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CANADA

DEPARTMENT OF MINES AND TECHNICAL SURVEYS

GEOLOGICAL SURVEY OF CANADA
BULLETIN 23

PETROLOGY OF THE RICHARDSON RADIOACTIVE DEPOSIT, WILBERFORCE, ONTARIO

BY
Robert B. Rowe

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
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PREFACE

In the Wilberforce region of southern Ontario are several deposits that possess some of the characteristics of pegmatites but that contain calcite and fluorite as essential minerals. Some of these deposits carry uraninite.

A method of detailed mapping of the internal structures of complex granitic pegmatites has recently been perfected in the United States, and has been found useful in appraising and exploring such occurrences. In the present report, the author has applied this method to an investigation of a radioactive calcite-fluorite deposit near Wilberforce on which previous underground work and diamond drilling permitted a three-dimensional study. This study has demonstrated that the method is applicable, at least to this deposit, and has thrown additional light on the probable origin of the deposit itself.

GEORGE HANSON,
Chief Geologist, Geological Survey of Canada

OTTAWA, April 30, 1952

PETROLOGY OF THE RICHARDSON RADIOACTIVE DEPOSIT, WILBERFORCE, ONTARIO

INTRODUCTION

The Richardson deposit, near Wilberforce, Ontario, is a radioactive occurrence in the Grenville sub-province of the Canadian Shield (*See* Figure 1). Discovered in 1922, it was one of the first deposits in Canada to be explored as a possible source of radium, and was brought to the attention of geologists by Ellsworth (1932)[1]. Because of the peculiar

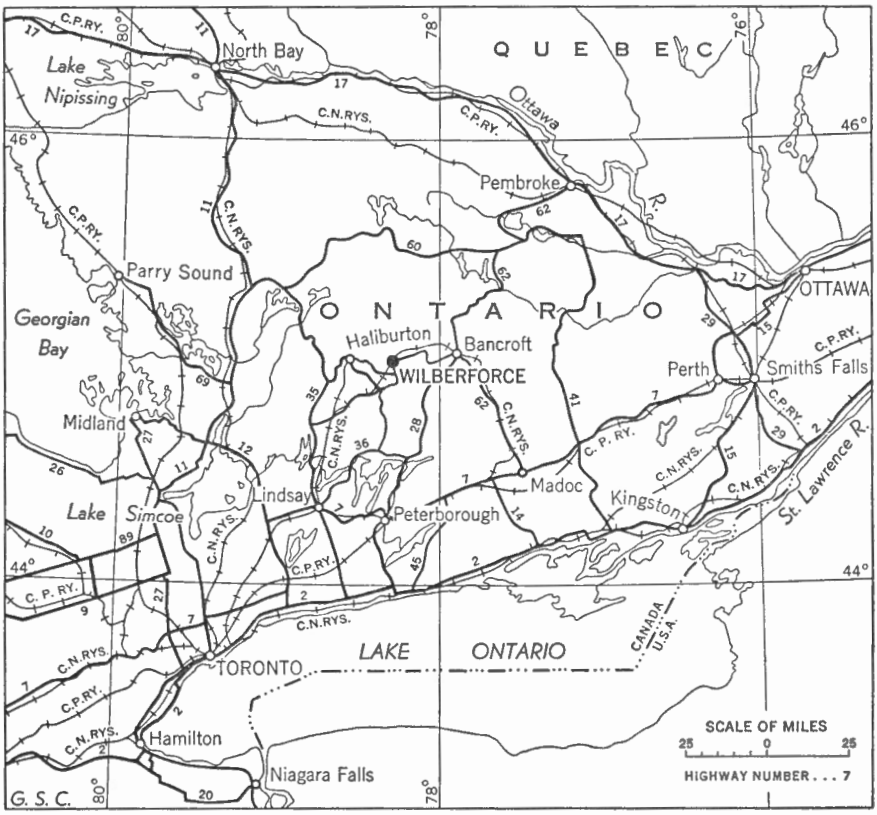

Figure 1. Index map, showing location of Wilberforce, Ontario.

association of feldspars, hornblende, calcite, fluorite, apatite, and uraninite, and the occurrence of excellent uraninite crystals, the deposit has become a well-known mineral locality. The deposit is also of interest because it is in the heart of the Haliburton-Bancroft area, made famous by the work of Adams and Barlow (1910). This area is about 70 miles north of Lake Ontario.

[1] Dates in parentheses are those of References at the end of this report.

Internal zoning, the occurrence of large crystals, and the peculiar mineral assemblage are the outstanding features of the deposit. Although the deposit has some characteristics that are common to granitic pegmatites, and others that are shown by many basic dykes that cut granitic rocks, the writer believes that the deposit formed by the action of high-temperature hydrothermal solutions containing silica, carbon dioxide, fluorine, and boron, and that it is composed of rearranged wall-rock material together with material deposited from these solutions.

In 1950 the Richardson deposit and the associated wall-rocks were mapped by the writer on a scale of 1 inch to 20 feet, and Geiger-counter readings were taken on all exposures. Chip and channel sampling supplemented these readings. The underground workings were also examined and mapped. Exposure to weather has removed the pencil markings from the diamond-drill core-boxes; however, the core was tested with a Geiger counter and a scintillometer. References to diamond-drill results in this report are based on logs supplied the writer by Fission Mines Limited.

The laboratory investigation was based on a study of fifty-four thin sections and about a hundred hand specimens.

ACKNOWLEDGMENTS

The writer thanks Professor E. N. Cameron of the University of Wisconsin, whose lectures on pegmatites provided much of the background for this study, and whose help in the field and in the laboratory greatly aided the writer in his interpretation of the deposit. Thanks are due to A. H. Lang of the Geological Survey of Canada, and to B. D. Weaver, geologist, Fission Mines Limited, for many courtesies. Fission Mines Limited kindly supplied an unpublished report by Mr. Weaver containing much useful information, including diamond-drill core-logs.

The field work was done under the auspices of the Geological Survey of Canada, to whom the writer is indebted for permission to use this material for thesis purposes. In the field, he was capably assisted by G. E. Taylor.

Laboratory work was done in the Economic Geology Laboratories at the University of Wisconsin.

LOCATION

The Richardson deposit is in lots 4, 5, 6, and 7, con. XXI, Cardiff tp., Haliburton county. A road leading south to the workings joins the Wilberforce-Bancroft road 3·8 miles from the post office at Wilberforce. At present, a new road to the town of Bancroft is under construction, and it will be necessary to use the old road to reach the deposit in future.

HISTORY

Ellsworth (1932, p. 213) states that uraninite was discovered by W. M. Richardson on lot 4, con. XXI, in 1922. The original find was referred to as the Richardson discovery and as the Baycroft pit. Further prospecting by Mr. Richardson revealed a radioactive area 3,100 feet long and 250 feet wide, extending north 55 degrees east from the original discovery.

In 1929, the Ontario Radium Corporation Limited of Toronto acquired the property, and in 1929, 1930, and 1931 much work was done on the Richardson deposit. This comprised driving an adit, sinking an inclined

shaft, and doing surface trenching and some open-cut mining. Inter Radium and Resources Limited succeeded the Ontario Radium Corporation, and was in turn succeeded share-for-share by Wilberforce Minerals Limited. The property is now owned by Fission Mines Limited, 1 Roncesvalles Avenue, Toronto, Ontario.

