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ORIGIN OF THE QUEBEC PHLOGOPITE- APATITE DEPOSITS

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INTRODUCTION

The origin of the phlogopite and apatite-bearing pyroxenites of western Quebec and eastern Ontario has been a subject of controversy practically since their discovery. In the early days the argument was whether the phosphatic material present was originally organic or inorganic. More recently the dispute has been between those who believe that the pyroxenites were formed through contact metamorphism of calcareous rocks, and those who believe them to be basic segregations akin to pegmatites. A proponent of the latter view, H. S. Spence, mining engineer of the Mines Branch, Canadian Department of Mines, knowing of my interest in pegmatites, invited me to investigate the Canadian deposits. This invitation was accepted, and the following paper describes the results of the investigation.

Field work was carried on during the month of July, 1934, when eleven mines were studied and extensive collections made, both from available parts of the deposits and from mine dumps. Over 400 specimens were collected and shipped to the mineralogical laboratories at the University of Kansas. There each specimen was examined megascopically and microscopically, the minerals identified, and their paragenesis determined wherever possible. This work was done during the academic years of 1934-35, 1935-36, and 1936-37.

I wish to express my gratitude to Mr. Spence for many courtesies shown me. During the course of the field work he spent many days with me in the field, and has been ever ready subsequently to supply essential data, specimens, photographs and helpful advice. Mr. Spence also read and criticized the manuscript copy of this paper.¹ The manuscript was also read by Dr. A. F. Buddington, who made some helpful suggestions. A former student at the University of Kansas, Mr. Harold Hoover, ably assisted me in the field. The field work was made possible through a grant (No. 151) from the Penrose fund of the Geological Society of America, which was sufficient to cover most of the field expenses. The Graduate Research Committee of the University of Kansas appropriated funds for the purchase of thin sections. I am grateful to both of these organizations for their assistance.

¹ Spence does not concur in all of the interpretations presented in this paper, however.

GENERAL GEOLOGY

Location of phlogopite-apatite deposits in eastern Canada. The occurrences of phlogopite and apatite in deposits of economic importance in Canada are practically confined to two districts. The larger one lies north of the Ottawa River and the city of Ottawa, in western Quebec (Fig. 1). A slightly smaller district lies southwest of Ottawa and north of the east end of Lake Ontario, near the eastern end of the province of Ontario. This district was not included in my investigation. A few isolated deposits occur outside of the two principal districts. One of these, the Liscombe, lying near Wilberforce, Ontario, was visited and is included in this report.

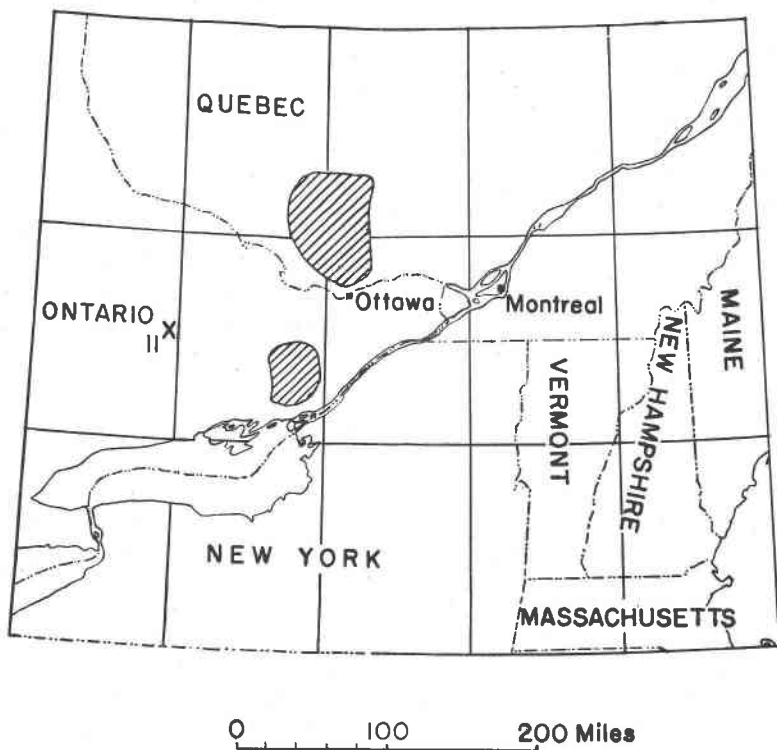


FIG. 1. Phlogopite-apatite districts in eastern Canada. The two principal districts are shown with diagonal lines. An isolated deposit near Wilberforce in southeastern Ontario is shown by the symbol 11X.

Country rock. Throughout the phlogopite-apatite area the country rock is a pre-Cambrian complex referred to by Young (1926, p. 56) as

the Grenville-Hastings group which "consists of various types of gneisses of sedimentary origin, quartzites and crystalline limestone. These beds in most places are much metamorphosed and have been folded and crenulated. They have been invaded by dikes, sill-like bodies, and larger masses of pyroxene-bearing rocks, largely gneissic and ranging in composition from granite to peridotite. These are accompanied also by pegmatitic phases. . . . This complex assemblage of igneous and sedimentary rocks has been penetrated by later dikes, stocks, and larger bodies of granitic rocks, frequently of gneissic habit." Wilson (1913, p. 202) includes some of the rocks occurring in the northern phlogopite-apatite district in the Buckingham series, which range in composition "from a pyroxene granite to peridotite and pyroxenite."

In only one (the Dacey) of the eleven deposits which I examined in detail, was limestone prominent in the country rock. In most places the country rock was a gneiss. The general geology of the deposits in Ontario, south of Ottawa, is supposed to be very similar to that north of Ottawa, although Penrose (1888, p. 25) calls attention to the greater abundance of hornblende in the rocks in the southern district.

Pyroxenite. The phlogopite and apatite invariably occur in or with a diopside-rich rock which is generally referred to as pyroxenite. This pyroxenite occurs in dikes and irregular-shaped bodies which are definitely intrusive into the country rock, transgressing the structure of the gneiss in many cases. The largest pyroxenite body seen in the course of this study was about 400 yards across. However, several in this area are three-quarters of a mile long and one-quarter of a mile wide, and one is one-half mile in width, as mapped by Wilson (1913) on the Buckingham sheet. Thin sections of the pyroxenite reveal a dense interlocking aggregate of anhedral crystals, as in any other igneous rock.

Accompanying the pyroxenite is microcline, mainly in pegmatite, the abundance and significance of which have been overlooked by most investigators. The microcline pegmatite may or may not contain quartz, and where quartz is present it is subordinate in most cases. The microcline occurs in various colors, but a rather unusual lilac or mauve color predominates. Calcite, phlogopite, and apatite occur in veins which cut both the pyroxenite and microcline pegmatite.

Later igneous activity. In several deposits the country rock, pyroxenite, microcline pegmatite, and calcite-phlogopite-apatite veins are cut by younger white microcline-quartz pegmatite veins. Later basic dikes also occur in the district.

THE PHLOGOPITE-APATITE DEPOSITS

Eleven deposits of phlogopite- and apatite-bearing pyroxenite were studied. Some of these are typical of the scores of mica and phosphate deposits in eastern Canada, and others were studied because of exceptional features.

The territory where the deposits occur is heavily wooded and good exposures are to be found only where the bed rock has been uncovered and penetrated by mine openings. Unfortunately, most of the mining activity took place years ago so that the majority of the openings are flooded, or caved, and only the shallower cuts and the rocks thrown out on the dump can be examined. For detailed descriptions of the deposits, written when mining was more active, the reader is referred to the monographs by de Schmid (1912) and Spence (1920 and 1929).

Composite description. Without exception, the phlogopite-apatite deposits examined occur in or bordering pyroxenite. The latter is in the form of a steeply dipping dike, in most cases. It is cut by veins and irregular masses of microcline pegmatite and finer grained facies of this rock. Quartz is present in the feldspar rock in widely varying proportions. It has a decided bluish tinge in some deposits, and is milky colored in others.

