Contents

7. UNCONFORMITY-ASSOCIATED URANIUM

7. UNCONFORMITY-ASSOCIATED URANIUM

V. Ruzicka

INTRODUCTION

Unconformity-associated uranium deposits typically consist of uranium concentrations at the base of a Proterozoic sandstone sequence where it unconformably overlies pre-Middle Proterozoic metamorphic basement rocks, which commonly include graphitic pelitic units. The deposits are associated with faults or fracture zones.

The principal commodity is uranium. It is commonly accompanied by other metals, particularly Ni, Co, and As, but none of these constitute significant recoverable byproducts at present. Examples of important deposits of this type in Canada are Cigar Lake, Key Lake, Rabbit Lake, McArthur River (also known as P2 North), and Eagle Point, all in Saskatchewan (Fig. 7-1). The most notable foreign examples are the Australian deposits Ranger I and III, and Jabiluka I and II in the Pine Creek Geosyncline, Northern Territory (Ruzicka, 1993).

IMPORTANCE

In 1993 about one third of the world's (excluding the former Soviet Union and China) Reasonably Assured Resources of uranium recoverable at prices up to US$130 /kg U was of the unconformity-associated type. This proportion is increasing as a result of new discoveries, and the diminishing viability of other types of lower grade uranium resources. Deposits of this type (Table 7-1) account for a major portion of Canadian uranium resources. In 1993 the annual output from unconformity-associated deposits in Canada and Australia represented about 30% of the world's total production of uranium. Canadian output in 1993 from deposits of this type was more than ten times the output from deposits of the paleoplacer (quartz-pebble conglomerate) type (see subtype 1.1) at Elliot Lake, Ontario.

Ruzicka, V.
1996: Unconformity-associated uranium; in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 197-210 (also Geological Society of America, The Geology of North America, v. P-1).

SIZE AND GRADE OF DEPOSITS

Unconformity-associated uranium deposits display a wide range of size and grade (Table 7-1, Fig. 7-2). In general, these deposits are much smaller than those of the quartz-pebble conglomerate type. For example, the Cigar Lake deposit is less than one hundredth the size of the Quirke zone at Elliot Lake. The average grades range from a few tenths of one per cent U (e.g., Ranger III, 0.17% U) to as much as 12.2% U (the main pod of the Cigar Lake deposit). As a result, the amounts of contained uranium metal range from a few thousand tonnes (e.g., Cluff Lake) to more than one hundred thousand tonnes (e.g., the main pod of the Cigar Lake deposit).

Australian deposits of the unconformity-associated type (Table 7-1) are of lower grade than the Canadian, but exhibit a larger range of ore tonnage (Battey et al., 1987). Because of the relatively sharp decline in grade at the fringes of mineralization, the sizes of orebodies are rather insensitive to lowering of cutoff grades.

GEOLOGICAL FEATURES

Geological setting

The majority of Canadian uranium deposits associated with pre-Middle Proterozoic unconformities occur in the Athabasca Basin, Saskatchewan. Some deposits of this type have been discovered in the Thelon Basin, Northwest Territories, and some occurrences are also known from the Otish Basin, Quebec (Ruzicka, 1984; Fig. 7-1).

Basement under the Athabasca Basin comprises Archean and Lower Proterozoic rocks. These include granulites of the Western Craton (2.6-2.9 Ga, Sm-Nd model ages; Bickford et al., 1990) and granitoid rocks of the Wollaston Domain (2.5-2.6 Ga, U-Pb zircon method; Ray and Wanless, 1980). The latter commonly form elongate domes, which are flanked by Lower Proterozoic folded strata that include graphitic, pyritic, and aluminous pelites and semipelites, calc-silicate rocks, banded iron-formation, volcanic rocks, and greywackes. These basement rocks experienced at least three main deformation events and various grades of metamorphism (Lewry and Sibbald, 1980) during early Proterozoic time.

The crystalline Archean and Aphebian basement rocks were subjected to peneplanation and development of regolith (Macdonald, 1985) prior to deposition of the Middle Proterozoic cover rocks of the Athabasca Group. These rocks, which compose the Athabasca Basin, consist of fluviatile and marine or lacustrine redbed sequences of unmetamorphosed, flat-lying and little disturbed sandstone, siltstone, and conglomerate. The sediments were deposited upon an intensely weathered surface or, where the regolith had been eroded, on the unaltered basement.

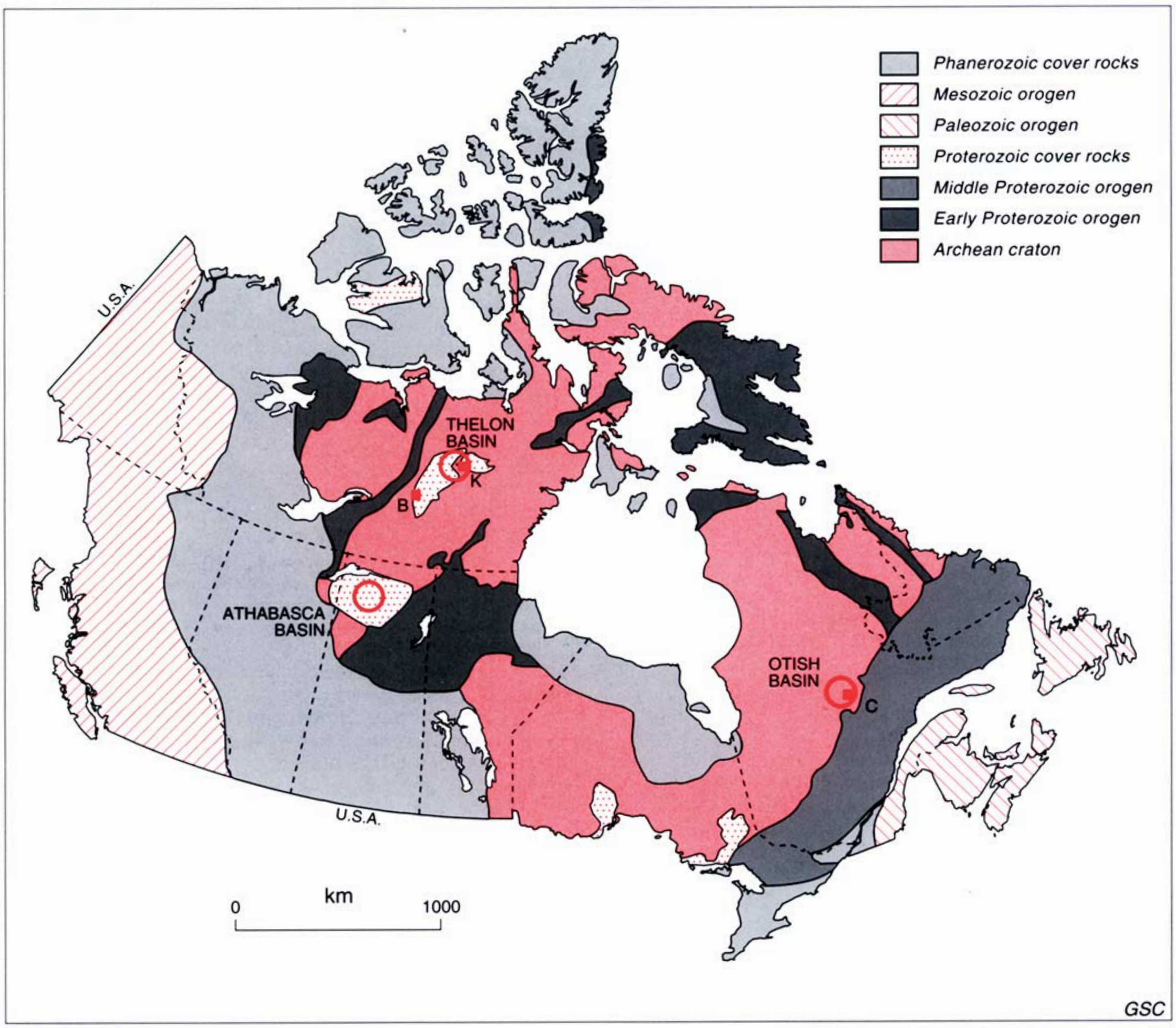

Figure 7-1. Areas with unconformity-associated uranium deposits in Canada. For location of deposits in Athabasca Basin see Figure 7-3; K = Kiggavik, formerly Lone Gull, deposit; B = Boomerang Lake deposit; C = Camie River occurrence.

There were initially three northeasterly trending tectonic depressions, the western Jackfish, central Mirror, and eastern Cree subbasins, which later coalesced into a single Athabasca Basin. Sedimentation was locally accompanied by volcanism. The clastic sedimentary rocks underwent diagenetic changes, such as silicification, hematization, clay alteration, and cementation by carbonates, and in some areas by phosphates. Layers of sulphides and organic substances, such as kerogen, occur locally (Ramaekers, 1990). Both basement rocks and cover rocks were intruded during the late Proterozoic by diabase dykes.

The deposits display two main types of metal association. Some deposits are polymetallic (U-Ni-Co-As) and occur immediately at the unconformity. Others are **monometallic** (U) and generally occur either below or (rarely) above the unconformity.

Deposits with mainly monometallic (U) mineralization generally occur either in basement rocks or in the upper parts of the Middle Proterozoic sedimentary sequence. For instance, the Rabbit Lake, Eagle Point, Raven, Horseshoe, and Dominique-Peter deposits (Fig. 7-1 and 7-3; Table 7-2) are within altered basement rocks beneath the unconformity; they are confined to various horizons of the Lower Proterozoic sequences, such as the Wollaston Group and Peter River Group. The Fond-du-Lac deposit is within sandstone in the cover rocks, some distance above the unconformity. The more recently discovered McArthur River (P2 North) deposit, which consists of monometallic mineralization directly at the unconformity, represents the only known exception from this rule. Several monometallic uranium deposits associated with the sub-Thelon unconformity occur in the Kiggavik Trend, which approximately parallels the southeastern margin of the Thelon Basin, Northwest Territories.