A second deposit was discovered parallel with the Richardson and 600 feet south of it. Although similar in many ways, both structurally and mineralogically, to the Richardson deposit, this deposit is not radioactive. Considerable attention has been given it by Fission Mines Limited because of its fluorite content, but exploration has been restricted to stripping, trenching, and diamond drilling.

There are forty-eight diamond-drill holes on the property now held by Fission Mines Limited; of these, thirteen were drilled on the Richardson deposit. The property was surveyed on a 100-foot grid system by H. G. Pitt in 1947. Lines were cut and stations at 100-foot intervals were marked by wooden pegs. In 1948, B. D. Weaver, geologist for Fission Mines Limited, and E. O. Foster, research engineer for Nepheline Products Limited, Lakefield, Ontario, mapped the pits and trenches and located the drill-holes with reference to Mr. Pitt's survey. Diamond-drill cores were logged, and samples were sent to Nepheline Products Limited for assay with respect to uranium or flourine content, or both.

During the exploration of the Richardson deposit, about 850 feet of drifting was done. The remains of a mill can be found near the adit. No commercial shipment of ore from the property, or production from the mill, has been recorded, and the property has been idle since 1949.

GENERAL GEOLOGY

REGIONAL GEOLOGY

The Richardson deposit is located in the heart of the Haliburton-Bancroft area, described by Adams and Barlow. An outline of the regional geology is given by the following quotation from these authors (1910, p. 49):

"The district was in Precambrian times covered by a sea, in which there was deposited an immense series of sediments aggregating many thousand feet in thickness. The thickness of the series shows that the period of deposition was a long one, and the prevailing calcareous character of the sediments shows that it was probably of marine origin. That there was land, however, in the vicinity, is shown by the fact that a certain amount of argillaceous and arenaceous sediment found its way into the sea. It was deposited at a time of violent volcanic activity, for there is reason to believe that a large part of the great volume of amphibolite interstratified with the normal sedimentary material represents volcanic ashes and other clastic material of volcanic origin, which was from time to time thrown into the sea in which normal sedimentation was going forward. There are also flows of porphyritic lava, and bosses of plutonic rocks, probably representing the deeper parts of volcanic centres.

"Concerning the nature of the basement upon which this immense accumulation of sedimentary material was laid down we have no certain knowledge, for no part of it can be recognized at the present time as the original floor.

"This great series was then folded in a general direction N. 30 degrees E., and probably contemporaneous with the folding, was invaded by an enormous body of granite. This granite slowly rose in the form of great batholiths into the overlying series, disintegrating it and becoming filled with countless fragments of the invaded rock. In the case of limestones this granite not only disrupted them, but changed them into amphibolite. The amphibolite produced in this way, as well as that referred to above as occurring interstratified with the limestones, and of different origin, was in many places dissolved by, or incorporated into, the substance of the granite, taking the form of basic streaks or schlieren.

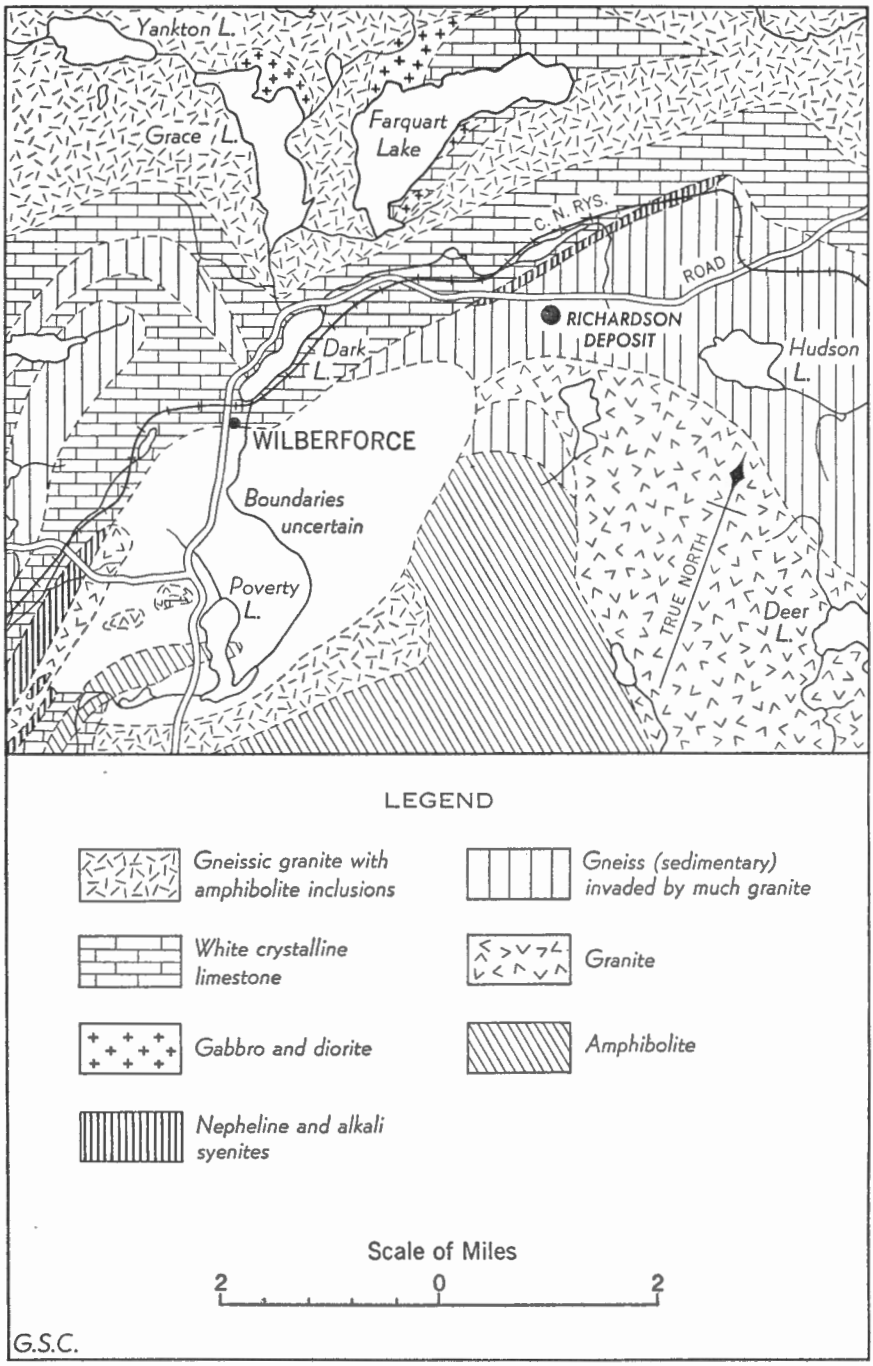

Figure 2. Geological map in the vicinity of Wilberforce, Ontario, showing location of the Richardson radioactive deposit (geology after Adams and Barlow, 1910).

"While in the southeast corner of the area the sedimentary cover is thick, and almost continuous, on going toward the northwest it becomes, as the result of more intense erosion, progressively thinner, while the volume of granite breaking up through it becomes greater until the northern limit of the Bancroft sheet is reached, where the sedimentary series is fretted away, and is represented only by occasional shreds and patches of amphibolite scattered through the batholiths of gneiss, and arranged in lines conforming to the strike of the foliation of the latter. The erosion to the north has cut down into and laid bare a deeper part of the section, where all the rocks, both invaded and invading, everywhere show indisputable evidence of great movement while in soft or plastic condition."

