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Uranium Occurrences in Northern Saskatchewan, Canada, and their Mode of Origin [and Discussion]

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Uranium occurrences in northern Saskatchewan, Canada, and their mode of origin

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Mineralogical, petrographical, geochemical, tectonic and palaeoclimatological studies suggest the following sequence of events in the formation of the Key Lake ore bodies:

(1) Uranium was deposited in Aphebian sediments surrounding Archaean cores;

(2) the Hudsonian orogeny metamorphosed the sediments, perhaps further concentrating the uranium;

(3) Middle Proterozoic weathering processes mobilized the uranium and nickel;

(4) both elements migrated into tectonic traps, where they were concentrated;

(5) the basement was covered by the Athabasca formation to a thickness of 1000 m and more;

(6) diagenetic processes mobilized and redeposited the uranium more or less *in situ* destroying the original radiogenic equilibrium and simultaneously forming a new 'primary' generation of uranium oxide with a rejuvenated age of about 1100 Ma;

(7) episodic uplift resulted in erosion of the overlying Athabasca formation, leading to the formation of new generations of uranium minerals (sooty pitchblende, coffinite).

An alternative explanation is that the weathering cycle of stages (3) and (4) can be disregarded and the uranium enrichment, involving mobilization, transportation and redeposition, attributed entirely to diagenetic processes.

Published data of similar deposits in Saskatchewan/Canada are compared with the Key Lake geological setting. They contain metallogenic parameters comparable with those of Key Lake indicating that all these orebodies or mineral occurrences probably belong to the same vein type of deposit.

INTRODUCTION

Numerous uranium occurrences have been discovered to date in the Athabasca region of northern Saskatchewan. Five areas with viable uranium deposits can be identified: (1) Beaverlodge–Gunnar, (2) Rabbit Lake, (3) Cluff Lake, (4) Key Lake, (5) Maurice Bay (figure 1). All these deposits have various geological, mineralogical, geochemical and geochronological features in common. Their essential metallogenetic parameters, as far as they are published, will be reviewed and compared with Uranerz's research results on the Key Lake mineralization. Similarities as well as differences lead to the conclusion that a polygenetic evolution of the uranium deposits has to be assumed. The essential metallogenic parameters for each of the five deposits are described individually.

KEY LAKE

The following descriptions are based on the fieldwork of B. Tan and K. Lehnert-Thiel and on mineralogical investigations by V. Voultsidis and D. Clasen, to name a few of the geological staff of Uranerz (see also Dahlkamp & Tan 1977; Dahlkamp 1978*b*) who have been involved in the investigation of this deposit.

Mineralogy and petrology of the host rocks

The major rock units hosting the deposit consist of metamorphosed and altered sediments of crystalline basement (Wollaston Group) comprising graphitic chlorite–sericite schist, chlorite schist, biotite–plagioclase–cordierite gneiss, coarse grained anatectic gneiss (pegmatoid) and, within the fault zone, Fe-chlorite mylonite, kaolinite mylonite and Mg-chlorite–sericite mylonite. Archaean (?) granites and granite gneisses occur in the vicinity. They form the core to the enveloping metasediments of the Wollaston Group as determined by Tan, Thiel and their coworkers (1975/76). The crystalline basement is overlain by unmetamorphosed clastic semi-redbed sediments of the Athabasca Formation. Kaolinite mylonite and Fe-chlorite mylonite are the main ore hosts. Locally, Athabasca sediments also contain mineralization.

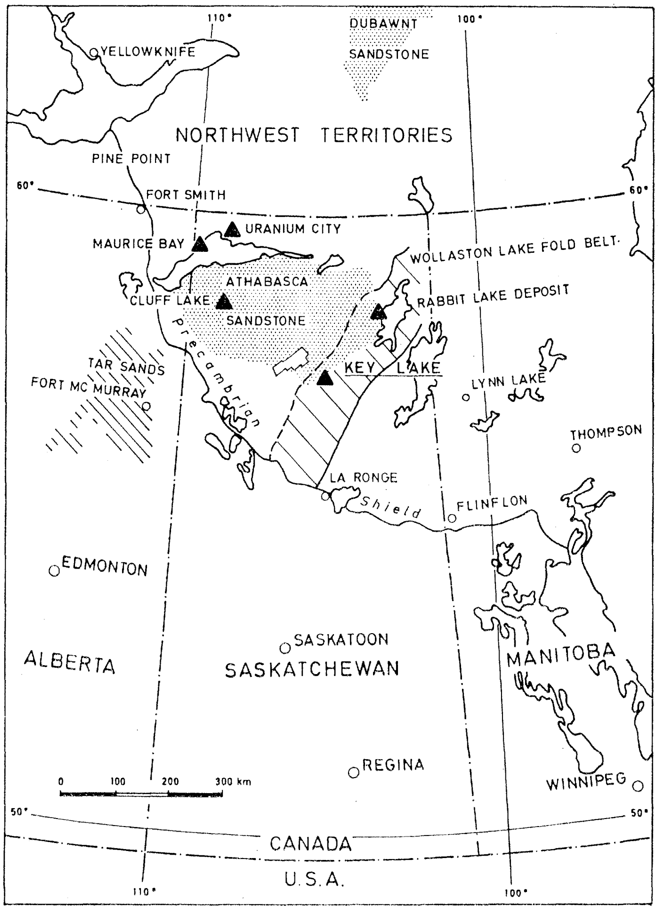


Figure 1. Location map of Key Lake deposit.

Mineralization

Ore minerals

The main metallic elements in the mineralized body are uranium and nickel. Nickel occurs as a sulphide and as a sulpho-arsenide; uranium as an oxide and a silicate.

The uranium ore minerals are 'pseudo pitchblende' I, pitchblende II and coffinite. The nickel minerals are mainly gersdorffite, millerite and niccolite, with bravoite and rammelsbergite as accessories. Further accessories are pyrite, sphalerite, chalcopyrite and ubiquitous galena. Minor amounts of molybdenum have been detected chemically (up to 0.2 %) but no molybdenum mineral identified.

