinel rocks indicates that cordierite replaces sillimanite, and its paucity in the metasomatized rocks is thus explained. Tilley (1) considers anthophyllite and sillimanite to be incompatible under all conditions, and it appears that in addition to anthophyllite, cordierite was antipathetic to sillimanite under the conditions prevailing at the time of the metasomatism of the paragneisses at Montauban-les-Mines.

Zircon and apatite are in minor amounts in the cordierite-anthophyllite rocks. The former mineral not only caused pleochroic haloes in the cordierite, but also formed haloes in the mica. It is important to note that the zircon crystals in the mica occur along cleavages, and apparently was introduced after the biotite was formed. Specimens of mica containing pleochroic haloes were examined by G.H. Henderson, of the Department of Physics, Dalhousie University, with the object of determining its age. Unfortunately, Henderson reported that although the haloes are large,

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(1) Tilley, C.E. - Granulites of the Lizard. Geo. Mag., Vol. 74, 1937, p. 308.

there is an absence of ring structures, and it is impossible to estimate the age from the haloes. He believes the haloes are of the uranium type.

Henderson also states that other specimens of metasomatic biotite which he has examined did not show ring structure.

5. Cordierite-staurolite-spinel Association

The association, cordierite-staurolite-spinel, is confined to the cordierite-anthophyllite zone. Its areal extent is unknown, for much of the staurolite and spinel occurs in grains of microscopic size, and their identification in the field is impossible. However, out of several thin sections of cordierite-bearing rocks examined under the microscope, only 2 contained staurolite or spinel, so the mineral association must be rather rare.

The staurolite is in small tabular crystals and is confined to thin bands which are separated from one another by biotite-rich bands. Spinel, which is subordinate to staurolite, forms small, rounded, colourless grains. The staurolite and spinel are accompanied by cordierite, plagioclase and quartz, and, the rocks in the hand specimen has the general appearance of a biotite paragneiss.

Specimens of staurolite were found on the dump at the St. Laurence shaft. Much of it is in a biotite gneiss, where it occurs in porphyroblasts (up to ½ inch in diameter). Spinel does not accompany staurolite in these rocks.

The most interesting megascopic specimens of staurolite, however, occur in cordierite. Like that in the biotite gneiss, it forms "balls", the largest observed being 1 inch in diameter. Staurolite is golden yellow, has an optic-axial-angle near 90°, and a positive sign. The pleochroism and refractive indices are as follows:-

X = colourless	α = 1.735
Y = yellow	β = 1.7395
Z = golden yellow	γ = 1.745

In thin section, the porphyroblasts are seen to be surrounded by cordierite, and in places appear to have been replaced by this latter mineral. The relationship between these two minerals is borne out by an examination of megascopic specimens, for various stages in the replacement process may be recognized. Cordierite first replaced staurolite along cleavage planes, giving rise to alternating bands of the two minerals. In a more advanced stage of the replacement the staurolite bands are thin, compared to the bands of cordierite, and finally, balls of cordierite, with the shape of the porphyroblasts of staurolite, show that replacement is complete, and that some of the cordierite is pseudomorphic after staurolite.

The porphyroblasts of staurolite contain large prisms of sillimanite, sharply bounded by (100) and (010) faces where they are enclosed in staurolite, but their outlines are embayed and irregular where they are in contact with cordierite. In addition, cleavage planes of sillimanite extend short distances into the cordierite, and there is no doubt that some of the sillimanite has been replaced. Sillimanite is preserved only because of the protection offered by staurolite, which was more resistant to replacement, and is what Eskola terms an "armoured relic".

A small amount of spinel also occurs with the staurolite, as small, colourless grains distributed along the contact between cordierite and staurolite. It is believed that most of the spinel in the cordierite-staurolite-spinel rocks has formed as the result of the replacement of staurolite by cordierite, and that spinel, as well as staurolite, was unstable under the conditions existing in those parts of the zone where there was intense metasomatism.

Megascopic spinel crystals, with octahedral faces, were found by Bancroft. The crystals are black, and about ¼ of an inch long. They occur in a cluster surrounded by chalcopyrite and anthophyllite. The spinel is colourless in fragments, and has a refractive index of 1.765, so it is probably the ordinary magnesia spinel, $MgAl_2O_4$.

6. Cordierite-corundum Association

Corundum is another mineral of rare occurrence. It has been observed in only one thin section, where it is clusters of microscopic, irregularly-shaped grains surrounded by a relatively thick shell of muscovite, which acts as a barrier between it and the surrounding cordierite, and is an "armoured relic". The corundum is colourless under the microscope, and has high relief, low interference colours, and is uniaxial negative.

Coarse, prismatic forms of sillimanite are present in the same thin section, and, like the corundum, the sillimanite is effectively separated from the cordierite by a shell of muscovite. The groundmass of this specimen consists mainly of cordierite, quartz, and plagioclase.

7. Hedenbergite-garnet Association

This zone occurs in the lower part of the Tétreault mine and apparently lies on top of the cordierite-anthophyllite zone and underneath the diopside-tremolite zone. However, because the lowest level in the mine is under water, the relationship of this zone to the neighboring zones could not be definitely determined.

Rocks of this type contain, in addition to the index minerals, hedenbergite and garnet, subordinate amounts of quartz, calcite, galena and sphalerite. The rocks are medium grained and in the hand specimen appear to consist of about equal parts of garnet and hedenbergite. The garnet is xenoblastic and fractured, and in places the fractures are filled with sphalerite, galena, or calcite. The optical properties of the garnet are: specific gravity = 3.78, refractive index = 1.765 ± 0.003. Correlation of optical properties and refractive index, as shown by Winchell's tables, indicate the garnet has the following composition.

56 percent pyrope
35 percent almandite
9 percent andradite.

The garnets are light pink, and rarely show crystalline outlines.

The hedenbergite is in short prismatic forms and has an optic-axial-angle of about 60^{o}, a positive sign, and a maximum extinction angle of $Z \wedge C$ of 43 . Refractive indices are as follows:-

$$\alpha = 1.710$$
$$\beta = 1.715$$
$$\gamma = 1.730$$
$$\gamma - \alpha = 0.020$$

The optical properties, according to Winchell's tables for the diopside-hedenbergite system, show that the mineral consists of 56 weight percent hedenbergite and 44 weight percent diopside. In the hand specimen the hedenbergite is dark green, but under the microscope is colourless.

Quartz and calcite fill interstices between the dominant minerals, and calcite also fills fractures in the garnet. Apatite and sphene are accessory minerals. Sphalerite and galena are rare.

Metallization

It is significant that, as a rule, cordierite-anthophyllite rocks in Fennoscandia are mineralized with magnetite, and/or sulphides of iron, zinc, lead, and copper, and that the formation of the gangue minerals antedated mineralization. Another characteristic feature of most of the occurrences of cordierite-anthophyllite rocks in Fennoscandia is that ore bodies are not generally in the cordierite-anthophyllite rocks, but are associated with "skarns" derived from limestones and dolomites intercalated in them. In addition, the distribution of the sulphides is apparently related to the mineralogical and chemical compositions of the rocks that contain the ore minerals. In the skarns, sphalerite and galena are more abundant than chalcopyrite, whereas in the cordierite-anthophyllite rocks chalcopyrite is in most localities more abundant than sphalerite and galena.

The ore minerals in the metasomatic rocks at Montauban have a distribution similar to those in the cordierite-anthophyllite and skarn rocks of Fennoscandia. Sphalerite and galena are the dominant sulphides in the diopside-tremolite rocks, and chalcopyrite occurs in only minor amounts. In the cordierite-anthophyllite rocks, chalcopyrite is more abundant than sphalerite and galena, and in the bytownite-anthophyllite (diopside) rocks, pyrrhotite is dominant. The distribution of ore minerals in the metasomatic rocks of the Montauban ore zone is shown in Table VI. For simplicity, the cordierite-spinel-staurolite and cordierite-corundum rocks are included with the cordierite-anthophyllite rocks.

TABLE VI

Distribution of Sulphide Minerals in the Rocks Of the Montauban Ore Zone

(In order of decreasing amounts)

	I	II	III
cordierite	staurolite spinel corundum anthophyllite (mica)	bytownite- anthophyllite (diopside)	diopside- tremolite (mica)
	chalcopyrite galena sphalerite pyrrhotite pyrite	pyrrhotite chalcopyrite	sphalerite galena pyrrhotite chalcopyrite arsenopyrite molybdenite grey copper

Metallization in the Diopside-tremolite Rocks

Lead and zinc are the only metals of economic importance in the Montauban ore zone, and production of these two metals has been from ore bodies in the diopside-tremolite rocks. The tremolitized paragneisses at, and near, the surface contain disseminated sphalerite and galena. However, the tension cracks are, in places, filled with these sulphides which have formed small, though rich, ore bodies. The most important ore bodies are associated with the diopside and tremolite gangue in the vicinity of the pod of carbonate rocks. Unfortunately, most of the ore has been stoped and a study of this mineralization is confined to the pillars in the stopes. The ore occurs with coarsely-crystalline masses of diopside and tremolite, and fills interstices between crystals, as well as penetrating the crystals along cleavage planes and fractures. The sulphides are disseminated through the finer-grained, fibrous masses of tremolite and diopside, and, according to Bancroft, were also uniformly distributed through the masses of fireite. Large masses of ore were commonly found in the diopside-tremolite rocks.

Although twelve polished sections containing sulphide minerals from various parts of the ore zone were examined under a reflecting microscope, it was found that the results were conflicting. The paragenetic sequence can be determined only by studying many more polished sections, and since the ore remaining in the pillars in the Tétreault Mine is probably not representative of the ore that has been removed, the conclusions would still be open to doubt.

The dominant sulphide in the Tetreault Mine is sphalerite. It is black in colour, which indicates a considerable content of iron in isomorphous mixture. Where sphalerite is in veins in the tremolitized paragneisses and in masses or fills the interstices between diopside and tremolite crystals, it is coarse-grained, but where disseminated it is generally fine-grained. The coarse-grained sphalerite under the metallographic microscope, contains many small inclusions of gangue material.

The galena-sphalerite ratio is about 1 to 3. Most of the galena is coarse-grained, and the cleavage faces are prominent. Pyrrhotite rarely occurs in coarse-grained aggregates, but is commonly in microscopic anhedra associated with galena, or in small irregular veins in the gangue. Chalcopyrite is generally in small irregular forms, and most of it is along the contact between galena and sphalerite, or moulded onto the sides of anhedra of pyrrhotite. Grey copper (tetrahedrite?) is rare.

Arsenopyrite is sporadic in occurrence, and is nowhere abundant. Crystals of arsenopyrite occur on the surface, in the tremolite, and are up to ½ inch in diameter. The (110) and (011) faces of the crystals are well developed. Cruciform twinned crystals are common and the twinning plane is (101). Striations are prominent.

Flakes of molybdenite are scattered through the tremolite on the surface, but this mineral is not abundant. Bancroft (1) has reported that minute flakes of graphite in places coat fibres and blade-like crystals of tremolite. Graphite was not observed by the writer.

Some gold and silver have been recovered from the ore. Bancroft (2) states that native gold was found on the Wilfley tables, and native silver is also known to occur in the ore. However, most of the gold and silver recovered was probably in electrum, which apparently occurs in relatively large pieces, for the caretaker on the Tétreault Mine showed the writer a "slug" of electrum measuring 3/4 inch long and ½ inch in diameter.

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(1) Bancroft, J.A. - op. cit. p. 127

(2) Bancroft, J.A. - op. cit. p.128

Metallization in the Cordierite-anthophyllite Rocks

The greatest part of the sulphide minerals in the cordierite-anthophyllite rocks occurs in lenticular veins, which tend to lie in the plane of the schistosity of the Grenville rocks which have not been intensely metasomatized. These veins are small, are generally only about 1 inch wide and 1 foot long, but in places they may be two or three feet wide and ten or fifteen feet long. The longest vein on the United Metals property reported by Bancroft was 120 feet long. The veins are irregular, pinching and swelling both along the strike and down the dip. Although assays show that the veins are rich enough in places to be economic, they are too discontinuous to yield appreciable tonnages of ore.

Many of the smaller veins consist of massive sulphides, and the larger veins were apparently bands in the paragneisses which wer more susceptible to mineralization than the surrounding rocks, so that the sulphides are distributed irregularly through the gangue material. In addition, there are a few white, rusty-weathering quartz veins which are generally irregularly mineralized with sulphides, but in places in the quartz veins ore minerals are so abundant that there is probably less than 10 percent of gangue material.

