# A GENETIC CLASSIFICATION OF CANADIAN URANIUM DEPOSITS[1]

S. C. ROBINSON[2]

*Geological Survey of Canada, Ottawa*

ABSTRACT

A genetic classification of Canadian uranium occurrences is presented, together with lists of elements and minerals characteristic of each type. Of the eleven types listed, three are known to be economic in Canada and two are potential sources of uranium; two others have proved to be economic in the United States. Thorium and the rare earth elements are closely associated with uranium in many types of deposits but are conspicuously lacking in others. Uranium minerals found in each type of deposit are discussed together with other minerals whose spatial distribution is the same as that of uranium. It is concluded that although the major factor controlling the type of deposit is the genetic process, marked differences in type may also be due to structures in, and type of, host-rock. For many deposits there is evidence of more than one period of mineralization; in an extreme case, the original deposit of pitchblende was formed $1.5 \times 10^9$ years before the latest period of hypogene mineralization in the same vein.

## INTRODUCTION

Uranium occurs almost ubiquitously in the Earth's crust and is locally concentrated in deposits whose geological aspects are exceptionally diverse. Most of these diverse types of deposits are represented in Canada. Although location of uranium deposits is governed principally by geological and metallogenic environment, by structure and by type of host-rock; the best evidence of the genetic processes which gave rise to the deposits is their mineral content, geochemistry and texture. These factors are, therefore, given prominence in this classification.

In Table 1, a genetic classification of Canadian uranium deposits is presented, together with examples of each type and their characteristic elements and minerals. The classification represents the writer's opinions and is necessarily controversial in parts. This is particularly true of the necessarily arbitrary classification of deposits that are genetically hybrid and that might, with justice, be listed under more than one type. Examples were chosen as best representatives of the range included in each type and there is no economic significance in their selection. For a general description of Canadian uranium deposits, reference may be made to Lang (1952). Characteristic elements and minerals are largely

[1]Published by permission of the Director, Geological Survey of Canada, Department of Mines and Technical Surveys, Ottawa.

[2]Chief, Mineralogy Division, Geological Survey of Canada.

the less common ones that characterize each type and do not include rock-forming elements and minerals except where their specific association with uranium is unmistakable. Elements listed in parentheses are less characteristic either because they are not present in all deposits of the type or are common to all types. Minerals that normally are recorded by autoradiography are included with the uraniferous group.

Of the eleven types of deposits listed, three are known to be economic. They are the granite dykes of Bancroft, the hydrothermal deposits of Great Bear Lake, Marian River, and Uranium City and the conglomerates of the Blind River camp. Two other types which might become economic if demand for uranium were to increase include metasomatic deposits such as those of Charlebois Lake and Central Saskatchewan and deposits traversed by meteoritic waters such as those of Fishhook Bay. Three other types of deposits that occur in Canada, and have proved to be economic elsewhere are the sandstone, phosphate, and carbonaceous deposits. It is possible also that uranium might be recovered as a by-product from deposits producing niobium or feldspar.

## Mineralogy and Geochemistry of Deposits of the Igneous Group

### *Granites, Syenites, etc.*

The average radioactivity of Canadian granites due to uranium, thorium and potassium is equivalent to a content of 0.003% $U_3O_8$, and the average ratio of thorium to uranium in them is 3 to 1. In the Canadian Shield, red granites are usually more radioactive than grey ones and pegmatitic facies are commonly more radioactive than normal facies.

Normal granite rocks usually contain zircon as the most abundant uraniferous mineral with lesser amounts of titanite, apatite, allanite and monazite and, less commonly, thorite and uraninite. Although few of these accessory minerals necessarily contain uranium or thorium, autoradiographs have shown that they are usually radioactive. One gneissoid granite near Parry Sound, Ontario, exhibits radioactivity equivalent to 0.01% $U_3O_8$, of which 70% may be removed by leaching with hot HCl. This indicates that most of its radioactivity is due to minerals other than the common, insoluble accessories. In most granites, uranium is associated with constituents of accessory minerals, particularly with thorium, rare earth elements, zirconium, titanium and phosphorus.

The abnormally radioactive granitic rocks of the Haliburton-Bancroft region (Satterly & Hewitt 1955), are usually irregularly lenticular in shape, have the grain size of a coarse granite, and are only locally pegmatitic. They vary from high-quartz granites to quartz-free syenites. Where they occur in carbonate-rich rocks, much pyroxene is developed