'Pseudo pitchblende' I occurs in two forms: (1) in aggregates with radiating texture and (2) as discrete euhedral crystals of tetragonal alpha U_3O_7, discovered and determined by Clasen & Voultsides (1976). Both forms are microcrystallographically and chemically identical.

Gersdorffite is commonly developed as euhedral crystals which may contain inclusions of the surrounding matrix, e.g. sooty pitchblende, coffinite or gangue. Niccolite forms colloform textures intergrown with galena and gangue, or spherulitic aggregates with strong anisotropic effects, showing a radiating internal texture. Of genetic significance is the nickel mineral bravoite, as euhedral crystals frequently intergrown with gersdorffite and millerite.

Table 1. Time relation of formation of minerals (generalized)

	I	II	III	IV	formation phases
'pitchblende' I	——	- - -			
pitchblende II		——	——		
coffinite			——	- - -	
gersdorffite	——	——	——	——	
millerite		——	——	——	
niccolite/pararammelsbergite			——	——	
pyrite	- - -	——	——	——	
bravoite		——	——	——	
galena	——	——	——	——	
sphalerite			——	——	
chalcopyrite				——	
chlorite	- - -	- - -	— - -	——	
quartz		——	- - -	- - -	
siderite			——	——	
calcite				——	

Gangue minerals

The massive ore is practically barren of introduced gangue. Only very minor quantities of kaolinite, chlorite, quartz, siderite, calcite, sphene and epidote are found locally.

Intergrowth, paragenesis and interrelation of ore minerals, gangue and host rock minerals

Pitchblende II (sooty pitchblende) reflects in different shades in polished section, probably indicating different generations. Pitchblende coatings on quartz grains are, in turn, coated with silica, testifying to renewed mobilization of silica.

Genetically noteworthy is the rhythmic intergrowth of galena, gersdorffite and Fe-chlorite, showing the formation of Fe-chlorite as being contemporaneous with these ore minerals. An interpretation of the intergrowths of ore minerals and gangue provides a scheme of formation phases as shown in table 1.

Lithological distribution of ore

The high grade (more than 1 %) uranium and nickel mineralization is concentrated predominantly along shears in the kaolinite mylonite and subordinately in the chlorite mylonite. The oldest 'pseudo pitchblende' I generation and niccolite are restricted to these rock facies. All the other rock types contain only minor amounts of ore.

The Athabasca Sandstone is mineralized only where tectonic activity produced open spaces in the form of cracks and fissures. Characteristically only sooty pitchblende, gersdorffite and millerite are present.

Mineral zoning

A vertical mineral zoning can be recognized within the metasedimentary section of the orebody. In the lower section the nickel arsenide, niccolite, predominates, whereas in the upper parts the sulphide, millerite, is the more abundant mineral. Also, the massive 'pseudo pitchblende' I (that of lowest oxidation state) gives way progressively upwards to sooty pitchblende.

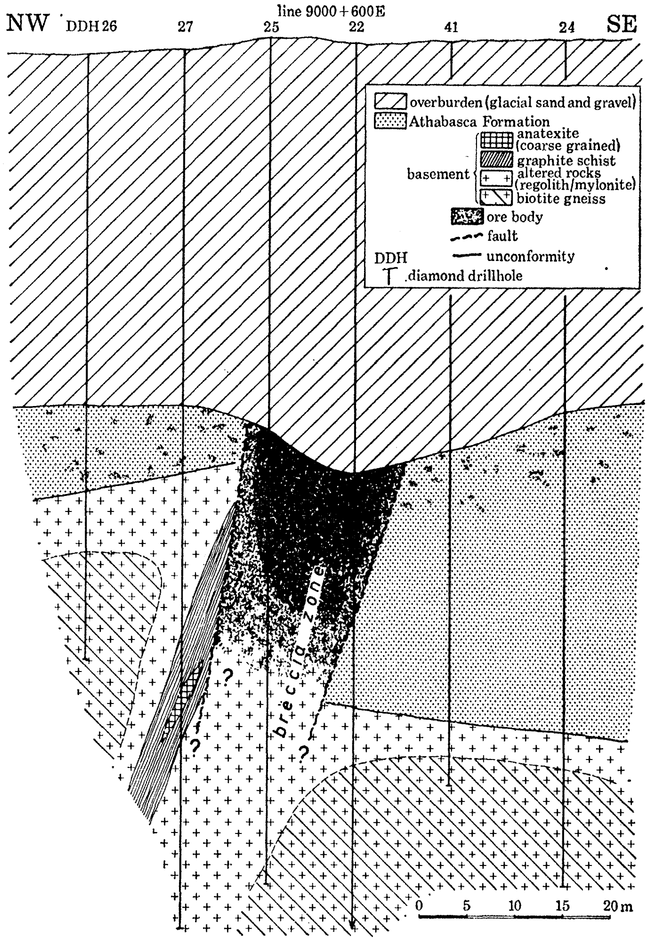


FIGURE 2. Geological cross section of Gaertner ore body (sketch).

Geochronology

To date, the age determination of radiogenic isotopes is only partly complete. Preliminary results according to Wendt and Höhndorf/B.G.R. (1976/77) are as follows: (*a*) formation of 'pseudo pitchblende' I. 1228–1160 Ma; (*b*) formation of pitchblende II within the metasedimentary section of the orebody, 960 and 370 Ma (samples consisted mainly of coffinite and may indicate two phases of silicification); (*c*) formation of pitchblende II (sooty) within the overlying Athabasca Formation, 250–107 Ma.

Geochemical distribution of uranium and nickel in the Aphebian metasediments

A research programme specifically directed at investigating the rôle of the Aphebian metasediments as potential source rocks for the ore resulted in the discovery that biotite-feldspar, cordierite gneisses, apatite-bearing hornblende pyroxenites, etc., contain up to several parts $U/10^3$ in the form of uraninite. The uraninite is associated with biotite, hornblende and apatite.