In places, the less intensely metasomatized paragneisses are more heavily mineralized than the massive cordierite-anthophyllite rocks, which, on the whole, contain a relatively small amount of ore minerals. In the latter rocks the sulphide minerals are in small masses, and, to a less extent, disseminated through the cordierite or anthophyllite.

The dominant sulphide mineral in the cordierite-anthophyllite rocks is chalcopyrite, which tends to develop strongly in large anhedra (up to 7 or 8 inches long, 3 inches thick and 2 inches wide) and is also in small grains scattered through cordierite. In the veins, chalcopyrite is generally accompanied by an equal amount of sphalerite, and, although anhedra up to 2 or 3 inches are common, it is not as coarsely-crystalline in the veins as it is in the massive cordierite-anthophyllite rocks. Surfaces of anhedra of chalcopyrite slightly tarnished by weathering show numerous twin bands, and in one specimen pyrite had replaced chalcopyrite along the twin bands.

Most of the sphalerite and galena is confined to the veins, and in places in the veins sphalerite is far more abundant than galena, but in other places the reverse is true. Galena also occurs in the massive cordierite, where it forms small, coarsely crystalline masses, and in anthophyllite, which it has replaced along cleavage planes. Galena seems to be more common than sphalerite in the quartz veins, but both these sulphides are subordinate to chalcopyrite.

Pyrrhotite is nowhere abundant. Most of it is associated with chalcopyrite, in which it occurs in round, or irregular shapes, in places an inch in diameter. Pyrite is rarely observed megascopically; examination of polished sections of chalcopyrite by a metallographic microscope shows that chalcopyrite contains small amounts of pyrite, which may have replaced chalcopyrite. The evidence of sequence, however, is conflicting.

Assays of samples taken from the underground workings on the United Metals property show that the sulphide minerals are accompanied by gold and silver. In order to show the proportions of lead and zinc, and the amounts of gold and silver, several assays of selected and channel samples are given in Table VII.

TABLE VII

Assays from the United Metals Property

Type of sample	percent lead	percent zinc	gold in dollars (35.00 oz.)	silver ozs.
Selected	5.50	-	64.40	20.68
Channel (5')	1.10	0.60	12.40	1.72
Channel (3')	1.20	0.70	5.20	2.72
Selected	2.70	11.40	1.20	1.44
Channel (3')	0.60	2.00	1.60	0.46
Selected	4.20	0.60	14.40	5.21
Channel (1')	-	0.55	3.60	0.82

(Assays taken from assay plan of United Metals Limited)

Metallization in the bytownite-anthophyllite and bytownite-diopside Rocks

These rocks contain pyrrhotite and chalcopyrite, but the latter sulphide is rather rare. Some specimens of bytownite-diopside rocks consist of 15 percent pyrrhotite, but as a rule, pyrrhotite is not abundant. The pyrrhotite is disseminated throughout the rock, and most of it moulds itself around the plagioclase crystals. The bytownite-anthophyllite rocks are not as heavily mineralized as the bytownite-diopside rocks.

GENESIS OF THE METASOMATIC ASSOCIATIONS

The metasomatism caused drastic alteration of the paragneisses and carbonate rocks in the Montauban ore zone. Certain general features are discussed below.

Cordierite-anthophyllite rocks, in many ways similar to those at Montauban-les-Mines, have been described by Eskola (1), Magnusson (2), Geijer (3), and others. The cordierite-anthophyllite rocks at Orijärvi were considered by Eskola to have formed from silicious leptites by a removal of lime, soda, and potash, with addition of magnesia and iron oxides derived from a magmatic source---a process termed "magnesia metasomatism" by Geijer. Most geologists who have studied the occurrences of cordierite-anthophyllite

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(1) Eskola, Pentti - Petrology of the Orijärvi Region. Bull. Comm. Geol. Finlande. No. 40, 1915, pp. 1-277.

(2) Magnusson, N.H. - Persberg malmtrakt. Kongl. Kommerskollegium Beskrivinger över mineralfyndigheter No. 1, Del. 1, 1925.

Iåkettagelser angaende mineralens paragens och succession i Kaveltorp. (English summary). G.F.F. Vol. 52, 1930, pp. 407-416.

(3) Geijer, Per - Falutraken berggrund och malmfyndigheter. S.G.U. Ser. No. 275, No. 1, 1923.

Riddarhytte malmfalt. Edited by the Dept. of Commerce and the Geol. Surv. of Sweden, Stockholm, 1923, p. 122.

rocks in Fennoscandia are convinced that magnesia metasomatism is the most logical explanation for such rocks, but many petrologists in England and the United States object to the theory on the grounds that magnesia is precipitated relatively early as silicates from a magma, and is not, therefore, present in the rest magma from which the emanations extract their dissolved substances.

There are not many descriptions of magnesia metasomatized rocks. Read (1) has shown that xenoliths in the Arnage district have been enriched in lime and magnesia, and that the magma in the vicinity of the inclusions is there poorer in these constituents than elsewhere. Thomas (2) has described an aluminous sedimentary rock which has been modified by "diffusion of lime, ferrous iron, and magnesia from the magma".

Buckland (3) has accounted for the magnesite of the Kilmar deposits by a magnesia metasomatism. He considered

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(1) Read, H.H. - Petrology of the Arnage District. Quart. Jour. Geol. Soc., Vol. 79, 1923, pp. 446-486.

(2) Thomas, H.H. - Xenolithic Tertiary Minor Intrusives in the Isle of Mull. Quart. Jour. Geol. Soc., Vol. 78, 1922, p. 255.

(3) Buckland, Frank - Unpublished Ph.D. Thesis, McGill University, 1937.

an aqueous differentiate from the Morin magma, from which magnesite was derived, was injected into fractured sillimanite gneiss of the Grenville series.

Other occurrences of cordierite-anthophyllite rocks are described elsewhere in the thesis. Without entering into a discussion of these occurrences in this place, their common association with metasomatic sulphides or oxides, and the diverse types of rocks from which they have been derived suggest a common mode of origin, which, in most cases, workers have considered to be magnesia metasomatism.

A thorough discussion of the chemical changes in the paragneisses at Montauban is, unfortunately, impossible, for there are no chemical analyses available of the paragneisses and their metasomatized equivalent. However, the original composition of the paragneisses may be quite accurately inferred from their mineral composition, and the alteration to another aggregate of minerals has involved so great a change in chemical composition that, at least the broader aspects of the alteration can be discussed.

The average analysis of the Grenville sillimanite-garnet paragneisses, No. II, Table VIII, shows a low content of magnesia, as does the calculated composition of the paragneisses, whereas cordierite-anthophyllite rocks have

TABLE VIII

	I	II	III	IV	V	VI
SiO_2	74.5	58.62	48.00	33.58	30.00	52.5
TiO_2	-	1.64	2.06	2.96	0.42	-
Al_2O_3	13.3	17.84	18.62	11.79	21.41	16.8
Fe_2O_3	1.3	4.23	1.07	11.27	7.06	-
FeO	1.5	6.57	16.18	17.50	21.22	11.0
CaO	1.4	0.63	0.64	0.89	-	-
MgO	3.5	3.42	11.85	15.55	11.54	19.0
Na_2O	2.1	0.93	0.23	0.60	0.58	-
K_2O	1.6	4.37	0.01	0.32	0.68	-
H_2O	0.5	1.55	1.50	4.73	6.84	0.7
MnO	-	0.10	0.13	0.21	0.22	-
P_2O_5	-	0.10	0.09	0.36	0.15	-
Fe_7S_8	-	-	0.15		-	-
S	-	-	-		0.56	-
Total	99.7	100.0	100.53	99.76	100.68	100.0

No. I. Average composition of paragneiss (leptite) at Montauban. Calc. from Rosiwal analyses. Aver. of Nos.1-4, Table II.

No. II. Average of 7 sillimanite-garnet gneisses of the Grenville Series. (M.E. Wilson, Journ. Geol. Vol. 33, No. 4, 1925, p. 393, Table 2, Nos. 1-7.

No. III. Cordierite-anthophyllite rock, Träskböle. P. Eskola. Petrology of the Orijärvi Region, Bull. Comm. Geol. Finland, 1915. (Cordierite - 46.55%, anthophyllite - 47.62%, ilmenite - 3.27%, quartz 1.40%)

No. IV. Anthophyllite-cordierite-(chlinochlore)-spinel-diaspore hornfels. Inner Quarry. Kenidjack, C.E.Tilley & J.S. Flett, Summ. Prog. Geol. Surv. Gt. Brit. pt. 2, 1930, p.33.

No. V. Dalmatianite (cordierite anthophyllite rock). Amulet Mines, P.Q. T.L. Walker, Univ. Toronto Studies, Geol. Ser. No. 29, 1930.

No. VI. Calculated composition of a rock composed of equal weights of cordierite and anthophyllite, using a ratio of Mg:Fe::7:2 in cordierite and Mg:Fe:3:1 in anthophyllite.

a relatively high content of magnesia. It is evident, therefore, that for the Montauban paragneisses to give rise to cordierite-anthophyllite rocks, they must be enriched in magnesia.

The changes in the proportions of other oxides are not as clearly shown by the analyses. The Baltic occurrences of metasomatized leptite characterized by cordierite and anthophyllite show that considerable iron, as well as magnesia, was added by solutions. At Montauban, however, the available chemical data are not adequate to show that iron was added, and when it is remembered that the anthophyllite has only a little of the ferroanthophyllite molecule, it is possible, though improbable, that sufficient iron was available for its formation in the paragneisses. The role played by iron can be settled only by a chemical investigation. As there is no evidence for deformation in the zone of metasomatism, such as might be expected from an increase in volume, the amount of material added to the paragneisses by solutions must have been compensated by the removal of equal proportions of other material. Potassia is somewhat lower, and silica much lower, in the cordierite-anthophyllite rocks than it is in the paragneisses, so that in all probability these two constituents were abstracted.

However, some, or all, of the potassia may have gone to form the mica associated with the cordierite and anthophyllite.

Source of Magnesia Solutions

Magnesia metasomatism offers some vexed but interesting problems. Sundius (1) has strongly critized the theory of magnesia metasomatism, holding that it has not been well substantiated. As an alternative explanation, he considers cordierite-anthophyllite rocks to be the product of magmatic consolidation, but Lindgren (2) in a review of the several papers written by Sundius and the chief advocates of magnesia metasomatism, states that it is difficult to accept the views of Sundius, and that the discussion suffers from lack of clearly-defined premises. The theory of Sundius may be safely disregarded as a possible explanation of the cordierite-anthophyllite rocks at Montauban, for the evidence is conclusive that these rocks have formed by replacement of paragneisses.

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(1) Sundius, N - Discussion of Paper by P. Geiger on Magnagaserna Sasom formedlare av regional metasomatisk omvandlung". G.F.F. Vol. 56(4), 1934, pp. 658-661.

(2) Lindgren, W. - Abstract of Paper by Sundius. Ann. Bibl. Econ. Geol., Vol. VIII (2), No. 199, 1935.

Tilley and Flett (1) considered cordierite-anthophyllite and related rocks, at Kenidjack, Cornwall, to have formed by contact metamorphism of weathered greenstones. They suggested that during weathering, lime and soda were removed and the residual rock was consequently enriched in magnesia. After a more extensive petrological and chemical investigation of the problem (Tilley (2) revised his previous explanation and concluded that basic igneous rocks of the composition of those at Kenidjack would not yield by weathering, a residual rock high in magnesia, and that hot solutions, emanating from a granitic source, passing through the greenstones removed lime and gave rise to anthophyllite and related types of hornfels. Chemical analyses showed that although most of the varieties of hornfels at Kenidjack were impoverished in magnesia, one type - a cordierite-anthophyllite-spinel-diaspore hornfels - was enriched in this constituent; he assumes, therefore, that magnesia was not introduced by the solutions, but that there was an "internal magnesia metasomatism".

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(1) Tilley, C.E. & Flett, J.S. - Hornfels from Kenidjack, Cornwall. Prog. Geol. Surv. Gt. Britain. Pt. 2, 1930 for 1929, pp. 24-41.

(2) Tilley, C.E. - Metasomatism Associated with the Greenstone-hornfelses at Kenidjack, Cornwall. Min. Mag., Vol. 24, 1935, pp. 181-202.

Although Tilley's theory fulfils the necessary conditions for the formation of the cordierite-anthophyllite rocks at Kenidjack, it cannot be applied to the similar rocks at Montauban, because there has been an extensive introduction of magnesia, which could not have been derived from rocks with a composition of the paragneisses in the area.