Table 7-1. Reasonably Assured and Estimated Additional Resources of uranium (including past production) in selected unconformity-associated deposits (data from Battey et al., 1987, and Geological Survey of Canada database).

Deposit	Ore (kt)	Grade (% U)	U (t)	Status as of 1992
MONOMETALLIC				
Canada				
Claude	583	0.36	2097	Depleted
Cluff Lake 'N'	505	0.34	1729	Dormant
Cluff Lake 'OP'	60	0.28	150	Depleted
Dominique-Janine	23	3.8	874	Producing
South Dominique-Janine	95	5.8	5510	Under development
Dominique-Peter	1756	0.66	11 587	Producing
Eagle Point	3300	1.55	51 152	Under development
Kiggavik	3022	0.51	15 384	Dormant
Rabbit Lake	5840	0.27	15 769	Depleted
McArthur River (P2 North)	2230	3.4	76 000	Advanced exploration
Australia				
Jabiluka I	1373	0.21	2883	Dormant
Jabiluka II	52 422	0.33	172 992	Dormant
Koongarra	4946	0.228	11 278	Dormant
Nabarlek	558	1.56	8700	Depleted
Ranger I	12 057	0.273	32 915	Dormant
Ranger III	42 425	0.17	72 123	Producing
POLYMETALLIC				
Canada				
Cigar Lake	902	12.2	110 000	Advanced exploration
Cluff Lake 'D'	128	3.41	4370	Depleted
Collins Bay 'A'	140	4.83	6500	Dormant
Collins Bay 'B'	3000	0.38	11 400	Depleted
Collins Bay 'D'	120	1.86	2500	Dormant
Key Lake	3518	1.99	70 000	Producing
McClean	352	1.53	5385	Dormant
Midwest	1200	1.6	19 300	Advanced exploration
Australia				
Kintyre	5936	0.5	29 680	Exploration

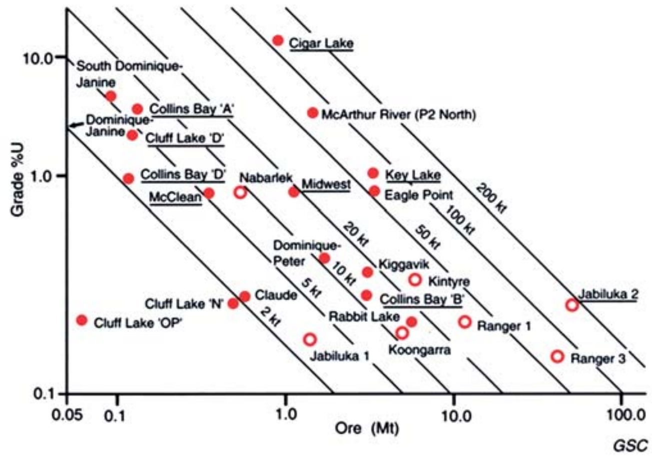

Figure 7-2. Grade/tonnage relationships in selected unconformity-associated uranium deposits (see Table 7-1). Dots = Canadian deposits; circles = Australian deposits. Deposits that are primarily polymetallic are underlined.

The principal host rocks of the Rabbit Lake deposit (Fig. 7-4 and 7-5) are albite-rich rocks, derived apparently from arkosic to semipelitic rocks, which were subjected to sodic metasomatism (producing rocks termed "plagioclasites" by Sibbald, 1976; Appleyard, 1984); meta-arkose; calc-silicate; and graphitic granulites. The plagioclasites form part of the footwall complex of the deposit. The host rocks also include a unit of partly graphitic semipelite and a layer of dolomite. The metasedimentary sequence has been intruded by granitic rocks.

The Eagle Point deposit is hosted by the lower pelitic unit of the Wollaston Group, which consists of quartzofeldspathic gneiss that is locally graphitic, quartzite, and granite pegmatite. This suite unconformably overlies folded Archean granitoid rocks. In the Eagle Point deposit Andrade (1989) identified two generations of euhedral uraninite, which belong to the oldest phases of mineralization, three forms of pitchblende (veinlets, coatings, and inclusions), which are younger than uraninite and represent the bulk of the mineralization, and minor amounts of boltwoodite and coffinite, which represent the youngest members of the uranium mineral assemblage.

The Raven and Horseshoe deposits occur within the quartz-amphibolite unit of the Wollaston Group, which consists of sillimanite meta-arkose, amphibolite, graphitic metapelite and quartzite, calc-silicate rocks, phosphates, and sillimanitic quartzite. The metasedimentary sequence has been folded into a syncline and intruded by dykes of granite pegmatite. The mineralization is confined mainly to the graphitic quartzite horizon, which is fractured and altered by sericitization, chloritization, and argillization.

The Dominique-Peter deposit, which is located in the Carswell Structure, is confined to a mylonite zone. This zone is entirely within basement gneisses at a contact between the Peter River gneiss and the Earl River gneiss complex. Most of the mineralization occurs in the mylonitized Peter River gneiss.

The Fond-du-Lac deposit occurs in hematitized, carbonatized, and silicified sandstone of the Athabasca Group, about 30 m above the unconformity. The mineralization is composed of a stockwork of steeply dipping fractures and disseminations in the adjacent porous, coarse grained facies of the sandstone.

The McArthur River (P2 North) deposit, which is located about 70 km northeast of the Key Lake deposit, contains prevailingly monometallic uranium (pitchblende) mineralization just above the sub-Athabasca unconformity and in the footwall of a thrust fault. The mineralized zone has been traced for 1850 m along strike by vertical drillholes. It averages 30 m wide and 7 m thick, but is locally more than 50 m wide and its vertical thickness is as much as 46 m. The main orebody is located from about 500 to about 600 m below the surface. As of 1992 it was estimated that the deposit contained in excess of 76 000 t of uranium metal in ores grading 3.4% U (Marlatt et al., 1992). The orebody consists of massive pitchblende and trace amounts of galena, pyrite, and chalcopyrite. The basement rocks in the footwall of the orebody consist of quartzite interbedded with garnetiferous and cordieritic gneisses, and are capped by a few metres of chloritic and hematitic regolith. The overthrust basement rocks consist of Aphebian graphitic and sericitic schists, quartzites, and minor amounts of pegmatites and calc-silicate rocks. The basement rocks are unconformably overlain by conglomerate and sandstone of the Helikian Athabasca Group. The host rocks are strongly silicified, but otherwise only relatively weakly altered by illite, chlorite, kaolinite, hematite, limonite, siderite, and dravite. Except for the silicification, the alteration of the deposit is restricted to a narrow aureole around the orebody. The pitchblende has yielded two main U-Pb ages: an older and prevailing age of 1514 ± 18 Ma and a younger age of 1327 ± 8 Ma (Cumming and Krstic, 1992). The older date represents the oldest known mineralization among the deposits associated with the sub-Athabasca unconformity.

The Kiggavik deposit is a large uranium concentration associated with the sub-Thelon unconformity in the Northwest Territories. The deposit occurs in Lower Proterozoic basement rocks, mica-rich nongraphitic quartzofeldspathic metasedimentary rocks, and unmetamorphosed fluorite-bearing granite (Miller et al., 1984; Ashton, 1988; Fuchs and Hilger, 1989; Henderson et al., 1991; LeCheminant and Roddick, 1991; Dudas et al., 1991). The mineralization lies at an undefined distance below the assumed sub-Thelon unconformity (Fuchs and Hilger, 1989).

Deposits of **polymetallic** (U-Ni-Co-As) character in the Athabasca Basin occur immediately at the sub-Athabasca unconformity. Examples include the Key Lake, Cigar Lake, Collins Bay 'A', Collins Bay 'B', McClean, Midwest, Sue, and Cluff Lake 'D' (Fig. 7-3; Table 7-2) deposits, which occur in the basal part of the Middle Proterozoic Athabasca Group clastic sedimentary sequence and/or the uppermost part of the Lower Proterozoic basement rocks.