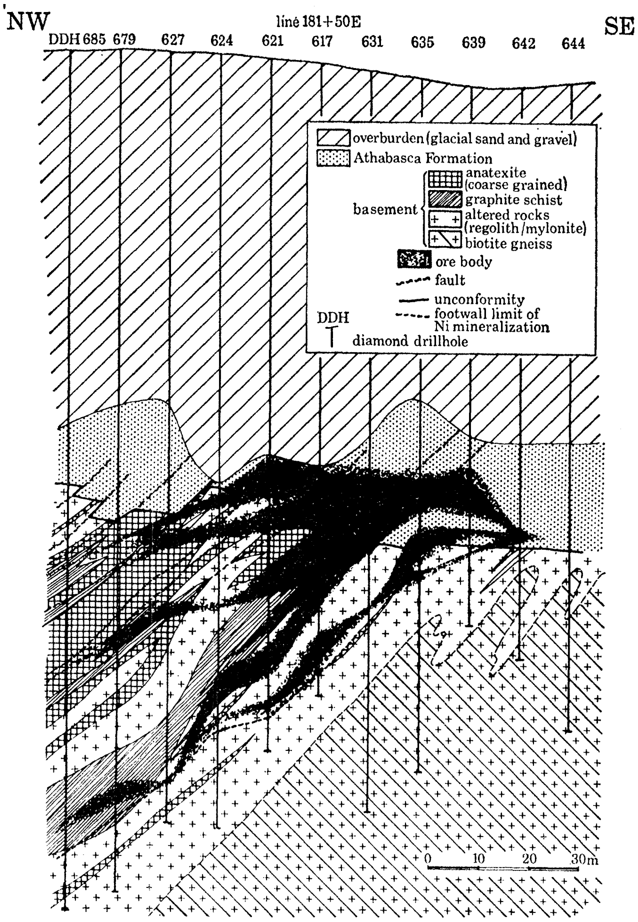


FIGURE 3. Geological cross section of Deilmann ore body (sketch).

Summary of genetically critical parameters of mineralization at Key Lake

Taking into account the lithological and structural development, as well as the ore mineralization and its paragenesis, the following parameters and their relations can be defined:

(1) The deposits occur in shear zones (figures 2 and 3) in Lower Proterozoic (Aphebian) metasediments of the Wollaston Group which mantle Archaean (?) cores (figure 4). Index minerals such as cordierite and (occasionally) sillimanite identify the grade of metamorphism as medium to upper amphibolite facies.

(2) High clarke values of uranium (average up to 50 parts/10^6) and nickel occur within certain types of pelitic and semi-pelitic sediments.

(3) In these protores the ore elements show an affinity to mafic mineral concentrations (biotite, hornblende, pyroxene).

(4) The protores are generally located adjacent to graphitic horizons.

(5) Locally uranium and/or nickel are concentrated to values in excess of the already high clarke values, to several parts/10^3 and even up to parts/10^2 in unaltered metamorphic rocks. Here the uranium occurs in the form of uraninite, i.e. the low oxygen/higher temperature, cubic variety of uranium oxide (formula $UO_{2.2}$). This indicates that it was probably formed during metamorphism (Hudsonian?). (Results of age dating are not yet available.)

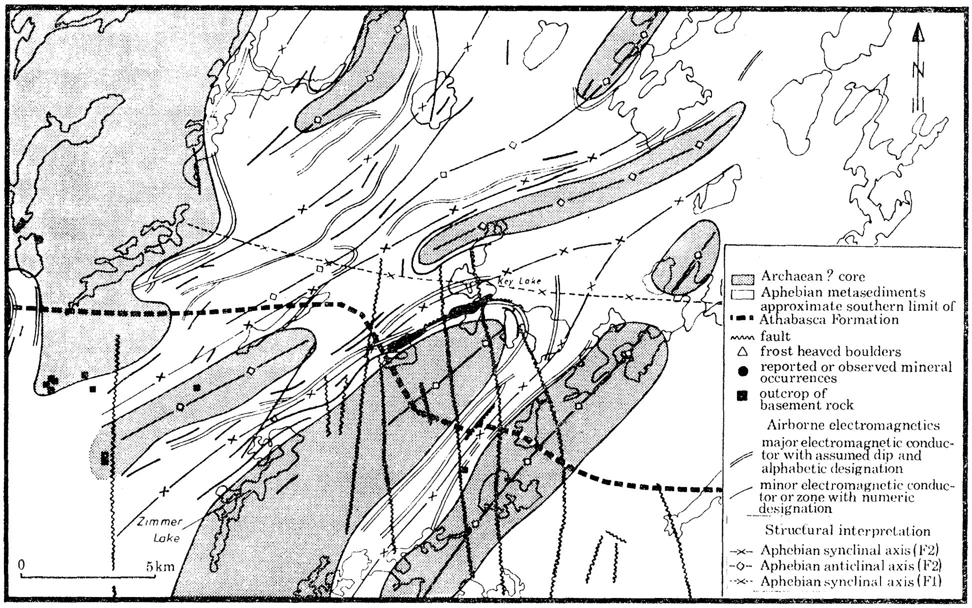


FIGURE 4. Zimmer Key Lake area: interpretation of basement geology, based on geophysical data and geological mapping (Uranerz 1975/76; Ray 1977).

(6) Before deposition of the Athabasca Formation a prolonged period of weathering took place, transforming the upper parts of the crystalline basement, to a depth of 60 m and more, into a regolith. This process must have occurred in pre-Athabasca time since regolith boulders occur in the basal part of the Athabasca Sandstone. The leaching effect of the weathering on the metasediments and protore can be demonstrated by the analysis of approximately located samples.

(7) In late Paleohelikian time the Athabasca region was located between latitudes 20° and 25° N (Fahrig & Jones 1969; Seyfert & Sirkin 1973) (figure 5) and must then have been subjected to a humid, subtropical and subsequently semi-arid to arid climate.