LOCAL GEOLOGY

The Richardson deposit is a series of lenses in a belt of rocks mapped by Adams and Barlow as "gneiss (sedimentary) invaded by much granite", and by Satterly (1943) as "granite, granite gneiss, pegmatite; hybrid gneisses of igneous and sedimentary origin". Banding in the gneisses strikes northeasterly and dips to the south (*See* Figure 2). The deposit has been traced at intervals for 3,100 feet (*See* Figure 3). Figure 4 shows the detailed geology at and near what is now called the "Richardson pit", near the west end of the deposit, and Figure 5 shows the detailed geology of the eastern part of the deposit; the intervening 1,400 feet of deposit is not illustrated in detail.

Four types of wall-rock are associated with the deposit: oligoclase-biotite-magnetite gneiss, scapolite-biotite gneiss, oligoclase amphibolite, and perthite-quartz pegmatite. The principal host rock, oligoclase-biotite-magnetite gneiss, is generally foliated, because of the orientation of the biotite, and appears massive where the biotite is unoriented. It is interbanded with oligoclase amphibolite and was probably formed by feldspathization of that rock. Towards the eastern end of the deposit, the wall-rock is mainly scapolite-biotite gneiss, with interbanded amphibolite, but includes some perthite-quartz pegmatite (*See* Figure 3). In general, the gneisses strike northeast and dip 20 to 40 degrees southeast.

In the light of what is known of the geology of the Haliburton-Bancroft region, it seems probable that the oligoclase amphibolite and scapolite-biotite gneiss are products of regional metamorphism. Later feldspathization produced oligoclase-biotite-magnetite gneiss. The Richardson deposit clearly transects this gneiss in places and, therefore, was formed subsequently to it. These relationships are discussed in detail on the following pages.

DESCRIPTION OF WALL-ROCK UNITS

OLIGOCLASE AMPHIBOLITE

Amphibolite, consisting principally of plagioclase and hornblende, with varying amounts of biotite, occurs as conformable bands and lenses in oligoclase-biotite-magnetite gneiss. The amphibolite is melanocratic, medium grained, and equigranular. Foliation, where present, is due to a parallel orientation of the mafic constituents.

Under the microscope, the hornblende of fresh or but little altered amphibolite is seen to be euhedral. It is pleochroic, from yellowish green to bluish green to dark green, has an extinction angle ($z \wedge c$) of 21 degrees, and resembles the common hornblende of the amphibolites described by Adams and Barlow. Most of the associated plagioclase is untwinned, but a few

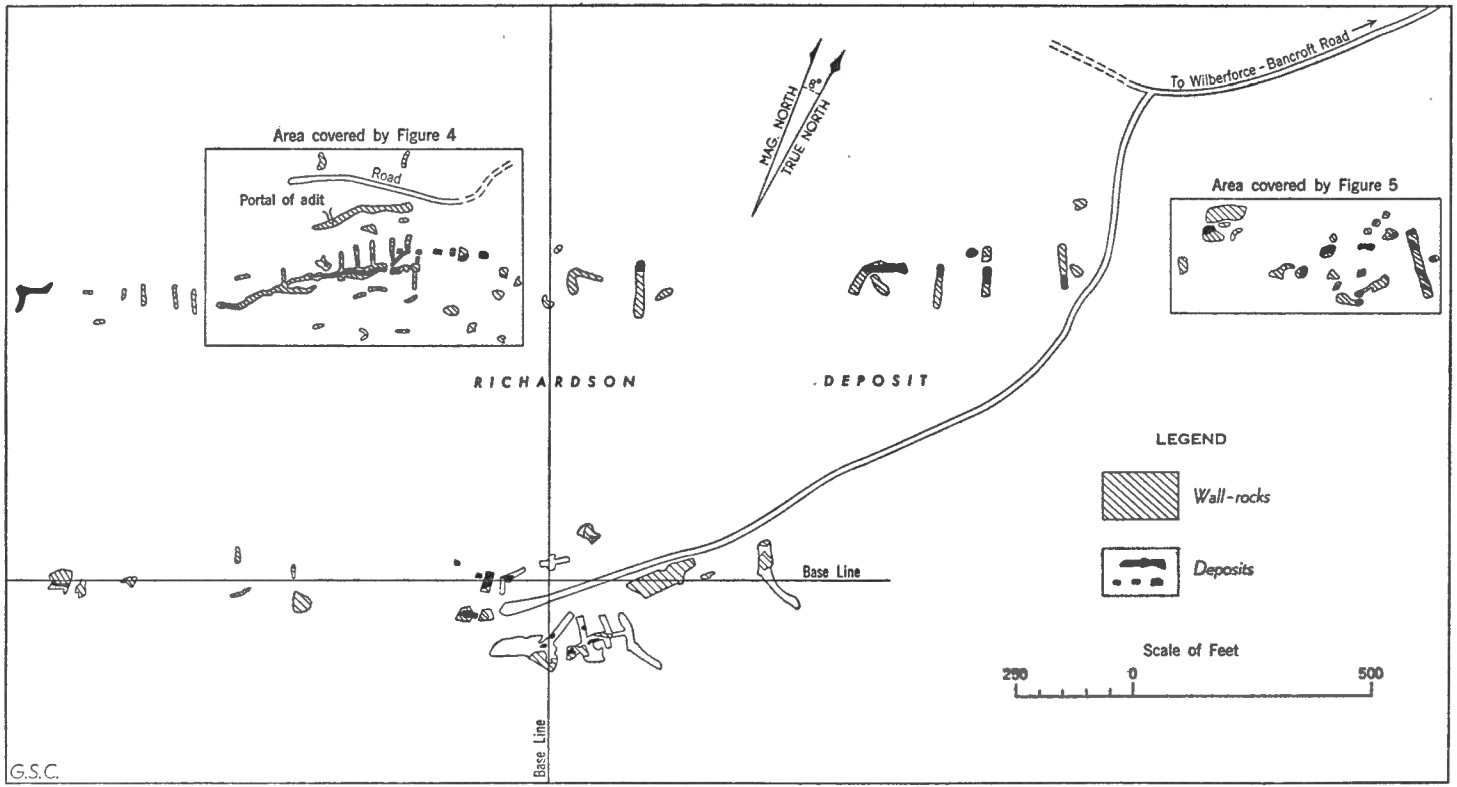

Figure 3. Generalized geological plan of a principal part of the property of Fission Mines Limited, showing parts of Richardson deposit mapped in detail (*See* Figures 4 and 5, in pocket).

grains exhibit albite twin-lamellæ, and measurements of their extinction angles ($x' \wedge 010$ in the zone perpendicular to 010) indicate a compositional range from An_{25} to An_{31}. The biotite of the amphibolite is pleochroic, from pale yellow to brown to opaque, and is probably the common iron-bearing type. Accessory minerals are titanite, apatite, zircon, pyrite, and black metallic minerals including magnetite. In general, titanite, apatite, and zircon are surrounded by pleochroic haloes where in contact with biotite. In places, titanite occurs as a selvedge around black metallic grains, or a rounded black metallic grain occurs in the centre of a titanite crystal, indicating that the black metallic minerals are, in part, ilmenite.