TABLE 1. GENETIC CLASSIFICATION OF CANADIAN URANIUM DEPOSITS

| Group | Types | | Examples | Characteristic Elements | Characteristic Minerals | |
|---|---|---|---|---|---|---|
| | | | | | Uraniferous | Other |
| IGNEOUS (MAGMATIC) | GRANITES, SYENITES (dykes, stocks, batholiths) | | Bicroft, Dyno, Faraday, Rare Earths and Greyhawk Mines | Th[1] U Zr Si (Ce Fe P F) | Uraninite, uranothorite, thorite, zircon, monazite, minor betafite | Magnetite, sphene allanite, fluorite |
| | PEGMATITES | | Viking Lake, Foster Lake, Richardson Mine | U Th Nb Ta (Zr Si Ce P Fe F Ti Mo C) | Uraninite, pyrochlore betafite, euxenite, samarskite, thucholite, brannerite, etc. | Molybdenite, biotite, magnetite, allanite |
| | METASOMATIC DEPOSITS | (*a*) General | Charlebois L., Beaverlodge migmatites, Cardiff Mine, Normingo | U Th Ce P Si (F Mo Fe S) | Uraninite, thorianite, thorite, monazite, rare earth silicates | Biotite, apatite, pyrite, fluorite, molybdenite, magnetite |
| | | (*b*) Fenites | Oka Deposits, Beaucage Mines, Basin Property | U Th Nb (Ta Ce P F Ti Fe S) | Pyrochlore, betafite, perovskite | Calcite, soda pyroxene and amphibole, apatite, biotite, magnetite |
| | HYDROTHERMAL DEPOSITS | | Rocher De Boule, B.C. Grt. Bear Lake, Marian R., N.W.T., Beaverlodge Camp, Sask., Theano Pt., Ont., East coast of Labrador | U C Fe (Cu Pb[2] S V Se Co Ni As) | Pitchblende, thucholite | Hematite, quartz, calcite, chlorite, chalcopyrite, galena, pyrite, arsenides, selenides, nolanite |

| | | | | | |
|---|---|---|---|---|---|
| SEDIMENTARY | PLACERS | Cordillera of B.C. & Yukon | Th U Ce P Zr Fe (Nb Ta Ti W Sn) | Monazite, uraninite, pyrochlore, zircon | Magnetite, garnet, ilmenite pyrite, etc. |
| | CONGLOMERATES | Blind River, Ont. | U Th Ti Ce P Fe (Cr Zr C) | Brannerite, uraninite, monazite, uranothorite, zircon | Pyrite, anatase, chromite, traces of common sulphides, hydrocarbon etc. |
| | SANDSTONES | Middle Lake, Sask. | U Ca P | Autunite, phosphuranylite | Hematite |
| | PHOSPHATE DEPOSITS | Fernie Group, Rocky Mountains | U Ca P C | Unknown | Collophanite, bitumen |
| | CARBONACEOUS DEPOSITS | Marine shales, lignite in Saskatchewan | U C H | Unknown | Bitumen, lignite |
| SUPER-GENE | GOSSAN CAPPINGS | On all hypogene deposits | Fe U Si Se V As S Al Mn (Pb Cu Co Ni) | Uranophane, liebigite, zippeite, "gummite" etc. | Limonite, erythrite, malachite, etc. |
| | DEPOSITS TRAVERSED BY METEORIC WATERS | Gunnar Mine (in part), Fish Hook Bay deposits | U Si S | Uranophane, secondary (?), pitchblende, thucholite (?) | Barite, gypsum |

(1) Thorium[230] is always present as traces in uranium deposits because it is a product of radioactive decay of uranium. Thorium listed in this table includes thorium[232] only.

(2) All radioactive deposits contain radiogenic lead. Lead is listed in this table only where significant amounts of "ore lead" are characteristic.

near their margins and around inclusions. Potash feldspar is less abundant than soda feldspar and the latter is commonly the variety peristerite. Biotite is usually abundant but muscovite occurs only sparsely and locally. Fluorite and calcite are sparsely developed but widely distributed. The principal uranium minerals are uraninite (Robinson & Sabina 1956), and uranothorite (Robinson & Abbey 1957), with minor pyrochlore. Although these minerals are found sparsely throughout the granite bodies, they are concentrated in areas rich in pyroxene or magnetite and locally in quartz-rich zones with abundant pyrite and pyrrhotite. Zircon and titanite are generally abundant in zones rich in uranium. Allanite is locally abundant in highgrade zones. Uranothorite has been observed enveloping uraninite. In these deposits the association of uranium is with thorium (the ratio of the two is about 1 to 1), and with zirconium, titanium and iron. The association with rare earths and niobium occurs only locally.

*Pegmatites*

Ellsworth (1922, 1932) has described many of the better known pegmatitic areas of Canada and has shown that, whereas the lithium and beryllium pegmatites are rarely radioactive, many pegmatites mined for mica and feldspar do contain uranium and thorium. Uranium occurs most commonly as the oxide uraninite containing varying, but significant amounts of thorium. In some pegmatites however, uranium occurs principally with thorium and calcium in complex niobium-tantalum-titanium oxides. Uranothorite is only rarely present in pegmatites despite the abundance of U, Th and silica in them.