The Key Lake deposit consists of two orebodies (Gärtner and Deilmann), which occur at the unconformity between the Athabasca Group rocks and the rocks of the underlying Wollaston Group. The deposition of the orebodies was controlled structurally by the intersection of the sub-Athabasca unconformity and a major reverse fault zone. The orebodies occur in proximity to graphitic metapelite layers of the Wollaston Group, which also contains biotite-plagioclase-quartz-cordierite gneiss, garnet-quartz-feldspar-cordierite gneiss, amphibolite, calc-silicate rocks, migmatite, and

Contents

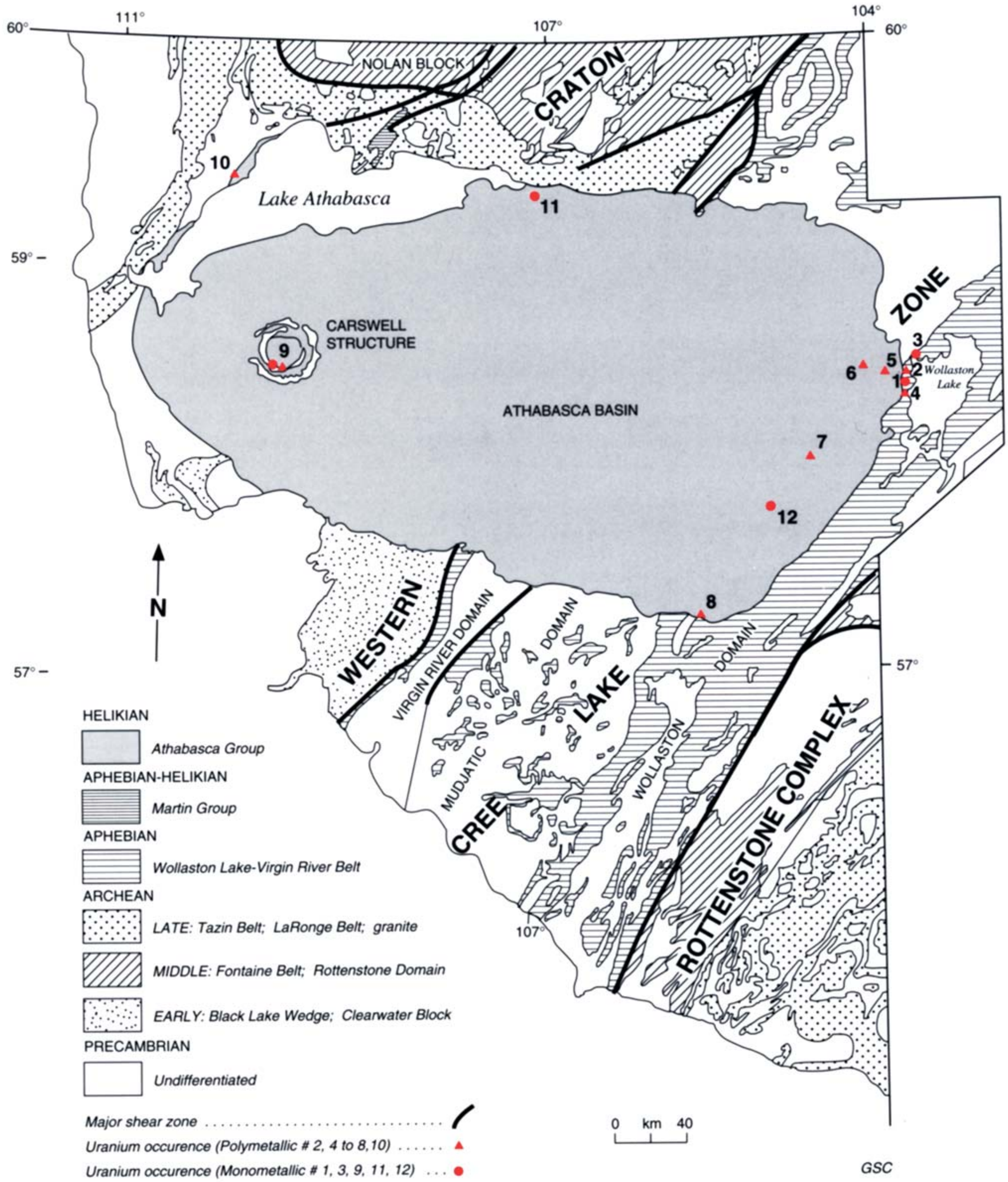

Figure 7-3. Unconformity-associated uranium deposits in the Athabasca Basin region, Saskatchewan. (Geology after Lewry and Sibbald, 1979.) 1 – Rabbit Lake; 2 – Collins Bay 'A' and 'B' zones; 3 – Eagle Point; 4 – Raven and Horseshoe; 5 – McClean Lake; 6 – Midwest and Dawn Lake; 7 – Cigar Lake; 8 – Key Lake; 9 – deposits in the Carswell Structure – (Cluff Lake 'D', Dominique-Peter, Claude, Cluff Lake 'OP', and Dominique-Janine); 10 – Maurice Bay; 11 – Fond-du-Lac; 12 – McArthur River (P2 North).

Contents

granite pegmatite. The Wollaston Group rocks unconformably overlie Archean granitic rocks, which are exposed in northeasterly elongated domal structures. The sedimentary rocks of the Athabasca Group have been subjected to alteration by diagenetic and mineralization processes. The diagenetic alteration, which is preserved outside the mineralized zone, is characterized by clay alteration of feldspars, corrosion of quartz grains by kaolinite and chlorite, partial bleaching (removal) of the original hematite, development of several generations of secondary hematite, and dravitization and carbonatization of the kaolinite matrix. In the immediate vicinity of ore, the Athabasca Group and the basement rocks have been altered to illite, chlorite, and kaolinite.

The world's largest high-grade uranium deposit (with ores of the world's highest average grade), Cigar Lake, contains not only polymetallic, but also some monometallic mineralization. Most of the mineralization occurs in clay-altered rocks at the base of the Athabasca Group, i.e., immediately at the unconformity (Fig. 7-6; Fouques et al., 1986). Small amounts of mineralization are contained within altered basement rocks just beneath the unconformity and up to 200 m above the unconformity in fractured Athabasca Group sediments. The mineralization is present in three assemblages of elements: (i) uranium, nickel, cobalt, and arsenic; (ii) uranium and copper; and (iii) uranium alone (mainly coffinite).

Table 7-2. Structural and lithological controls of selected unconformity-associated uranium deposits.

Deposit (ore type)	Relation of orebodies to Unconformity	Mineralized structures	Principal host rock	Main age of mineralization	Principal alteration
Cigar Lake (polymetallic)	Along	Two sets of faults	Athabasca sandstone, cordierite-feldspar augen gneiss	1.33 Ga (U-Pb)	Cover: Fe-Mg-illite; Basement: chlorite, Mg-illite
Cluff Lake 'D' (polymetallic)	Along	Mylonite zone and faults	Athabasca sandstone, garnet-rich aluminous gneiss	1.2 Ga (U-Pb)	Hematitization, bleaching
Collins Bay 'A' (polymetallic)	Along	Collins Bay Fault	Athabasca sandstone, quartzofeldspathic gneiss	N/A	Illitization, kaolinization, bleaching, hematitization
Collins Bay 'B' (polymetallic)	Along	Collins Bay Fault	Athabasca sandstone, paragneiss	1.38 Ga (U-Pb)	Illitization, kaolinization, bleaching, hematitization
Dominique-Peter (monometallic)	Below	Mylonite zone and 2 sets of faults	Quartzofeldspathic gneiss	1.05 Ga (U-Pb)	Chloritization, sericitization, illitization
Eagle Point (monometallic)	Below	Collins Bay and Eagle Point faults, wrench faults	Quartzofeldspathic gneiss, locally graphitic, quartzite, pegmatite	1.4 Ga (U-Pb)	Chloritization, illitization, hematitization, bleaching
Key Lake (polymetallic)	Along	Key Lake Fault	Graphitic metapelite, Athabasca sandstone	1.39 Ga (U-Pb)	Illitization, kaolinization
Maurice Bay 'A' (monometallic)	Below	Two faults	Mylonitic gneiss	1.3 Ga (U-Pb)	Chloritization, illitization
McClean (polymetallic)	Along	Fracture zones	Athabasca sandstone, regolith	1.3-1.17 Ga (Ar-Ar, U-Pb)	Illitization, chloritization, kaolinization
Midwest (polymetallic)	Along	Fracture zone	Athabasca sandstone, pelitic gneiss	1.3 Ga (U-Pb)	Sericitization, chloritization, kaolinization
Rabbit Lake (monometallic)	Below	Rabbit Lake Fault	Plagioclasite, meta-arkose, calc-silicate rock, granulite	1.3 Ga (U-Pb)	Mg-chloritization, carbonatization, tourmalinization

N/A = Not available

Contents

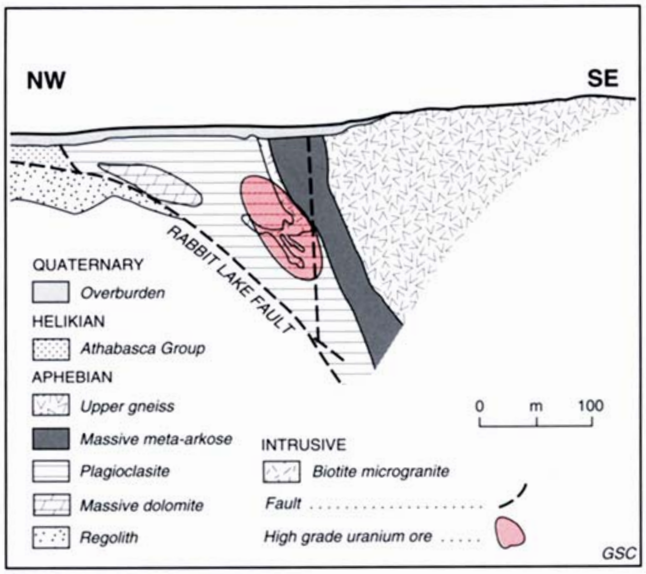

Figure 7-4. Geology of the Rabbit Lake deposit; cross-section (after Sibbald in Heine, 1981).

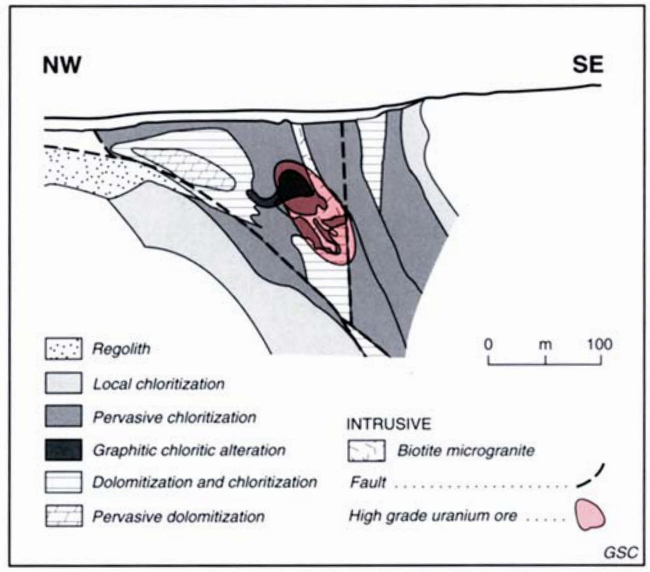

Figure 7-5. Rock alteration at the Rabbit Lake deposit; cross-section (after Sibbald in Heine, 1981).