Phlogopite or apatite, or phlogopite and apatite, occur in calcite veins which transect microcline pegmatite and pyroxenite, and in a few places extend out into the country rock. These veins exceed 15 feet in width in some deposits. They have been classified into two types, "fissure" and "contact." In the former the calcite and associated minerals are found scattered through pyroxenite. In the "contact" type they occur on the hanging wall, foot wall, or on both walls, of the pyroxenite body. The relative proportions of phlogopite, apatite, and calcite vary greatly from one deposit to another. In some all three are abundant; in others only two are common, with the third relatively scarce; and in still other deposits one mineral is predominant and the other two insignificant.

Scapolite is present in many deposits, especially in the contact zone between microcline pegmatite and pyroxenite (Fig. 2). Actinolite may occur in the same environment, and also in calcite veins. Many other accessory minerals, which are listed and described on subsequent pages, are to be found in the deposits. Some of these belong to the feldspar phase, and others to the calcite vein stage.

In the course of my study, cavities were observed at only one deposit, the Dacey. Most of these "pockets" were lined with crystals of diopside or, more rarely, with crystals of apatite or scapolite. Spence,² who had

² Letter dated October 12, 1937.

opportunity to visit the mica and phosphate mines during exploitation, states that cavities are very common, in fact typical, and that they "often attain very large dimensions, and, where calcite filling has been leached out at the surface, may be large caves, the walls lined with diopside or phlogopite crystals."

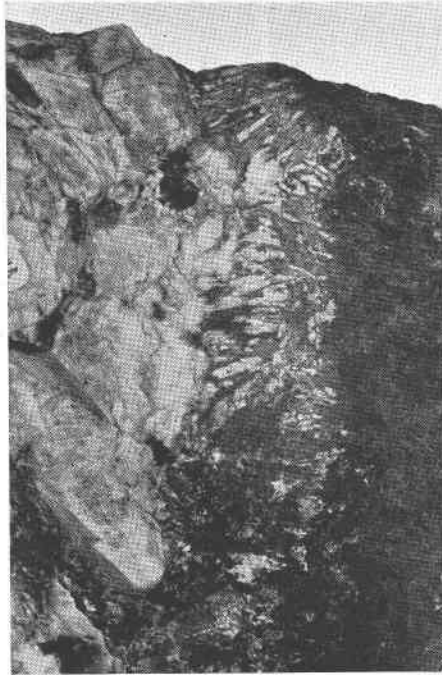


FIG. 2. Bladed scapolite zone in pyroxenite (dark) adjacent to microcline pegmatite (light). Nellie and Blanche mine. (Scale for all specimens pictured is approximately one-half natural size).

Deposits examined. In order to conserve space and avoid duplication, detailed descriptions of the eleven deposits examined have been eliminated from this paper and a composite description substituted. The following paragraphs, therefore, include only data as to location, accessibility, and type of deposit, plus a very brief description of any unusual features that may be present. The deposits are numbered to correspond with the numbers on figure 3. Deposit No. 11 is not on the map area covered by figure 3, but is shown on figure 1.

1. Nellie and Blanche Mine. This mine is in lot 10, Range X, Hull Township. It lies a short distance east of Gatineau River and about 2 miles southwest of Cantley Village. Ells (1899, p. 38) reports that the

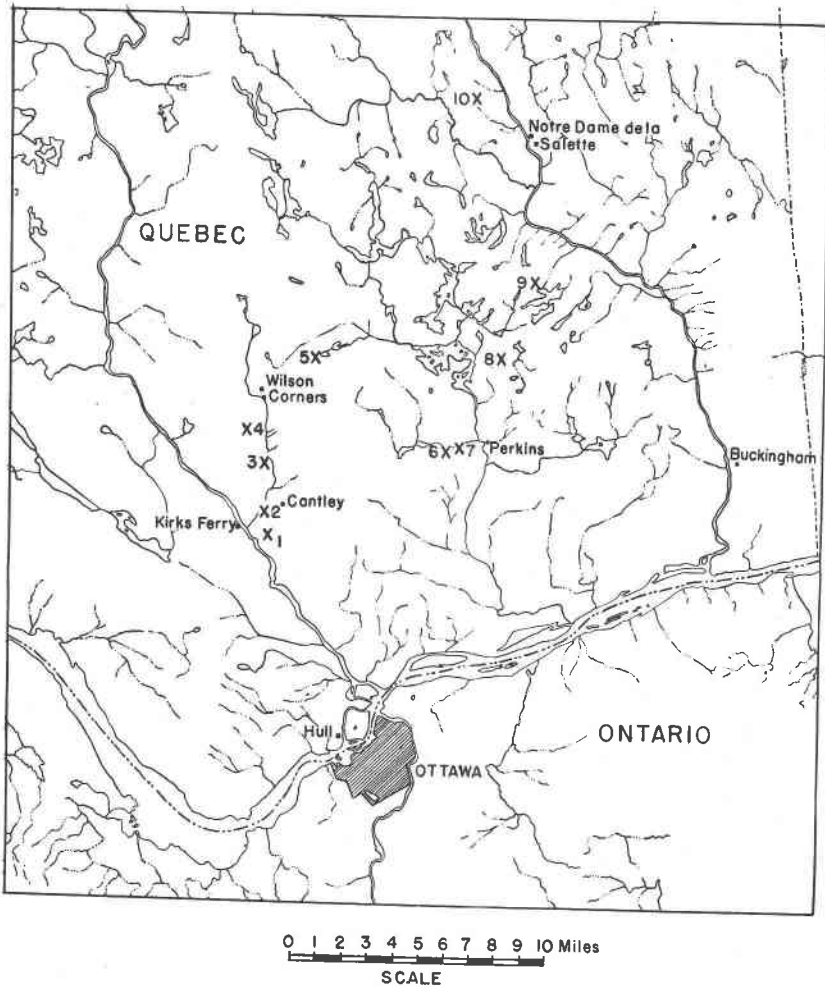


FIG. 3. Map of Quebec mica-phosphate district, showing locations of deposits described in this paper.

Nellie and Blanche was operated to a depth of 170 feet. The mine was last operated about 40 years ago, and the workings are now filled with water.

Apatite and calcite are relatively scarce in the Nellie and Blanche, which was exclusively a mica mine. Scapolite is present in large crystals.

2. Vavasour, Gemmill, or Nellis Mine. This mine is in lot 10, Range XII, Hull Township, about one-half mile southwest of Cantley and 10 miles north of Ottawa. It had not been worked for some years prior to

1934, but as the outcrops are topographically high the shallower pits were not filled with water and could be entered. (Spence reports that this mine was reopened in 1937).

The Vavasour Mine produced both apatite and phlogopite. These minerals occur in pyroxenite in discontinuous deposits along five parallel leads which crop out across a low hill. These leads apparently mark the position of fractures in the country rock which were penetrated by magmatic solutions precipitating diopside, microcline, phlogopite, apatite and other minerals. De Schmid shows a sketch of the veins and mine workings (1912, p. 98).

A few hundred yards northwest of the Vavasour Mine, in lot 11A, are the abandoned workings of the Lucky Reserve or Brown Mine. This mine lies over the edge of the bluff on the south side of Blackburn Creek. The mineral occurrence here is very similar to that at the Vavasour Mine.

3. McClelland or McLelland Mine. This mine occupies a knoll on the west side of Blackburn Creek, about 2 miles north of Cantley in the north half of lot 10, Range XIV, Hull Township. Exploitation was mainly for phosphate, and apatite is still a very abundant constituent of the deposit. It is reported that mining was carried to a depth of 100 feet. Operations ceased in 1908 (de Schmid, 1912, p. 101).

This is one of the few deposits seen in which microcline pegmatite is not a prominent feature in the mineralization.

4. Dacey Mine. The Dacey Mine is about one and one-half miles southwest of Wilson Corners in Range XV, lot 12A, Hull Township. The property has been worked intermittently for many years, but was closed down when visited.

The Dacey deposit is unique among those visited in that limestone is the country rock for a part of the deposit.

Pink calcite is especially abundant, and is accompanied by both apatite and phlogopite. These minerals occur in the pyroxenite contact zones, and the main mass or core of the pyroxenite body is barren of commercial quantities of either mica or phosphate.