Other specimens of the oligoclase amphibolite with the same megascopic appearance are slightly different under the microscope. The hornblende has a decided bluish tint, indicating an enrichment in soda, whereas the biotite is pleochroic from pale yellow to olive-green to a slightly darker olive-green, indicating a loss in iron. In places, the biotite assumes a peculiar fibrous habit. Titanite may be partly altered to a creamy, opaque

Figure 6. Camera-lucida drawing of oligoclase amphibolite, showing relations of hornblende (H), oligoclase (O), biotite (B), carbonate (C), titanite (T), and apatite (A). Note replacement of oligoclase by carbonate. (Magnification, X27.)

material, probably leucoxene. Microcline grains are associated with biotite or along cleavages in biotite. Some of the plagioclase twin-lamellæ are bent or wedged shaped, and red dust appears along some of the lamellæ. In one thin section calcite has partly replaced plagioclase (*See* Figure 6), and fluorite has partly replaced biotite. The loss of iron in the biotite, the

occurrence of microcline at the expense of biotite, and the occurrence of red dust along some of the plagioclase twin-lamellæ represent an incipient stage in the transformation of amphibolite to oligoclase-biotite-magnetite gneiss.

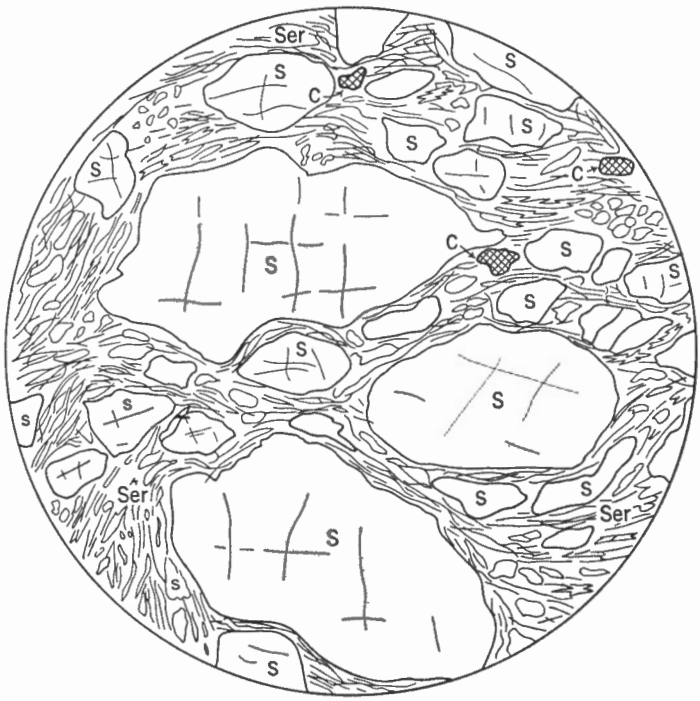

Figure 7. Camera-lucida drawing of scapolite gneiss, showing augen of scapolite (S) in a groundmass of sericite (Ser), scapolite, and carbonate (C). (Magnification, X27.)

SCAPOLITE-BIOTITE GNEISS

Scapolite-biotite gneiss is the principal host rock at the eastern end of the Richardson deposit. It is layered, and strikes and dips can be measured at the contacts between layers. Individual layers vary in grain size, but are generally massive and contain euhedral scapolite grains up to 8 mm. in greatest dimension. Biotite grains are commonly 2 or 3 mm. in length, and are interstitial to the scapolite; in places, the biotite is oriented, producing foliation. The greenish grey scapolite and the black biotite give the rock a melanocratic appearance.

Microscopic examination reveals that plagioclase feldspar may occur in amounts up to 46 per cent, or may be entirely lacking. The plagioclase is andesine (An_{44}). Refractive indices, determined by the coloured Becke line method (Emmons and Gates, 1948), indicate that the scapolite ranges in composition from 66 per cent marialite and 34 per cent meionite (Ma_{66} Me_{34}) to 47 per cent marialite and 53 per cent meionite (Ma_{47} Me_{53}). Mostly fresh, it is altered in places along cleavages and fractures to a green, fine-grained, platy, chlorite-like substance. The biotite is brown and similar

to that of the oligoclase amphibolite, with many flakes a beautiful blue-green around their edges; it occurs in amounts up to 35 per cent. Very minor amounts of carbonate, apatite, titanite, zircon, and black metallic minerals were observed in most thin sections. The titanite is usually partly altered to leucoxene. Other, less common accessory minerals are chlorite, sodic hornblende, fluorite, white mica, tourmaline, and pyrite.

The relationship of the scapolite-biotite gneiss to the other rocks is obscure, but it and amphibolite are common associates as products of regional metamorphism in the Grenville sub-province. As the alteration of the titanite and biotite is similar in both these rocks it seems probable that both were affected by the same solutions.

In one thin section, augen of scapolite were observed in a groundmass of white mica, crushed scapolite, and carbonate (*See* Figure 7). This suggests that the permeating solutions were capable of producing the common minerals of hydrothermal alteration when pressure-temperature conditions were favourable.

OLIGOCLASE-BIOTITE-MAGNETITE GNEISS

Oligoclase-biotite-magnetite gneiss is the principal rock on the property of Fission Mines Limited. It is medium grained and equigranular, and has the pinkish colour of the plagioclase, the major constituent. In most places the rock is foliated because of the orientation of the contained

Figure 8. Camera-lucida drawing of oligoclase-biotite-magnetite gneiss, showing replacement of plagioclase (at extinction) by microcline (cross-hatched). Note bent and wedged-shaped plagioclase lamellæ. (Magnification, X43.)

biotite, but where the biotite is unoriented the rock appears massive. The proportions of biotite and magnetite vary, with, generally, the amount of magnetite increasing as biotite decreases. In many places the rock is essentially plagioclase-magnetite gneiss, with little or no biotite, and many outcrops contain veinlets of hornblende bordered by narrow selvedges in which biotite and hornblende have been removed.

Figure 9. Camera-lucida drawing illustrating alteration of biotite (B) to a fine-grained aggregate of chlorite (Ch) and magnetite (M) in oligoclase-biotite-magnetite gneiss. (Magnification, X27.)

Microscopic examination shows that the plagioclase varies in composition from An_{25} to An_{33}, with most of it An_{28} to An_{30}. Twin-lamellæ are commonly wedge shaped, bent or dislocated by micro-faults (*See* Figure 8), and red dust, probably hematite, appears along lamellæ, cleavages, fractures, and grain boundaries. The plagioclase is generally only slightly altered, but in one thin section was seen to be largely replaced by sericite, carbonate, and a dusty material, probably kaolinite. Biotite comprises up to 50 per cent of the rock, and is usually pleochroic from pale yellow to olive-green to yellowish green; in some sections it is pale bluish green around the edges. In places the biotite assumes a peculiar fibrous habit. Aggregates of fine-grained, olive-green biotite flakes were seen in some specimens and, apparently, have replaced hornblende and larger biotite grains. Remnant hornblende appears in several sections, some of it veined or partly replaced by a yellow, fine-grained, platy material. Magnetite

increases as biotite decreases, and in one section occurs along fractures, cleavages, and lamellæ in plagioclase. As the biotite content diminishes, microcline appears, and may comprise as much as 80 per cent of the rock. In small amounts, it occurs interstitially to the plagioclase, but the grain size increases with the amount. Most of the microcline is clear, whereas the plagioclase contains red dust. Titanite, apatite, and zircon exhibit pleochroic haloes where in contact with biotite, and, as a group, constitute up to 12 per cent of the rock. The titanite is much altered, commonly to a brownish yellow substance. As the biotite content decreases, so also does the content of these accessory minerals; titanite is the first to disappear, whereas zircon is the most stable and may be found even where biotite is lacking. Carbonate occurs in amounts up to 12 per cent, and is generally interstitial, but some micro-veinlets were seen. In places chlorite occurs, apparently at the expense of biotite (*See* Figure 9). A little tourmaline can generally be seen, and a few grains of fluorite were encountered.