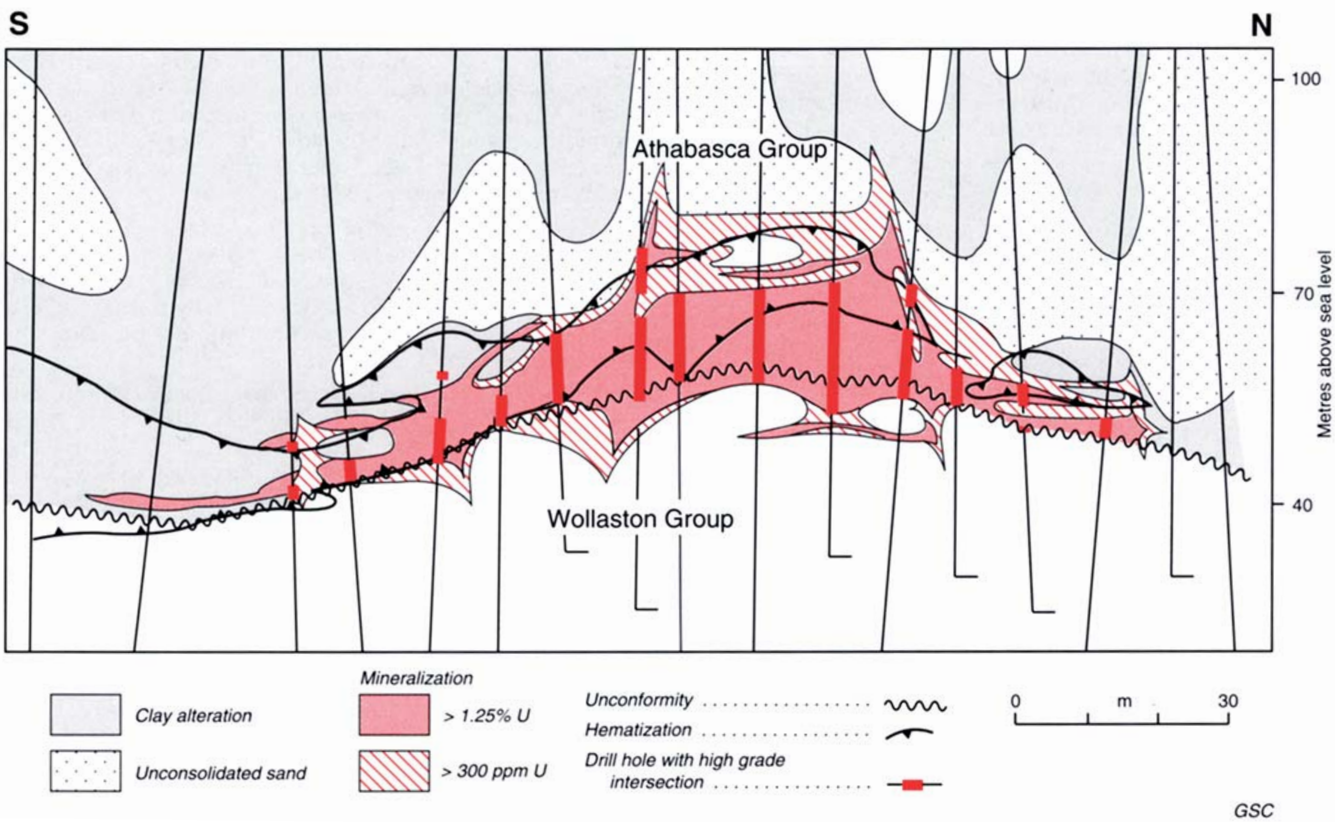

Figure 7-6. Cross-section through the Cigar Lake deposit (after documentation of Cogema Canada Limited).

The Collins Bay 'A' and 'B' zones occur at the unconformity, partly in clay-altered sedimentary rocks of the Athabasca Group and partly in altered metamorphic rocks of the Wollaston Group, along the Collins Bay Fault.

The Sue deposits occur within the submeridional part of the Sue structural trend, which consists of a series of faults adjacent to the southwestern margin of the Collins Bay Granitic Dome. The trend includes a layer of graphitic gneiss within the Aphebian sequence. The mineralization is predominantly polymetallic (U, Ni, Co, As, V, Cu, and Pb) and hosted by sandstone, but is in part monometallic (U) and hosted by basement rocks. The mineralization occurs in several zones, such as the Sue 'B', Sue 'A', Sue 'C', Sue 'CQ', Sue 'D', and Sue 'E'. The Sue deposits are excellent examples of the consanguinity of the sandstone- and basement-hosted mineralization (Ruzicka, 1992).

In the Thelon Basin region the only known polymetallic uranium occurrence is at Boomerang Lake, at the southwestern rim of the basin (Fig. 7-1). The mineralization occurs at the unconformity in altered sandstone of the flat-lying Helikian Thelon Formation and in the underlying graphitic metapelites of the Elk River belt, of inferred Early Proterozoic age (Davidson and Gandhi, 1989).

In the Otish Basin, Quebec (Fig. 7-1) polymetallic uranium occurrences are associated with an unconformity between the Archean volcanic rocks and the overlying Lower Proterozoic unmetamorphosed Otish Group. Sedimentation in the Otish Group varied from fluvial in the basal Indicator Formation to marginal marine in the overlying Peribonca Formation. The basement and the sedimentary cover rocks have been intruded by gabbroic sills and dykes. Age dating of the uranium mineralization and the associated rocks indicates Hudsonian events in the basin.

Age of host rocks and deposits

Unconformity-associated uranium deposits are in general hosted by Proterozoic rocks (about 2.5 to 0.6 Ga old). The mineralization is diagenetic and epigenetic, and formed during several stages.

Mineralization in the Athabasca Basin region is hosted by Lower Proterozoic and Middle Proterozoic (Athabasca Group) rocks, whose age is bracketed by Archean granitoid units (about 2500 Ma) and by intrusion of diabase dykes of the Mackenzie swarm (U-Pb age of 1267 ± 2 Ma on baddeleyite, LeCheminant and Heaman, 1989). Uranium-lead analyses of fluorapatites from the Upper Wolverine Point and Fair Point formations of the Athabasca Group indicated at least two distinct ages in the range 1650-1700 Ma (Cumming et al., 1987).

An important source of uranium apparently was older granitic and metasedimentary rocks. Archean granitic plutons containing above normal contents of uranium occur in the vicinity of most deposits. Uraninite-bearing pegmatites and metasedimentary rocks (U-Pb age >2.2 Ga; Robinson, 1955) are present in the Beaverlodge area, a short distance to the north of the Athabasca Basin. Hudsonian felsic intrusive rocks, and particularly their pegmatitic derivatives, are abundant, for instance, in the source area for the Manitou Falls Formation that surrounds the Key Lake deposits. Concerning metasedimentary sources, Ray (1977) speculated that "the initial Aphebian sedimentation under anaerobic conditions could have produced suitable conditions for syngenetic concentration of uranium within the basal pelites; these may have formed a source for some uranium deposits in northern Saskatchewan". Ramaekers (pers. comm., 1981) considered the Athabasca Group sedimentary rocks as the "immediate source for uranium and base metals found in the unconformity deposits at their base...".

Numerous age determinations have indicated that the ores in the majority of the deposits in this region were formed and/or remobilized and isotopically reset during the period between 1.4 and 0.8 Ga ago (Cumming and Rimsaite, 1979; Worden et al., 1985). However, more recently, Cumming and Krstic (1992) presented results of geochronological studies on a number of the uranium deposits of the Athabasca Basin, including the major deposits at Collins Bay, Cigar Lake, Dawn Lake, Eagle Point, Midwest, Rabbit Lake, and McArthur River, and concluded that "almost all the deposits formed in a restricted time interval between about 1330 and 1360 Ma. The one major exception is, however, the recently discovered NiAs-free deposit at McArthur River where a well determined age of 1521 ± 8 Ma (2σ) has been obtained" (pitchblende U-Pb). Remobilization and redeposition of pitchblende in the deposits took place at about 1070 Ma, 550 Ma, and 225 Ma ago (Cumming and Krstic, 1992). The main 1360-1330 Ma stage of mineralization corresponds to the age of 1326 ± 10 Ma published earlier by Ruzicka and LeCheminant (1986) for ore from the main pod of the Cigar Lake deposit. Other age determinations also fall close to the main mineralization stage established by Cumming and Krstic (1992). For example, U-Pb isotope analyses for 26 anisotropic uraninites from the Key Lake deposit, done at the Institut für Geowissenschaften und Rohstoffe in Germany, yielded a slightly older age of crystallization for uraninite of 1386 ± 4 Ma (Federal Institute for Geosciences and Natural Resources, 1989).

A Rb-Sr isochron age of 1477 ± 57 Ma was obtained for illites from various deposits associated with the sub-Athabasca unconformity (Kotzer and Kyser, 1990b). This age apparently reflects the beginning of the diagenetic-hydrothermal ore-forming process that led to accumulation of uranium and associated metals.