The Montauban occurrence of cordierite-anthophyllite rocks is the only one of its kind known in the Grenville sub-province in Canada, but certain features of it, particularly indications of magnesia metasomatism, are found in areas which are closely connected with the Morin series of igneous rocks. Deposits of magnesite and brucite, with serpentinized quartzites and sillimanite gneisses (as at Kilmar), the occurrence of amphibolitized limestones on a regional scale, and the so-called "metamorphic pyroxenites" and related rocks, which are metasomatized para-rocks or contaminated granitic pegmatites, all strongly suggest that magnesia has been added to other rocks by solutions from an igneous source. Most of the examples cited above occur in the vicinity of differentiates of the Morin series, and the conclusion may be drawn that the magnesia-rich solutions have been derived from the magma giving rise to the differentiates.

Igneous rocks belonging to the Morin series are not exposed in the immediate vicinity of the Montauban ore zone, but a large batholith of the series occurs about 10 miles to the east, and apophyses of the same series cut gneisses between the batholith and the ore zone. In view of the relative proximity of Morin rocks to the Montauban ore zone, and because of the common occurrence of magnesia-metasomatized rocks in the vicinity of differentiates of the Morin series, it is believed that there is a cupola belonging to the Morin stem at no great depth below the surface at Montauban, and the ore-bearing, magnesia-rich solutions were derived from this source.

Because of the refractoriness of anhydrous magnesia silicates, it is a difficult matter to explain the differentiation of a magma so that it will give rise to magnesia-rich solutions. Osborne (1) has suggested in the case of the Kilmar magnesite deposits that if sillimanite gneiss were incorporated into a differentiate of the Morin series at such a late stage in its differentiation that quartz had started to crystallize, the anorthite molecule, derived from the incorporated alumina, would stabilize lime and magnesia would perhaps be left in the rest solution.

Osborne, F.F. - Unpublished Report of the Quebec Bureau of Mines.

H. von Eckermann (1) outlined in a recent paper a course of differentiation of a gabbro magma to give anorthosite, pegmatites, porphyritic gabbro, and related rocks such as occur at Nordin Grå, Sweden. He concludes that anorthositic magma formed from a gabbro magma by rising of plagioclase crystals, with an enrichment of the rest-magma in ferromagnesian silicates. The differentiation ceased, however, because of changes in temperature, pressure, and viscosity, and volatiles concentrated beneath a cover of anorthosite, where temperature and pressure were lowest. Plagioclase in turn crystallized, and magnesia-iron silicates remained in the salic pegmatitic rest-differentiate. von Eckerman draws special attention to the rest-differentiate, pointing out that if the hydrous magnesia silicate liquid were squeezed out of the plagioclase mesh, it would be of appropriate composition to cause magnesia metasomatism.

The postulated differentiation at Nordin Grå is particularly interesting, because the Morin rocks are somewhat similar to them mineralogically and chemically

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(1) von Eckermann, Harry - The Anorthosite and Kenningite of the Nordingrå-Rödö Region. G.F.F. Stockholm, No. 4B, Vol. 60, 1938, pp. 262-269.

(gabbro, anorthosite, granite, etc.), and it may be that the magnesia rich solutions have been derived from the parent magma of the Morin series of rocks which has undergone a differentiation similar to that outlined by von Eckermann.

Eskola (1) points out that there is no evidence indicating the form in which magnesia travelled in the solutions. Fugitive constituents, such as boron, chlorine, and fluorine, are commonly considered to have been extremely active agents in replacement deposits, but in the case of magnesia metasomatism there is no indication that fugitive materials played any part. Eskola in his first papers on Orijarvi accepted magnesia metasomatism as a logical explanation of the cordierite-anthophyllite rocks, but later revised his opinion (2), and considered the rocks to be the result of "enrichment in the stablest minerals". In making this change he was doubtless influenced by the difficulties in, and theoretical objection to, the simple

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(1) Eskola, Pentti - Conditions During the Earliest Geological Times. Annales Acadamiae Scientiarum Fennicae, Series A, Vol. 36, No. 4, 1924, p. 62.

(2) Eskola, Pentti - On the Principles of Metamorphic Differentiation. Bull. Comm. Geol. Finlande, No. 5, 1932, pp. 74, 75.

hypothesis of magnesia metasomatism. He states:

"I have therefore brought in question whether the transfer of magnesia into the leptitic rocks could not be accounted for by applying the principle of enrichment in the least soluble constituents, besides a metasomatism caused by an addition of silica, sulphides, and volatiles. The large amounts of solutions soaking into the leptites would, of course, also carry some amounts of magnesia, which, due to the poor solubility of magnesium metasilicate could replace the alkalies and lime of the feldspar and crystallize as anthophyllite and cordierite, while the iron content of the solutions was mainly deposited by the sulphides. This explanation seems to offer the most probable solution of the problem of magnesia metasomatism".

Eskola says that the stablest minerals would be formed, but it is apparent that, as a rule, unstable minerals would not develop, and his statement contributes little to the discussion. Eskola believes that perhaps some of the magnesia was abstracted from neighboring rocks by solutions, and migrated to the zone of magnesia metasomatism, but it is more difficult to find rocks in the Montauban area which would yield sufficient magnesia than it is to postulate the addition of magnesia from a magmatic source.

Role of Temperature, Pressure and Concentration

The continuity of exposures of cordierite and anthophyllite for at least 5,000 feet along the ore zone, and the uniformity of structure of the surrounding paragneisses, indicate the probability that temperature and pressure were fairly uniform throughout the zone, otherwise cordierite and anthophyllite would not be so widely developed in the paragneisses. In accounting for the changes in the mineralogical composition of the metasomatized rocks in the vicinity of the carbonate rock on the Tétreault property, the remaining variable - the concentration of the solutions - must have been the determining factor. Because the cordierite-anthophyllite rocks occur in paragneisses underneath and around the diopside-tremolite zone, from which it is separated by a zone of bytownite-anorthite and bytownite-diopside rocks, and extends for considerable distances to the north, the composition of the solutions when they entered the paragneisses must have been uniform, but, on entering the lime-rich carbonate rocks their concentration and composition were changed by the reaction with the wall-rocks, and minerals rich in lime, such as diopside and tremolite, were formed.

Effect of Solutions on the Migmatites

The solutions had no effect on the migmatites where they were some distance removed from the paragneisses, and were slightly altered only in places near the shell of paragneisses surrounding the carbonate zone. It is a perplexing problem why the migmatites more or less escaped alteration, and the paragneisses, which do not greatly differ from them in mineralogy, were drastically altered. It is possible that because of the regional metasomatism which preceeded the magnesia metasomatism, the pore spaces im the migmatites were filled with the solutions from the regional metasomatism, and were thus able to escape metasomatism. It is also possible, that the paragneisses which were granitized were able to escape the magnesia metasomatism because they had the physical characteristics of orthogneisses.

The core from a bore-hole drilled underneath the syncline of paragneisses shows that a shear zone extends downward through the migmatites. Cordierite, anthophyllite, and mica are developed in this zone, and it appears logical to assume that the shear zone acted as a channel for the solutions, which, rising from below, had no marked effect on the surrounding rocks until they reached the paragneisses, where metasomatism became active.

Effect of Solutions on the Amphibolites

The amphibolites, like the migmatites, were little affected by the magnesia-rich emanations. In the Tétreault Mine the amphibolites feather out or end bluntly against the ore zone. In places the margins of the amphibolites are altered to biotite, and in other places the amphibolites have a garnetiferous margin. The garnetiferous margin, however, is found in amphibolites in the carbonate rocks, as well as in amphibolites in the cordierite-anthophyllite rocks, so there is considerable doubt if the magnesia solutions were the cause of these garnet selvages. If garnet selvages developed in the cordierite-anthophyllite rocks because of the magnesia solutions, then selvages similar in mineralogy would not be expected in amphibolites in the carbonate rocks, where the composition of the solutions was much different.

The marginal garnetiferous zones in the amphibolites probably antedated the metasomatism of the paragneisses, and are perhaps the altered, marginal phase of the intrusives which gave rise to the amphibolites. The marginal phase did not form along intrusives in the migmatites, but were developed along intrusives which penetrated the paragneisses and carbonate rocks. The intrusives are probably related to the Morin magma.

The garnetiferous marginal zones of the amphibolites show no deformation such as might be expected from volume changes. Although garnets are abundant in the selvages, and the plagioclase in the selvages is about An_{30}, whereas the plagioclase of the main body of amphibolite is from An_{45}-$_{55}$, the chemical compositions of the amphibolite and its garnetiferous margin, calculated from Rosiwal analyses, are very similar. Iron and magnesia are a little higher, and lime is lower in the selvages than in the normal amphibolite, but lacking precise data as to the composition of the garnets, the results of the comparison of the analyses are questionable. However, some magnesia has probably been added to the amphibolites, for veinlets of breunnerite, and one or two small crystals of dravite in the selvages suggest that magnesia solutions had access to parts of the amphibolite.

Amphibolites in other areas of cordierite-anthophyllite rocks were also resistant to alteration by magnesia solutions. Eskola[(1)] has described amphibolites in the Orijärvi region which have been altered along their margins to cummingtonite-amphibolite, but he states that they were more resistant to metasomatism than the surrounding rocks. The physical character of the amphibolites no doubt plays an important part in their resistance to metasomatism.

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(1) Eskola, P. - Petrology of the Orijarvi Region. Bull. Comm. Geol. Finlande, Vol. 40, 1915, P. 262.

Effect of Solutions on the Paragneisses

The paragneisses are characterized by a high content of silica and alumina, and minor quantities of lime and magnesia. The average analysis of seven paragneisses from the Grenville series show that these rocks have more potash than soda, and the mineralogical composition of the paragneisses at Montauban suggests that soda is in excess of potash. Although all the paragneisses have probably been derived from argillaceous sediments, it is difficult to explain why the paragneisses at Montauban have soda in excess of potash.

The first effects of the magnesia-rich solutions on entering the paragneisses was to combine with the alumina and silica of sillimanite to give cordierite.

$$4Al_2SiO_5 + 4MgO + 6SiO_2 \rightarrow 4MgO.4Al_2O_3.10SiO_2$$

Sillimanite, normally fairly abundant in the paragneisses, occurs only along the margins of the metasomatic zone, where alteration was not intense, or as armoured relics. Anthophyllite is never present in thin sections containing cordierite and sillimanite, and Eskola (1) and Tilley (2)

Eskola, P. - Petrology of the Orijärvi Region. Bull. Comm. Geol. Finlande, Vol. 40, 1915, p. 180.

(2) Tilley, C.E. - Granulites of the Lizard. Geo. Mag., Vol. 74, 1937, p. 308.

believe that anthophyllite is antipathetic to sillimanite. Tilley states that staurolite is the "phase bridge" separating the two minerals (anthophyllite + sillimanite $\longrightarrow$ staurolite + cordierite) but this relationship does not apply to the cordierite-anthophyllite rocks at Montauban, because available data indicate that staurolite antedated cordierite, and was replaced by the latter mineral.

The replacement of staurolite by cordierite probably took place contemporaneously with the replacement of sillimanite by cordierite, but staurolite was somewhat more resistant to replacement than sillimanite.

$$2FeO.5Al_2O_3.4SiO_2 + 3MgO + 6SiO_2 \longrightarrow MgO.Al_2O_3 + 4(MgFe)O.4Al_2O_3.10SiO_2.$$

It is doubtful if all the spinel in the cordierite-staurolite-spinel zone was formed by replacement of staurolite by cordierite, but the common association of spinel with staurolite partly replaced by cordierite is strongly suggestive of this relationship. Spinel could also have formed from sillimanite, as shown by the following equation:-

$$Al_2SiO_5 + MgO \longrightarrow MgO.Al_2O_3 + SiO_2$$

However, the large amount of silica available in the paragneisses would probably cause the reaction to proceed as shown below.

$$4(MgO.Al_2O_3) + 10SiO_2 \rightarrow 4MgO.4Al_2O_3.10SiO_2.$$

Spinel is rare in the metasomatized rocks, and was probably an unstable mineral. The question of its formation can only be settled by a more detailed petrographic investigation. It may be pointed out that spinel is a common constituent mineral in cordierite-anthophyllite rocks from other areas, where it is apparently a stable mineral, so that there is considerable question whether spinel was an unstable mineral at Montauban. Petrographic evidence is strongly suggestive that corundum was unstable, since it occurs only as armoured relics. Corundum was probably altered to cordierite by combining with magnesia and quartz:-

$$4Al_2O_3 + 4MgO + 10SiO_2 \rightarrow 4MgO.4Al_2O_3.10SiO_2$$

The course of replacement of plagioclase, quartz, and garnet is not clearly shown in thin sections, but the development massive cordierite and anthophyllite attest to the efficacy of magnesia metasomatism in replacing these minerals. Inclusions of quartz and plagioclase with a common orientation in cordierite show that the former two minerals have been replaced. The conversion of plagioclase to cordierite can be expressed by the following reactions:-

$$4NaAlSi_3O_8 + 2MgO \rightarrow Mg_2Al_4Si_5O_{18} + 7SiO_2 + 2Na_2O$$

$$2CaAl_2Si_2O_8 + 2MgO + SiO_2 \rightarrow Mg_2Al_4Si_5O_{18} + 2CaO$$

Thus, the plagioclase can be converted to cordierite by the addition of magnesia and silica; the formation of anthophyllite necessitates the addition of more magnesia and ferrous iron.