The Grenville sub-province of the Canadian Shield abounds with pegmatites many of which are described by Ellsworth (1922, 1932) and by Satterly & Hewitt (1955). Pegmatites in this region that contain uraninite are usually rich in quartz, micas and microcline and in many of them quartz is more abundant than feldspar. Thucholite is associated with uraninite in some of these deposits and minor amounts of allanite and zircon are typical. Pegmatites that contain euxenite and/or pyrochlore, betafite, ellsworthite or other niobium-tantalum-titanium oxides are usually well-zoned dykes consisting dominantly of microcline with minor quartz and plagioclase. Plagioclase feldspars commonly form the outer envelope of this type of dyke. Finally there is a group of anomalous pegmatites having an outer zone made up usually of hornblende, apatite and microcline and a distinctive inner core of calcite and fluorite. Uraninite occurs largely at the border of the two zones, but is found also with uranothorite as discrete crystals in the core. In the Macdonald and Woodcox pegmatites, the ellsworthite and hatchettolite varieties of pyrochlore occur associated with calcite. The cores of these pegmatites appear to be transitional to calcite-fluorite "vein-dykes" in which feldspar, apatite, muscovite, uraninite and traces of uranothorite occur.

An exceptional zoned pegmatite near Viking Lake in the Beaverlodge region of Saskatchewan (Robinson 1955) has an outer envelope of quartz and euhedral microcline, an intermediate zone of highly sericitized sodium feldspar with some biotite and accessory magnetite and pyrochlore, and a core of brecciated but fresh microcline-albite-quartz-biotite rock which contains abundant pyrochlore, titanite and magnetite and accessory uraninite, uranothorite, cyrtolite, allanite and pyrite.

A pegmatite at Nunn Lake, Saskatchewan, is a zoned sill-like body (Ford 1955). In this deposit, uraninite occurs in the wall-zone, which is composed of microcline, quartz, altered plagioclase and coarse-grained biotite with accessory zircon; and also with orthoclase and biotite in fractures intersecting both the border zone and the wall zone. These fractures also contain magnetite, monazite, allanite and fluor-apatite.

Mawdsley (1957) describes a pegmatite dyke on Foster Lake composed principally of microcline and quartz with minor biotite. The dyke's margin with the wall-rocks is marked by a granitized wall zone in which discrete masses of uraninite, anatase, rutile and brannerite occur.

In the zoned pegmatites of the Huron and adjoining claims of Southeastern Manitoba, Rowe, (personal communication) found monazite uraninite, columbite-tantalite and beryl in what appears to be the same plagioclase-rich zone, but the uraninite, columbite-tantalite and beryl each occur in separate outcrops.

*Metasomatic Deposits*

(*a*) *General.* There is great diversity in types of metasomatic deposits containing uranium. Examples of only the more representative types are described. Fenite deposits are discussed separately.

Many bands of migmatite in the Tazin gneisses of the Beaverlodge region, Saskatchewan, are radioactive (Robinson 1955). These bands are composed of older, altered Na-feldspar, younger fresh microcline, quartz, biotite and accessory apatite, molybdenite and titanite. The radioactive minerals are uraninite, monazite, thorite and cyrtolite. Intervening bands of gneiss are not radioactive. A highly-differentiated facies of this type of migmatite is composed of almost solid biotite containing euhedral grains of monazite which, in small lenses, may comprise 25% of the whole band. Some feldspar is usually associated with these narrow biotite segregations.

Mawdsley (1950) has classed deposits of the Charlebois Lake region as granite pegmatites but in the present classification they have more in common with metasomatic deposits. They occur in bands along the metasediment-granite contact and are apparently consanguineous with the granite. Their contacts with the granite are sharply defined but their contacts with the metasediments are transitional. They exhibit marked differentiation from granite pegmatite, through quartz-biotite rock, to solid biotite bands containing molybdenite. The general differentiation seems to be parallel to, and controlled by, the banded metasediments. Feldspars in the pegmatitic faces are microcline and oligoclase in varying proportions. Quartz is usually abundant. Femic minerals are biotite with minor muscovite and hornblende. Uraninite is disseminated in biotite-rich pegmatitic bands and in quartz-biotite bands rich in molybdenite. U:Th ratios in the uraninite are usually about 10:1. Other epigenetic minerals include thorite, cyrtolite, thucholite, apatite, monazite, titanite, magnetite, tourmaline, pyrite, pyrrhotite and locally, chalcopyrite. Uranium is associated with thorium, rare earths, and other elements commonly found in skarn zones. The distribution of molybdenum also seems to parallel that of uranium.