In the Thelon Basin, which is lithostratigraphically correlative with the Athabasca Basin (Miller et al., 1989), U-Pb isotope dating on ores in the Kiggavik deposit suggests three mineralization events; the oldest at 1400 Ma, a later one at about 1000 Ma, and the youngest indicating rejuvenation of mineralization at 10 Ma (Fuchs and Hilger, 1989). The mineralization thus postdates the deposition of the Thelon Formation, for which a minimum U-Pb age of 1720 ± 6 Ma was obtained by Miller et al. (1989) by dating uraniferous phosphate minerals that cement sedimentary units within the Thelon Basin. The mineralization associated with the sub-Thelon unconformity has been described by Miller (1983) and Miller et al. (1984).

Structural features

The most important structures controlling localization of unconformity-associated deposits are the unconformity itself, and faults and fracture zones that intersect this surface. In the Athabasca Basin, the mineralization is structurally controlled by the pre-Middle Proterozoic (sub-Athabasca) unconformity and by intersecting northeasterly and easterly trending faults. For instance, the Rabbit Lake deposit is localized at the intersection of the sub-Athabasca unconformity and the northeast-trending Rabbit Lake thrust fault. The Eagle Point deposit occurs in the hanging wall of the Collins Bay Fault at its intersection with the sub-Athabasca unconformity. Similarly the Key Lake deposit is associated with a regional northeast-trending steep fault where it intersects the sub-Athabasca unconformity. The Cigar Lake deposit is located where the sub-Athabasca unconformity is intersected by an east-trending fracture zone that coincides with graphitic pelite layers in the Lower Proterozoic basement. The Dominique-Peter deposit in the Cluff Lake area is confined to a mylonite zone which occurs at the contact between two gneissic lithostratigraphic units, presumably not far below the unconformity. Distribution of the orebodies of the Kiggavik deposit is controlled by several intersecting fault zones. Structural controls of selected deposits are summarized in Table 7-2.

Form of deposits

The forms of the orebodies are controlled by generally subvertical faults, shear zones, and fracture zones, and by the subhorizontal plane of the unconformity. Orebodies of the monometallic subtype consist typically of lenses in veins and thin veinlets in stockworks. Orebodies of the polymetallic subtype form pods and lenses aligned along the controlling structures and, to a lesser extent, veinlets and impregnations in the host rocks. A typical shape for such orebodies is plume-like lobes that formed from ascending fluids. The orebodies are commonly surrounded by clay, chlorite, or carbonate alteration zones.

Ores

Ores of the monometallic deposits, such as Rabbit Lake and Eagle Point, consist of pitchblende (in massive, globular, and sooty forms), coffinite, and, locally, secondary uranium minerals such as boltwoodite, sklodowskite, and kasolite. Carbonates (calcite, dolomite, siderite), sericite, chlorite, clay minerals (illite, kaolinite), celadonite, and tourmaline (dravite) are common gangue minerals.

The polymetallic ores, such as the Key Lake, Cigar Lake, Collins Bay 'B', and Midwest consist of several generations of pitchblende and coffinite; arsenides and sulpharsenides of nickel and cobalt; sulphides of nickel, copper, lead, molybdenum, iron, and zinc; and oxides and hydroxides of iron. Silver, gold, and platinum group minerals occur locally. Chlorite, illite, kaolinite, and siderite are the most common gangue minerals.

Some deposits of the polymetallic subtype (e.g., Cigar Lake) have vertically zoned mineral assemblages. At the unconformity, U-Ni-Co-Ag-As assemblages grade locally upward into a zone with the U-Cu assemblage, whereas monometallic uranium is found in upper and lower extremities of the orebodies. The zonal arrangement of these assemblages suggests that they are contemporaneous and are apparently related to the geochemical mobilities of individual elements and stabilities of the minerals.

Proportions of metals in ores of the polymetallic subtype differ from one deposit to another. In the Key Lake ores, the contents of the principal constituents, uranium and nickel, are 1:0.55 (A. de Carle, verbal comm., 1986); whereas in the ores of the main pod of the Cigar Lake deposit the contents of these metals are 1:0.078 (Fouques et al., 1986).

Alteration

Both the monometallic and polymetallic deposits have associated zones of host rock alteration that appear to result from three distinct processes.

1. Paleoweathering of the metamorphic basement rocks prior to deposition of the Middle Proterozoic clastic sedimentary rocks led to formation of regolith. The regolith persists throughout the basin and shows many features compatible with present-day lateritic soil profiles formed in subtropical to tropical climates (Macdonald, 1985). Development of regolith was characterized by chloritization and hematitic alteration of ferromagnesian minerals, sericitization, illitization, or kaolinization of K-feldspars, and saussuritization of plagioclase (de Carle, 1986). The weathered material was an important source of metals for the Athabasca Group rocks. Regolith is also host for mineralization of some deposits (Tremblay, 1982; Table 7-2).
2. Diagenetic and epigenetic alteration was coeval with the mineralization, and affected not only the rocks of the Atahabasca Group, but also the basement rocks, particularly in the vicinity of the deposits. Oxygen- and hydrogen-isotope analyses of illite, kaolinite, and chlorite associated with uranium mineralization indicated (Kyser et al., 1989; Kotzer and Kyser, 1990a, b; Kotzer, 1992) that (i) the basement fluids produced clinochlore with $\delta^{18}O$ = +2 to +4‰ and δD = -45 to -15‰ and sudoite with $\delta^{18}O$ = -25 to -60‰ and δD = 7 to 9‰; (ii) the basinal fluids produced illite and kaolinite with $\delta^{18}O$ = +2 to +4‰ and δD = -60 ± 20‰; and (iii) the retrograde fluids (i.e., meteoric waters that circulated along fault zones) produced a late stage kaolinite with $\delta^{18}O$ = -16‰ and δD = -130 ± 10‰. The alterations have various forms and intensities depending on the character of the host rocks and the nature of the fluids. For example, at Key Lake kaolinization of the Athabasca Group rocks was superimposed on illitization and extends for several hundred metres laterally from the mineralization. At Cigar Lake the orebody is surrounded by an alteration halo, which contains hematite, illite, ferromagnesian illite, chlorite and its Al-Mg variety – sudoite, kaolinite, iron-rich kaolinite, locally unconsolidated sand (quicksand), and a quartz-cemented cap (Fouques et al., 1986; Percival and Kodama, 1989). At Rabbit Lake, where mineralization is entirely hosted by the basement rocks, chloritization, graphitic chloritic alteration, and dolomitization are the main forms of alteration (Fig. 7-5). At the Midwest deposit, uranium and boron, and at Key Lake, boron and lead, are enhanced in the host rocks around mineralization (Sopuck et al., 1983). The orebodies are commonly surrounded by clay envelopes. Quartz grains in rocks at the unconformity are corroded or even totally replaced by clay. Silicification of the sandstone in the form of vein systems and pervasive cements has occurred in places in the overlying sandstone and is a manifestation of intense illitization and desilicification at depth. Partial destruction of graphite and carbon from metapelitic rocks and formation of limonite and hematite, or bleaching of the host rocks, are other

characteristics of the alteration zones. Brecciation and development of collapse structures in the immediate vicinity of the mineralization were associated with the alteration processes. The diagenetic and epigenetic alterations were apparently enhanced by ionization effects of the radionuclides, particularly by the radiolysis of water and by reactions of hydrogen and oxygen with the rocks. Effects of water radiolysis were observed at the Cigar Lake deposit (Cramer, 1986).

3. Postore alteration (about 1.2 to 0.8 Ga) succeeded the main episode of uranium mineralization. Tectonic uplift of the Athabasca Basin about 300 Ma ago (Hoeve and Quirt, 1984) triggered circulation of basinal fluids, which caused corrosion of the ores; formation of new alteration minerals, particularly chlorite, smectite, and mixed-layer clays; and kaolinization of illite and quartz (Ruhrmann and von Pechmann, 1989).

Mineralogy

Pitchblende is the principal uranium mineral in deposits of both the monometallic and polymetallic types. A crystalline variety of pitchblende (alpha-triuranium heptaoxide-U_3O_7-tetrauraninite) has been identified in some deposits (e.g., Key Lake, Cigar Lake, and Eagle Point). Coffinite is another common uranium mineral. Locally thucholite and uranoan carbon are present as veinlets, globules, and lenses. Thorium-bearing uraninite, brannerite, and U-Ti mineral aggregates are rare. Secondary uranium minerals are present in some deposits, even at depths exceeding 100 m (e.g., in the Eagle Point and Rabbit Lake deposits). They include uranophane, kasolite, boltwoodite, sklodowskite, becquerelite, vandendriesscheite, woelsendorfite, tyuyamunite, zippeite, masuyite, bayleyite, and yttrialite (Ruzicka, 1989). Minerals of nonradioactive metals occur in relatively large quantities in the polymetallic subtype, but minor amounts are present also in the monometallic subtype. Nickeline and rammelsbergite are the most common arsenides. Skutterudite, pararammelsbergite, safflorite, maucherite, and modderite occur locally. Gersdorffite is the most common representative of the sulpharsenides. Cobaltite, glaucodot, and tennantite are relatively rare. Chalcopyrite, pyrite, and galena are the most common sulphides; others include bornite, chalcocite, sphalerite, marcasite, bravoite, millerite, jordisite, covellite, and digenite. Some deposits contain selenides such as clausthalite, freboldite, trogtalite, and guanajuatite. Tellurides, such as altaite and calaverite, occur in some deposits in the Carswell Structure. Locally native metals, such as gold, copper, and arsenic, accompany the uranium minerals. A detailed list of ore-forming minerals in individual deposits has been given by Ruzicka (1989).