5. Lake Girard Mine. The Lake Girard Mine was at one time a very important producer of mica, but has been idle since 1904. During mining activity, workings were carried down to a total depth of 210 feet. The mine is on the south shore of Lake Girard, near the west end, in lot 24, Range II, Wakefield Township, about $3\frac{1}{2}$ miles northeast of Wilson Corners.

Apatite is quite subordinate in the Lake Girard deposit. The microcline pegmatite contains bluish quartz.

6. Wallingford Mine. This mine is in the west half of lot 16, Range VIII, Templeton Township, about $1\frac{1}{2}$ miles west of Perkins Mills Village. The Wallingford was originally a phosphate mine, then became an important mica producer. The mica marketed was a light-silver amber, and it occurred in exceptionally large "books." Phlogopite from this mine won first prize at several international expositions. One crystal is reported to have yielded \$33,000 worth of mica (de Schmid, 1912, p. 70). The mine has been worked to a depth of 200 feet.

7. Rainville Mine. This mine lies a short distance east of the Wallingford Mine and about a mile west of Perkins Mills, in the east half of lot 15, Range VIII, Templeton Township. As is so often the case in this district, the mine was originally worked for phosphate and then became a mica mine. It is reported that mica sheets as large as 40 by 45 inches were produced (de Schmid, 1912, p. 68).

8. Blackburn Mine. This is a large phosphate and mica mine which is still intermittently active. The main workings are in lot 10, Range XI, Templeton Township, 4 miles north of Perkins Mills. The largest surface opening is a pit 300 feet long, 180 feet wide, and 120 feet deep. Underground workings have been carried to a depth of 280 feet. A short distance to the northeast, in lot 9, are the North Hill workings, which are also a part of the Blackburn Mine.

The Blackburn pyroxenite is honeycombed by veins, pockets, and chimneys of calcite containing phlogopite and apatite. Quartz, both blue and milky, is unusually abundant in the microcline pegmatite. Some of the pyroxenite has been serpentinized.

9. King Edward Mine. This mine is situated in the northern part of Templeton Township, in lot 8 in the Gore Mt. It lies on the west shore of Rheaume Lake, between 3 and 4 miles northeast of the Blackburn Mine. It has not been extensively developed, the workings consisting only of a few shallow pits and trenches.

Sphene is exceptionally abundant at this deposit. It occurs scattered through the pyroxenite in the neighborhood of the microcline pegmatite body.

10. High Rock Mine. At one time, this was the largest apatite mine in Quebec. The workings were on the flank and crest of a ridge west of Lievre River, in lots 5 to 8, Range VII, and lots 1 and 2, Range VIII, Township of Portland West. The summit of the ridge is about 600 feet above the river. Operations ceased about 1892, and most of the workings are now inaccessible. The deposit is about 3 miles northwest of Notre Dame de la Salette Village. To the northwest and southeast, scattered along a ridge that, in general, parallels the course of Lievre River, are many other abandoned phosphate mines.

An outstanding feature at the High Rock deposit is the extraordinary development of microcline pegmatite, consisting of mauve-colored microcline and subordinate quartz. Along the top of the ridge, great masses of pegmatite are exposed in veins, lenses, and irregular bodies cutting both the pyroxenite and the country rock. Many of the microcline individuals exceed four inches in maximum dimension. One peculiar phase of the microcline pegmatite is "leopard rock," composed of granular microcline and quartz, cut by arcuate "dashed line" veins of augite. The latter occurs in unconnected, short, prismatic, black crystals (Fig. 4).

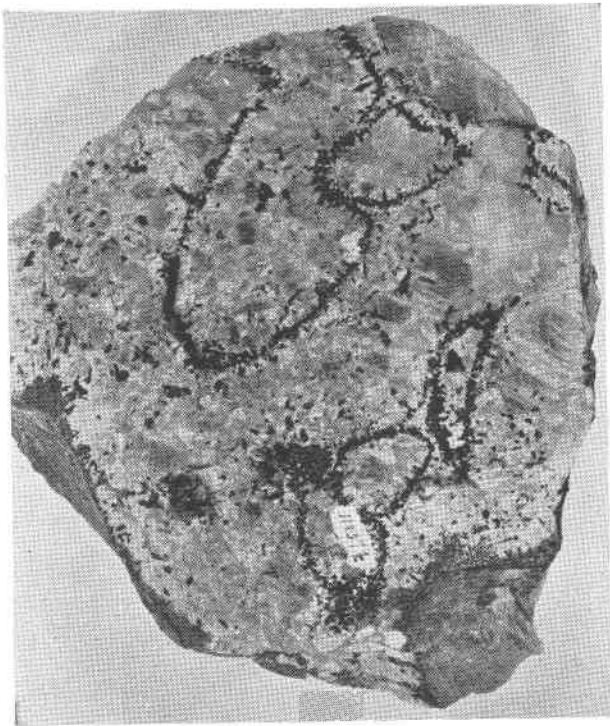


FIG. 4. Arcuate veins of augite in microcline pegmatite (leopard rock). High Rock deposit.

Phlogopite is very scarce both here and in the other phosphate deposits in this district. Calcite is present with the apatite, but it is not as abundant as it is in the various mica mines visited.

11. Liscombe Mine. This deposit lies far outside the main mica and phosphate districts, about 140 miles west and a little south of Ottawa

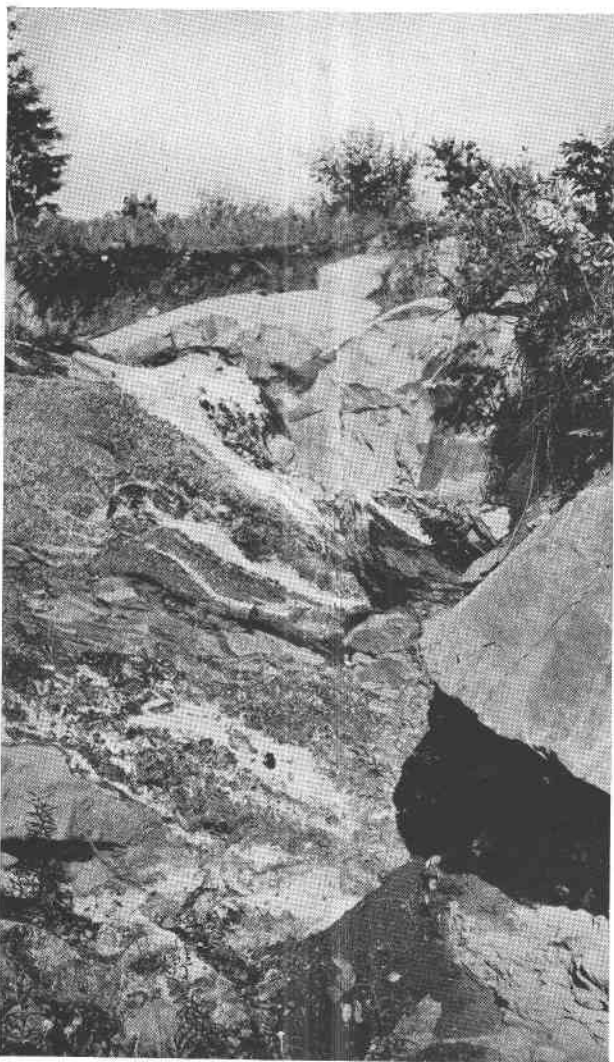


FIG. 5. Open cut in Liscombe Mine. Light-colored rock in background is microcline rock. Streaked and spotted rock is pyroxenite, cut by veins of calcite, apatite, and phlogopite. Photograph by H. S. Spence, Canadian Department of Mines.

in central Ontario. The location is shown in figure 1. The mine is in lot 34, concession 15, Monmouth Township, Haliburton County, about one mile from Wilberforce Station. It is in a district that is very interesting from a mineralogical standpoint. The mine has been intermittently operated for phlogopite, the workings consisting of four relatively

shallow pits, one above the other, on the side of a hill, and a shaft 100 feet deep that is now inaccessible.

Typical diopside pyroxenite, containing a small amount of scapolite, is present, but is subordinate. The principal feature of this deposit is the presence in great abundance of a fine granular to sugary rock consisting of dominant microcline and subordinate quartz (Fig. 5). This rock grades imperceptibly into microcline pegmatite, similar to that found in other deposits. According to the theory developed later in this paper, the original acidic magma was less contaminated by dolomite at depth at the Liscombe deposit than were similar magmas in the districts north and south of Ottawa. Consequently microcline-quartz rock is more abundant than pyroxenite.