(8) Within the ore zone a hydrous (hydrothermal?) phase led to the formation of new hydrous minerals such as kaolinite (by hydration and removal of cations from the chlorite–sericite–schist) and Fe-chlorite (from an amphibolite with Fe-rich, Ca-free hornblende (grunerite: $Fe_7Si_8O_{22}(OH)_2$)). Both rock types show intense mylonitization as well as post tectonic recrystallization of kaolinite and Fe-chlorite, indicating synonymous tectonic and hydrothermal events.

(9) Contemporaneously with the recrystallization of kaolinite and Fe-chlorite, uranium and nickel minerals crystallized along shears and fissures mainly within these two host rocks.

(10) The oldest determinable ore generation consists of radially textured and crystallized tetragonal uranium oxide (U_3O_7), gersdorffite and millerite. The various generations of sooty

pitchblende, as well as coffinite, were derived from 'pseudo pitchblende' I, as shown by their intergrowth one with the other. A younger generation of millerite and niccolite was also developed. Galena occurs in all rock types of the fault zone with the exception of the Athabasca Sandstone. Its lead content has been determined as being radiogenic.

(11) The iron oxides and hydroxides, which appear as accessory components in the host-rock, have to be considered separately from the other ore minerals. The rounded magnetite grains in the mylonite zone, for example, are primary relics of the metasediments, and the formation of haematite laths is probably due to the regolith environment. The existence of limonite (goethite) indicates a more recent oxidation of the entire deposit (figure 6).

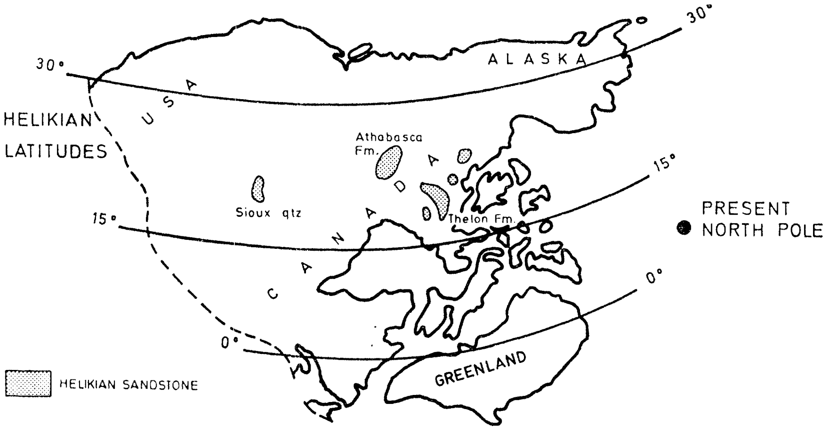


FIGURE 5. Helikian palaeogeography (after Fahrig & Jones (1969) and Seyfert & Sirkin (1973) in Ramaekers & Dunn (1977)).

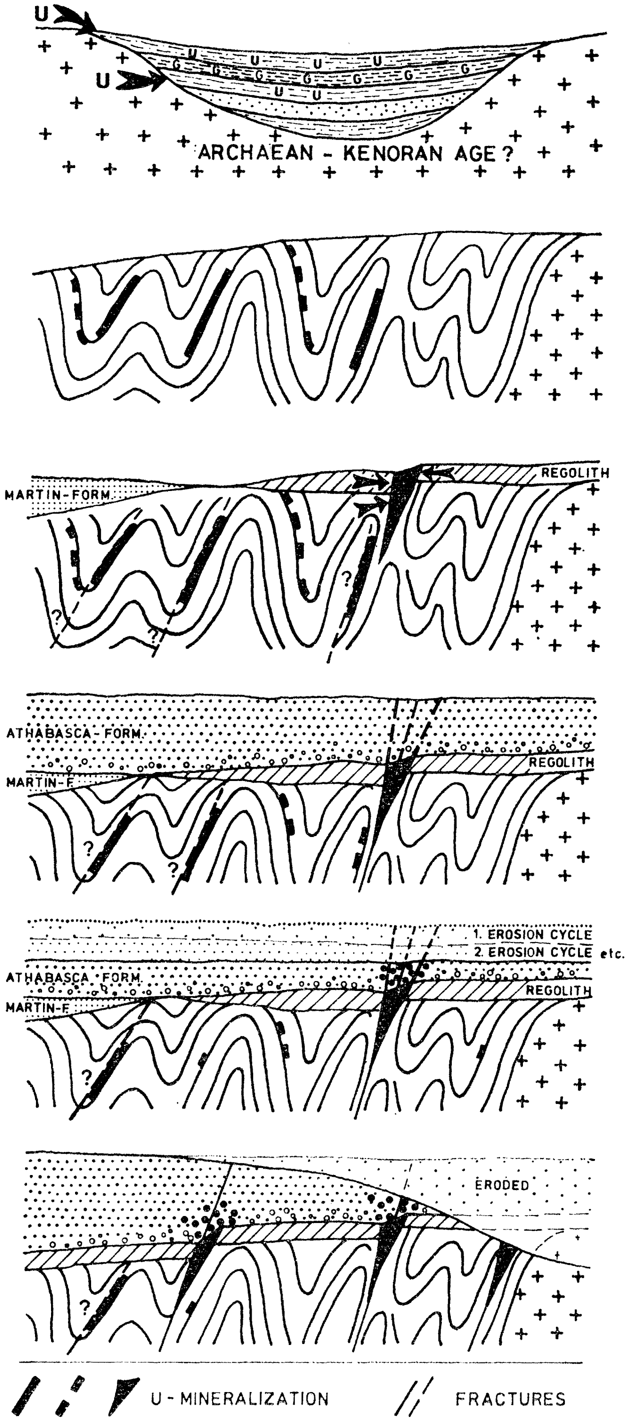
(12) U/Pb isotope ratios indicate an age of 1228–1160 Ma for the first uranium generation (U_3O_7 = 'pseudo pitchblende' I). The oldest age concurs with the 1230 Ma age of a diabase dyke cutting the Athabasca Formation at Cree Lake, about 60 km to the west of Key Lake (Burwash *et al.* 1962).