Several features exhibited by the oligoclase-biotite-magnetite gneiss tend to support the conclusion that it has formed by the feldspathization of the oligoclase amphibolite:

(1) Remnant hornblende grains occur in the gneiss.

(2) Radioactive titanite, apatite, and zircon are accessory minerals in both rocks.

(3) The plagioclase of the gneiss is strikingly similar in composition to that of the amphibolite.

(4) The grain sizes of the two rocks are similar.

(5) The altered biotite of the amphibolite is similar to the biotite of the gneiss.

(6) The amphibolite is characterized by incipient development of red dust in the plagioclase grains, whereas the occurrence of red dust in the plagioclase is an outstanding feature of the gneiss.

PERTHITE-QUARTZ PEGMATITE

Perthite-quartz pegmatite is an important host rock in the eastern part of the Richardson deposit, but is lacking in the vicinity of the Richardson pit. In places, the rock appears to be merely a highly feldspathic rock containing quartz stringers, but where viewed at a favourable angle the cleavage surfaces of the large perthite crystals can be seen. Apparently the rock was deformed so that the interstitial quartz was drawn out into vein-like lenses. This opinion is substantiated by the fact that nowhere does a quartz stringer cut a large perthite crystal.

Ellsworth (1932, p. 216) suggests that the calcite-fluorite body, with its feldspar borders, is genetically related to the perthite-quartz pegmatite. In view of what is known concerning the paragenesis of granitic pegmatite units (Cameron, Jahns, McNair, and Page, 1949, pp. 97-106), it seems highly improbable that the Richardson deposit represents a late phase in the crystallization of a granitic pegmatite. The writer is inclined to consider the relationship between the perthite-quartz pegmatite and the Richardson deposit as being structural rather than genetic.

THE RICHARDSON DEPOSIT

GENERAL DESCRIPTION

The Richardson deposit belongs to a group of deposits found between Wilberforce and Bancroft, which Ellsworth (1932, p. 216) describes as "vein-shaped bodies consisting chiefly of either calcite or calcite intergrown with dark purple fluorite, along with a certain amount of feldspar (plagioclase mostly) which occurs typically at the edges of the vein-like bodies next to country rock". It lies within an area 3,050 feet long and 200 feet wide, trending north 55 degrees east (*See* Figure 3). At the Richardson pit (*See* Figure 4), the deposit is represented by a vein about 12 feet in maximum thickness and 190 feet long, and several small, subparallel veins that strike north 48 degrees east and dip 32 degrees southeast. These veins are lenticular masses that pinch out at depth, as evidenced by the underground workings and diamond-drill cores. The veins cross the foliation of the gneiss at a slight angle, this relationship being clearly shown at the Richardson pit, where drag in the hanging-wall gneiss can be seen. The structure of the extreme east end of the deposit, where several small, apparently unconnected veins of random orientation and irregular shape cross the structure of the gneisses, is complicated (*See* Figure 5), and lack of sufficient outcrops and subsurface data make an analysis of the structure difficult.

The veins of the Richardson deposit are zoned, and exhibit internal structural and textural features remarkably similar to those of granitic pegmatites (Cameron, Jahns, McNair, and Page, 1949), although lithologically different. From the walls inward, the zones comprise the following mineral assemblages: oligoclase-microcline, oligoclase-microcline antiperthite, hornblende, and a calcite-fluorite-apatite core. Zones may be missing or telescoped so that the full sequence is represented only in a few places.

Radioactivity at the eastern end of the deposit is associated chiefly with the oligoclase-microcline zone, whereas at the western end, it is associated chiefly with the calcite-fluorite-apatite core.

Deformation later than the crystallization of the calcite and fluorite has caused granulation and flowage of these minerals of the core zone.

STRUCTURAL AND MINERALOGICAL FEATURES OF THE DEPOSIT

General Statement. Although the Richardson deposit exhibits structural features similar to those described by Cameron, Jahns, McNair, and Page (1949) for granitic pegmatites, it varies greatly from granite in chemical composition and, therefore, comprises entirely different mineral assemblages.

Zones, structurally comparable to those of granitic pegmatites[1], are recognizable in the field, and constitute the most outstanding megascopic feature of the deposit. As in the case of granitic pegmatites, these zones

[1] The zones of granitic pegmatites are concentric shells, complete or incomplete, that generally reflect the shape or structure of the pegmatite body. Incompletely developed zones form lenses, trough-like or hood-like bodies, or chains of lenses. The zones are differentiated according to mineralogical or textural differences, and are classified as follows: (1) border zones; (2) wall zones; (3) intermediate zones; and (4) cores. The outermost zone of a pegmatite is the border zone; the next zone is the wall zone; and the zones between the wall zone and the core are intermediate zones. Not all types of zones are everywhere represented in a zoned pegmatite; for instance, many pegmatites have no intermediate zones, and hence are composed of border zone, wall zone, and core. Two or more zones may merge along their strike or dip to form a single unit corresponding to the bulk mineralogy of the two combined zones: this is referred to as 'telescoping'.

are distinguished by textural and lithological differences. Ellsworth (1932, p. 222) recognized that the deposit was banded, and described the bands as they appeared at the Richardson pit. The zones comprise the following mineral assemblages: oligoclase-microcline, oligoclase-microcline antiperthite, hornblende, and a calcite-fluorite-apatite core. The following is a description of the structural and mineralogical features of each zone.

Oligoclase-microcline Zone. The outermost, oligoclase-microcline zone is the most consistent of the deposit. It is structurally similar to the border zone of granitic pegmatites, and is composed almost entirely of medium-grained, equigranular, pink to red feldspar, much of which is iridescent and striated. In places, grains of black metallic minerals and of biotite, hornblende, carbonate, and fluorite are recognizable in hand specimens, and commonly occur as small aggregates. In general, this zone seems to be more radioactive than the wall-rocks or the other zones,

Figure 10. Camera-lucida drawing, showing calcite veins cutting grains of oligoclase and microcline in oligoclase-microcline rock. (Magnification, X27.)

with the possible exception of the core. Radioactivity in the core tends to be localized and attributable to recognizable uraninite crystals, whereas the writer found only two uraninite grains in the oligoclase-microcline zone. The textural difference between the oligoclase-biotite-magnetite gneiss of the walls and the oligoclase-microcline zone of the Richardson deposit seems to be due merely to the lack of biotite in the latter. In general, granitic pegmatites exhibit a more pronounced textural difference between

border zone and wall-rock. Because the feldspar of the wall-rock is pink to red and of the same grain size as the feldspar of the oligoclase-microcline zone, the writer was impressed in the field by the possibility that the oligoclase-microcline zone may represent an originally gneissic wall-rock from which the biotite and magnetite had been removed.