A distinctive group of radioactive deposits occur in metasomatized zones in crystalline limestone of the Grenville sub-province. They are distinguished by recrystallization of limestone to coarser-grained, salmon-pink calcite containing euhedral to sugary diopside and euhedral phlogopite. Tremolite is locally developed. The radioactive mineral in all these deposits is uranoan thorianite or uraninite with a $ThO_2$ content in excess of 25% (Robinson & Sabina 1955). Traces of thorite and rare earth silicates such as lessingite and melanocerite are found in some of these deposits, and betafite occurs in one of them. Geochemically the significant feature of these deposits is the high thorian composition of uraninite as compared with the usual development of both low-thorian uraninite and low-uranium thorite in other deposits.

In the same region, somewhat analogous deposits occur in lime-rich amphibolites. These deposits usually exhibit linear development within the host rock as though they had healed a shear or fault. In these zones, coarse-grained biotite, diopside, feldspar, apatite, calcite and fluorite are common. Molybdenite is present in many of them. Uraninite is the radioactive mineral in the majority of these deposits, pyrochlore in the remainder. In a few irregularly-shaped deposits in lime-rich amphibolites, uranothorite has developed as discrete euhedral crystals.

(*b*) *Fenite deposits*. The term fenite as here applied, refers to deposits developed from original country rocks by metasomatism associated with alkaline intrusives. In these deposits, uranium and minor thorium and rare earths substitute for the calcium cations of complex niobium-titanium-tantalum oxides. In Canadian deposits of these oxides, niobium is dominant, with minor, but locally predominating titanium, and usually little tantalum. Minerals are pyrochlore, betafite, euxenite, perovskite, samarskite, niocalite, and traces of uraninite. The rocks in which these minerals occur are characterized by Na-pyroxene, Na-amphibole, calcite, magnetite, biotite and apatite, with traces of monazite and fluorite. Throughout Canada, deposits containing this mineral assemblage are commonly associated with undersaturated alkaline intrusives (Rowe 1955).

*Hydrothermal Deposits*

These are dominantly in the Canadian Shield and of Precambrian age; however, a group of deposits in British Columbia are associated with Jurassic and Cretaceous granites and another group occur in Palaeozoic rocks of New Brunswick. Deposits of four groups serve to illustrate the occurrence of uranium in Canadian hydrothermal deposits. They are: 1. the hypothermal deposits of British Columbia, 2. the Eldorado mine on Great Bear Lake, 3. the Beaverlodge (Goldfields) camp in northern Saskatchewan and 4. the Theano Point-Montreal River camp.

Stevenson (1951) has described an unusual group of deposits scattered through the Jurassic-Cretaceous batholithic areas of British Columbia. In all these deposits, crystalline uraninite is associated paragenetically with hornblende, biotite, apatite, allanite, monazite and orthoclase. Later minerals are cobaltite, loellingite, arsenopyrite, skutterudite, molybdenite, gold and minor quartz and chlorite. There are no data on the composition of the uraninite and monazite. These deposits occur in well-defined lenticular veins which Stevenson assigns to the hypothermal class of Lindgren. Geochemically and mineralogically these deposits are of particular interest because they have some characteristics of the hydrothermal type and some of other types in the Igneous group.

Deposits of the Eldorado mine are narrow highgrade veins and stockworks that have been described by several geologists, but a paper on their mineralogy by Kidd & Haycock (1935) is a classic. They recognized 40 minerals in the deposits of which the significant ones are hematite, two types of pitchblende, chalcopyrite, sulpharsenides of cobalt, nickel and iron, native silver and bismuth, magnetite, molybdenite, and pyrite. Paragenetically the authors suggest that pitchblende is restricted to a single period of mineralization in which it is associated with quartz, safflorite-rammelsbergite and minor glaucodot, polydymite and gersdorffite. The sulphides, carbonates, silver, etc., were deposited later. This is borne out by diminution of silver with depth whereas the only change in uranium deposition is from colloform pitchblende near the surface to massive pitchblende at depth.

Geology of the Beaverlodge camp has been described by Christie (1953), Dawson (1956), Tremblay (1955, 1957), Fraser (1954) and many others. The mineralogy and many of the deposits are described by Robinson (1955). Hydrothermal deposits comprise veins, breccia zones and replacements. Essential minerals are pitchblende, hematite and calcite, with ubiquitous but minor chalcopyrite, pyrite and galena. Age determinations have shown that pitchblende has been deposited over a period from 200 m.y. to 1800 m.y. ago. There is also evidence indicating that palaeotemperatures of ore minerals have fluctuated widely. As would be expected, paragenetic relationships are complex, but it is probable that most of the minerals recognized are associated with one or more generations of pitchblende. Significant minerals locally associated with pitchblende are: 1. nolanite, a primary iron vanadate, 2. a group of primary copper, cobalt and lead selenides, 3. arsenides and sulph-arsenides of cobalt, nickel and iron, 4. hisingerite and a hydrocarbon resembling thucholite but lacking thorium and 5. gold. Titanium in anatase, rutile, titanite and ilmenite is commonly present in the vein walls and locally in the veins. Calcite and chlorite are the principal gangue minerals with subordinate quartz. It is of interest that uraniferous migmatites and pegmatites also occur in this camp.