The garnet and biotite of the paragneisses were converted to cordierite by the addition of alumina and silica, as shown by the following reactions:-

$$(MgFe)_3Al_2(SiO_4)_3 + Al_2O_3 + 3SiO_2 \rightarrow (MgFe)_2Al_4Si_5O_{18} + MgFeSiO_3$$

$$K_2(MgFe)_2Al_2(SiO_4)_3 + Al_2O_3 + 2SiO_2 \rightarrow (MgFe)_2Al_4Si_5O_{18} + K_2O$$

There is considerable question as to the source of the alumina. The reactions given above indicate that alumina played an important part in the metasomatism; in addition, the massive cordierite, which theoretically contains 33.6% alumina, indicates that alumina has moved appreciable distances. A paragneiss with a chemical composition suitable for the formation of massive cordierite must be much richer in sillimanite than the normal paragneisses in the area. The nodular sillimanite gneiss, which in places has about 60% sillimanite, would probably contain enough alumina for the formation of massive cordierite, but available data indicate that massive cordierite was developed in the paragneisses, and not in the nodular sillimanite gneiss. Alumina must therefore, have moved appreciable distances, but its source is open to question. There is not sufficient evidence to definitely state that the alumina was derived from the same source as the magnesia solutions, so that, in all probability, alumina migrated from the surrounding rocks, and has taken part in what Tilley characterizes as an "internal metasomatism". The problem concerning alumina can only be settled by chemical analyses of samples taken from one bed and from the metasomatic rock derived from that bed.

The replacement of biotite by cordierite offers a possible explanation for variations of optical properties in cordierite. Mineralogists who have attempted to correlate the optical properties with the composition of cordierite, are agreed that variations in optical properties are probably due to differences in the amount of iron in the cordierite. Since massive cordierite is apparently made up of numerous small crystals, and small amounts of the magnesia of cordierite can be replaced by ferrous iron, it is possible that the iron of replaced biotite (or staurolite) is not evenly distributed through the surrounding cordierite. Thus, cordierite which has replaced biotite, or staurolite, is richer in iron, and hence has different optical properties than that which replaced iron-free minerals such as plagioclase and quartz.

Anthophyllite is apparently later than cordierite;

this relationship is uncertain, however, because the crystallizing force of cordierite is so much lower than that of anthophyllite that the relative ages of the two minerals cannot be definitely determined. It must be recalled, however, that the Montauban occurrence is not an isolated example of the association of anthophyllite with cordierite, and it is possible that the two minerals were stable under the same equilibrium conditions. The anthophyllite of cordierite-anthophyllite rocks in Fennoscandia contains a considerable amount of the ferroanthophyllite molecule, and investigators of the Fennoscandia occurrences have shown that iron oxides were introduced by the magnesia solutions. At Montauban, however, the low content of the ferroanthophyllite molecule in the anthophyllite suggests that iron oxides were not abundant, and it is questionable if the iron of cordierite and anthophyllite was obtained from the paragneisses, or introduced into them by the magnesia emanations.

In summary, the effects of the solutions on the paragneisses were to replace the constituent minerals of the paragneisses by cordierite and anthophyllite, by addition of magnesia, and perhaps iron.

Effect of Solutions on the Carbonate Rocks

At the Tétreault Mine the course of metasomatism was away from the carbonate rocks like that to the north, viz. cordierite, anthophyllite, and mica developed in the paragneisses surrounding the carbonate rocks and in the sheared zone in the migmatites along which the solutions advanced. As the solutions advanced upwards, however, they encountered carbonate rocks, which contained considerable quantities of magnesia. The source of the magnesia in the recrystallized carbonate rocks is open to question. Chemical analyses show that as a rule the carbonate rocks of the Grenville series have a relatively low content of magnesia, so in all probability the fireite at Montauban had magnesia introduced into it, either by solutions connected with the cordierite-anthophyllite metasomatism, or by solutions of an earlier metasomatism.

The first effect of the magnesia of the solutions on the carbonate rock was to combine with silica, either brought in by the solutions or present in the fireite impurity, and with lime, giving rise to diopside.

$$MgO + CaO + 2SiO_2 \longrightarrow CaMg(SiO_3)_2$$

Complete diopsidization of the carbonate band was stopped by the exhaustion of available silica, and masses of fireite have probably thus been preserved. Solutions enriched in lime, however, permeated the silicious paragneisses around the fireite and much diopside was formed in the paragneisses.

The solutions also probably introduced magnesia into the carbonate rocks, and the magnesia combined with silica and lime to give the tremolite in the fireite. Much of the tremolite, however, was formed in the surrounding and overlying paragneisses which had been partly diopsidized and where much silica was available. Some of the diopside in the paragneisses was replaced by tremolite,

$$CaMg(SiO_3)_2 + 2MgO + 2SiO_2 \rightarrow CaMg_3(SiO_4)_3$$

but much of the tremolite in the tremolitized paragneisses overlying the carbonate rocks was formed independently of diopside.

A small amount of diopside and tremolite was found on the dumps at the St. Laurence and Shawinigan shafts. The presence of these minerals in the cordierite-anthophyllite rocks indicates that diopside and tremolite were stable in the zone of cordierite and anthophyllite, but the lack of lime prevented their abundant formation. Some of the available lime combined with alumina to form bytownite, and the very small excess of lime probably accounts for the small amount of diopside and tremolite.

The cordierite-anthophyllite and the diopside-tremolite rocks are separated from one another by a zone that can be sub-divided into several transitional mineral associations. The zone may be considered to be characterized by bytownite, anthophyllite, and diopside. This zone lies near the margins of the diopside-tremolite zone in the paragneisses and the constituent minerals show it has a fairly high content of lime. The origin of the bytownite-anthophyllite rocks is difficult to explain, unless it is assumed that lime was available in the paragneisses surrounding the carbonate rocks. If this was the case, then the first effects of the solutions on entering these rocks was to combine with all available lime, and convert plagioclase from An_{30} to An_{70-76}. The plagioclase was stable under the equilibria conditions, and was not replaced by cordierite. Anthophyllite, however, was stable.

The bytownite-anthophyllite rocks surrounded by the cordierite-anthophyllite rocks near the southern boundary of the United Metals property can be explained by assuming lime to be locally available. Sufficient lime was present to convert the plagioclase to An_{70-76}, but there was not sufficient quantities of lime to form tremolite, and instead, anthophyllite formed. In the rocks of this occurrence, one thin section contained two or three grains of wollastonite. Wollastonite was not normally stable in the metasomatic zones, but was altered to anthophyllite by the solutions, and the lime was taken up by plagioclase. The wollastonite does not occur near anthophyllite, and is surrounded by bytownite.

An alternative explanation for the bytownite-anthophyllite rocks is that the necessary lime for the formation of such rocks was introduced by solutions which had entered the carbonate rocks and become enriched in lime, and because the calcic plagioclase rocks occur underneath, and along the sides of the carbonate rocks, the solutions must have migrated laterally, as well as downward. The surrounding paragneisses had previously been altered to cordierite-anthophyllite rocks, and the lime-rich solutions converted all plagioclase which had escaped the effects of the previous solutions to An_{70-76}, and, cordierite, which is apparently antipathetic to lime feldspar, is proxied for by anorthite and anthophyllite.

$$(MgFe)_2Al_4Si_5O_{18} + 2CaO + SiO_2 \rightarrow 2CaAl_2Si_2O_8 + 2(MgFe)SiO_3$$

The bytownite-anthophyllite rocks on the United Metals property are not easily explained by such a theory. This zone is so far away from the carbonate rocks in the Tétreault Mine that the introduction of lime from this source is highly improbable. It is possible, however, that lime was obtained from an intercalated lime-rich bed lying at a lower elevation, or from lime-rich rocks at a slightly higher elevation. There are lime-rich rocks in the vicinity: tremolite, surrounded by migmatites, is exposed 300 feet to the southwest.

It can be seen from the genesis of the diopsidic and tremolitic skarns outlined above that the amount of available silica has played an important role in the formation of the lime-rich gangue minerals, and it is noteworthy that silica is not so abundant as a late stage mineral in the carbonate zone as it is in the tremolitized paragneisses, where tension cracks are filled with quartz, carbonate and actinolite.

There is no definite evidence that, except for magnesia, and perhaps iron, the solutions added any oxides to the paragneisses or carbonate rocks. However, the rocks consisting of anorthite (An_{97}) and sphene call for particular comment. The only known exposure of these rocks on the surface is near the margin of the tremolitized paragneisses, which it appears to have replaced, but the rather large amount of wilsonite (accompanied by sphene) around the margins of the diopside-tremolite zone suggests that it was once more abundant than it is now. Anorthite contains a high quantity of alumina (36%). There is no evidence from a study of the other gangue minerals in the carbonate rocks that alumina was introduced into the zone of metasomatism by solutions. On the other hand, the paragneisses are rich in alumina, and it is probable that alumina was concentrated when the paragneisses were replaced by tremolite, and the alumina combined with lime and silica to give anorthite, which replaced the tremolite.

$$CaO + Al_2O_3 + 2SiO_2 \rightarrow CaO.Al_2O_3.2SiO_2$$

The modus operandi suggested necessitates the transfer of alumina, but since the most probable explanation for massive cordierite also involves transfer of alumina, alumina migration seems quite possible. The alumina of the intensely replaced paragneisses must have been removed, for it does not enter into the composition of tremolite, and it is as logical to suggest that the alumina, combining with lime and silica to form anorthite, was carried higher and laterally and deposited there.

The lime necessary for the formation of the anorthite rock on the surface was probably obtained from thin bands of carbonate rocks in the vicinity, as there is an exposure of fireite not far away. However, anorthite rocks in the lower part of the mine, particularly those underlying the carbonate rocks, suggest that there was a downward transfer of lime, and supports the contention, in the case of the origin of the bytownite-anthophyllite rocks, that the downward migration of lime was an active, and important, feature in the formation of the calcic feldspars.

It is difficult to explain the rocks characterized by garnet and hedenbergite, mainly because there is no definite information on their relation to the other metasomatic rocks. However, the garnet-hedenbergite rocks probably are between the diopside-tremolite rocks and the bytownite-anthophyllite rocks where concentrations were such that the garnet and hedenbergite, instead of bytownite and anthophyllite, were stable.

plagioclase + hornblende $\longrightarrow$ pyroxene and garnet

$$CaAl_2Si_2O_8 + 4MgSiO_3 \rightarrow CaMg(SiO_3)_2 + Mg_3Al_2(SiO_4)_3 + SiO_2$$

Application of ACF Diagrams To The Metasomatic Mineral Associations

It has been shown that the availibility of lime, magnesia, alumina, and silica has been largely instrumental in determining the type of mineral association formed. The ternary faces of the tetrahedron representing the quaternary system, CaO, MgO, Al_2O_3, SiO_2, have been investigated, but it is doubtful if the results are applicable to the metasomatic rocks at Montauban, because the data do not take into account iron or water.

Quaternary systems are difficult to represent graphically, but Eskola (1) has applied a relatively simple graphical method to the cordierite-anthophyllite, and related rocks of the Orijärvi region. The graphical representation is based on the concept of mineral facies, viz., that "in any rock of a metamorphic formation which has arrived at a chemical equilibrium through metamorphism at constant temperature and pressure conditions, the mineral composition is controlled only by the chemical composition". Eskola graphically represents the various mineral groupings on triangular diagrams, known as ACF, and AKF diagrams. The ACF diagram has A = Al_2O_3 - (Na_2O + K_2O), C = CaO, and F = Mg, Mn, FeO, and in the AKF diagram A = Al_2O_3- (K_2O + Na_2O + CaO), K = K_2O, and F = Mg, Fe, MnO.