Thin sections show that the principal constituent of the oligoclase-microcline rock is pink to red plagioclase, varying in composition from oligoclase to andesine (An_{27} to An_{34}). The plagioclase lamellæ are commonly wedge shaped or bent. Red dust along grain boundaries, cleavages,

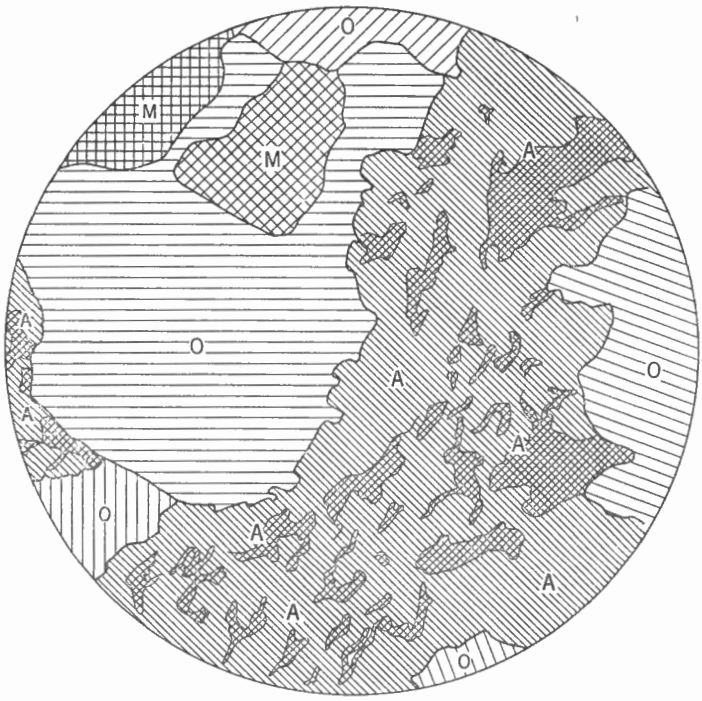

Figure 11. Camera-lucida drawing of antiperthite (A)—an intergrowth of microcline feldspar (cross-hatched) in oligoclase feldspar (close diagonal ruling)—replacing oligoclase feldspar (O) and microcline (M) in oligoclase-microcline rock. Note 'caries' texture. (Magnification, X43.)

fractures, and twin-lamellæ causes the coloration. In the thin sections examined, microcline occurs in amounts ranging from 3 to 70 per cent of the rock, and is usually free from the red dust. Where present in small amounts, it is interstitial to the plagioclase grains, but, as the microcline content increases, so does its grain size. Carbonate mineral generally constitutes less than 3 per cent of the rock, but one thin section contained about 20 per cent. It veins and replaces the feldspars (*See* Figure 10). Most thin sections showed some blue or green tourmaline and in places grains of zircon are scattered through the feldspars. A few apatite crystals, some rimmed by a fine-grained, platy, reddish brown material, were also observed.

Black metallic minerals, fluorite, small grains of olive-green biotite, hornblende remnants in various stages of alteration to a fine-grained, brownish aggregate, and highly altered titanite grains were seen. The presence of apatite, zircon, altered titanite, green biotite, altered hornblende, and black metallic minerals, and the composition of the plagioclase, suggest that the rock of this oligoclase-microcline zone was originally oligoclase-biotite-magnetite gneiss, which, in turn, was originally an oligoclase amphibolite.

Antiperthite Zone. This zone is structurally comparable to the wall zone of a granitic pegmatite (*See* footnote p. 12), and is composed of pegmatitic, pink, antiperthite crystals ranging mostly from 1 inch to 4 inches in size. It is commonly 'telescoped' with the hornblende zone, or with the core, or with both, thus producing a variety of mineral assemblages. Although the antiperthite zone may be missing in many sections of the deposit or present only on one side, it is more commonly present than the adjacent hornblende zone. Where it is incompletely developed, isolated antiperthite crystals may occur partly, or completely, surrounded by the grains of the oligoclase-microcline zone. All antiperthite crystals are euhedral with respect to hornblende, calcite, and fluorite; in one place they were found oriented perpendicular to the walls of the deposit. Although the antiperthite zone (wall zone) is coarser in texture than the oligoclase-microcline zone (border zone), it is usually thinner, whereas the wall zones of granitic pegmatites are usually thicker than the border zones. Where antiperthite crystals project into calcite of the core, they are commonly coated with a black substance referred to by Ellsworth (1932, p. 218) as similar to "Russian leather". Excellent uraninite crystals, as well as magnetite, were found in the coarse feldspars at the Baycroft pit by Ellsworth and others (Ellsworth, 1932, p. 219).

In thin section, the coarse feldspar crystals of the antiperthite zone are seen to be composed of finely twinned plagioclase and microcline. Refractive index determinations indicate that the plagioclase is oligoclase, ranging in composition from An_{23} to An_{27}. The antiperthite crystals contain grains of black metallic minerals, fluorite, tourmaline, and zircon, and their pink colour is due to disseminated red dust. Where they are in contact with the grains of the oligoclase-microcline zone, the boundaries are irregular, curving surfaces, some of which exhibit a 'caries' texture (*See* Figure 11). Corroded oligoclase grains, distinguished from the plagioclase of the antiperthite by their coarser twin-lamellæ, are common in the antiperthite. These features suggest that the antiperthite crystals have replaced the feldspar of the oligoclase-microcline zone.

The antiperthite and oligoclase-microcline zones are chemically alike, and the writer is inclined to believe that the antiperthite rock represents recrystallized oligoclase-microcline rock. Because fluorite is abundant in the deposit, such recrystallization would probably have been aided in part by the fluxing action of fluorine.

Hornblende Zone. The hornblende zone is more commonly missing than the other zones of the Richardson deposit. It is structurally comparable to the intermediate zones of granitic pegmatites, and in common with them tends to be coarser grained than the wall and border zones; in this instance, the largest crystal in the zone is one of hornblende, which, if

fully exposed, would probably exceed 6 feet in length. However, the hornblende zone rarely occurs as a distinct unit; rather, it 'telescopes' with the wall or core zones, thus producing a hornblende-feldspar or a hornblende-calcite-fluorite-apatite assemblage. All the hornblende is euhedral with respect to the calcite and fluorite of the innermost zone or core. In places, wall zone, intermediate zone, and core all telescope to produce a hornblende-feldspar-calcite-fluorite-apatite assemblage, in which all feldspar is euhedral with respect to other minerals. In places, black biotite occurs with the hornblende. The hornblende zone is missing in many places, where, in consequence, the core is in direct contact with the antiperthite zone or even with the outermost, oligoclase-microcline zone. A common feature is the development of the hornblende zone only on one side of the core.

Calcite-fluorite-apatite Core. The innermost zone, or core, is symmetrically situated with respect to the sides of the Richardson deposit, and is composed mainly of white to grey calcite, deep purple fluorite, and green or brown apatite. Post-mineralization shearing movements have caused granulation and banding of the calcite and fluorite, whereas the apatite and magnetite are undeformed and occur as euhedral crystals in the centres of augen-like lenticles. In many places, too, fragments of the other zones have been incorporated in the mineral assemblage. Apatite crystals in the sheared core are oriented like logs in a stream. The pre-deformation texture is preserved in places, where calcite and fluorite are uniformly distributed with respect to each other, usually immediately adjacent to the next zone. The size of the core is variable, and does not seem to be related to a change in the size of the other zones. Calcite-fluorite veinlets project into the other zones, but veinlets composed of the minerals of the other zones do not project into the core.

Fluorite constitutes about 20 per cent of the core, whereas apatite, which occurs as euhedral crystals up to a foot or more in length, comprises less than 2 per cent. The maximum grain size of undeformed calcite and fluorite is about 1 inch. Fluorite from the Baycroft pit and from a pit at the east end of the deposit becomes colourless when exposed to the atmosphere. Euhedral uraninite and magnetite crystals occur in places; the uraninite crystals are generally cubic, but some are cubes modified by the octahedron. Uraninite crystals up to 1 cubic inch and magnetite crystals up to 2 cubic inches in size were seen by the writer, but larger crystals of both minerals have been found by others at the Richardson deposit. Red hematite dust occurs along calcite grain boundaries for several inches around some uraninite crystals, and an intense red halo, up to ½ inch wide, surrounds others. Under the microscope, the halo around one crystal was seen to consist of a very thin layer of fine-grained carbonate, surrounded by a layer of feldspar laths impregnated with hematite dust (*See* Figure 12). The feldspar was determined as labradorite (An_{56}). Minute fractures containing dusty hematite cross much-sheared aggregates of calcite and fluorite at the Richardson pit.