Deposits in the Theano Point-Montreal River camp are most common in small fissures at the contacts of diabase dykes with granite. It has been suggested by Nuffield (1950) that the deposits are genetically related to diabase dykes. An alternative suggestion that location was probably governed by dilation at the contact of two rocks of differing competency seems more likely. Pitchblende, the only primary uranium mineral, is typically associated with hematite in a calcite gangue. Small amounts of pyrite and lead and copper selenides occur in some of the deposits with pitchblende.

A group of vein and replacement deposits in Palaeozoic rocks of New Brunswick contain pitchblende as the primary uranium mineral, Gross (1957). In these deposits it is variably associated with hydrocarbon, pyrite, galena and sphalerite.

## Mineralogy and Geochemistry of Deposits of the Sedimentary Group

### *Placer Deposits*

Owing to widespread glaciation and consequent dislocation of drainage, placer deposits are scarce in Canada except in the Cordillera of British Columbia and the Yukon. Uraninite has been recognized from three deposits in that region, (Steacy, H. R. personal communication) and monazite, pyrochlore and cyrtolite are more widely found. Associated minerals and elements in these deposits—magnetite, hematite, pyrite (abundant in the Yukon), cassiterite, scheelite, chromite, wolframite, titanite, etc.—do not necessarily have a similar association in the original primary deposits. They are of interest, however, for comparison with minerals found in conglomerates.

*Conglomerate Deposits*

Origin of the large deposits of the Algoma (Blind River) region of Ontario is still in dispute (Roscoe 1957), but as shown in the guidebook of the Sixth Commonwealth Mining and Metallurgy Congress (1957), field evidence of distribution, and laboratory evidence of mineralogy, favour a placer origin. Wide diversity of Pb/U dates, combined with evidence of more than one generation of uranium and other minerals suggest that there has been fairly widespread remobilization of original constituents. The ore is composed of round pebbles of quartz and quartzite cemented in a matrix of quartz, sericite and pyrite. The radioactive minerals (brannerite, uraninite and monazite) occur in the matrix and are usually too finely divided to be recognized in a hand specimen. The average uraninite contains 8% $ThO_2$ and occurs in rounded discrete grains that are locally fractured. Pyrite, much of it rounded "buckshot pyrite", comprises between 5% and 15% of the ore. Accessory minerals in the matrix include magnetite, chromite, zircon, rutile, anatase, feldspar and traces of gold. Sulphides other than pyrite occur locally and include pyrrhotite, galena, chalcopyrite, sphalerite, molybdenite, marcasite and cobaltite. The elements associated with uranium in these deposits belong to no one geochemical environment and are more likely to be the result of clastic deposition than of igneous origin.

*Sandstone Deposits*

The only known deposit of uranium minerals interstitial to grains of a sandstone occurs in coarsely cross-bedded sandstone and pebble conglomerate of the Athabasca series at Middle Lake, Saskatchewan. The deposits occur at the unconformable contact where the sandstone rests on the older Tazin series. Uranium minerals are autunite and phosphuranylite, which occur irregularly in the sandstone and are known also in shears in the softened and kaolinized Tazin rocks immediately below the unconformity. Intense hematitization of the sandstones in sharply-defined, horizontal bands which intersect the cross-bedding, is not related spatially to the uranium deposits. Hypogene uranium deposits occur in the Tazin rocks within two miles of these sandstone deposits. The geochemistry and distribution of minerals in these deposits suggest that the uranium minerals may have been deposited from surface waters prior to consolidation of the sandstone.

*Phosphate Deposits*

Certain phosphatic strata of the Fernie Group in the Rocky Mountains of southern Alberta are slightly radioactive. The uranium mineral has not been identified but the radioactivity is associated with nodular collophanite. Bitumen commonly is found in these phosphatic strata.

*Carbonaceous Deposits*

Testing of black marine shales in Canada has confirmed that some of them exhibit slightly abnormal radio-activity. Ash from lignite mined at Eastend, Saskatchewan is significantly radioactive. No radioactive mineral has been identified from these deposits and it is possible that uranium has formed a complex with, or been adsorbed on, the hydrocarbon.