The metasomatic rocks at Montauban have either excess alumina (cordierite-anthophyllite, cordierite-staurolite-spinel, cordierite-corundum) or excess lime (diopside-tremolite, bytownite-anthophyllite, bytownite diopside) and may be graphically represented on the ACF projection. The effect of variations of the chemical composition on the mineralogical composition is represented by the ACF diagram (Plate I).

The compositions of migmatites and paragneisses are graphically represented on AKF projections (Plate I).

Effect of the Gangue Minerals on the Mineralizing Solutions

The diopside of the diopside-tremolite zone and the cordierite of the cordierite-anthophyllite zone were probably formed nearly contemporaneously, their formation depending solely on the composition of the wall-rocks. Tremolite was formed later than diopside, and was possibly formed at the same time as anthophyllite, although data on their time relationship are not conclusive. Following the formation of the gangue minerals, tension cracks and fractures, which are particularly noticeable in the tremolitized paragneisses at and near the surface, were formed. Finally, solutions carrying zinc, lead, copper, iron, sulphur, and other elements advanced into the metasomatic rocks, and sulphide minerals were deposited in fractures and other open spaces in the gangue minerals, and a dissemination of the sulphides was produced in the diopsidized and tremolitized paragneisses.

The carbonate rocks in the diopside-tremolite zone were more favourable loci for the precipitation of sphalerite and galena than were the cordierite-anthophyllite rocks, which tended to precipitate larger quantities of copper than the lime-rich rocks. Pyrrhotite was formed in the bytownite-anthophyllite and bytownite-diopside rocks.

The solutions which introduced the sulphide minerals also brought in coarsely crystalline calcite, quartz, and actinolite, that filled some of the tension cracks. In addition, the quartz veins on the United Metals and Shawinigan properties were formed by these solutions. Other effects of the mineralizing solutions were to alter some of the calcic-placioclase to wilsonite, and to form small quantities of antigorite, chlorite (Leuchtenbergite), apatite, and other younger minerals. Hisingerite in other localities is known to occur at the end stage of mineralization, and, together with barite, was probably formed from the excess of sulphur in the mineralizing solutions, which was oxidized to sulphate by carbon dioxide. It was also probably the mineralizing solutions which formed brucite and scapolite, and deposited breunnerite in the metasomatic rocks.

OTHER OCCURRENCES OF CORDIERITE-ANTHOPHYLLITE ROCKS

Although cordierite occurs in contaminated igneous rocks, in contact metamorphosed clay rocks, and in crystalline schists that have been subjected to deficient shearing stresses during regional metamorphism, the occurrence of cordierite, with or without anthophyllite, in metasomatized rocks is relatively rare. Examination of the literature shows that occurrences of cordierite-anthophyllite metasomatic rocks have some significant features in common, and that the investigators of many of the occurrences believe that magnesia metasomatism was responsible for the formation of cordierite and anthophyllite.

The greater number of, and the most intensively studied occurrences are in the Archean rocks of Finland, Sweden, and Norway. Of these occurrences, one of the best known is that at Orijärvi, which has been described by Eskola (1). The cordierite-anthophyllite rocks are developed in silicious leptites which are very similar to the Grenville paragneisses at Montauban-les-Mines. The cordierite-antho-

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(1) Eskola, Pentti - Petrology of the Orijärvi Region. Bull. Comm. Geol. Finlande. No. 40, 1915, pp. 1-277

phyllite rocks of Orijärvi are so much like those at Montauban that whole passages of Eskola's descriptions might be applied almost verbatim to the similar rocks at Montauban. The similarities of the two occurrences do not stop at this point, for, as at Montauban, although the cordierite-anthophyllite rocks contain chalcopyrite, sphalerite, pyrrhotite, pyrite and galena, bodies of ore are confined to skarn, which has been derived from limestones and dolomites intercalated in the leptites.

The Orijärvi Mine has yielded about 4,000 tons of copper; lead and zinc were not recovered, but Trüstedt (1) has estimated that about 1,500 tons of zinc and 450 tons of lead can be recovered from the dumps.

Magnetite commonly accompanies the sulphide minerals, and in places in the Orijärvi region this mineral is so abundant that it has been mined.

Eskola believes that the leptites have been altered to cordierite-anthophyllite and related rocks by pneumatolytic agencies, which introduced magnesia and iron into the leptites; concurrently lime, soda, and potash were removed.

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(1) Trüstedt, O. - cited by Eskola, p. 234.

Most of the Baltic occurrences of cordierite-anthophyllite rocks are, in general, like that at Orijärvi. The significant features are that these rocks occur in leptites, they are mineralized with chalcopyrite, sphalerite, galena, pyrrhotite, pyrite, and magnetite, and bodies of ore are, as a rule, associated with skarn rather than with the cordierite-anthophyllite rocks. Because of the significant features these occurrences of cordierite-anthophyllite rocks have in common, they are regarded by the writer as belonging to a definite type, - the Orijärvi type.

A few of the better known occurrences of cordierite-anthophyllite rocks of the Orijärvi type are described in the following paragraphs, and references to others are given below.

At the Kaveltorp Mine in Sweden, Magnusson (1), has outlined the paragenetic sequence of the various skarns, and their relationships to the sulphide minerals, as follows:-

"Olivine and clinohumite first developed in the dolomite, and was later followed by diopside and still later by actinolite. This series of replacements was confined to

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(1) Magnusson, N.H. - Iakttagelser ångaende mineralens paragens och succession i Kaveltorp. (English summary). G.F.F. Vol. 52, 1930, pp. 407-416.

the dolomitic bodies, but after the formation of the actinolitic skarn the intensity of the metamorphism increased, and the surrounding leptites developed in them cordierite, gedrite, almandine, hornblende, and biotite. At the same time the central parts of the dolomite were altered to a light coloured skarn high in magnesia (tremolite, anthophyllite, cummingtonite, and talc) and a hornblende-biotite-chlorite skarn developed at the margins of the dolomitic bodies. Pyrite, chalcopyrite, cubanite, and pyrrhotite are associated with the hornblende-biotite-chlorite skarns and sphalerite and galena formed in the magnesia-rich skarns. The types of skarn have moved, one behind the other, and older skarns have, in part, been consumed by later varieties".

Magnusson believes the alumina and alkalis required for the hornblende-biotite-chlorite skarn were from the leptite, but that the other skarns were formed as the result of a large-scale addition of silica, magnesia, fluorine, and metallic elements.

References to occurrences of cordierite-anthophyllite rocks not described in this thesis are as follows:-

Brogger, W.C. - Vid.-Selsk. Skrifter. 1. Math. Naturv. Kl. 1934, No. 1, p. 225.

Stelzner-Bergeat - Die Erzlagerstätten, II, 1905-06, pp. 966-967.

Pehrman, Gunnar - Uber eine Sulfid lagerstätte auf der insel Attu im Sudwestlichen Finnland. Acta Acad. Abo. Math. & Phys. Vol. VI, 6, 1931.

Beck, R. - Ueber der Gesteine der Zinkblendelagerstätte bei Rafvala im Schweden. T.M.P.M. Vol. 20, 1901, p. 382.

Tilley, C.E. - Granulites of the Lizard. Geol. Mag., Vol. 74, 1937, pp. 300-309.

Magnusson, N.H. - Langbans malmtrakt. S.G.U. Ser. Ca, No. 23, 1930.

In the Falun district in Sweden (1, 2) leptites are intruded by great bodies of granitic rocks, and in places have been altered by magnesian-bearing emanations derived from the granite to give cordierite-anthophyllite "quartzite". The "ores" associated with the cordierite-anthophyllite rocks are classed as "hard ores" and "soft ores"; the former is rich enough in copper to be a copper ore. The "soft ores" are pyrite bodies with some chalcopyrite, sphalerite, and galena, and show the relations typical of replacement deposits in limestone. At Falun, most of the production of copper has come from ore bodies associated with the cordierite-anthophyllite rocks.

Many of the occurrences of cordierite-anthophyllite rocks in the Baltic shield are characterized by the presence of magnetite, which, usually accompanied by pyrrhotite, in some areas has yielded considerable iron ore. At Riddarhyttan, Sweden, cordierite-anthophyllite rocks developed in leptites, are closely related to sulphide-magnetite deposits. At

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(1) Torneböhm, A.E. - Om Falu grufvas geolig. G.F.F. Vol. 15, 1893, p. 609.

(2) Geijer, Per - Falutraken bergrund och malmfybdigheter. S.G.U. Ser. No. 275, No. 1, 1923.

Geijer, Per - Riddarhytte malmfalt. Ed. Dept. Comm. and the Geo. Surv. Sweden. Stockholm, 1923.

Filipstad, Sweden (1), most of the iron ore accompanies a garnet-pyroxene-amphibole skarn derived from carbonate rocks, and the surrounding leptites are altered to cordierite-anthophyllite rocks. Similar relations hold in the neighboring Nordmark district (2), where the iron ores (magnetite) occur in skarn, and the surrounding leptites are altered to cordierite-anthophyllite rocks. Johansson (3) has described a similar association of cordierite and anthophyllite with sulphide minerals in the ores of the Grangesberg Iron Ore fields.

In the United States, cordierite-anthophyllite rocks are rare. At Blue Hill, Maine (4), cordierite and anthophyllite are found in the Ellsworth schists, and are accompanied by chalcopyrite, pyrite, pyrrhotite, pentlandite, molybdenite, sphalerite, and galena. The deposits of sulphide minerals have yielded a few million pounds of copper. Lindgren believes that the cordierite-anthophyllite rocks at Blue Hill

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(1) Magnusson, N.H. - Persberg malmtrakt. Kongl. Kommers-kollegium, No. 1, Del. 1, 1925.

(2) Magnusson, H.H. - Nordmarks malmtrakt. S.G.U. Ser. Ca, No. 13, 1929.

(3) Johansson, H.E. - Die eisenerzfuhrende Formation in der Gegend von Grängesberg. G.F.F. Vol. 32, 1910, p. 239.

(4) Lindgren, W. - The cordierite-anthophyllite mineralization at Blue Hill, Maine, and its relation to similar occurrences. Proc. Nat. Acad. Sci., Vol. 2, 1925, pp. 1-4.

were formed by magnesia metasomatism, but Gillson and Williams (1) point out that cordierite and anthophyllite are present in only minor amounts, and chemical data show no evidence of magnesia metasomatism.

Cordierite and anthophyllite also occur in the emery deposits developed in the Manhattan schist at Peekskill, New York (2,3). However, cordierite and anthophyllite are not abundant, and there is no evidence of magnesia metasomatism, although the emery and gangue minerals are believed to have formed by emanations given off by a magma.

Zapfee (4) has described cordierite-anthophyllite rocks from the Gunflint iron formation in northeastern Minnesota. The rocks contain a large proportion of cordierite (up to 50%), magnetite, pyrrhotite, and smaller amounts of anthophyllite, pleonaste, actinolite, hedenbergite, hypersthene,

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(1) Gillson, J.L. & Williams, R.M. - Ec. Geol., Vol. 24, 1929, pp. 182-194.

(2) Gillson, J.L. & Kania, J. - Emery Deposits near Peekskill, N.Y. Ec. Geol., Vol. 25, 1930.

(3) Butler, J.W. - Am. Min., Vol. 24, 1936, pp. 537-574.

(4) Zapfee, Carl - The Effects of a Basic Igneous Intrusion on a Lake Superior Iron-Bearing Formation. Ec. Geol., Vol. 7, 1912, pp. 145-178.

quartz, and many other minerals. The iron formation rests on greenstones, and is intruded by sills of basic igneous material related to the Duluth gabbro. The sills are altered near their contacts with the iron formation, and in the altered zone contain small amounts of anthophyllite, magnetite and pyrrhotite. The cordierite-anthophyllite rocks are always accompanied by magnetite and pyrrhotite, and near the bottom of the formation magnetite is present in large enough proportions to be classed as ore.