DEFINITIVE CHARACTERISTICS

1. Unconformity-associated uranium deposits typically occur in close spatial association with unconformities that separate crystalline (Archean and Lower Proterozoic) basement rocks from overlying Middle Proterozoic clastic sedimentary rocks, which are generally unmetamorphosed and flat-lying.
2. Granitic rocks, which commonly form domal structures, and metamorphosed graphitic pelitic rocks are the most distinctive members of the basement complexes. Most of the deposits are located along the flanks of the domal structures and in proximity to the metapelitic rocks.
3. The clastic sedimentary cover rocks were deposited on weathered basement rocks, in large intracratonic basins.
4. The deposits are commonly associated with the unconformity where it is intersected by faults, shear zones, or fracture zones.
5. The uranium mineralization is either monometallic (containing predominantly uranium minerals), or polymetallic (i.e., accompanied by arsenides, sulpharsenides, and sulphides of nickel and cobalt, and sulphides of copper, iron, lead, zinc, bismuth, and molybdenum). Locally a transitional phase of mineralization, consisting of uranium and only one or a few other base metal minerals (e.g., at Cigar Lake) may occur.
6. The polymetallic mineralization generally occurs at the unconformity, either in the overlying sedimentary cover (e.g., Athabasca Group) or in subjacent crystalline basement rocks, whereas the monometallic mineralization is farther from the unconformity, usually localized in the basement rocks or, less commonly, in the cover rocks.
7. The mineralization occurs only in areas of alteration, which comprises illite, kaolinite, and chlorite.

GENETIC MODEL

Three conceptual genetic models have been proposed for Canadian uranium deposits associated with a Middle Proterozoic (particularly sub-Athabasca) unconformity (Hoeve et al., 1980):

1. a near-surface supergene origin, which involves derivation of uranium and other ore constituents from basement rocks by supergene processes, their transport by surface and ground waters, and their deposition in host rocks under reducing conditions;
2. a magmatic or metamorphic hydrothermal origin, whereby the uranium is derived from deep-seated sources, and transported by and deposited from ascending solutions; and
3. a diagenetic-hydrothermal origin, which relates uranium mineralization to diagenetic processes active under elevated temperatures in Athabasca Group sediments after their deposition, and precipitation of uranium from diagenetic fluids by local reductants. Ruzicka (1993) analyzed the geological features of unconformity deposits of the Athabasca Basin and Pine Creek Geosyncline metallogenic provinces and established two sets of models for each province: regional models, which summarized the geological histories, and deposit models, which reflected the ore-forming processes and environments within these provinces. A modified version of these models, applied to Athabasca Basin deposits, is presented here (Fig. 7-7):

Contents

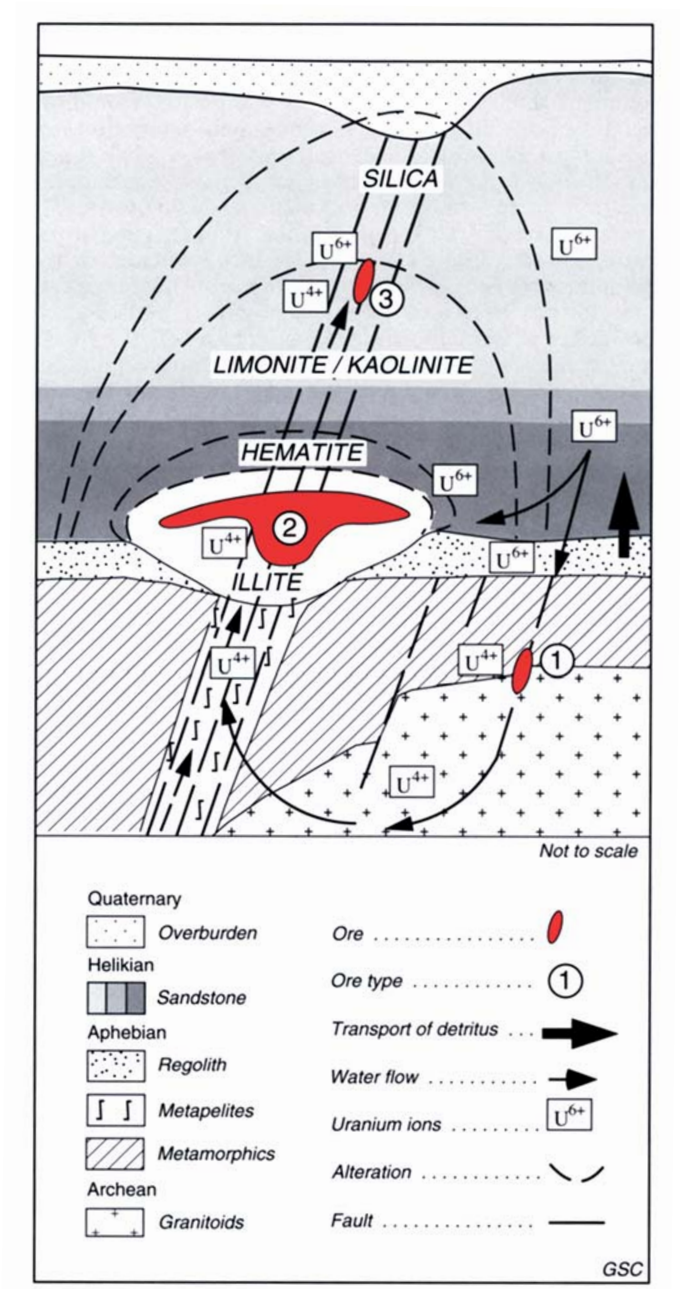

Figure 7-7. Conceptual model of unconformity-associated uranium deposits. A generalized vertical cross-section. Arrows indicate flow paths of oxidized and reduced convective waters. Circled numbers indicate locations of various styles of mineralization: (1) high grade polymetallic mineralization at the unconformity, (2) medium grade monometallic mineralization below the unconformity, (3) low grade monometallic mineralization in sedimentary cover rocks above the unconformity.

i) The deposits are part of a uranium-enriched subprovince within the Churchill Structural Province. The uranium may originally have been introduced into the geochemical cycle in the form of granitic magmatism, during the late Archean or Early Proterozoic. Uraniferous monazite and uraninite yielding U-Pb ages >2.2 Ga are present in pegmatites.

ii) In a subsequent stage uranium was concentrated in sedimentary rocks (e.g., certain Lower Proterozoic metasedimentary rocks contain up to 50 ppm uranium).

iii) Further concentration of uranium took place during the waning phase of the Trans-Hudson Orogeny, at which time the pitchblende-brannerite deposits (Type 13; "Vein uranium") in the Beaverlodge area were formed.

iv) Subsequent peneplanation and lateritic weathering of the uranium-enriched rocks resulted in liberation of uranium- and associated metal-bearing minerals and their incorporation in the detritus. The detritus was deposited in Middle Proterozoic intracratonic basins, which thus became reservoirs for the metals. The basinal sediments underwent profound diagenesis from about 1700 to 1400 Ma. During that time portions of the sequence evolved in chemical maturity, accompanied by breakdown of minerals and release of metals.

v) Tectonic events associated with rapid subsidence and rifting of the basin activated hydrological systems and thus caused convective cycling of fluids and mobilization of the metals from the reservoirs. The events are reflected in the Rb-Sr isochron age of 1477 ± 57 Ma for illites from deposits associated with the sub-Athabasca unconformity; the date thus marks a diagenetic ore-forming process that led to mineralization with uranium, nickel, cobalt, and other associated metals. Three types of fluids took part in the hydrological system: (a) oxidized basinal fluids, which also included metalliferous connate waters brought into the basins along with detritus; (b) reduced basement fluids; and (c) retrograde fluids, derived from meteoric waters. The oxidized metalliferous fluids moved laterally and downwards (their salinity and metal contents caused their high density); when these fluids encountered the hydrological barrier at the unconformity, they continued flowing laterally along the unconformity. However, part of the fluids circulated through fault and fracture zones in the basement rocks, and became reduced. These reduced basement fluids then re-entered the sedimentary rocks in ascending flows along faults and fracture zones, where they mingled with the oxidized metalliferous basinal waters at the unconformity and in the upper parts of the cover rocks. Whether or not the ascending fluids also contained water from deep-seated sources is not known.

vi) Deposition of the metals and associated gangue minerals, took place at the interface between the oxidizing and reducing fluids, i.e., at the redox front, during the diagenesis and epigenesis of the sedimentary cover rocks. Depending upon the location of the redox front, mineralization took place in diverse parts of the basin and the basement: (a) high grade polymetallic mineralization directly at the unconformity (see location 1 in Fig. 7-7; examples are at the Key Lake, Cigar Lake, and Midwest deposits); (b) medium grade monometallic mineralization in fractures and faults below the unconformity (see location 2 in Fig. 7-7; examples are the Rabbit Lake and Eagle Point deposits); and (c) low grade monometallic mineralization in the sedimentary cover sequence at some distance above the unconformity (see location 3 in Fig. 7-7; examples are the Fond-du-Lac deposit and the "perched" mineralization at Cigar Lake).

vii) The mineralization was accompanied by alteration of the host rocks, primarily argillization (illitization, kaolinization) and chloritization. The argillic alteration was superimposed on the earlier lateritization. The hydrothermal fluids introduced carbon dioxide, hydrogen sulphide, and methane, and caused dissolution of quartz in the area of mineralization, and silicification of the sandstone (including crystallization of euhedral quartz in vugs) more distant in an aureole around the orebodies. Local tourmalinization (e.g., at Key Lake) and magnesian metasomatism (e.g., at Rabbit Lake) accompanied the ore-forming process. The alteration was enhanced by the ionization effects of radiation and by partial hydrolysis of the waters.

viii) Deposition of uranium and associated metals was structurally controlled by the unconformity and intersecting faults and fracture zones. It was lithologically controlled by altered graphitic pelites in the basement, and altered and porous clastic sediments above the unconformity. Geochemical processes (e.g., Eh and pH changes, adsorption, and complexing) gave rise to the deposition of the ore-forming minerals, the specific mineral assemblages that formed, and their zonal arrangement (Wallis et al., 1986).

ix) The mineralization was remobilized and redeposited in at least two later periods, but this had little effect on the main concentrations or economic viability of the uranium deposits.