The apatite at the Liscombe deposit occurs imbedded in calcite in beautiful transparent green euhedral crystals (Fig. 6).

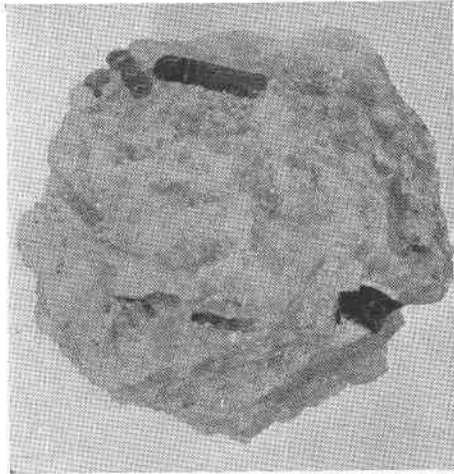


FIG. 6. Apatite crystals in calcite. Liscombe Mine.

DESCRIPTION OF MINERALS AND PARAGENESIS

Twenty-one primary minerals were identified in the specimens collected from the deposits described in the preceding section. Of these, diopside, as the sole essential constituent of the pyroxenite, is the most abundant. Microcline, occurring in microcline pegmatite and in finer grained feldspar rock, ranks second. Calcite is third. The other eighteen minerals, although varying greatly in relative abundance, may be considered to be merely accessory minerals in either the feldspar rock or the calcite veins.

The minerals occurring in the mica deposits of Ontario and Quebec have been described in some detail by de Schmid (1912, pp. 281-301). In the following paragraphs the minerals observed and collected by the writer are described in alphabetical order. Particular attention is paid to the associations and relative age of each mineral.

Actinolite. Actinolite is especially abundant at the Nellis and nearby Brown deposits, but it also occurs at most of the other localities visited. It is dark green or, more rarely, bluish green in color. A few crystals, up to one-half inch across, were found, but the mineral occurs mainly in dense fibrous masses. A few thin, cross-fibered veins were seen. The actinolite is light green under the microscope. Its mean index of refraction lies between 1.62 and 1.63, and the angle between Z and c is between 15 and 18 degrees. Some of the actinolite in the Wallingford deposit has been serpentinized.

Actinolite is most commonly associated with calcite. It occurs both in stubby crystals scattered through veins of coarse pink calcite and in contact zones. Pyroxenite bordering calcite veins may be rich in actinolite, and actinolite may be abundant in small crystals scattered along the contact between calcite veins and microcline pegmatite. The cross-fibered veins noted in the preceding paragraph cut both pyroxenite and microcline pegmatite, but probably have their source in the calcite masses.

Actinolite is not universally associated with calcite, however. It also occurs in small crystals scattered through microcline pegmatite, and in a dioritic-appearing aggregate with microcline, especially where this feldspar rock invades pyroxenite. The actinolite accompanying the microcline pegmatite and its finer grained facies is cut by calcite veins.

It is obvious that the greater part of the actinolite was brought in by the calcite depositing solutions. However, actinolite deposition also accompanied the intrusion of veins and masses of microcline pegmatite. The actinolitization of diopside in contact zones probably took place during both periods of mineralization.

Apatite. Apatite was found in all of the deposits in varying abundance. One, the High Rock, was exclusively a phosphate mine, and most of the other mines either started as phosphate mines and later became mica mines, or produced both minerals at the same time.

Two types of apatite occur in the deposits investigated. One is the "crystalline" type consisting of both anhedral and euhedral crystals of varying size. The other is "sugar" apatite, in which the individual anhedral are minute. At some of the deposits, especially the High Rock, apatite occurs in elongate nodules several inches in length.

Although most of the apatite observed is green, several other colors were observed, including nearly white, straw, pale brown, and blue. A wide variation was also observed in transparency. Some crystals, especially those at the Liscombe deposit, are unusually transparent.

Apatite, like the calcite with which it is associated, is distinctly younger than the country rock, pyroxenite, and feldspar rock. Isolated crystals of apatite occur in pyroxenite, beyond the calcite vein boundaries, at several localities.

Apatite is apparently slightly later in age than phlogopite. The "crystalline" apatite is older than some of the calcite, as it is cut by veins and partially replaced by this mineral. However, the "sugar" apatite occurs in veins which not only cut through apatite crystals and masses of "crystalline" apatite (Fig. 7), but also cut calcite. In all probability, apatite deposition was continuous, overlapping the period of calcite precipitation, but toward the end of the period of mineralization the relatively fine-grained "sugar" apatite was precipitated.

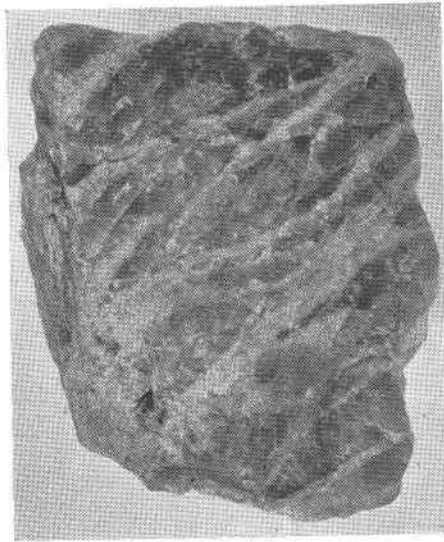


FIG. 7. "Sugar" apatite veining "crystalline" apatite.

Barite. Small, white, tabular crystals of barite imbedded in coarse white calcite were found in the Blackburn deposit. De Schmid (1912, p. 283) records the occurrence of barite in calcite in another deposit in the Ontario district. Evidently the calcite depositing solutions likewise introduced an insignificant amount of barite.

Calcite. Calcite is present in all of the deposits investigated, but varies greatly in abundance. Large quantities occur at the McLelland deposit, and the mineral was sorted out and stock piled during mica mining operations. At the other extreme is the High Rock deposit in which calcite, although present, is decidedly subordinate.

The calcite ranges in texture from very coarse to fine. Euhedral crystals were found at but two localities, Lake Girard and Wallingford, where small vugs in coarse calcite are lined with crystals, probably secondary, up to one-half inch long. The calcite varies in color from white, through pale pink and orange, to deep salmon and brick red; most, however, is pink. Vein calcite may change color from pink to white in a few inches. Also, bands or ribbons of white calcite cut through pink calcite, probably due to leaching along minute joint or fracture planes. Pink calcite at one deposit is brick red along fractures, where oxidation, instead of leaching, took place.

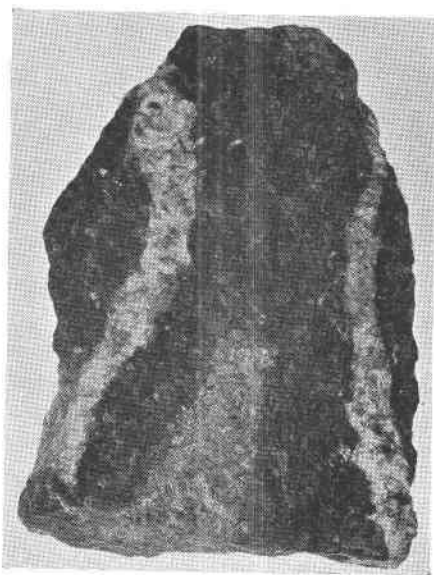


FIG. 8. Calcite veins cutting actinolite.

The calcite veins cut country rock, pyroxenite, and feldspar rock, including scapolite and actinolite (Fig. 8). Calcite also replaces pyroxenite as shown by partially calcitized zones in pyroxenite adjacent to large calcite masses. Specimens of pyroxenite collected at considerable distance from calcite bodies may effervesce with acid even though the calcite is too fine to be visible.

The most abundant minerals associated with calcite are apatite and phlogopite. Other minerals belonging to the same general period of mineralization are euhedral diopside, sphalerite, and some of the pyrite and actinolite.