(13) On the evidence of a variety of geothermometers, the first generation of ore minerals formed below a temperature of about 137 °C.

(14) Emplacement of the primary mineralization was followed by tectonic movements which fractured 'pseudo pitchblende' I and other minerals in this phase and which were in turn re-cemented by secondary ore minerals and gangue.

(15) A very important observation has been made by Clasen and Voultsidis. In the overlying Athabasca Sandstone no 'pseudo pitchblende' I, no molybdenum and almost no galena are detected. Only sooty pitchblende and coffinite occur in fractured rocks along the displacement fault. Subsequent silicification cemented the mineralization. U/Pb ratio determinations indicate an age of this rejuvenated mineralization of about 250–107 Ma. Consequently it has to be deduced that the present displacement of the Athabasca Sandstone occurred after the formation of 'pseudo pitchblende' I and before the emplacement of the 250 Ma old pitchblende II generation.

(16) A final uplift in pre-Pleistocene time permitted erosion of the cover sediments by glaciation to take place. In particular, the formation of esker penetrated and partly destroyed the deposit. The latest glacial deposition buried the deposit, and limonitization most probably occurred at this stage.



I. *Middle–upper Aphebian*
(*ca.* 2200–1900 Ma)

Transport into shelf or lagoonal sediments (U, uranium; G, graphite).

II. *Hudsonian orogeny*
(*ca.* 1900–1800 Ma)

Mobilization and preconcentration. Formation of uraninite–pitchblende in veins and disseminations (first generation: 1800 Ma).

III. *Palaeo–Helikian*
(*ca.* 1800–1350 Ma)

Sedimentation of Martin formation in the north; regolithization in the south: (*a*) orebodies under cover of Martin formation stable; (*b*) without protective cover, weathering, leaching and reconcentration in structural traps. Formation of second U generation (? sooty pitchblende).

IV. *Neo-Helikian*
(*ca.* 1350–1000 Ma)

Sedimentation of Athabasca Formation. Diagenetic transformation and recrystallization; formation of colloidal and tetragonal uranium oxide. Formation of third U generation: about 1100–1200 Ma.

V. *Hadrynian–Phanerozoic*
(*ca.* 1000–200 Ma)

Periodic uplifts and erosion. Formation of coffinite and sooty pitchblende (fourth, fifth, etc., generations). At 200 Ma, introduction of U into Athabasca Formation (sooty pitchblende).

VI. *Recent*
(*ca.* 200 Ma–present)

Erosion and destruction of orebodies.

FIGURE 6. Genetic evolution of Key Lake mineralization.

RABBIT LAKE

According to Knipping (1974), Hoeve & Sibbald (1977) and Rimsaite (1977), the Rabbit Lake ore body has the following features:

(1) The ore body is located in originally pelitic to psammitic and partly calcareous shelf

facies sediments of Aphebian age, which were metamorphosed to calc-silicate rocks, meta-arkoses and gneisses of the amphibolite facies during the Hudsonian orogeny.

(2) Granitic rocks located in the vicinity of Rabbit Lake are assumed to be of Archaean (Kenoran) age.

(3) The metasediments contain, as a primary constituent, a U, Th, rare earth mineral (yttryalite according to Rimsaite 1977), which is overgrown by pitchblende.

(4) The basement was subjected to intense chemical weathering during Middle Proterozoic time.

(5) The basement is covered by the Middle Proterozoic Athabasca Formation of clastic, unfolded sediments of semi-red bed facies.

(6) The mineralization is monometallic. The main ore mineral is pitchblende associated with haematite, quartz and carbonates.

(7) The structural setting of the ore body is characterized as follows: (*a*) the body fills a NNE-trending fracture and breccia zone, which was reactivated several times; (*b*) this mineralized zone is cut off by a low angle ENE-trending thrust with the mineralization occurring in the overthrust block; (*c*) similarly to Key Lake and Cluff Lake, the mineralization occurs immediately under the Middle Proterozoic paleosurface from where it extends to a maximum depth of 150 m; (*d*) as at Key Lake and Cluff Lake, the mineralization forms a continuous orebody within the breccia zone.

(8) The minero-lithological setting of the ore body is characterized by an alteration zone of (*a*) chloritization; (*b*) silicification; (*c*) dolomitization. The chloritized zone underwent firstly an oxidizing process and subsequently a reducing process, characterized respectively by the development of haematite and sulphide. The bulk of the ore occurs in the chloritic rock.

(9) Studies of fluid inclusions in euhedral quartz and dolomite indicate a formation temperature within the ranges 180–225 °C and 160 ± 10 °C respectively (Little 1974; Pagel 1975*b*) and a pressure of 700 bar.†

(10) Pb/U and Pb/Pb analyses provided a formation age for the 'oldest' pitchblende generation of 1000–1100 Ma, followed by younger generations. However, an unconfirmed age of about 1700 Ma was reported recently.

Summary of events

The sequence of geological events according to Hoeve & Sibbald 1977 appears to have been as follows: (*a*) weathering of basement before 1350 Ma; (*b*) sedimentation of Athabasca Formation, 1350 ± 50 Ma; (*c*) brecciation (preparation for later ore location); (*d*) emplacement of primary mineralization, 1100 Ma; (*e*) brecciation, formation of Rabbit Lake Fault? – probably connected with the chloritization in an oxidizing environment (haematite) and with dolomitization; (*f*) chloritic alteration in reducing environment, formation of sulphides and of secondary uranium mineralization, silicification.

Acceptance of Hoeve's & Sibbald's (1977) ideas would have the following implications: (*a*) the initial mineralization took place well after deposition of the Athabasca Formation; (*b*) the chloritic alteration was unrelated to the palaeo-surface and is younger than the primary mineralization; (*c*) the chloritic alteration remobilized and dispersed the primary ore; (*d*) uranium was redeposited during later stages of (reducing) chloritization.