Zapfee concludes that the "cordierite-magnetite" rocks have formed by the recrystallization of rocks originally composed of bands of (1), cherty, iron, pyritic carbonate, (2), argillaceous matter in the form of ferruginous slates, and (3) ferrous silicate rocks as the result of the intrusion of the sills, which were altered autolyically. Zapfee dismisses the possibility of the introduction of iron and magnesia by solutions as unlikely. However, it must be remembered that Zapfee's work was done before magnesia-iron metasomatism had been seriously considered, and a renewed study might demonstrate that the "cordierite-magnetite" rocks in the Gunflint formation have been formed by metasomatism, rather than by recrystallization.

Although magnetite is a characteristic mineral in cordierite-anthophyllite rocks, the only occurrence known to the writer in which other oxides are present in cordierite-anthophyllite rocks has been described by Eskola (1). Chrome oxides (pictotite and kämmererite) are associated with pyrrhotite, chalcopyrite, and pyrite in cordierite-anthophyllite rocks occurring at the edge of a chromite-bearing dolomite at the Outukumpu copper mine in Eastern Finland.

Cordierite-anthophyllite occurrences of the Orijarvi type have not been described from locations in Canada. However, at the Amulet Mine (2) in northwestern Quebec, cordierite and anthophyllite are abundant minerals in meta-rhyolites and meta-andesites surrounding sulphide ore bodies. The cordierite-anthophyllite rocks are spotted, and have such a distinctive appearance that they are called "dalmatianite". The sulphide minerals are pyrite, pyrrhotite, chalcopyrite, and sphalerite; magnetite is present, though it is not abundant. Wilson (3) has shown that magnesia, alumina, water and ferrous

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(1) Eskola, P. - On the Chrome Minerals of Outukumpu. Bull. Comm. Geol. Finlande, No. 7, 1933, pp. 26-43.

(2) Walker, T.L. - Dalmatianite, the Spotted Greenstone from the Amulet Mine, P.Q. Univ. Toronto Studies, Geol. Ser. No. 29, 1930, p. 9.

(3) Wilson, M.E. - Ec. Geol., Vol. 30, 1935, p. 484.

iron have been added to the greenstones, and that lime, potash, and soda were abstracted.

The general characters of the Amulet occurrence are different from those of the Orijärvi type, and because the significant features of the cordierite-anthophyllite rocks at the Amulet Mine are to be found in other occurrences, it is considered to represent a second definite type of cordierite-anthophyllite rocks - the Amulet type - which is due to the alteration of lavas.

Bray (1) has described a sulphide zone (pyrite, pyrrhotite, chalcopyrite, magnetite), 200 to 300 feet wide, lying in meta-andesite and meta-dacite flows at Gull Lake, Newfoundland, in which cordierite and anthophyllite (described as tremolite by Bray) are developed. The cordierite (2V-80°, negative) occurs in small xenoblasts and large porphyroblasts, and much of it is altered to a light green chlorite. Pleochroic haloes are scarce. It is separated from grains of sulphide by a narrow rim of chlorite. The anthophyllite occurs in felts, small radiating aggregates, and sheaf-like forms, and in some sections is the dominant mineral. The

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(1) Bray, A.C. - Unpublished Master's Thesis, 1929, McGill University.

optic-axial-angle of the amphibole is 70°-75°, the sign is negative and Z is parallel to -c. The refringence appears much lower than that of the anthophyllite at Montauban-les-Mines, but the birefringence is about the same (0.022). The Gull Lake occurrence is markedly similar to that at the Amulet Mine, although at the former occurrence cordierite is probably less abundant.

The above examples are the only occurrences of the Amulet type known to the writer in which sulphides are associated with the metasomatism. However, Tilley and Flett (1), and Tilley (2), have described occurrences of cordierite and anthophyllite in greenstones at Kenidjack and Botallack, Cornwall, These occurrences are more of petrographic than of economic interest, and the interpretation the authors have placed on them is rather interesting. Tilley and Flett considered the cordierite-anthophyllite and related rocks were formed as the result of "intense weathering, whereby lime was leached out of the weathered

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(1) Tilley, C.E. & Flett, J.S. - Summ. Progr. Geol. Surv. Gt. Britain, 1930 for 1929, pt. 2, pp. 24-41.

(2) Tilley, C.E. - Metasomatism Associated with the Greenstone-hornfelses of Kenidjack and Botallack, Cornwall. Min. Mag., Vol. 24, 1935, pp. 181-202.

products and these on contact metamorphism gave rise to the variety of rock types bearing anthophyllite, cummingtonite, and cordierite. At a later date, however, Tilley revised this explanation and considered it was more likely that "hot solutions emanating from a granitic source.... passed through the greenstones and produced an effective removal of lime with the production of anthophyllite and related types of hornfels". Although he admits that the cordierite-anthophyllite rocks at Orijärvi were probably formed by magnesia metasomatism, he is loathe to suggest such an origin for the Kenidjack occurrences, and considers that there has been only an "internal magnesia metasomatism".

Mention may also be made of an amphibolite which consists of cordierite, anthophyllite, garnet, quartz, biotite, iron ore, and rutile from Harcourt Township, Ontario. Adams and Barlow (1) considered the rock, which lies in granite gneiss between two masses of limestone, to have been a block of limestone detached from the main mass and very highly altered by the granitic magma which envelops it. The cordierite-anthophyllite rock in Harcourt Township has not the

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(1) Adams, F.D. & Barlow, A.E. - Geology of the Haliburton and Bancroft Areas, Ont. Can. Geol. Surv. Mem. No. 6, 1910, p. 170.

general features of either the Amulet or the Orijärvi type of cordierite-anthophyllite rocks. It might be considered as a third type.

There are several features of the Orijärvi and Amulet types of cordierite-anthophyllite rocks which are worthy of discussion. The distribution of radioactive haloes in the two types is particularly interesting. In the Orijärvi type, pleochroic haloes are common in the cordierite, but in the Amulet type they are rare (Gull Lake), or absent (Amulet Mine and Kenidjack). The significance of this distribution is unknown, but it may be that the magma giving rise to the mineralizing solutions was poorer in radioactive constituents in the Amulet type of occurrences than it was in the Orijärvi type. The radioactive elements were introduced, in the case of the Montauban occurrence, after the formation of the gangue minerals.

Spinel is another mineral of rather widespread occurrence in the cordierite-anthophyllite rocks. It is found in both types of occurrences, and is usually the zinc-bearing spinel, gahnite, although the ordinary magnesia spinel, such as that at Montauban, is almost as common in occurrence. Gahnite is significant in indicating a close genetic relationship between the ore-bearing solutions and the solutions which formed the silicate gangue minerals.

The common occurrence of magnetite has been mentioned. It is surprising that magnetite does not occur in the cordierite-anthophyllite rocks at Montauban. However, magnetite is not present in the magnesite deposits at Kilmar, so it is probable that the differentiates of the Morin magma which gave rise to the emanations did not contain sufficient iron, or conditions were not suitable, for the formation of magnetite.

The cordierite-anthophyllite rocks at Montauban have the general features of the Orijärvi type. They have formed from paragneisses which had a chemical composition not dissimilar to the leptites of Fennoscandia, they are mineralized with copper, zinc, iron, and lead sulphides, and ore bodies are developed only in skarns derived from carbonate rocks.

POSITION OF THE MONTAUBAN ORE ZONE IN THE CLASSIFICATION OF ORE DEPOSITS

In his study of the lead and zinc deposits of Canada, Alcock (1) distinguishes three main types of epigenetic lead-zinc deposits. The first type---those dependent for their formation on cavities or fractures in the country rocks---are subdivided into fissure veins, gash veins, stockworks, saddlereefs, and breccia fillings. In the second type---replacement or metasomatic deposits---no open spaces existed in the wall rocks, and the orebodies were formed by replacement of the country rock by the mineralizing solutions; the third type---pyrometasomatic or contact metamorphic deposits---are formed as the result of the effects of a magma on the surrounding country rock, and the nature of the wall rock itself has influenced the character of the deposit.

In Eastern Canada, the zinc-lead veins of central Gaspé, Quebec, and the many calcite-barite-galena veins of Ontario (Kingdon Mine, Frontenac Lead Mine, and others) are

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(1) Alcock, F.J. - Lead and Zinc Deposits of Canada. Geol. Surv. Can. Ec. Geol. Ser., No. 8, 1930, pp. 22-28

considered by Alcock to be typical fissure veins. The temperature at the time of their formation was apparently rather low, and most of these deposits occur in sedimentary rocks of relatively late geological age.

The replacement and pyrometasomatic lead-zinc deposits of Eastern Canada are more or less confined to the PreCambrian rocks. Alcock cites the Tétreault Mine as a typical example of a contact metamorphic deposit formed at high temperatures, because of the abundance of pyrrhotite, the presence of garnet, phlogopite and other high temperature minerals, and the lime-silicate-gangue minerals developed in the vicinity of the carbonate lens.

Lindgren (1) classifies deposits accompanied by cordierite as pyrometasomatic on the grounds that they are developed in slates, schists or quartzite, but not in limestone.

There can be no doubt but that the intercalated carbonate band has had a marked influence on the character of the gangue minerals developed, which would at once place this part of the deposit in the pyrometasomatic group. On

(1) Lindgren, W. - Economic Geology, 1933, pp. 743-745.

the other hand, it is open to question if Lindgren is justified in considering all deposits with cordierite gangue as pyrometasomatic because the chemical environment in places is not favourable for the formation of this mineral. Graton (1) has also questioned Lindgren's conclusions; he remarks "contact metamorphic deposits are a definite and integral part of the hydrothermal group, of which they represent a well-defined sub-division <u>chiefly</u> because of the special nature of the wall rock involved .... if the contact metamorphic ores are not representatives of the hydrothermal zone in limestones, then there would appear to be virtually no representatives of that zone in such rocks; this would lead to the quite improbable conclusion that hypothermal ores form in other kinds of rock but practically refuse to form in limestone".

If Lindgren's classification of ore deposits is accepted, the zinc-lead deposits at Montauban would belong to the pyrometasomatic group. However, the author prefers to regard the deposits as hypothermal, with metasomatism playing the dominant role in their formation, and in which the country rock has played an important part in determining the minerals formed.

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(1) Graton, L.C. - The Depth Zones in Ore Deposits. Ec. Geol., Vol. 28, 1933, pp. 531-532.

SUMMARY OF CONCLUSIONS

The Montauban ore zone is confined to Grenville metasedimentary rocks which have a generally synclinal structure. The Grenville rocks are garnet-biotite-sillimanite and related paragneisses, and, on the Tétreault property, a band of carbonate rocks is intercalated in the paragneisses. The Grenville rocks in this area are believed to lie in the lower part of the Upper Grenville series.

The syncline of Grenville rocks is surrounded by, and underlain by, migmatites, which have formed from paragneisses by potash metasomatism on a regional scale. The solutions entered the paragneisses which were granitized along schistosity planes, which dip consistently to the east and are inclined to the foliation and bedding of the Grenville rocks. The paragneisses in the core of the syncline lack the schistosity surfaces and were not granitized. The absence of the schistosity planes that controlled the migmatization may be explained by the manner of the paragneisses surrounding the carbonate rocks.

Following regional metasomatism, amphibolites, possibly derived from a differentiate of the Morin series, were injected along the inclined schistosity planes in the migmatites. The amphibolites became solid, and were metamorphosed before the decline of the regional stress. The amphibolites tend to feather out or end bluntly against paragneisses in the ore zone.

Later, a shear zone was formed that extends through the syncline and the underlying migmatites. Solutions possibly derived from a cupola of a differentiate of the Morin series, advanced upwards along the shear zone. The solutions formed cordierite and anthophyllite in the shear zone, but the surrounding migmatites were not altered, perhaps because the pore spaces in the migmatites were filled during the regional metasomatism, which did not allow the entry of the magnesia solutions, or because the migmatites had the physical characters of granite. The amphibolites also escaped alteration by the solutions.

The paragneisses which form the core of the syncline were drastically altered. The solutions introduced large quantities of magnesia, and, perhaps, some iron oxides, and the constituent minerals of the paragneisses were replaced by cordierite and anthophyllite.

The carbonate rocks intercalated in the paragneisses on the Tétreault property were in places altered to diopside by the solutions, but because there was only little silica available, much of the carbonate rocks were unaltered. The solutions, however, were enriched in lime picked up from the carbonate rocks, and entered the silicious paragneisses surrounding and overlying the carbonate rocks where they precipitated much diopside. In both carbonate rock and paragneisses, some diopside was replaced by tremolite, but most of the tremolite did not replace diopside. The extensive conversion of silicious paragneisses to the skarn association was the result of solutions coming from depth combined with the effect of abundantly available silica.