Although calcite, apatite, and phlogopite belong to the same general period of mineralization, there is some difference in their relative age. Much of the calcite is definitely later than the coarse apatite, cutting it in thin veins. However, veins of "sugar" apatite cut both "crystalline" apatite and calcite, so this type is apparently later. Calcite veins cut phlogopite, showing that calcite continued to deposit after the mica had formed.

Chalcopyrite. Small crystals of chalcopyrite were found in the Blackburn (North Hill) deposit perched on vuggy quartz crystals. The age of this chalcopyrite cannot be definitely determined, but it probably belongs to the hydrothermal (calcite) phase.

Feldspar. With one exception, all of the feldspar collected proved to be microcline. The one exception is a single specimen collected at the Dacey Mine which consists of crystals of albite-oligoclase lining a vug in a rock composed of coarse white microcline with residual diopside. Microcline pegmatite and finer grained facies were found at every deposit visited. Microcline is especially abundant at the High Rock deposit, and was quantitatively more important than pyroxenite at the Liscombe deposit.

As previously noted, pyroxenite, microcline pegmatite, and calcite veins are alike cut by later thin dikes of feldspar and quartz, some of which are pegmatitic. All of this feldspar likewise proved to be microcline upon examination. These later dikes do not enter into the problem of the origin of the phlogopite-apatite deposits, so will not be considered further. Spence³ reports that such veins and dikes are abundant throughout this part of eastern Canada.

The microcline in the phlogopite-apatite deposits varies from very coarse, with cleavage faces up to 4 inches across, to fine sugary intergrowths. Both coarse and fine-grained feldspar rock may be present in the same deposit, in several instances with perfect gradation between. One specimen of graphic granite with elongate quartz blebs surrounded by gray microcline was picked up at the High Rock deposit.

A conspicuous and unusual feature of many of the coarser microcline anhedral grains in the microcline pegmatite is the presence of curved cleavage faces.

Almost all of the microcline observed is anhedral. One vug, which

³ Spence, H. S., Informal communication.

was found in the gneiss adjoining the Liscombe deposit, is lined with half-inch euhedral crystals of pink microcline and colorless quartz. A specimen collected at the King Edward deposit consists of a group of microcline crystals 3 inches long which are etched for depths as great as one-half inch.

Most of the microcline observed is either white or some shade of pink, such as flesh color, mauve, or lilac. Spence³ suggests that the mauve or lilac color may be due to the presence of titanium, one of the "fugitive" elements in the original magma. Less common colors are gray and smoky. A few specimens of glassy microcline were collected, and one specimen was slightly opalescent.

Thin sections of the granular feldspar rock show it to consist of interlocking anhedrons of microcline. Some of the feldspar exhibits the characteristic microcline twinning. However, this twinning is not always present, especially in crushed fragments of the coarser anhedrons, and identification must be based on extinction angles.

In every deposit visited the feldspar rock invades and replaces pyroxenite. It occurs both in well-defined veins and in large irregular masses, measuring many feet across at the High Rock deposit. At some localities mauve-colored microcline pegmatite extends out beyond the confines of the mica-phosphate deposit and cuts biotite schist or other country rock.

Quartz is a highly variable constituent of the feldspar rock. It may be entirely absent, but in most deposits is present to a small per cent and at a few places makes up over 50 per cent of the rock. Actinolite occurs with feldspar in some deposits, and scapolite may also be present, especially in pyroxenite contact zones (Fig. 2). Other minerals found in feldspar rock include pyrite, sphene, and zircon. Feldspar rock is cut by veins of coarse calcite in all of the deposits visited.

The microcline is very definitely younger than pyroxenite, and is older than the calcite vein minerals.

Fluorite. Small, glassy crystals of fluorite, both green and purple in color, were found in the Wallingford and Rainville deposits. With one exception, this fluorite is intimately intermixed with calcite and obviously belongs to the same period of mineralization. It occurs in small veins and masses, and in euhedral crystals. The exception is a specimen collected from the Wallingford deposit in which crystals of fluorite and colorless quartz line a vug in calcitized pyroxenite. The age of this fluorite is in doubt, but it also may have been introduced by the calcite depositing solutions.

Hornblende. Coarse, black hornblendite, in what is apparently a later dike, occurs at the Nellis Mine. Hornblende was also found in the

Dacey and High Rock deposits as a minor accessory mineral in microcline pegmatite.

Hydromica. Lake Girard tremolite was found to be altered to semi-fibrous hydromica in one specimen studied. The hydromica is white, with a very pale greenish cast and a pearly luster. It is biaxial negative with $n = 1.58$.

Kaolin minerals. Incipient kaolinization is present in the microcline lying at or near the surface. A euhedral crystal of phlogopite picked up at the Blackburn (North Hill) deposit was found to be completely altered to kaolin. Small pink nodules of pisolitic montmorillonite were found resting on apatite in a specimen collected at the Wallingford Mine. The montmorillonite is probably supergene.

Phlogopite. Phlogopite is present at all of the localities visited, but is very scarce at the High Rock deposit which was exploited for phosphate exclusively.

Phlogopite occurs as crystal intergrowths and as individual "books" of varying size. The largest book collected was five inches in diameter and eight inches thick. However, during mining operations, crystals many times this size were uncovered. The phlogopite varies in color from pale amber to nearly black. Books are creased, crumpled, and even broken in some instances, evidence of local post-mineralization diastrophism.

Phlogopite occurs mainly with calcite, but it may extend out into pyroxenite in narrow veins and isolated books. It is definitely younger than both the pyroxenite and the feldspar rock, but is older than some of the calcite, which cuts it in distinct veins. The richest "shoots" of phlogopite in calcite are generally found near the vein walls.

Pyrite. Pyrite occurs mainly in isolated anhedrons, rarely in euhedral crystals. In some deposits it forms thin veins. The common host rock for pyrite is microcline pegmatite. Pyrite was found in a few places extending out into gneissic country rock. It also occurs in etched grains in calcite. Some of these grains are shattered and veined with calcite.

Most, and perhaps all, of the pyrite was formed as an accessory mineral in the microcline pegmatite. It may also have been deposited by the solutions that precipitated calcite, apatite, and phlogopite, but the relationships between calcite and enclosed pyrite suggests that the latter is residual from an earlier period of mineralization.

Pyroxene minerals. Diopside, as the dominant constituent of pyroxenite, is the most abundant mineral found in the phlogopite-apatite deposits. No deposits were examined in which pyroxenite was not present and, conversely, Spence⁴ reports that in his field work in this district,

⁴ Spence, H. S., Informal communication.

he has encountered only two pyroxenites which do not have phlogopite or apatite, or both, associated with them. Even these deposits contain calcite veins, scapolite, zircon and sphene crystals, and other minerals belonging to a later generation.

Three types of pyroxene were found among the specimens collected. These are distinguishable, in some instances megascopically, and in every instance microscopically. The most abundant is the diopside composing pyroxenite. Least abundant is a pyroxene, near augite in composition, occurring in microcline pegmatite at the High Rock deposit. The third pyroxene is a second generation of diopside, appearing in veins cutting pyroxenite and in euhedral crystals which occur both along contacts between pyroxenite and calcite veins, and in the calcite veins themselves.

The pyroxenite diopside varies in color from nearly white through light green and dark green to nearly black. It is anhedral, and the individuals vary considerably in size, even in the same deposit, so that some pyroxenites are fine, dense rocks, and others are coarse intergrowths with the diopside anhedrons up to one-half inch across.

The pyroxenite diopside is so filled with inclusions that this type is readily identifiable under the microscope. The included material is mainly calcite, in excessively fine grains. The angle between Z and c is 41 degrees, which places the pyroxene between diopside and salite, in the diopside-hedenbergite series. Much of the diopside has been altered, or partially altered, in some instances to uralite, and in other instances to serpentine.

The relationship between the pyroxenite diopside and the feldspar, scapolite, and actinolite is of great importance in unraveling the paragenesis of these deposits. Microcline, abundant in the microcline pegmatite and its finer grained facies, invades and replaces pyroxenite. In some instances, this invasion is in the form of veins with clean cut boundaries, but in many places the microcline pegmatite has replaced outward from the main body so that all stages can be found between pure microcline pegmatite and pure pyroxenite. Large isolated masses of pyroxenite were observed completely surrounded by invading microcline pegmatite. Furthermore, individual partially digested grains of diopside occur scattered through the invading pegmatite. Scapolite and actinolite likewise cut the pyroxenite in veins, but in most cases occur in contact zones in pyroxenite, bordering veins and masses of microcline pegmatite. These zones are formed through replacement of diopside, and all stages from incipient to complete scapolitization and actinolitization were observed among the specimens collected.