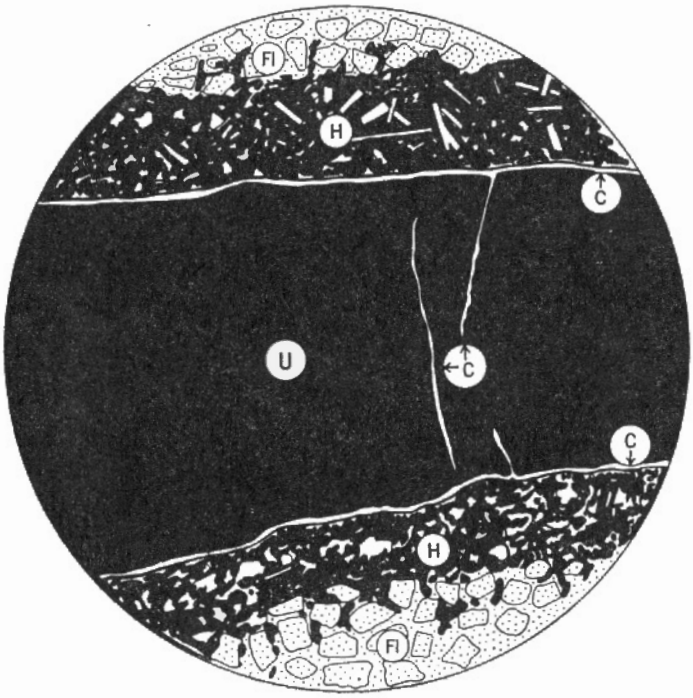

Figure 12. Camera-lucida drawing of uraninite (U) and halo in granulated fluorite (Fl). The uraninite is bordered by a thin layer of carbonate (C) and a layer of feldspar grains and laths impregnated with hematite dust (H). (Magnification, X43.)

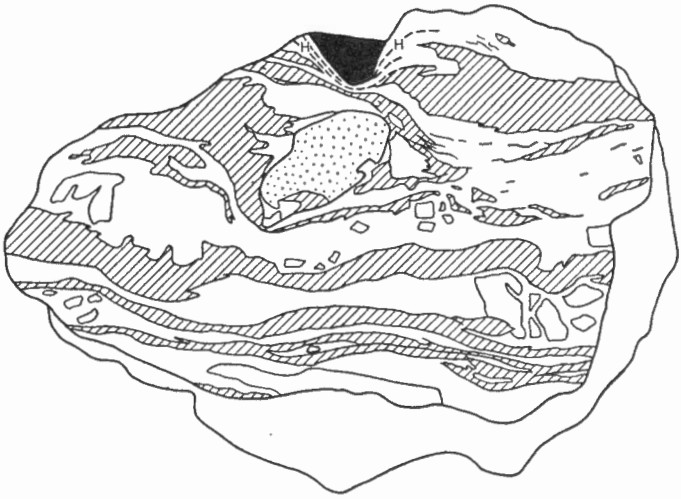

Figure 13. Sketch from polished surface of calcite-fluorite-apatite-uraninite rock, showing segregations of calcite (white) and fluorite (ruled) due to flowage; also flowage around apatite (stipple) and uraninite (black) with associated hematite (H). Large grains of calcite shown here are grey, and occur in a pink to red calcite groundmass. (Magnification, X1·5.)

The following analysis of uraninite from the Richardson deposit was made by Ellsworth (1923, p. 20):

	Per cent
H_2O at 100°	1·49
H_2O above 100°	0·11
Insoluble	0·67
SiO_2	0·58
PbO	11·05
ThO_2	13·56
UO_2	13·55
UO_3	52·04
Ce group oxides	1·85
Yt group oxides	1·24
Fe_2O_3	0·47
Al_2O_3	0·11
MnO	0·003
TiO_2	0·001
CaO	0·25
MgO	0·07
CO_2	0·67
SO_4	0·58
P_2O_5	0·04
F, alkalis	Present
Loss by ignition for 10 minutes in air in closed platinum crucible at low red heat	(4·42)
Total	98·33

PARAGENETIC SEQUENCE

The paragenetic sequence of the minerals of the Richardson deposit is in order, from first to last, as follows:

(1) Oligoclase of the oligoclase-microcline zone

(2) Microcline of the oligoclase-microcline zone

(3) Antiperthite crystals

(4) Hornblende crystals

(5) Calcite-fluorite-apatite core

(6) Uraninite and associated haloes

Uraninite crystals were found in augen-like lenticles (*See* Figure 13), suggesting that shearing took place after uraninite deposition, or that the calcite-fluorite yielded under the pressure of the growing uraninite. On the other hand, the other calcite-fluorite body on the Fission Mines property is neither sheared nor radioactive, which indicates a probable relationship between the occurrence of uraninite and the late shearing movements, regardless of the explanation of the augen structure. Although a few crystals were found in relatively undeformed core, most of them are in highly sheared calcite-fluorite.

Pyrrhotite, pyrite, chalcopyrite, molybdenite, and allanite were observed in very minor amounts in the Richardson deposit, and their position in the paragenetic sequence could not be determined.

ORIGIN OF THE DEPOSIT

OPINIONS OF OTHER INVESTIGATORS

Ellsworth (1932, p. 216) points out that many of the granitic pegmatites of the Wilberforce-Bancroft area contain calcite, dark purple fluorite, and radioactive minerals. He favours the theory that all gradations may exist between the calcite-fluorite bodies—of which the Richardson deposit is one—and the calcite-fluorite-bearing granitic pegmatites, and that the calcite-fluorite bodies represent "a late phase of pegmatite-forming activity". He believes that calcite-fluorite-bearing granitic pegmatites and the calcite-fluorite bodies were deposited from the residual solutions of a granitic magma that had acted on limestone, and thus had a high content of calcium carbonate.

An alternative theory, mentioned by Ellsworth, suggests that the calcite-fluorite bodies were originally limestone inclusions that were caught in the granitic magma and "partly recrystallized and pegmatitized". Ellsworth objects to this theory because the bodies lack such minerals as scapolite, vesuvianite, garnet, and other calcium silicates, which commonly occur near limestone-granite contacts.

Ellsworth presents the views of some other investigators. He quotes A. G. Burrows of the Ontario Department of Mines, who refers to the deposit as "a number of pegmatitic dykes of fine and coarse texture". Professor Charles Palache of Harvard University is quoted as follows: "I am inclined to classify it as a pegmatite in which calcite and fluorite are abnormally abundant". M. E. Wilson of the Geological Survey (Ellsworth, 1932, p. 217) favours Ellsworth's alternative theory.

Professor W. W. Moorhouse of the University of Toronto (oral communication) has suggested a somewhat different mode of origin. He proposes that the calcite-fluorite represents a limestone lens and that the oligoclase-microcline was intrusive syenite. According to this theory, the hornblende crystals were formed by reaction between syenite magma and limestone, and uranium and fluorine were supplied by the syenite magma.