RELATED DEPOSIT TYPES

The unconformity-associated deposits exhibit some geological features that are also typical of other types of uranium deposits, such as Phanerozoic sediment-hosted and vein (subtype 8.1, "Sandstone uranium"; Types 13, "Vein uranium"; and 14, "Arsenide vein silver, uranium") deposits.

Phanerozoic, sediment-hosted uranium ("Sandstone uranium"; subtype 8.1) deposits, also are associated with coarse clastic sedimentary rocks in continental intracratonic basins; however, they contain orebodies of lower grade and usually of different morphology. Their mineralization is commonly disseminated to semimassive and occurs in 'C-shape', 'blanket', or 'stack' orebodies. Their principal uranium minerals are carnotite, tyuyamunite, coffinite, and urano-organic complexes; pitchblende is less abundant than in the unconformity deposits. Vanadium, molybdenum, and selenium are commonly associated with uranium in the sandstone deposits, whereas nickel, cobalt, and arsenic are the elements that typically accompany uranium in the unconformity-associated deposits. The sandstone uranium deposits formed from flowing intrastratal oxidizing fluids at their entry into reducing parts of the sandstone (i.e., at a moving redox front), whereas the unconformity-associated deposits may have formed at the confluence of flows of oxidized basinal and reduced basement waters (i.e., at a stationary redox front). The difference in grades of these two deposit types seems to be related to the different forms of the redox processes. Effects of hydrolysis are less intense in formation of the Phanerozoic sediment-hosted deposits and their clay envelope is small or absent.

The U-Ni-Co-As mineral assemblages that are typical for the polymetallic unconformity-associated deposits are also found in uranium vein deposits (subtype 14.2, "Arsenide vein uranium-silver"), such as those at Port Radium; the Jáchymov deposit, Czech Republic; and the Shinkolobwe deposit, Zaire. However, polymetallic vein deposits consist of relatively irregular discontinuous orebodies, in contrast to the massive concentrations that comprise unconformity-associated deposits. Monometallic uranium vein deposits contain, as do the monometallic unconformity-associated deposits, only a few principal ore-forming minerals, namely pitchblende and coffinite.

Mineralization of both the vein and unconformity deposits is structurally controlled. For example, the structural locus of the Eldorado (Ace-Fay-Verna) vein deposit (Type 13, "Vein uranium") in the Beaverlodge area is the St. Louis Fault; the unconformity-associated Eagle Point deposit is spatially related to the Eagle Point and Collins Bay faults. The Ace-Fay-Verna deposit is also spatially related to the sub-Martin Formation unconformity.

EXPLORATION GUIDES

Exploration criteria for uranium and uranium-polymetallic deposits associated with unconformities include the following:

1. Regional scale guides are:
   - i) Middle Proterozoic intracratonic basins containing clastic sediments, which rest unconformably on Lower Proterozoic or Archean supracrustal and granitoid rocks. The Middle Proterozoic basinal cover rocks must be thoroughly oxidized.
   - ii) Presence of a regolith at the top of the basement rocks.
   - iii) Presence in the basement terrane of reductants such as carbonaceous/graphitic or pyrite-bearing pelitic units.
2. District and local scale guides are:
   - i) Features indicating the presence of an unconformity, a regolith, steep faults or fracture zones; the bedrock surface below the overburden may exhibit effects of glacial scouring in areas occupied by these faults or fracture zones.

ii) Alteration of the rocks and mineralization; zones of alteration may have a low density and be detectable by gravity surveys.

iii) Reducing horizons, particularly graphitic/pyritic pelites, may comprise geophysically detectable conductive layers.

iv) Radiometric anomalies, although weak, and particularly those with a high U/Th ratio. However, weak or even negative results of ground radiometric surveys (using Geiger-Müller counters, scintillometers, or gamma-ray spectrometers) do not preclude the possible existence of uranium mineralization at depth.

v) Geochemical anomalies of U and/or associated elements, such as As, Ni, Co, Pb, Cu, Bi, Li, and B.

vi) During geological and radiometric logging of drill core particular attention should be paid to: argillized (illitized/kaolinized) and chloritized rocks; recognition of the unconformity, and intersecting faults and fracture zones along the unconformity; limonite/hematite alteration; dilational and hydrothermal effects associated with the mineralization process; presence of collapse structures; vugs filled with euhedral quartz and silicification aureoles within the clastic sedimentary cover rocks; depletion of graphite in pelitic layers in the basement; sampling for chemical analyses for U, Ni, Co, and for other elements (discretional).

ACKNOWLEDGMENT

Critical reading of the manuscript and helpful recommendations by A.R. Miller and R.I. Thorpe of the Geological Survey of Canada are gratefully acknowledged.

SELECTED BIBLIOGRAPHY

References marked with asterisks (*) are considered to be the best sources of general information on this deposit type.

Andrade, N.
1989: The Eagle Point uranium deposit, northern Saskatchewan, Canada; in Uranium Resources and Geology of North America, Proceedings of a Technical Committee Meeting, Saskatoon, 1987, International Atomic Energy Agency, IAEA-TECDOC-500, Vienna, p. 455-490.

Appleyard, E.C.
1984: The origin of plagioclasite in the vicinity of the Rabbit Lake uranium deposit; in Summary of Investigations 1984, Saskatchewan Geological Survey, Saskatchewan Energy and Mines, Miscellaneous Report 84-4, p. 68-71.

Ashton, K.E.
1988: Precambrian Geology of the southeastern Amer Lake area (66H/1), near Baker Lake, N.W.T.; PhD. thesis, Queen's University, Kingston, Ontario, 335 p.

Battey, G.C., Miezitis, Y., and McKay, A.D.
1987: Australian uranium resources; Australia, Bureau of Mineral Resources and Geophysics, Resource Report 1, Canberra, Australia, 67 p.

Bickford, M.E., Collerson, K.D., Lewry, J.F., van Schmus, W.R., and Chiarenzelli, J.R.
1990: Proterozoic collisional tectonism in the Trans-Hudson orogen, Saskatchewan; Geology, v. 18, p. 14-18.

***Cameron, E.M. (ed.)**
1983: Uranium Exploration in Athabasca Basin, Saskatchewan, Canada; Geological Survey of Canada, Paper 82-11, 310 p.

Cramer, J.J.
1986: A natural analog for a fuel waste disposal vault; in Proceedings of the Second International Conference on Radioactive Waste Management; Winnipeg, Manitoba, September 7-11, 1986; Canadian Nuclear Association, p. 679-702.

Cumming, G.L. and Krstic, D.
1992: The age of unconformity-related uranium mineralization in the Athabasca Basin, northern Saskatchewan; Canadian Journal of Earth Sciences, v. 29, p. 1623-1639.

Cumming, G.L. and Rimsaite, J.
1979: Isotopic studies of lead-depleted pitchblende, secondary radioactive minerals and sulphides from the Rabbit Lake uranium deposit, Saskatchewan; Canadian Journal of Earth Sciences, v. 16, p. 1702-1715.

Cumming, G.L., Krstic, D., and Wilson J.A.
1987: Age of the Athabasca Group, northern Alberta; in Geological Association of Canada/Mineralogical Association of Canada, Program with Abstracts, v. 12, p. 35.

Davidson, G.I. and Gandhi, S.S.
1989: Unconformity-related U-Au mineralization in the Middle Proterozoic Thelon Sandstone, Boomerang Lake Prospect, Northwest Territories, Canada; Economic Geology, v. 84, p. 143-157.

de Carle, A.
1986: Geology of the Key Lake deposits; in Uranium Deposits of Canada, (ed.) E.L. Evans; The Canadian Institute of Mining and Metallurgy, Special Volume 33, p. 170-177.

Dudás, F.Ö., LeCheminant, A.N., and Sullivan, R.W.
1991: Reconnaissance Nd isotopic study of granitoid rocks from the Baker Lake region, District of Keewatin, N.W.T., and observations on analytical procedures; in Radiogenic Age and Isotopic Studies: Report 4, Geological Survey of Canada, Paper 90-2, p. 101-112.

***Evans, E.L. (ed.)**
1986: Uranium Deposits of Canada; The Canadian Institute of Mining and Metallurgy, Special Volume 33, 324 p.

Federal Institute for Geosciences and Natural Resources
1989: Activity Report 1987/88; Federal Institute for Geosciences and Natural Resources, Hannover, p. 43.

***Ferguson, J. (ed.)**
1984: Proterozoic unconformity and stratabound uranium deposits; International Atomic Energy Agency, IAEA-TECDOC-315, Vienna, 338 p.

***Fouques, J.P., Fowler, M., Knipping, H.D., and Schimann, K.**
1986: The Cigar Lake uranium deposit: discovery and general characteristics; in Uranium Deposits of Canada, (ed.) E.L. Evans; The Canadian Institute of Mining and Metallurgy, Special Volume 33, p. 218-229.

Fuchs, H. and Hilger, W.
1989: Kiggavik (Lone Gull): an unconformity related uranium deposit in the Thelon Basin, Northwest Territories, Canada; in Uranium Resources and Geology of North America, Proceedings of a Technical Committee Meeting, Saskatoon, 1987, International Atomic Energy Agency, IAEA-TECDOC-500, Vienna, p. 429-454.