Coarse mauve-colored microcline pegmatite at the High Rock deposit contains irregularly curved "dotted" veinlets (Fig. 4) of minute stubby black pyroxene crystals ("leopard rock"). Under the microscope, this pyroxene has higher indices of refraction than diopside, and the angle between Z and c is approximately 45 degrees. It is green in crushed fragments and non-pleochroic, but has typical pyroxene cleavage, and is apparently near to augite in composition. It belongs to the microcline pegmatite period of mineralization, but is later than the microcline itself.

The diopside occurring in crystals and veins breaks into clear, glassy green fragments where fresh, and can be readily distinguished from the pyroxenite diopside under the microscope by its lack of inclusions. Diopside of this type was collected at the Nellie and Blanche, Nellis, McLelland, Dacey, and Lake Girard mines. The vein diopside occurs in coarse, glassy anhedrons cutting pyroxenite. Euhedral diopside crystals from this region have been extensively collected, and are on display in all of the larger museums. The crystals occur in groups with no discernible orientation. Some large crystals have been found, but those now available range from one to eight inches in length, and from a fraction of an inch to three inches in diameter. The dominant form shown is the prism, with front and side pinacoids present, but less prominent. Basal parting is very pronounced in some of the crystals collected. A few crystals are severely etched.

The euhedral diopside typically occurs along the wall between calcite veins and bodies of pyroxenite. The crystals jut out from the pyroxenite into the calcite and, in some instances, isolated crystals occur out beyond the pyroxenite, completely surrounded by calcite. Some crystal groups were found in which calcite and other minerals of the same generation completely fill the spaces between the diopside crystals. In other specimens, some of this calcite has been removed and the balance severely etched, and still other groups were found in which no calcite was present. The evidence is quite clear that, where diopside crystals line cavity walls, these cavities were at one time filled with calcite and associated minerals, the former having subsequently been leached away.

The conclusion is that three generations of pyroxene are present in the deposits examined. The oldest is the diopside making up the pyroxenite. This diopside is the oldest mineral in the deposits, as it is cut and replaced by all of the other minerals. At one mine only, the High Rock, a pyroxene near to augite in optical properties occurs in "leopard rock," and is assumed to have formed during the time of intrusion of the microcline pegmatite. The third generation of pyroxene is the diopside which occurs in veins cutting pyroxenite, and in euhedral crystals in and

bordering the calcite. This diopside unmistakably belongs to the calcite period of mineralization.

Quartz. Quartz is relatively scarce in most of the deposits studied. It occurs, as does feldspar, both in the phlogopite-apatite deposits and in later veins. In the latter case, the quartz may be by itself, or it may be intermixed with microcline.

Most of the quartz in the mica-apatite deposits is anhedral, although a few quartz-lined vugs were found. A three-inch fragment of a vug collected from the Rainville deposit is lined with crystals of pale amethystine quartz up to three-eighths of an inch long. At the Wallingford Mine, small colorless quartz crystals were observed nesting, with montmorillonite, on apatite. Three small vugs found in dense pink calcite from the North Hill shaft of the Blackburn Mine are lined with half-inch crystals of colorless quartz. Very minute quartz crystals perched on half-inch crystals of microcline in a vug in gneissic country rock were observed at the Liscombe deposit. In all probability these euhedral quartz crystals belong to a period of mineralization later than that which produced the mica-phosphate deposits.

Most of the quartz in the feldspar rock is milky, but in a few localities, especially at the Blackburn (including North Hill) deposit, it has a decided bluish tinge. The quartz in the microcline pegmatite may be insignificant in amount, and except where blue, practically indistinguishable to the naked eye in finer-grained facies of the rock.

Quartz obviously belongs to the same mineralization period as feldspar. However, in some of the deposits at least, it completed its crystallization after the feldspar, as shown by its tendency to align in veins. Examples of this are the graphic granite found at the High Rock deposit, and a microcline specimen crossed by paper-thin, roughly parallel quartz veins which was collected at the Liscombe Mine.

Scapolite. Scapolite is one of the commoner minerals in the Quebec deposits. It was found at almost every deposit examined, and was especially abundant at the Nellie and Blanche and Dacey Mines. A few specimens collected are white, but most are yellowish and a few are green. Glassy blue scapolite was found at the King Edward Mine. At the Nellie and Blanche, the scapolite is exceptionally coarse, fragments eight inches in length being not uncommon. It is typically bladed. Microscopic examination showed the Nellie and Blanche scapolite to be mizzonite with $\omega = 1.574 \pm .003$ and $\epsilon = 1.550 \pm .003$. Some of the scapolite in the Wallingford deposit has altered to lilac wilsonite.

The characteristic location for scapolite is in the contact zone between microcline pegmatite and pyroxenite. In many instances, the scapolite

blades are roughly normal to the contact between these two rocks (Fig. 2). Scapolite also occurs in narrow veins cutting pyroxenite. At the Nellis Mine, parallel veins of white scapolite cutting pyroxenite produce "zebra rock." At a few localities scapolite occurs in dense intergrowths with microcline in a relatively fine-grained phase of microcline pegmatite. An exceptional occurrence is at the Dacey deposit where small crystals of white scapolite and diopside line a vug.

Scapolite is cut by veins of phlogopite, calcite, apatite, and other minerals belonging to later phases of mineralization.

It is evident that scapolite was formed at the same time as the feldspar rock. The depositing solutions travelled out beyond the microcline pegmatite veins into pyroxenite, so that scapolite replaces diopside in contact zones. Reaction between the feldspar-depositing solutions and diopside probably caused the formation of this scapolite. The single occurrence noted at the Dacey deposit, where scapolite crystals belong to the same generation as euhedral crystals of diopside, is decidedly exceptional. It is possible that the calcite depositing solutions introduced a second generation of scapolite, but on a relatively insignificant scale.

Serpentine. The pyroxenite in several deposits is partially serpentized. The serpentine varies in color from light green or brown to nearly black. It ordinarily occurs in veins and masses cutting pyroxenite and, more rarely, microcline pegmatite. At the Wallingford deposit actinolite has been serpentized. A vein of serpentine at the Blackburn deposit is in turn cut by a quarter-inch vein of light-green glassy diopside, which apparently belongs to a second generation of pyroxene mineralization.

The serpentization is obviously post-feldspar in age. It may have been accomplished by solutions accompanying the calcite mineralization.

Sphalerite. A single specimen of sphalerite was found at the Dacey Mine. Yellow resinous sphalerite was observed in a lens about one inch long surrounded by coarse white and pale pink calcite. De Schmid (1912, p. 298) reports sphalerite from one other locality in the Quebec district. The sphalerite in the Dacey deposit apparently belongs to the calcite period of mineralization.

Sphene. Tabular dark-brown crystals of sphene up to 2 inches in maximum dimension are very abundant in some of the deposits examined. In almost every instance, the sphene crystals are disseminated through microcline rock, so sphene must belong to the same period of mineralization as the feldspar. Where unusually abundant in a matrix

of microcline grains, "zebra rock" is produced. Sphe­ne rarely extends beyond feldspar rock into pyroxenite. It is replaced and cut by veins of "sugar" apatite in the vicinity of calcite veins.

Tourmaline. At three mines, the Nellis, Dacey, and Nellie and Blanche, crystals of black tourmaline occur in calcite veins with phlogopite. Similar crystals were found in microcline pegmatite at the Blackburn Mine. At the Lake Girard deposit, crystals of brown tourmaline occur in pyroxenite.

The black tourmaline occurring in calcite veins is of approximately the same age as the calcite. The tourmaline in microcline pegmatite and pyroxenite may have been introduced by the calcite-depositing solutions, or may belong to an earlier period of mineralization.