A CRITICAL REVIEW OF THESE OPINIONS

Two distinct theories have been proposed to account for the origin of the Richardson deposit:

(1) The deposit represents a late phase of pegmatite-forming activity, and is genetically related to the granitic pegmatites of the area that contain calcite and fluorite.

(2) The deposit represents a limestone lens that has been acted upon by magmatic solutions.

With respect to the first theory, it seems possible that the calcite-fluorite could represent late pegmatitic solutions, because these minerals are found elsewhere in granitic pegmatites (Jahns, 1946, p. 56). However, the writer believes that this theory entirely fails to explain: (a) the reaction sequence—oligoclase amphibolite to oligoclase-biotite-magnetite gneiss to oligoclase-microcline; and (b) the occurrence of oligoclase-andesine and hornblende, and the lack of quartz, in the deposit.

As a complex granitic pegmatite crystallizes, a progressive decrease in calcium and increase in silica occurs (Cameron *et al.*, 1949, pp. 100-102):

thus, it is difficult to explain the presence of oligoclase-andesine plagioclase and hornblende as products of late pegmatitic solutions. Furthermore, hornblende should crystallize before the plagioclase, but this is not the case in the Richardson deposit. The remarkable similarity between the plagioclase of the oligoclase-biotite-magnetite gneiss and the plagioclases of the deposit, and the presence of remnant minerals of the oligoclase amphibolite in the feldspathic zones of the deposit, are difficult to explain by this process. It is the opinion of the writer, too, that the association of perthite-quartz pegmatite and calcite-fluorite at the eastern end of the deposit is structural, and not genetic.

The second theory does not explain the following features: (a) the reaction sequence—oligoclase-amphibolite to oligoclase-biotite-magnetite gneiss to oligoclase-microcline; and (b) the discordant nature of the deposit.

If the deposit represents a limestone lens altered in situ, the deposit should be conformable with the surrounding paragneisses. Ellsworth's alternate theory and Moorhouse's theory both suggest the presence of a magma. It seems reasonable to assume that, if contact action took place, the rock representing the magma should show an increase in calcium. In the absence of mafic minerals, this increase should be apparent in the anorthite content of the feldspars. But this is not the case, as the anorthite content is remarkably similar in the plagioclases of the amphibolite and the gneiss, and in the oligoclase-microcline and antiperthite. Six large hand specimens containing oligoclase-biotite-magnetite gneiss, oligoclase-microcline, and antiperthite were examined with respect to the plagioclase composition of the several rock types. It was found that the anorthite content in any one specimen did not vary by more than 3 per cent. According to Moorhouse, the oligoclase-microcline represents the syenitic magma that supplied the fluorine. It is difficult to assign the large amount of fluorine necessary to produce the fluorite of the deposit to such a small magma (*See* Figures 4, 5). The general concept provides a source for the calcite, but because calcite is a common gangue mineral in veins, and because it was unquestionably a common constituent of the original Grenville sediments, the writer believes that its abundance in the Richardson deposit can be better explained in another way.

THE WRITER'S THEORY

The writer proposes that the feldspathization of the amphibolite and the production of the zoned Richardson deposit were the result of a single process that was motivated by the introduction of high-temperature hydrothermal solutions carrying silica, carbon dioxide, fluorine, and boron. These solutions penetrated slightly deformed amphibolite and were available when larger fractures, the loci of the zoned bodies, developed. In general, pressure-temperature conditions were not conducive to the abundant production of typical hydrothermal minerals such as sericite and chlorite. The zonation and mineralogy of the deposit can be explained by the rearrangement of pre-existing material, with addition of material from the solutions.

It seems reasonable to assume that the original rocks were Grenville-type sediments that were regionally metamorphosed to produce oligoclase amphibolite and scapolite-biotite gneiss containing abundant radioactive accessory minerals. The oligoclase amphibolite (possibly also the scapolite-biotite gneiss) was feldspathized to produce oligoclase-biotite-magnetite

gneiss. Slight deformation, as evidenced by bent and wedge-shaped twin-lamellæ and micro-faults in the plagioclases, probably facilitated the movement of the feldspathizing solutions. The ferromagnesian minerals were unstable under the new environmental conditions, and the silica necessary for the production of feldspar from them was supplied by the solutions. Alteration of hornblende could provide the sodium and potassium necessary for the production of new oligoclase, and the biotite could provide the potassium necessary for the formation of microcline. Radioactive accessory minerals were also unstable and were destroyed, releasing uranium and other radioactive material. Carbon dioxide, fluorine, and boron were present in the feldspathizing solutions, as evidenced by the occurrence of carbonate, fluorite, and tourmaline in those wall-rocks that show feldspathization. In places, especially where the wall-rock was more highly fractured, sericite and chlorite occur in significant quantities. This suggests that these minerals were formed when the pressure-temperature conditions were suitable, and implies that the feldspathizing solutions contained water.

At some time during the feldspathizing period, larger fractures were developed into which the solutions migrated. Increased activity in the vicinity of these fractures produced a zone of ultra-feldspathization, which became the oligoclase-microcline zone. Because the antiperthite zone is similar chemically and mineralogically to the oligoclase-microcline zone, it is reasonable to postulate that it represents a recrystallization of the oligoclase-microcline, possibly aided by the fluxing action of fluorine. Some of the mafic material released by feldspathization and ultra-feldspathization could well be the source of the hornblende of the deposit. Emmons, Reynolds, and Saunders (unpublished report) have recently provided evidence that the mafic minerals of basic dykes in the granite quarries of Wisconsin have migrated into fractures from the bleached zone that surrounds the dykes. The Richardson deposit and the hornblende veinlets in the oligoclase-biotite-magnetite gneiss bear a strong resemblance to the dykes described by these workers.

The process probably took place by the movement of solutions towards a major fracture rather than away from it. In support of this contention, it may be pointed out that the deposit pinches out at a shallow depth, as shown by the underground workings and diamond-drill cores.

As a corollary to this theory, the writer suggests an explanation for the red dust that occurs along the cleavage planes, lamellæ, fractures, and grain boundaries of the plagioclase feldspars. At the Richardson deposit, the occurrence of hematite and the increase in the abundance of magnetite can be correlated with the alteration of hornblende and biotite, the FeO from the ferromagnesian minerals being used to form magnetite and the Fe_2O_3 to produce hematite dust.

Conybeare and Campbell (1951) have discussed the origin of red dust in the feldspars of the radioactive rocks at Goldfields, Saskatchewan. They suggest three possible explanations: (1) the iron of the hematite was introduced by solutions or by diffusion; (2) the hematite was liberated from pre-existing iron-bearing minerals by radioactive bombardment; and (3) the hematite is an exsolution product of ferro-microcline and ferro-albite.

Any theory on the origin of the Richardson deposit must account for the presence of uraninite. It seems possible that either the hydrothermal solutions or the break-down of the radioactive accessory minerals of the wall-rocks could supply the uranium and the small amount of thorium necessary for the formation of uraninite. The occurrence of uraninite in the sheared Richardson deposit, and lack of it in the calcite-fluorite body to the south, would appear to indicate that the formation of uraninite is related to the late shearing movements regardless of the origin of the uranium.

Because the uranium of uraninite is believed to have been deposited mostly as UO_2 rather than UO_3 (Ellsworth, 1932, p. 45), the occurrence of hematite, a mineral containing ferric iron, with uraninite must be explained. It is possible that the hematite was originally magnetite that has been oxidized by oxygen released by auto-oxidation (Ellsworth, 1925, p. 137).

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