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† 1 bar = 10^5 Pa.

Based on drill core investigations only, Knipping (1974) concluded that supergene processes led to the formation of the deposit. Hoeve & Sibbald (1977), using observations in the open pit and additional research work, favour a diagenetic–hydrothermal origin.

Cluff Lake

According to Tapaninen (1976) and Amok (1974), the following features are characteristic of the three ore bodies ('D', 'N', Claude) at Cluff Lake:

(1) Host rocks are phyllitic and graphitic metapelites of Aphebian origin. Metamorphism took place within granulite facies, followed by upper amphibolite facies. The metamorphic event is dated at 1973 Ma, i.e. the time equivalent of the early phases of the Hudsonian orogeny.

(2) The basement was intensely weathered during pre-Athabasca time.

(3) The basement is overlain by Middle Proterozoic, unfolded but strongly faulted clastic sediments of the Athabasca Formation (Carswell structure!).

(4) Two types of mineralization occur: (*a*) in the 'D' ore body the mineralization is polymetallic and comprises U (uraninite, pitchblende), Au and Se, with accessory Bi, Ni, Co and Pb; (*b*) the 'N' and Claude bodies are monometallic, the ore minerals consisting of uraninite (Claude) and pitchblende ('N').

(5) The structural setting is characterized by: (*a*) north ('N' ore body) and north-easterly (Claude) striking mineralized fracture and shear zones – no structural control of the 'D' ore body has been identified; (*b*) the restriction of all ore bodies to the vicinity of the Middle Proterozoic unconformity; (*c*) maximum depth extension of the ore to 150 m.

(6) The minero-lithological setting for the 'N' and Claude ore bodies is characteristic of a 'hydrothermal' alteration zone consisting of kaolinite, chlorite and sericite within pelites and quartzo-feldspathic gneisses. The highest uranium concentrations are located at the intersection of retrogressive zones and steeply dipping faults of later age. In the 'D' ore body, the ore control seems to be lithological. Uraninite and pitchblende are disseminated through the graphitic and phyllitic matrix of a pelite bed, located stratigraphically beneath the basal conglomerates of the Athabasca Formation. However, disseminated mineralization is also present in the structurally underlying Athabasca sandstones.

(7) Studies of fluid inclusions (Pagel 1975*a*) indicate a formation temperature of about 220 °C and a pressure of 1500 bar.

Summary of events

The sequence of geological events appears to be as follows (Amok 1974): (*a*) surficial regolithic weathering of crystalline basement during pre-Athabasca time; (*b*) sedimentation of Athabasca formation, 1350–1200 Ma; (*c*) deposition of the oldest uranium ore in 'D' ore body, 1050 Ma; (*d*) 'hydrothermal' and tectonic event (chloritization, sericitization, kaolinitization), probably redistribution of ore, 988 Ma; (*e*) formation of Carswell structure, 480–470 Ma.

The Amok paper (1974) presents the following genetic hypothesis: emplacement of mineralization took place during the pre-Athabasca weathering period in organic rich pelites ('D' ore body) and shear zones ('N', Claude), the uranium source being gneisses and pegmatites. Subsequently to the Athabasca sedimentation there was 'hydrothermal' modification of the initial mineralogy, which also affected ore distribution.

Pagel (1975*a*) suggests the 'hydrothermal' phase, which he considers to have been produced by diagenesis, as the sole ore forming mechanism.

BEAVERLODGE

According to Robinson (1955), Koeppel (1968), Tremblay (1968), Beck (1969, 1970) and Sassano *et al.* (1972) the following geological features of the Beaverlodge deposits can be observed:

(1) The major ore bodies in the Uranium City area (Fay–Ace–Verna) occur in originally pelitic to psammitic sediments of Aphebian age, which were metamorphosed during the Hudsonian orogeny to partly graphite-bearing quartzo-feldspathic gneisses; feldspathic quartzites; argillite, amphibolite and hornblende schist, all interlayered. Granitic facies ('Young' granite) are also present and all the rocks were subsequently altered to varying degrees. The metamorphic facies range from amphibolite to granulite, with partial anatexis leading to granitization. At Gunnar the host rock is a metasomatic granite altered to a quartz-deficient rock probably by albitization.

(2) 'Old' granites (Beck 1969, 1970) of Archaean age are observed in contact with the metasediments.

(3) Syngenetic uranium mineralization, as uraninite, occurs in various pegmatitic rocks. Koeppel (1968) determined two periods of syngenetic uranium formation with minimum ages of 2200 and 1930 Ma respectively. These periods can be related to the emplacement of the 'Old' and 'Young' granites. Beck (1970) has already considered the possibility that the pegmatitic rocks represent stages of the transformation or granitization of country rock to granite.

(4) The Tazin rocks do not exhibit Middle Proterozoic, pre-Martin weathering as is otherwise typical in the southern Athabasca region.

(5) The crystalline basement is covered by the early Middle Proterozoic Martin Formation. This consists of continental, clastic sediments of the red bed facies with locally interbedded volcanic flows and gabbroic sills. The Martin rocks were still slightly affected by the latest Hudsonian movements. Broad folds were generated, trending NE and parallel to the Tazin fold axes.

(6) Over 90% of the deposits are monometallic, with pitchblende accompanied by pyrite, galena, calcite, quartz and chlorite as gangue. Several generations of ore and gangue are present. In addition to colloform and massive pitchblende, euhedral 'pitchblende' and/or uraninite are described. Typically, all crystallized uranium oxide specimens yield ages around 1800–1770 Ma (Koeppel 1968). In a narrow belt within the Beaverlodge area (e.g. at the Consolidated Nicholson Mine), small deposits with multi-metallic mineralization occur.

(7) The ore minerals occur in massive veins or veinlets as well as being disseminated in the crystalline basement and, locally, in Martin sediments (type of uranium mineral not yet precisely determined).