## Mineralogy and Geochemistry of Deposits of the Supergene Group

*Gossan Cappings*

As a result of recent glaciation, there is rarely more than a thin veneer of supergene minerals on Canadian deposits. Such minerals are most abundant capping hydrothermal deposits and less common on pegmatites and metasomatic deposits. On the hydrothermal deposits particularly, supergene uranium minerals are often in cracks and vugs indicating some migration of uranium. In one instance, talus downhill from a hydrothermal deposit is partly cemented by supergene uranium minerals. It is more common, however, to find supergene uranium minerals mantling the hypogene minerals. In Canada, the principal supergene uranium minerals are the hydrous silicates, various hydrous sulphates, carbonates, and oxides, and less commonly the phosphates, vanadates, and arsenates. Cations found with uranium in these minerals are mainly calcium, lead and copper; thorium and rare earths are absent. In most such minerals, uranium is in the uranyl state. Commonly associated minerals are limonite, kaolin, and locally malachite, gypsum, erythrite and annabergite.

*Deposits Traversed by Meteoric Waters*

These deposits usually occur in rocks containing abundant carbonate and may attain depths in excess of 400 feet. At the Gunnar mine, meteoric water encountered at 500 feet in an artesian drill hole (450 feet below the surface of neighbouring Lake Athabasca), contained 0.0014 gm. $U_3O_8$ per litre (Robinson 1955). Drilling has indicated similar depths of supergene alteration at Fish Hook Bay, also on Lake Athabasca. Uranium minerals are uranophane and dusty pitchblende which here appears to be supergene. Barite, gypsum, malachite, limonite and kaolin are all found sparingly in zones of supergene alteration. In mineralogy and geochemistry, these zones are similar to other supergene deposits.

## SUMMARY

### *Geological Environment*

It is particularly in the igneous group that the geological environment has been a major factor in determining the type of deposit that results. With the exception of hydrothermal deposits and those of the fenite type, there are many similarities in mineralization in granites, metasomatic deposits and even pegmatites. In the Bancroft area for example, the occurrence of uranium with thorium and rare earths in uraninite and uranothorite, associated with fluorite, calcite, titanite, zircon, biotite, pyroxene and pyrite is common to granite dykes, to pyroxenite deposits, to pegmatites and to calcite-fluorite veins. The pronounced differences in type of these deposits and in the relative abundances of the minerals they contain are due largely to variation in reaction with wall-rocks and to available openings. These differences are governed by marked differences in composition and competency of the host rocks. In the less competent and highly reactive carbonate rocks, deposits are usually small and highgrade, whereas the larger deposits occur in the more competent and less reactive amphibolites, schists and gneisses.

Hydrothermal uranium deposits characteristically were emplaced by fissure-filling; replacement has played a very subordinate role. The deposits occur almost universally in structurally dilatant zones. They are not found along main faults but in the small tensional fractures and breccia zones that complement the major structures. Type of host-rock has only a limited effect although in the Beaverlodge camp it is apparent that the deposits do favour host-rocks least like granite in composition (Robinson, 1955).

No general similarities exist in geological environment of the sedimentary group. They represent coarsely clastic continental sediments, biological sediments and chemical sediments. Evidence suggests that uranium in the placers, conglomerates and phosphate deposits is syngenetic. In the sandstones it is probably epigenetic and may well have been introduced by meteoric waters in the permeable sandstones where they overlie the impermeable Tazin schists.

Recent glaciation has removed most of the supergene cappings from uranium deposits and the relatively cold climate has not been conducive to formation of extensive ones subsequently. Where supergene minerals persist to depth, there is evidence of circulation of artesian waters in fractured zones partly sealed by carbonate.

*Geochemistry of Deposits*

Table 2 summarizes the distribution of each of the elements in the different types of uranium deposits. In evaluating such a table, it is not safe to infer that elements that do not occur in the same mineral with uranium have the same genetic source as uranium or are of the same age. In compiling the table, many compromises were necessary. For example uranium occurs in many zircons and yet zirconium is only rarely detected in significant amount in the principal uranium minerals of a deposit. In such cases zirconium is not shown as occurring in an uranium mineral.

Uranium deposits are of exceptional interest to students of ore deposition because there is such diversity in the geochemical associations of this amphoteric element and because different generations of minerals in a deposit can be distinguished by dating the uraniferous minerals. In Canada, thorium and usually the rare earth elements, occur with uranium in all igneous deposits except the hydrothermal ones; in clastic but not in chemical sediments; and are absent in supergene deposits. Niobium and tantalum occur characteristically in fenite deposits, are present in many pegmatites and non-fenite metasomatic deposits, and are known locally in granites. Titanium's occurrence in minerals containing uranium is the same as Nb and Ta, but its distribution in non-radioactive minerals is much wider. Carbon as hydrocarbon has an affinity for uranium in a diverse group of deposits, possibly due to polymerization of methane. Iron is always present but in hydrothermal deposits and in supergene deposits its association with uranium is so close as to be geochemically significant. The association in igneous deposits of zirconium and molybdenum with uranium is sufficiently consistent to indicate probable similarity of source. In view of their wide occurrence in the Colorado plateau region, local occurrence of vanadium and selenium in hydrothermal deposits in Canada is noteworthy. Because of the postulated transfer of uranium as the hexafluoride, presence of traces of fluorite in deposits of the igneous group may be significant. It will be noted that association of nickel, cobalt, and silver with uranium is poorly represented in Canada.