In places in the paragneisses where lime was available, for example, around the boundaries of the carbonate rocks, the solutions converted the oligoclase of the paragneisses to bytownite; anthophyllite was formed in these rocks. Cordierite was apparently antipathetic to lime feldspars, and was not formed. Bytownite was the stable plagioclase under the conditions of equilibrium, and excess lime entered into diopside.

The alumina of the paragneisses combined with lime and gave rise to anorthite rocks, which tended to develop around the margins of the diopside-tremolite skarn. Much of the anorthite was later altered to wilsonite.

Following the formation of the lime and magnesia silicate minerals, tension cracks and fractures developed in the metasomatized Grenville rocks. Tension cracks were particularly well developed in the tremolitized paragneisses overlying the carbonate rocks, and solutions carrying zinc, copper, lead, iron, sulphur, and other elements, advanced from below and deposited sphalerite, galena, and smaller quantities of chalcopyrite, pyrrhotite, and pyrite in the tension cracks. Sulphides were also precipitated in open spaces in the diopsidized paragneisses, and sulphide minerals were disseminated through the skarn and the carbonate rocks. The cordierite-anthophyllite rocks were favourable loci for the precipitation of chalcopyrite, and consequently, chalcopyrite is more abundant in these rocks than sphalerite and galena.

Small quantities of gold and silver were precipitated with the sulphides.

The solutions deposited small amounts of breunnerite, calcite, quartz, actinolite, tourmaline, hisingerite, leuchtenbergite, barite, molybdenite, arsenopyrite, and gray copper; they also altered some of the gangue minerals to antigorite, chlorite, brucite, and pinite.

Because the Montauban ore zone lies in silicious paragneisses which have been altered to cordierite-anthophyllite rocks, and because ore bodies are associated with skarn derived from carbonate rocks, the ore zone is considered to belong to the <u>Orijärvi type</u> of mineral deposits.

The Montauban ore zone is regarded as a hypothermal (high temperature) deposit in which metasomatism played the dominant role.

The whole zone affords a particularly effective demonstration of the importance of structure and composition of country rock on the formation of ore deposits of this type. A significant feature of the ore zone is the diversity of the gangue minerals which have been produced by solutions presumably of the same original composition.

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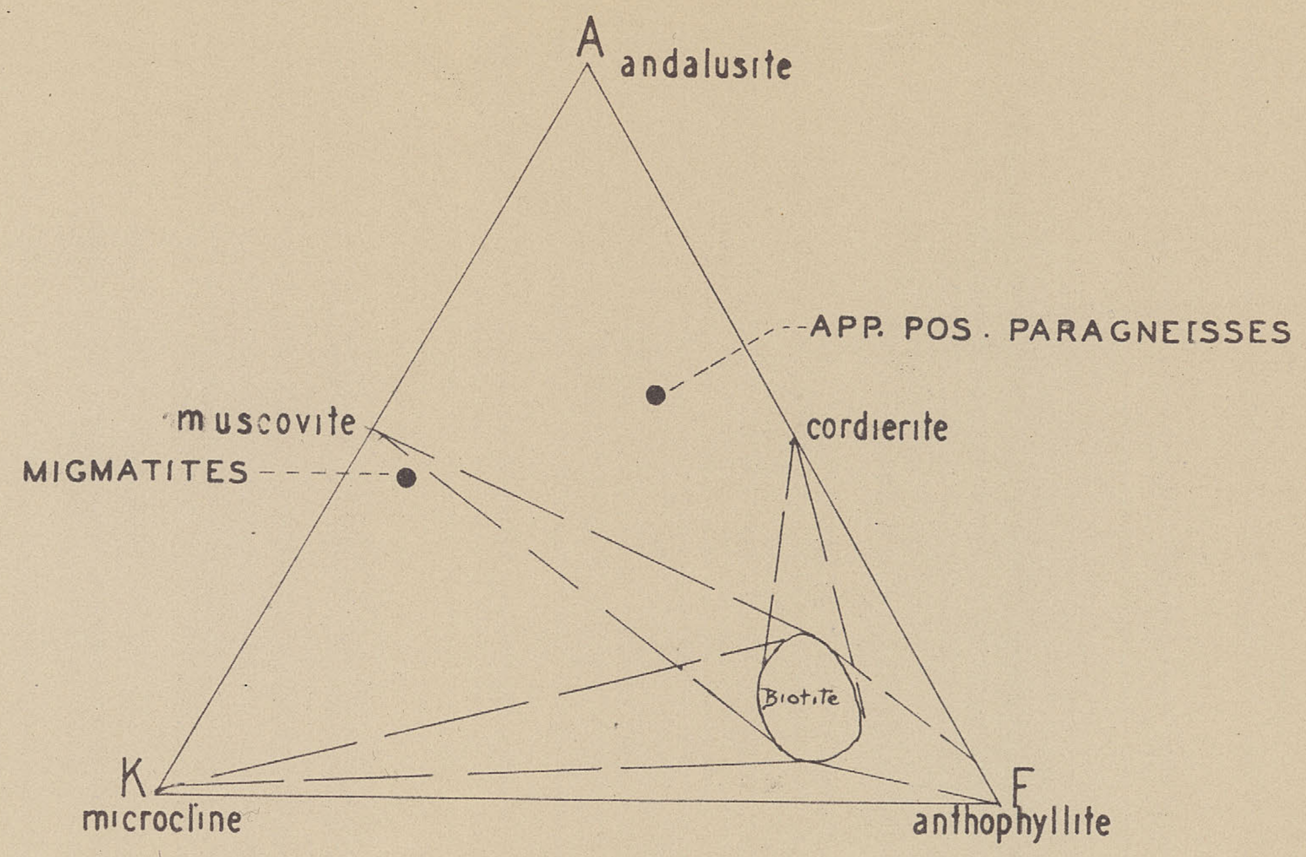
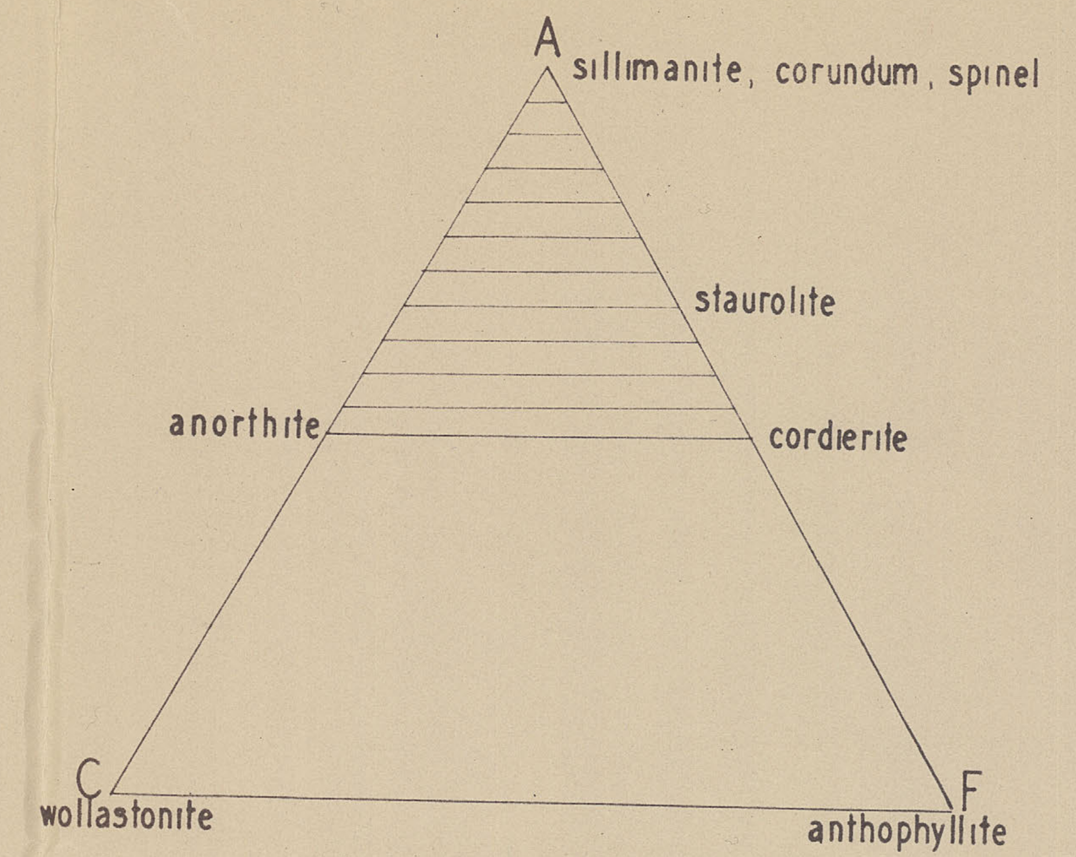