(8) The structural setting of the ore bodies appears as follows: (*a*) in structures subsidiary to major faults, but underground there is a striking, almost concordant relation of the individual ore lenses to the bedding of the enclosing strata, and they have the appearance of seams; (*b*) some of the ore bodies occur only at depth whereas others extend to the Middle Proterozoic unconformity; (*c*) a considerably deeper vertical extension (down to 2000 m in the Fay Mine) than in the southern Athabasca deposits (Cluff Lake, Key Lake, Rabbit Lake); (*d*) the mineralization, although commonly consisting of individual lenses of considerable planar dimensions, appears in a more regional framework to consist of a discontinuous accumulation of ore lenses.

(9) The common minero-lithological setting of the ore bodies is characterized by wall-rock

alteration which includes haematitization, chloritization, epidotization, silicification, carbonization and albitization. In the Fay Mine the bulk of the mineralization seems to prefer a graphite and sericite bearing chloritic rock (named 'Mica Schist'), which is in contact with a haematitic, silicified feldspathic rock ('Orange Porphyroclastic Mylonite'). In the Gunnar Mine the ore occurs in a mylonite zone within albitized, quartz-deficient granite ('syenite').

(10) Studies of fluid inclusions and stable isotopes (^{13}C, ^{18}O) by Sassano *et al.* (1972) of dolomite, calcite and quartz from ore of the Fay and Bolger mines, indicate a cooling sequence from the initial phase of mineralization at 440 ± 30 °C down to the final stages at around 80 ± 10 °C. Five generations of carbonate can be distinguished in the ore veins. Sassano *et al.* (1972) conclude that the deposits were generated by metamorphic hydrothermal fluids and that the final stages of mineralization were possibly effected by some influx of surface waters into an otherwise essentially 'closed' system.

Age datings and postulated sequence of geologic events are as follows (Robinson 1955; Koeppel 1968; Tremblay 1968; Beck 1969, 1970; Burwash *et al.* 1962; Wanless *et al.* 1966):

(*a*)	2500–2200 Ma	and older: ages (rejuvenated?) of 'old' granites and 'greenstones';
	2200 Ma	uraninite and monazite in pegmatites, and mafic minerals of metasediments.
(*b*)	1930 Ma	sedimentation of Tazin sediments and volcanic activity.
(*c*)	1930–1780 Ma	Hudsonian orogeny;
	1940–1920 Ma	uraninite and monazite in pegmatites and 'young' granites and mafic portions of metasediments; regional metamorphism; followed by thrust and tear faults with mylonitization and brecciation;
	1840–1815 Ma	retrograde metamorphism; emplacement of late and post-tectonic granites (Gunnar muscovite);
	1795–1740 Ma	retrograde metamorphism with 'hydrothermal' alteration; formation of epigenetic euhedral and massive, colloform pitchblende.
(*d*)	1740–1490 Ma	deposition of Martin Formation;
	1640 Ma	basalt sills;
	1490–1410 Ma	gabbro and diabase dykes cutting Martin Formation;
(*e*)	1125–1110 Ma	reworking of epigenetic pitchblende; formation of second generation of pitchblende together with haematite; emplacement of diabase dykes in the Athabasca region.
(*f*)	270 Ma	reworking of pitchblende; generation of pitchblende together with haematite; epeirogenic uplift of shield; rejuvenation of faults; erosion; (introduction of sooty pitchblende into Martin Formation?).
(*g*)	100 Ma	reworking of pitchblende; epeirogenic uplift of shield; rejuvenation of faults. There followed: erosion due to glaciation, supergene alteration (limonitization), and destruction of ore bodies.

Most of the early investigators of the Beaverlodge uranium deposits postulate a hydrothermal genesis, although some of them considered uraniferous Aphebian sediments as the source. In recent years Smith (1974) and other geologists have suggested a supergene origin.

However, by considering all available research data is appears more likely that the Beaverlodge 'pitchblende veins' originated as sedimentary deposits which were modified by metamorphism resulting in further concentration. Later, probably during relatively recent times, the deposits were attacked and partly altered by meteoric waters.

Such a geological position would place the Beaverlodge deposits as the source rocks for the southern Athabasca deposits.

Maurice Bay

Little research has been done as yet. All that can be said is that the pitchblende occurs in Aphebian metasediments and Athabasca sandstones, including regolith adjacent to the Middle Proterozoic, pre-Athabasca unconformity.

Conceptual metallogenetic model

Based on the foregoing metallotectonic and minerogenetic data, the following polygenetic evolution of the deposits in the Athabasca region is proposed (figure 6). It is emphasized, however, that earlier authors, e.g. Beck (1969, 1970), Pagel (1975*a*, *b*), Little (1974), Sullivan (1957), Koeppel (1968), Knipping (1968), Sassano *et al.* (1972), Robinson (1955), Tapaninen (1976) and other Amok geologists (1974), Tremblay (1968), Hoeve & Sibbald (1977), to name only a few, have already proposed one or the other hypothesis and all credit should be given to their geological pioneer work. Recent research results available to the author allow the establishment of a broader and perhaps more comprehensive regional model for the formation of the various deposits of the Athabasca region to be made.

(1) During the middle to upper Lower Proterozoic (Aphebian), uranium was transported syn- or post-sedimentation into marine or lagoonal basins, located around or between Archaean highlands, and containing pelitic to semi-pelitic partly carbonaceous and calcarous sediments. The mobilization of uranium must have occurred after oxygenation of the atmosphere (about 2200 Ma?), otherwise uranium could not have been liberated and transported as an ion or uranyl complex into this environment.

(2) The Hudsonian orogeny (about 1900–1700 Ma) effected a further concentration of uranium by the following processes: (*a*) syngenetic deposition in granitic–pegmatitic rock and in mafic portions of metasediments in the form of uraninite (dated 1930 Ma at Beaverlodge); (*b*) syngenetic to epigenetic mineralization in peneconcordant seams or lenses in the form of uraninite and euhedral and colloform pitchblende, dated 1790 Ma and generated by hydrous metamorphic or 'hydrothermal' activity during the final stages of the Hudsonian orogeny. The deep deposits of the Beaverlodge district in the northern part of the Athabasca region fall into this category of deposits (the mode of formation of the deposits, or parts thereof, in the Northern Territory, Australia, may be analogous).