Heine, T.
1981: The Rabbit Lake deposit and the Collins Bay deposits; in Uranium Guidebook; The Canadian Institute of Mining and Metallurgy, Geology Division, September 8-13, Saskatchewan, p. 87-102.

Henderson, J.R., Henderson, M.N., Pryer, L.L., and Cresswell, R.G.
1991: Geology of the Whitehills-Tehek area, District of Keewatin: an Archean supracrustal belt with iron-formation-hosted gold mineralization in the central Churchill Province; in Current Research, Part C; Geological Survey of Canada, Paper 91-1C, p. 149-156.

Hoeve, J. and Quirt, D.H.
1984: Mineralization and host-rock alteration in relation to clay mineral diagenesis and evolution of the Middle Proterozoic Athabasca Basin, northern Saskatchewan, Canada; Saskatchewan Research Council, Technical Report No. 187, 187 p.

***Hoeve, J., Sibbald, T.I.I., Ramaekers, P., and Lewry, J.F.**
1980: Athabasca Basin unconformity-type uranium deposits: a special class of sandstone-type deposits?; in Uranium in the Pine Creek Geosyncline, (ed.) J. Ferguson and A.B. Goleby; International Atomic Energy Agency, Vienna, p. 575-594.

Kotzer, T.
1992: Origin and geochemistry of fluid events in the Proterozoic Athabasca Basin; PhD. thesis, University of Saskatchewan, Saskatoon, Saskatchewan, 329 p.

Kotzer, T.G. and Kyser, T.K.
1990a: Fluid history of the Athabasca Basin and its relation to uranium deposits; in Summary of Investigations 1990; Saskatchewan Geological Survey, Saskatchewan Energy and Mines, Miscellaneous Report 90-4, p. 153-157.

Kotzer, T.G. and Kyser, T.K. (cont.)
1990b: The use of stable and radiogenic isotopes in the identification of fluids and processes associated with unconformity-type uranium deposits; in Modern Exploration Techniques, (ed). L.S. Beck and T.I.I. Sibbald; Saskatchewan Geological Society, Special Publication 9, p. 115-131.

Kyser, T.K., Kotzer, T.G., and Wilson, M.R.
1989: Isotopic constraints on the genesis of unconformity uranium deposits; in Geological Association of Canada/Mineralogical Association of Canada, Program with Abstracts, v. 14, p. A120.

***Laine, R., Alonso, D., and Svab, M. (ed.)**
1985: The Carswell Structure uranium deposits, Saskatchewan; Geological Association of Canada, Special Paper 29, 230 p.

LeCheminant, A.N. and Heaman, L.M.
1989: Mackenzie igneous events, Canada: Middle Proterozoic hotspot magmatism associated with ocean opening; Earth and Planetary Science Letters, v. 96, p. 38-49.

LeCheminant, A.N. and Roddick, J.C.
1991: U-Pb zircon evidence for widespread 2.6 Ga felsic magmatism in the central District of Keewatin, N.W.T.; in Radiogenic Age and Isotopic Studies: Report 4, Geological Survey of Canada, Paper 90-2, p. 91-99.

***Lewry, J.F. and Sibbald, T.I.I.**
1979: A review of pre-Athabasca basement geology in northern Saskatchewan; in Uranium Exploration Techniques, Proceedings of a Symposium, Regina, 1978, (ed.) G.R. Parslow; Saskatchewan Geological Society, Special Publication No. 4, p. 19-58.
1980: Thermotectonic evolution of the Churchill Province in northern Saskatchewan; Tectonophysics, v. 68, p. 45-82.

Macdonald, C.
1985: Mineralogy and geochemistry of the sub-Athabasca regolith near Wollaston Lake; in Geology of Uranium Deposits, (ed.) T.I.I. Sibbald and W. Petruk; The Canadian Institute of Mining and Metallurgy, Special Volume 32, p. 155-158.

Marlatt, J., McGill, B., Matthews, R., Sopuck, V., and Pollock, G.
1992: The discovery of the McArthur River uranium deposit, Saskatchewan, Canada; in New Developments in Uranium Exploration, Resources, Production and Demand, Proceedings of a Technical Committee Meeting jointly organized by the International Atomic Energy Agency and the Nuclear Energy Agency of the Organization for Economic Cooperation Development, Vienna, 26-29 August, 1991, IAEA-TECDOC-650, p. 118-127.

Miller, A.R.
1983: A progress report: uranium-phosphorous association in the Helikian Thelon Formation and sub-Thelon saprolite, central District of Keewatin; in Current Research, Part A; Geological Survey of Canada, Paper 83-1A, p. 449-456.

Miller, A.R., Blackwell, J.D., Curtis, L., Hilger, W., McMillan, R.H., and Nutter, E.
1984: Geology and discovery of Proterozoic uranium deposits, central District of Keewatin, Northwest Territories, Canada; in Proterozoic Unconformity and Stratabound Uranium Deposits, (ed.) J. Ferguson; International Atomic Energy Agency, Vienna, IAEA-TECDOC-315, p. 285-312.

Miller, A.R., Cumming, G.L., and Krstic, D.
1989: U-Pb, Pb-Pb and K-Ar isotopic study and petrography of uraniferous phosphate-bearing rocks in the Thelon Formation, Dubawnt Group, Northwest Territories, Canada; Canadian Journal of Earth Sciences, v. 26, p. 867-880.

Percival, J.B. and Kodama, H.
1989: Sudoite from Cigar Lake, Saskatchewan; Canadian Mineralogist, v. 27, p. 633-641.

Ramaekers, P.
1990: Geology of the Atahabasca Group (Helikian) in northern Saskatchewan; Saskatchewan Geological Survey, Report 195, 49 p.

Ray, G.E.
1977: The geology of Highrock Lake-Key Lake vicinity, Saskatchewan; Saskatchewan Geological Survey, Report 197, 29 p.

Ray, G.E. and Wanless, R.K.
1980: The ages of the Wathaman Batholith, Johnson River Granite and Peter Lake Complex and their geological relationships to the Wollaston, Peter Lake and Rottenstone Domains of northern Saskatchewan; Canadian Journal of Earth Sciences, v. 17, p. 333-347.

Robinson, S.C.
1955: Mineralogy of uranium deposits, Goldfields, Saskatchewan; Geological Survey of Canada, Bulletin 31, 128 p.

Ruhrmann, G. and von Pechmann, E.
1989: Structural and hydrothermal modification of the Gaertner uranium deposit, Key Lake, Saskatchewan, Canada; in Uranium Resources and Geology of North America, Proceedings of a Technical Committee Meeting, Saskatoon, 1987; International Atomic Energy Agency, IAEA-TECDOC-500, Vienna, p. 363-377.

***Ruzicka, V.**
1984: Unconformity-related uranium deposits in the Athabasca Basin region, Saskatchewan; in Proterozoic Unconformity and Stratabound Uranium Deposits, (ed.) J. Ferguson; International Atomic Energy Agency, Vienna, IAEA-TECDOC-315, p. 219-267.
1989: Monometallic and polymetallic deposits associated with the sub-Athabasca unconformity in Saskatchewan; in Current Research, Part C; Geological Survey of Canada, Paper 89-1C, p. 67-79.
1992: Uranium in Canada, 1991; in Current Research, Part D; Geological Survey of Canada, Paper 92-1D, p. 49-57.
1993: Unconformity-type uranium deposits; in Mineral Deposit Modelling, (ed.) R.V. Kirkham, W.D. Sinclair, R.I. Thorpe, and J.M. Duke; Geological Association of Canada, Special Paper 40, p. 125-149.

Ruzicka, V. and LeCheminant, G.M.
1986: Developments in uranium geology in Canada, 1985; in Current Research, Part A; Geological Survey of Canada, Paper 86-1A, p. 531-540.

Sibbald, T.I.I.
1976: Uranium metallogenic studies: Rabbit Lake; in Summary of Investigations 1976 by the Saskatchewan Geological Survey, (ed.) J.E. Christopher and R. Macdonald; Province of Saskatchewan, Department of Mineral Rersources, p. 115-123.

***Sibbald, T.I.I. and Petruk, W. (ed.)**
1985: Geology of uranium deposits; The Canadian Institute of Mining and Metallurgy, Special Volume 32, 268 p.

Sopuck, V.J., de Carle, A., Wray, E.M., and Cooper, B.
1983: Application of lithogeochemistry to the search for unconformity-type uranium deposits in the Athabasca Basin; in Uranium Exploration in Atahabasca Basin, (ed.) E.M. Cameron; Geological Survey of Canada, Paper 82-11, p. 192-205.

Tremblay, L.P.
1982: Geology of the uranium deposits related to the sub-Athabasca unconformity, Saskatchewan; Geological Survey of Canada, Paper 81-20, 56 p.

Wallis, R.H., Saracoglu, N., Brummer, J.J., and Golightly, J.P.
1986: The geology of the McClean uranium deposits, northern Saskatchewan; in Uranium Deposits of Canada, (ed.) E.L. Evans; The Canadian Institute of Mining and Metallurgy, Special Volume 33, p. 193-217.

Worden, J.M., Cumming, G.L., and Baadsgaard, H.
1985: Geochronology of host rocks and mineralization of the Midwest uranium deposit, northern Saskatchewan; in Geology of Uranium Deposits, (ed.) T.I.I. Sibbald and W. Petruk; The Canadian Institute of Mining and Metallurgy, Special Volume 32, p. 67-72.

Author's address

V. Ruzicka
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario
K1A 0E8

Printed in Canada