Tremolite. Tremolite occurs in the Lake Girard deposit in two different associations. A gray, near-fibrous form is abundant in microcline-blue quartz pegmatite. The other occurrence, much less common, is in light-green and glassy blades in "knots" in dense pale-green pyroxenite. The latter tremolite appears to have been formed through the alteration of diopside.

Wilsonite. One mineral specimen collected at the Wallingford Mine has a beautiful lilac color. It proved to be scapolite altered in part to wilsonite (pinite). Other occurrences of wilsonite have been noted by de Schmid (1912, p. 300).

Zircon. Zircon was found in the High Rock deposit. It occurs in small, glassy, hyacinth-colored crystals as a minor accessory mineral in microcline pegmatite.

Conclusions in regard to paragenesis. The first mineral to form was the diopside that makes up pyroxenite. After the pyroxenite had crystallized, microcline was deposited in veins and large irregular masses. Accessory minerals accompanying the microcline include quartz, scapolite, sphe­ne, pyrite, actinolite, tremolite, zircon, and hornblende. The crystallization of the feldspar rock was followed by the formation of veins of calcite. Phlogopite, apatite, actinolite, euhedral diopside, tourmaline, fluorite, barite, chalcopyrite, and sphalerite were precipitated with calcite during this phase of mineralization. Subsequently, unrelated dikes containing microcline and quartz were intruded into the country rock (and mica-phosphate deposits, where present). Supergene activity has caused the formation of a few secondary minerals in the phlogopite-apatite deposits.

The sequence of mineralization is shown graphically on the accompanying chart (Fig. 9).

Mineral	"Pyroxenite" phase	Microcline pegmatite phase	Hydrothermal phase
Pyroxene		_____	_____
Microcline		_____	
Quartz		_____	
Scapolite		_____	
Sphene		_____	
Pyrite		_____	
Actinolite		_____	_____
Tremolite		_____	
Zircon		_____	
Hornblende		_____	
Calcite			_____
Phlogopite			_____
Apatite			_____
Tourmaline			_____
Fluorite			_____
Barite			_____
Sulphides			_____

FIG. 9. Chart showing sequence of mineralization in the phlogopite-apatite deposits.

GENESIS OF THE PHLOGOPITE-APATITE DEPOSITS

The observations recorded in the preceding pages were made for the purpose of determining, if possible, the genetic history of the mica-phosphate deposits, which has been a matter of controversy for many years. In the following paragraphs a brief statement first will be given of the views previously held. This will be followed by a review of pertinent factual data with which any acceptable theory of origin must be in accord, and the discussion will be concluded with the presentation of a partially new theory advanced in an attempt to satisfactorily explain the origin of the phlogopite-apatite deposits of eastern Canada.

Views previously held. The evolution of ideas in regard to the origin of the mica-phosphate deposits has been given in detail elsewhere and repetition here is unnecessary. A complete digest of early opinions was published by Ells (1888). Twenty-four years later, de Schmid (1912, pp. 260-272) reviewed the theories of genesis that had been propounded up to that time. An extensive bibliography is also included in his report. As most of the papers written on this subject were published during the closing decades of the nineteenth century, the reviews by Ells and de Schmid are fairly complete. Subsequently, Spence (1920 and 1929)

published bulletins on "Phosphate" and "Mica" which contain briefer, but more up-to-date, historical reviews.

Writers on the origin of the Canadian mica and phosphate deposits include Baker (1916), Bell (1885), Cirkel (1905), Corkill (1904), Davidson (1893), de Schmid (1912), Ells (1889, 1893, 1894, 1904a and 1904b), Harrington (1878), Osann (1902), Penrose (1888), Spence (1920, 1929 and 1930), Spence and Carnochan (1930), Torrence (1885), and Wilson (1913, 1914, 1915, and 1924). The theories and beliefs of these men may be found in the reviews previously cited or in their original articles listed in the bibliography at the end of this paper.

At the present time, two distinct genetic theories are held by investigators in this field. The one that is perhaps the more widely adopted is that the pyroxenites and contained minerals are contact metamorphic deposits due to alteration *in situ*, or practically so, of lenses of Grenville limestone in the pre-Cambrian complex. The leading champion of this theory is Wilson (1915, pp. 159 and 161), and his views can best be expressed by quoting his own words:

PYROXENITE. From a study of the character and relationships of the pyroxenite in the field, it seems evident that this rock is a secondary type formed from the limestone of the Grenville series by the action of pegmatitic solutions derived from the intrusives of the Buckingham series. Throughout the Buckingham area, the rocks of the Grenville series have been intimately intruded by pegmatite and other rocks belonging to the Buckingham series, so that the pyroxenite, while not generally occurring at the contact of the crystalline limestone and the intrusive, nevertheless occurs in a contact zone where the limestone has been subjected to attack by solutions emanating from the intrusive. The pyroxenite can, therefore, be best described according to its genesis as a pegmatitic contact zone deposit.

MICA-APATITE. The mica and apatite found in the Buckingham district are generally associated with one another in the same deposit and have apparently originated in the same way and on this account can best be described together. Both minerals are evidently genetically related to the pyroxenite, since they either occur in the pyroxenite or in the rocks of the Grenville and Buckingham series near their contact with the pyroxenite.

With regard to the origin of these mineral occurrences, it has already been stated, in the section in which the pyroxenite was described, that it was believed they are a special type of contact metamorphic deposit, having been formed by the action of pegmatitic solutions emanating from the intrusives of the Buckingham series. Accompanying and following the formation of the pyroxenite there was developed a great variety of other lime-silicate minerals some of which crystallized out, partly as single crystals, partly in aggregates, and partly in veins, and in this way the deposits of mica and apatite were apparently developed.

The other theory, which has been championed by Spence in recent years, is that the pyroxenite is a basic igneous intrusion, and that the phlogopite and apatite are formed through pegmatitic emanations from the pyroxenite magma. The following is quoted from Spence (1929, pp. 40 and 41):

Various characteristics of the pyroxenites and mica-apatite bodies lend considerable support to the view that they are of igneous origin, and are basic intrusives, akin to pegmatites. Chief of these is the fact that the pyroxenite exhibits sharp, frozen contacts with the enclosing gneiss or limestone. The writer has observed no instance of a gradual transition of mica-bearing pyroxenite to country rock, as might be expected if the pyroxenite were a product of metamorphism. The fact that the usual constituent minerals of the pyroxenites—augite, hornblende, scapolite, apatite, sphene, pyrite, and pyrrhotite—are all typical of high temperature rocks, and that the four first-named, with their associated phlogopite, frequently occur in the form of "giant" crystals so typical of pegmatites, lends support to the view that the parent rock is of igneous origin and represents a basic counterpart to normal granite pegmatite. The often drusy character of the pyroxenites, also, is common to many igneous rocks, and is especially characteristic of pegmatites.

A year later Spence and Carnochan (1930, p. 10) described the uraninite-bearing syenite pegmatites of the Wilberforce, Ontario, district and compared them with the mica- and phosphate-bearing pyroxenites of the Ottawa district. Their conclusions follow:

The close structural similarity exhibited by these two rock types, and the fact that both often carry crystals of apatite and mica in a calcite filling of pockety cavities, provides strong evidence that the pyroxenites are of igneous, intrusive origin, rather than metamorphosed sediments as has often been believed.

It will be seen subsequently that some ideas from both of these theories have been incorporated in the theory suggested in this paper.

Pertinent factual data. In the years that the mica-phosphate deposits of eastern Canada have been investigated, a number of observations have been made which bear upon their genetic history. The present investigation has added a few more. The observations that are pertinent to the history of mineralization and the origin of the solutions from which the minerals crystallized are listed in the following paragraphs. Any acceptable theory of mineral origin must be in accord with these field and laboratory observations.

1. Sequence of mineralization. In the preceding pages, evidence is presented to show that all of the minerals occurring in the phlogopite-apatite deposits (exclusive of the supergene minerals) belong in one of three groups: the pyroxenite group, the microcline-pegmatite group, and the calcite group. It is believed that the third group is a separate phase.

2. Replacement of earlier minerals by later. Close examination of the specimens has shown that replacement was a very important process during the mineralization of the mica-phosphate deposits. Diopside has been replaced by actinolite, scapolite, and microcline; calcite has replaced all of the earlier minerals; and many other replacements have taken place.