## Hybrid Deposits—Recurrence of Mineralization

Applications of Pb/U ratios to determinations of age of uranium minerals have indicated that in some Canadian deposits, deposition of such minerals occurred in more than one period and at intervals measured

### Table 2. Occurrence of Other Elements with Uranium

| Group | Type | Th+ R.E. | Nb Ta | Ti | C | Zr | Mo | Fe | Ni, Co | V | Se | F | $CO_3$ | $PO_4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Igneous | Granites, syenites | C* | L* | A | — | C | L | A | — | — | — | A | L | A |
| | Pegmatites | C* | A* | A | L* | A | L | A | — | — | — | L | L | L |
| | Metasomatic—General | C* | L* | A | — | A | A | A | — | — | — | A | A | L |
| | Metasomatic–Fenites | U* | C* | A* | — | A | — | A | — | — | — | L | A | L |
| | Hydrothermal | — | — | L | L | — | L | C | L | L | L | — | C | — |
| Sedimentary | Placers | A | L | A | — | A | — | C | L | — | — | — | — | A |
| | Conglomerates | C* | L | C* | L | A | — | C | L | — | — | — | — | A |
| | Sandstones | — | — | — | — | — | — | L | — | L | — | — | — | C* |
| | Phosphate deposits | L | — | — | A | — | — | L | — | — | — | — | L | C* |
| | Carbonaceous deposits | L | — | — | C* | — | — | — | — | — | — | — | — | — |
| Supergene | Gossan cappings | — | — | — | — | — | — | C | L | L* | L* | — | L* | A* |
| | Deposits traversed by meteoric waters | — | — | — | L | — | — | A | — | — | — | — | L | — |

C—Characteristic of Type of Deposits.
A—Commonly present in abundance.
L—Locally present or present in minor amounts.
——Absence is characteristic.
*—Elements occur mainly in same mineral as uranium. Although small amounts of uranium may occur in such minerals as zircon, the chief uranium mineral does not contain significant amounts of those elements not marked by an asterisk.

in hundreds of millions of years. Eckelman & Kulp (1956) ascribe such ages in the Beaverlodge region to initial introduction of uranium followed by at least two periods of exsolution of lead. Mineralogical evidence (Robinson 1955) indicates clearly that the deposits were reopened on more than one occasion accompanied by brecciation of pitchblende which was variably dissolved and redeposited with separation of lead as clausthalite and galena. Some of this clausthalite and galena is composed almost wholly of $Pb^{206}$ and $Pb^{207}$ indicating that it was derived from radioactive decay of uranium. Inasmuch as some of the clausthalite concentrations appear to be hundreds of feet from the nearest deposit of pitchblende large enough to have generated their lead, it is apparent that redistribution is of major proportions. Moreover it is found that ages of massive pitchblende associated with copper, lead, and iron sulphides in one geographical area of the region are all in the youngest group, that pitchblende deposits containing selenides are in a medium age group and that the oldest pitchblende is associated with hematite and only traces of sulphides. This suggests that redistribution of earlier constituents was accompanied by introduction of selenium and later of additional sulphur.

Widely-differing ages have been reported for uraninite from the conglomerates of the Algoma region (Wanless & Traill 1956, and Stieff & Stern in Sixth Commonwealth Congress 1957). Here too, mineralogical evidence points to introduction of "thucholite" and calcite, with galena, sphalerite, and other sulphides, in late fractures and veining earlier minerals.

In the Eldorado mine, Kidd & Haycock (1935), pointed out that there appear to be two different types of pitchblende. Although most ages for pitchblende from this mine are consistent in the range 1200–1300 m.y., mineragraphic work suggests that distinct groups of elements and minerals were formed in different periods.

It is essential that the possibility that any mineral deposit is the product of more than one period of mineralization be evaluated, before making geological, geochemical, or geochronological interpretations based on mineralogical data. Insistence on the old concept that a mineral deposit is the product of a single period of mineralization has unneccessarily complicated interpretations or origin and age.

*Genesis of Deposits*

The granitic, pegmatitic and metasomatic deposits are largely characterized by field evidence pointing to dominance of replacement processes with fracture-filling playing a minor role. Elements such as thorium and the rare earths are invariably present, the niobium-tantalum-titanium group are locally important and zirconium and phosphorous are usually present. These components suggest that uranium probably was introduced in the same quadrivalent state as thorium, etc. By contrast, in hydrothermal deposits, fissure-filling is dominant and replacement is rare. Prevalence of carbonate and absence of thorium suggests that uranium travelled in the hexavalent state, probably complexed as a carbonate under high pressures of $CO_2$. Where the solutions encountered dilatant zones, $CO_2$ pressures would be reduced and uranium would be precipitated (Boyle, R. W., personal communication). This process finds partial support in Gruner (1956).