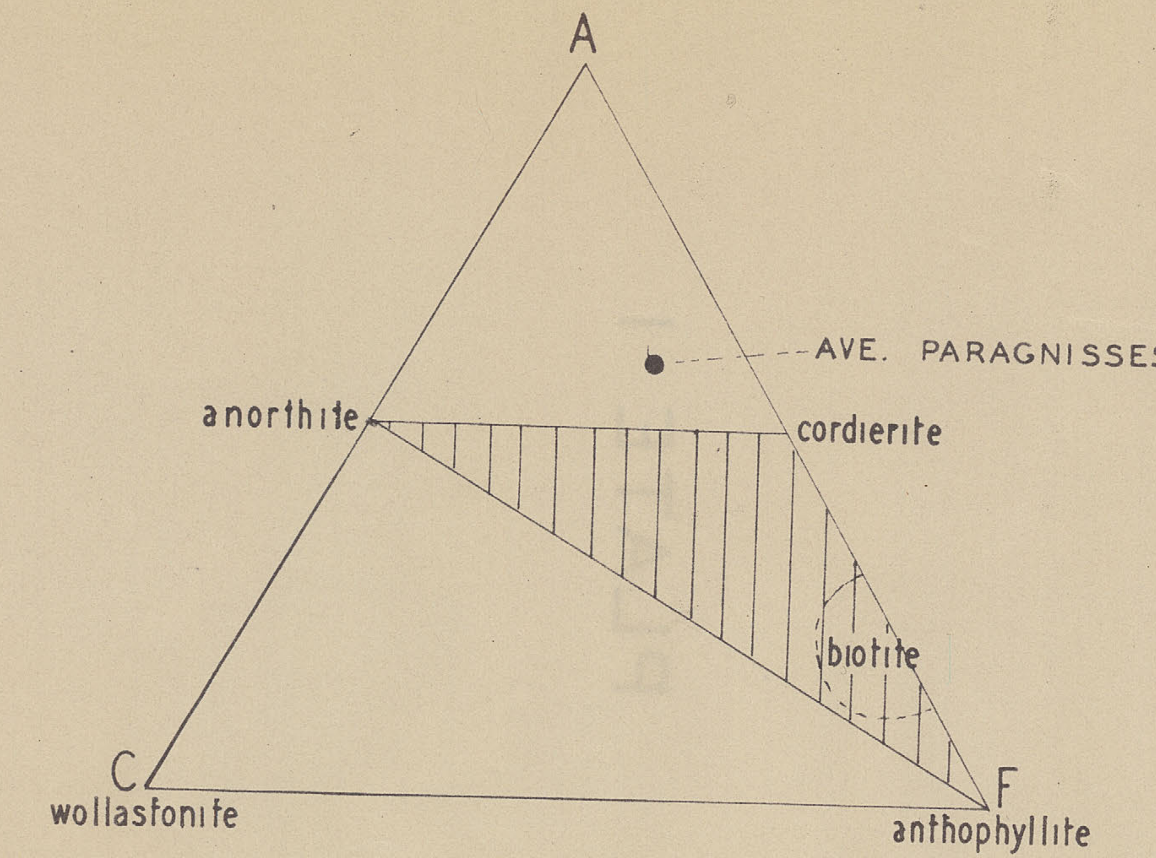
PARAGNEISSES & MIGMATITES



EXCESS ALUMINA

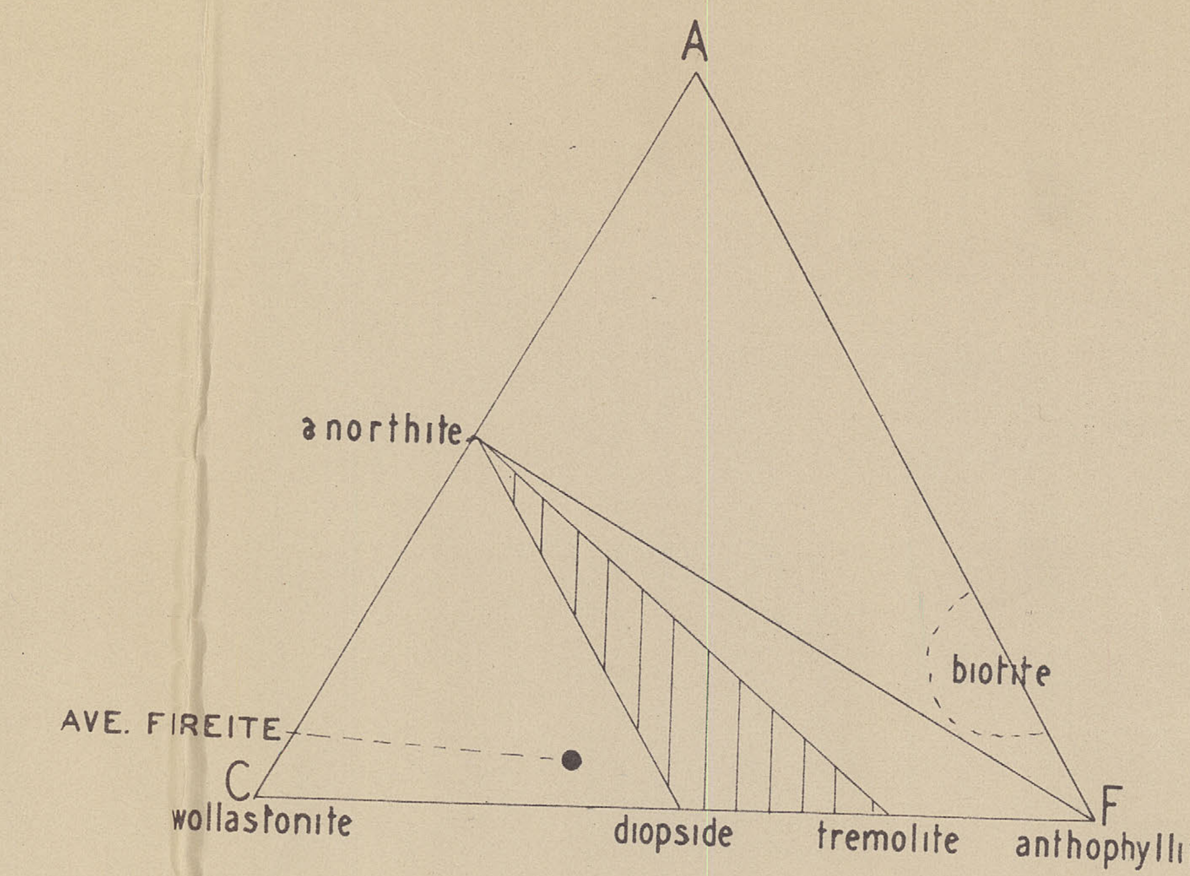
CORDIERITE — STAUROLITE — SPINEL

CORDIERITE — CORUNDUM



EXCESS ALUMINA

CORDIERITE — ANTHOPHYLLITE



EXCESS LIME

DIOPSIDE — TREMOLITE

ANORTHITE — ANTHOPHYLLITE (DIOPSIDE)

PARAGNEISSES

SECT. NO.	SILLIMANITE	GARNET	BIOTITE	QUARTZ	PLAGIOCLASE % AN. MOL.	SERICITE	CHLORITE
	1. QUARTZ GARNET BIOTITE PARAGNEISS						
76		■	■	■	30		
28		■	■	■	28		■
8		■	■	■	28–32	■	■
23		■	■	■	26		■
58		■	■	■	30	■	■
	2. GARNET BIOTITE SILLIMANITE PARAGNEISS						
B17	■	■	■	■	30		■
79	■	■	■	■	32	■	■
51	■	■		■	30-40		
	3. QUARTZ SILLIMANITE BIOTITE PARAGNEISS						
43	■		■	■	47		
70	■		■	■	30	■	
42	■		■	■	34		
7	■		■	■	26–29		
B4	■		■	■	30	■	
	4. NODULAR SILLIMANITE PARAGNEISS						
35	■		■	■	20–30		
36	■			■	20–30		
54	■		■	■	37	PLUS CORDIERITE	
75	■		■	■	28		
	5. QUARTZ BIOTITE PARAGNEISS						
10			■	■	25	■	
73			■	■	48	■	
44			■	■	30		
B20			■	■	25	PLUS CARBONATE	
	6. MICROCLINE SILLIMANITE PARAGNEISS						
5	■	+ MICROCLINE	■	■	10–20	■	■
9	■	PLUS MICROCLINE		■	28–34	■	■

MIGMATITES

SECT. NO.	HORNBLENDE	BIOTITE	EPIDOTE & ZOISITE	CARBONATE	QUARTZ	POTASSIC FELSPAR	PLAGIOCLASE % AN. MOL.	SERICITE	CHLORITE
52	■	■	■	■	■	■	22		
57	■	■	■	■	■	■	30	■	
B29	■	■	■	■	■	■	30–42	■	
B3	■	■	■		■	■	30–40		
B15	■	■	■		■		18	PLUS GARNET	
	■	■	■		■		26		
56	■	■	■	■	■		42		
6	■	■			■		36–42		
B2	■		■	■	■		22–30	■	
48		■	■		■	■	37	■	
3		■	■		■	■	38–40	■	
B28		■	■		■	■	32	■	
41		■			■	■	22	■	■
39		■			■	■	21	■	
15		■			■	■	17–20	■	■
16		■			■	■	28	■	
B23		■			■	■	37	■	■
33		■			■	■	25	■	
50		■			■	■	18	■	
4		■			■		17	■	
80		■			■		29	■	
78		■			■		30	■	
13		■		■	■		33–40	■	

■ – MINERAL PRESENT

□ – MINERAL PRESENT IN MINOR QUANTITY

METASOMATIC ASSOCIATIONS

SECT. NO.	CORDIERITE	ANTHOPHYLLITE	OMIT	STAUROLITE	SPINEL	CORUNDUM	SILLIMANITE	QUARTZ	PLAGIOCLASE % AN. MOL.	BIOTITE	GARNET	SERICITE	CHLORITE
					ANTHOPHYLLITE — ANORTHITE								
17	□	■	■				■	■	76				
60	□	■	■				■	■					
71	□	■	■				■	■	70	PLUS WOLLASTONITE			
47	□	■	■					■	76				
40		■	■					■	70				
61								■	72				
20								■	73				
									97			■	
					CORDIERITE — ANTHOPHYLLITE								
27	■	■						■		■		■	■
18	■	■						■		■	■		■
32	■	■					■	■	33	■	■		
77	■	■					■	■		■	■		■
					CORDIERITE — STAUROLITE — SPINEL								
53	■			□			■	■	32	■	■		■
31	■			□	□		■	■	31	■	■	■	■
69	■			■	□		■						■
26	■			□	□			■	27	■	■		
						CORDIERITE — CORUNDUM							
30	■	■				□	■	■	38	■		■	■
B2	■					□	■	■		■	■		■
						LATE METASOMATIC STAGE							
						ACTINOLITE, CARBONATE & QUARTZ							

SECT. NO.	PYROXENE	TREMOLITE	CARBONATE	GARNET	QUARTZ
		HEDENBERGITE — GARNET			
45	■		■	■	■
62	■		■	■	■
63	■			■	■
		DIOPSIDE — TREMOLITE			
34	■		■	PLUS ZOISITE	
21	■	■			
24	■	■	■		
11		■	PLUS EPIDOTE & ZOISITE		
12		■			
38		■			
29		■	■	PLUS QUARTZ	
19		■	■		

AMPHIBOLITE

SECT. NO.	HORNBLENDE	BIOTITE	GARNET	PLAGIOCLASE % AN. MOL.	QUARTZ
1	■	■		47–55	■
37	■	■		43–52	■
57	■	■		48–60	■
72	■	■		44–53	■
		ALTERED SELVAGE			
67	■	■	■	24–34	■
55	■	■	■	28–38	■

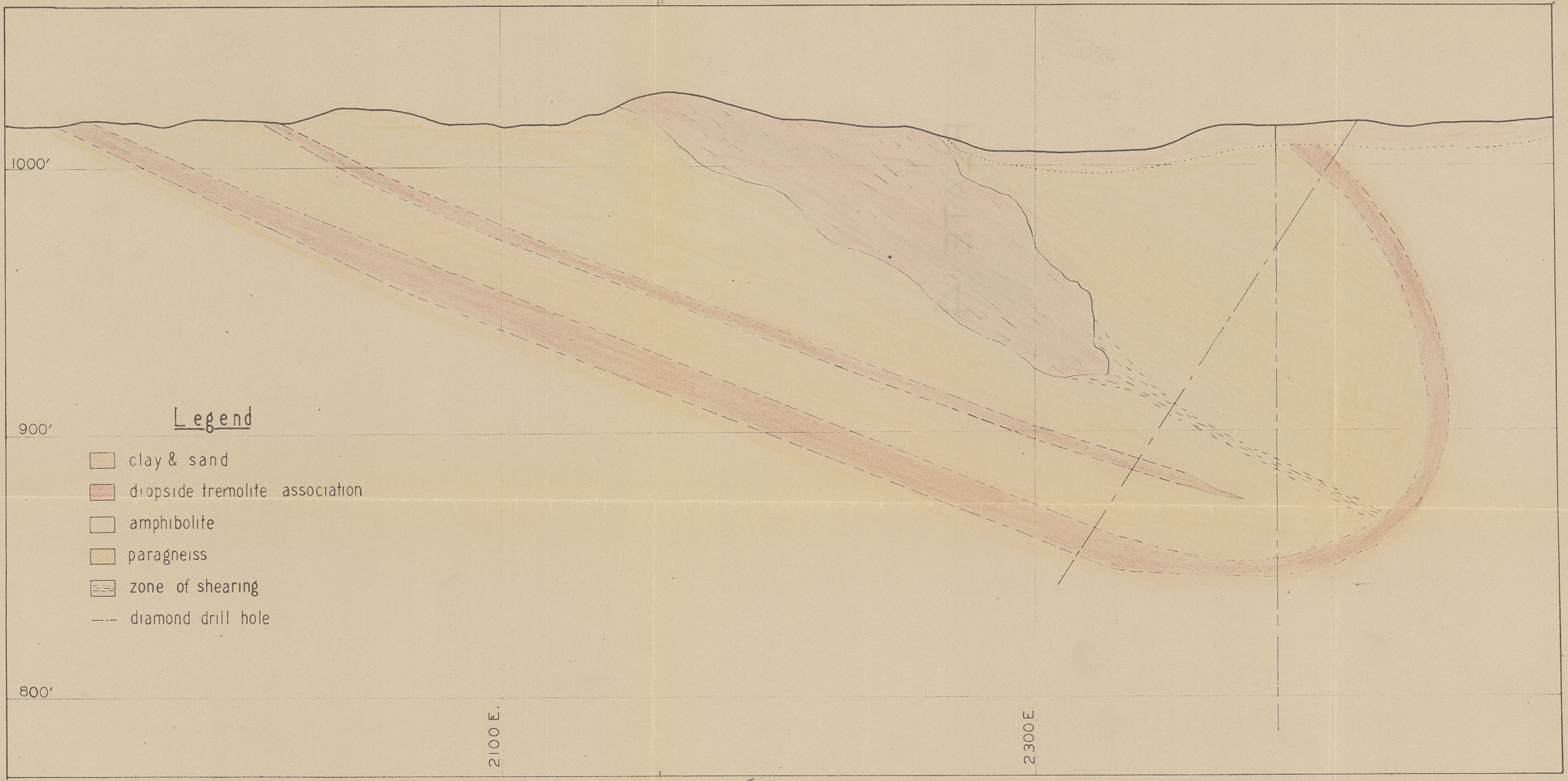
MINERAL GROUPINGS

MONTAUBAN ORE ZONE — MONTAUBAN LES MINES P.Q.

PLATE I

MONTAUBAN ORE ZONE — TÉTREAULT MINE — MONTAUBAN LES MINES, P.Q. — SCALE 1" = 100'

MONTAUBAN ORE ZONE—UNITED METALS & SHAWINIGAN PROPERTIES—MONTAUBAN-LES-MINES, P.Q.—SCALE 1" = 100'



SECTION 9 SOUTH — TÉTREAULT MINE — SCALE 1″=30′
(AFTER BRITISH METALS CORPORATION)