3. Vein character of minerals belonging to calcite stage. These minerals transgress the pyroxenite and feldspar rock in veins and irregular masses. They appear to be hydrothermal deposits.

4. Openings in the deposits. The presence of cavities in these deposits suggests the existence of a hydrothermal phase which caused the dissolution and removal of some of the earlier minerals. It is believed that the euhedral diopside crystals grew outward into solution cavities which were subsequently filled with hydrothermal calcite.

5. Cross-cutting relationship of pyroxenite to country rock. In some cases the pyroxenite conforms to the regional strike and dip of the pre-existing metamorphic rocks, but in other instances it is decidedly transgressive. In the latter case, at least, the pyroxenite could not have been formed by the complete metamorphism of limestone *in situ*.

6. Some of the minerals are characteristic of contact metamorphism of magnesian limestone. Such minerals as diopside, scapolite, and phlogopite are formed, in most instances, where interaction has taken place between siliceous solutions emanating from a magma and dolomitic country rock.

7. Magnesian limestone is scarce in the immediate vicinity of the majority of mica-phosphate deposits. In reply to this observation the proponents of the contact metamorphic theory state that such limestones were originally present, but have been completely pyroxenized. However, in the one deposit (Dacey) studied during the present investigation where limestone occurs in the country rock adjacent to pyroxenite, this limestone is not greatly metamorphosed. Evidently, the magma from which the pyroxenite and associated minerals crystallized was relatively cool by the time this point was reached or the metamorphism of the limestone would have been more intense.

8. The abundance of microcline pegmatite and finer grained feldspar rock. The existence of so much microcline necessitates postulating a source magma with a high content of potash. No rocks are known to me which consist dominantly of pyroxene and potash feldspar. The nearest approach is an intermediate rock, shonkinite, which contains as essential constituents potash feldspar, augite, and plagioclase feldspar, in the order named. Therefore, it is difficult to conceive of a primary pyroxenite magma from which potash feldspar only would precipitate in any great abundance.

The prevalence of the microcline rock has been largely overlooked by previous investigators.

Suggested theory. The microcline pegmatite is believed to be the key to the origin of the phlogopite-apatite deposits. The suggested steps in the formation of these deposits follow.

1. The crystallization of a deep-seated, phosphorus-rich granite magma. The original magma must have been rich in phosphorus to account for the relatively large volume of apatite. In this respect, the deposits of eastern Canada are different from those of Madagascar (Savornin, 1934) where phlogopite also occurs in pyroxenite, but is not accompanied by abundant apatite.

2. The escape of aqueous pegmatite magma rich in silica, alumina, potassium, phosphorus, water, and minor "fugitives" such as zirconium and titanium.

3. The addition of calcium, magnesium, and carbon dioxide to the pegmatite magma, through contamination by dolomitic limestone encountered during the upward movement of this magma. The contamination no doubt took place at a level far below that of the present surface, where temperatures were high and the reaction between magma and carbonate country rock great. The temperatures which prevailed at the level now exposed by erosion in eastern Canada were relatively low, as shown by the insignificant amount of contact metamorphism of country rock (including limestone) adjacent to both the phlogopite-apatite deposits and the pegmatites in this district.

Reactions between granite or granite pegmatite magmas and limestone or dolomite country rock, producing diopside, phlogopite, sphene, and other minerals, have been postulated by various investigators, including Eskola (1922), Kinosaki (1932), Shaub (1929), and Watson (1929). The theory advanced here, however, involves reaction on a much greater scale, producing a mixed magma. Fersman (1931) refers to a "migmatic line" of pegmatite in which a pronounced interaction takes place between country rock and residual solutions, producing new equilibria and mineral associations.

4. Intrusion of the contaminated pegmatite magma into the crust at levels now exposed by denudation. It is probable that the present levels lie near the top of the intrusions.

5. Crystallization of the mixed (contaminated pegmatite) magma. The first to crystallize was diopside, and it practically completed crystallization before the next mineral, microcline, began to form. The precipitation of diopside used up some of the calcium and magnesium in the mixed magma, and also a considerable quantity of silica. The latter was abundant in the original magma, but its percentage had been lowered through contamination, and the crystallization of diopside brought about further desilication. This process did not go far enough to produce feldspathoids during subsequent mineralization, but the desilication was sufficient to cause a notable decrease in the amount of quartz present in the microcline pegmatite.

The crystallization of diopside was followed by precipitation from fluid residual magma of veins and masses of microcline pegmatite. Finer grained phases of feldspar rock resulted where cooling was rapid. My best guess as to why some of the calcium did not unite with the silica and alumina to make lime feldspar is that there was an excess of potash available, which had greater affinity for the alumina and silica than the calcium. Also, the absence of a potash-lime isomorphous series in the feldspar group prevented the formation of a feldspar containing both oxides.

Accompanying the microcline were quartz (where diopside crystallization did not rob the magma of all its excess silica), scapolite, sphene, pyrite, actinolite, tremolite, zircon, and hornblende in widely varying abundance. The diopside was especially susceptible to replacement by actinolite and scapolite.

The microcline pegmatite bodies appear to be similar to the "off-shoot dikes" or "dissogénites" of Savornin (1934), LaCroix (1922, p. 373-375), and others who describe the phlogopite deposits of Madagascar.⁵

The crystallization of feldspar and associated minerals completed the magmatic (mass crystallization) phase. Water, phosphorus, carbon dioxide (added by contamination), some of the potash, much of the calcium and magnesium (likewise mainly added during contamination), and other substances did not enter into the minerals formed during this phase. They became fugitive material, forming highly attenuated magmatic solutions which introduced a hydrothermal phase. These solutions travelled through the deposits dissolving older minerals and depositing new minerals in veins and cavities. The most abundant mineral deposited during this period was calcite. Common associates were phlogopite and apatite. Accessories include second generations of actinolite and diopside, and tourmaline, fluorite, barite, chalcocopyrite, and sphalerite.

The hydrothermal phase ended the hypogene mineralization of the mica-phosphate deposits.

The differences between this theory and that of Spence are not great, and are based to a considerable extent upon differences in nomenclature. Spence considers the mica-phosphate deposits to be pegmatitic segregations from a pyroxenite magma. I consider the magma to have been originally granite pegmatite, made partially basic by contamina-

⁵ My attention was called to this similarity through correspondence with H. S. Spence, who also sent me specimens of "dissogénites" from several localities beside those visited by me.

tion with dolomite. In either case the deposits themselves are considered to be pegmatitic off-shoots from the same magma that produced the pyroxenite.

In an earlier paper, Spence (1920, p. 122) was in close accord with my present views:

The origin of the mica-apatite-calcite bodies is probably to be attributed to the agency of later pegmatitic phases of this granite and of the aqueous solutions accompanying the pegmatites. These solutions were charged with phosphoric acid, and the apatite is, therefore, to be considered of igneous origin, rather than to have been derived from the original limestones. The calcite probably represents calcium carbonate dissolved from the limestones by heated waters, and redeposited in cavities in the pyroxenites, while the mica is of contact-metamorphic origin.

SUMMARY OF CONCLUSIONS

The theory of contact metamorphism that has been advanced to explain the origin of the phlogopite-apatite deposits of eastern Canada is untenable because of the cross-cutting relationship of the pyroxenite to the country rock. Furthermore, the calcite in these deposits is hydrothermal in origin and not residual, and, in the exceptional cases where limestone does border pyroxenite, the contact metamorphic effects are slight, due to the relatively low temperature of the intrusive magma at that level. The "basic intrusive" theory needs modification in order to account for the high potash content of these rocks.

The theory advanced in this paper as best fitting the observations made in the field and laboratory is that a granite pegmatite magma, unusually rich in phosphorus, became contaminated with dolomite or dolomitic limestone at much deeper levels than the present surface, where the temperatures were considerably higher. This contaminated magma moved upward into the rock now exposed, and crystallized. Diopside (pyroxenite) was the earliest product, followed by microcline and several associated minerals. Finally, aqueous solutions from the deeper crystallizing magma introduced a hydrothermal phase in the already solidified parts of the pegmatite, during which calcite, apatite, phlogopite, and many other minerals were deposited.

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