In deposits of the sedimentary group, except those containing minerals residual from other rocks, thorium and the rare earth elements are absent or present only in insignificant amount. Similarly thorium and rare earths are not found in supergene deposits. It seems probable, therefore, that uranium in both these groups travelled in solution and only in the hexavalent state.

## Acknowledgments

In the course of discussions over the past decade, the writer has assimilated many ideas about uranium deposits from others for which individual acknowledgment has not been made. The kindness of my colleagues, J. W. Griffith, H. R. Steacy and R. J. Traill, in criticizing this paper is much appreciated.

## References

Only those references quoted in the text are listed here.
For a more exhaustive list see Griffith (1956).

Christie, A. M. (1953): Goldfields-Martin Lake Map-area, Saskatchewan, *Geol. Surv., Canada*, Mem. **269**.

Dawson, K. R. (1956): Petrology and red coloration of wall-rocks, radioactive deposits, Goldfields region, Saskatchewan, *Geol Surv., Canada*, Bull. **33**.

Eckelmann, W. R., & Kulp, J. L. (1956): Uranium-lead method of age determination. Part 1: Lake Athabasca problem; *Bull. Geol. Soc. Am.*, **67**, 35–54.

Ellsworth, H. V. (1922): Radium-bearing pegmatites of Ontario, *Geol. Surv., Canada*, Summ. Rept. 1921, part D.

——— (1932): Rare-element minerals of Canada, *Geol. Surv., Canada, Econ. Geol. Ser.* **11**.

Ford, R. B. (1955): Mineralogy of a uranium-bearing pegmatite, Lac La Ronge, Saskatchewan, *Econ. Geol.*, **50**, 196–205.

Fraser, J. A. (1954): Crackingstone, Saskatchewan, *Geol. Surv., Canada*, Paper 54–8.

Griffith, J. W. (1956): A bibliography on the occurrence of uranium in Canada and related subjects, *Geol. Surv., Canada*, Paper 56–5.

Gross, G. A. (1957): Uranium deposits in Gaspe, New Brunswick and Nova Scotia, *Geol. Surv., Canada*, Paper 57–2.

Gruner, J. W. (1956): Concentration of uranium in sediments by multiple migration-accretion; *Econ. Geol.*, **51**, 495–520.

KIDD, D. F. & HAYCOCK, M. H. (1935): Mineragraphy of the ores of Great Bear Lake, *Bull. Geol. Soc., Am.*, **46**, 879–960.

LANG, A. H. (1952): Canadian deposits of uranium and thorium, *Geol. Surv., Canada, Econ. Geol. Ser.* **16**.

MAWDSLEY, J. B. (1950): The geology of the Charlebois Lake area, *Dept. Nat. Res., Saskatchewan, Precambrian Geol. Ser.*, **5**.

——— (1957): The geology of the Middle Foster Lake area, northern Saskatchewan, *Sask. Dept. Nat. Resources*, Rept. **26**.

NUFFIELD, E. W. (1956): Geology of the Montreal River area, *Ontario Dept. Mines*, Ann. Rept., 1955, **64**, part 3.

ROBINSON, S. C. (1955): Mineralogy of uranium deposits, Goldfields, Saskatchewan, *Geol. Surv., Canada*, Bull. **31**.

——— & Abbey, Sydney (1957): Uranothorite from eastern Ontario, *Can. Mineralogist*, **6**, 1–14.

——— & SABINA, A. P. (1955): Uraninite and thorianite from Ontario and Quebec, *Amer. Mineral.* **40**, 624–633.

ROSCOE, S. M. (1957): Geology and uranium deposits, Quirke Lake-Elliot Lake, Blind River area, Ontario, *Geol. Surv. Canada*, Paper 56–7.

ROWE, R. B. (1955): Association of columbium minerals and alkaline rocks, *Can. Min. Jour.*, **76**, 69–73.

SATTERLY, J., & HEWITT, D. F. (1955): Some radioactive mineral occurrences in the Bancroft area; *Ontario Dept. Mines*, Geol. Circular **2**.

Sixth Commonwealth Mining & Metallurgy Congress Canada (1957): *Mining, metallurgy and geology in the Algoma uranium area.*

STEVENSON, J. S. (1951): Uranium mineralization in British Columbia; *Econ. Geol.* **46**, 353–366.

TREMBLAY, L. P. (1955, 1957): Uranium city, Saskatchewan; *Geol. Surv., Canada*, Papers 54—15, 55—28.

WANLESS, R. K., & TRAILL, R. J. (1956): Age of uraninite from Blind River, Ontario; *Nature*, **178**, 249–250.