(3) In early Middle Proterozoic (= Paleohelikian) time the area north of Lake Athabasca, containing the Hudsonian Beaverlodge deposits, was covered and protected by the red bed Martin sediments. In the southern Athabasca region, probably during middle Paleohelikian time, chemical weathering decomposed the palaeosurface of the Hudsonian metasediments (= protore) and Archaean cores to a depth of several tens of metres and formed a regolith. The uraniferous crystalline rocks, including the Beaverlodge type of deposits, served as protore, i.e. as a source for the subsequent generation of deposits.

Uranium and other elements were mobilized by these processes, migrated into tectonic traps and were deposited where they encountered suitable conditions for precipitation (reductants such as ferrous (Fe^{2+}) minerals; argillaceous and chloritic zones; changes of permeability, pH and E_h). Subsequently the Athabasca Formation covered the newly formed deposits.

Unfortunately two important phenomena apparently contradict this simple metallogenetic concept of the formation of the south Athabasca deposits: (*a*) fluid inclusions (Little 1974; Pagel 1975*a*, *b*) point to local formation temperatures of up to 200 °C for the Rabbit and Cluff Lake deposits, which is much too high for purely supergene emplacement; (*b*) age dating indicates 1350 Ma for deposition of the Athabasca Formation (Ramaekers 1976), which predates the present day oldest generations of uranium oxides of 1228 Ma at Key Lake and 1100 Ma at Rabbit Lake and Cluff Lake. This means that the period of formation of regolith must have ended at least 120 Ma and 250 Ma respectively before deposition of the oldest uranium in these deposits.

This conflict of evidence may be resolved by the following hypothesis:

(4) After the formation of ore deposits as described under (3), the semi-red bed facies of Athabasca Formation was deposited. The great thickness of sediment, possibly up to several thousand metres, affected the underlying mineralization in two ways: (*a*) by promoting diagenetic processes with hydrous (hydrothermal?) phases and the temperatures deduced from fluid inclusions and other geothermometers. The uranium already present (and nickel at Key Lake) was thereby mobilized and re-deposited more or less *in situ* with the destruction of the original radiogenic equilibrium by uranium–lead separation and simultaneous formation of a new 'primary' generation of uranium oxide with a rejuvenated age of about 1230–1100 Ma. This process is assumed to have been accompanied by regional structural movements permitting the local intrusion of contemporaneous diabase dykes dated 1230 Ma (at Cree Lake: Burwash *et al.* 1962). (*b*) by protecting the ore bodies against further weathering and leaching.

(5) Successive periodic uplift, at about 960 (?), 370 (?), 250, 100 Ma and later, resulted in erosion of the overlying cover formations which consequently changed the static equilibrium. Limited redistribution of the uranium within the ore deposits occurred. New generations of mineralization such as sooty pitchblende and coffinite were formed, which also penetrated the overlying cover sediments along fracture zones at Key Lake, at about 250–100 Ma.

(6) Pleistocene erosion removed the Athabasca and Martin cover rocks and began to erode the deposits.

Alternatively, the rôle of the whole weathering cycle outlined in (3) above may be disregarded and the metallogenesis attributed solely to diagenetic processes. However, to substantiate such a hypothesis the following conditions have to be proved:

(*a*) that diagenetic processes are capable of mobilizing uranium, and more particularly nickel (Key Lake) and additional elements (Cluff Lake), and transporting these over long distances, perhaps up to several kilometres, in order to form the huge metal concentrations of up to several tens of thousands of tonnes of uranium, with nickel, as occur at Key Lake;

(*b*) that the tectonic host zones and migration channels, which are open and permeable at surface, remain so under the static pressure of up to several thousand metres of cover rocks.

Nevertheless, an explanation to satisfy these conditions could still be found, but there are difficulties in providing answers to the following questions: (*a*) why, at Key Lake, the 'pseudo pitchblende' I formed only within the crystalline basement and did not enter the overlying Athabasca sandstones; (*b*) why the apparent paragenetic Mo did not also enter the Athabasca sandstones; and (*c*) why radiogenic galena is virtually absent from the Athabasca sandstone but abundant in the metasediment.

To summarize: the uranium deposits of the Athabasca region were developed through polygenetic processes by means of which the uranium was extracted from uraniferous Aphebian metasediments and deposited in two consanguineous and interrelated categories of vein-type deposits: (1) the Beaverlodge type, presumed to have been formed by late orogenic metamorphic–hydrous processes, and (2) the Key Lake type formed by destruction of type 1 deposits and associated mineralization by means of supergene and subsequent diagenetic hydrous processes.

The paper is the result of the close cooperation of all Uranerz's geological staff directly or indirectly involved in the exploration of the Key Lake deposits. However, special acknowledgement has to be given to B. Tan, Chief Geologist at Key Lake, who guided the field work, and to V. Voultsidis and D. Clasen, Uranerz's mineralogists. The latter conducted all the essential mineralogical, crystallographical and minerochemical work and, combined with the interpretation of regional geophysical data by K. Lehnert-Thiel (Exploration Manager, Central Canada) and with the scarce outcrop geology, this formed the basis of the author's interpretation of the genesis of the Key Lake deposits. Credit has to be given also to D. Clasen and V. Voultsidis for their determination of the tetragonal α-U_3O_7 mineral not hitherto described from a natural deposit. Thanks have to be given to B. Free and D. Ostle for reviewing, condensing and anglicizing the text. G. Möller prepared all of the drawings. Finally the author wishes to express his gratitude to the management of Uranerz under Dr Young, who kindly gave permission to publish this paper.

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Discussion

G. R. RYAN (2 *Gardenia Street*, *Nightcliff*, *N.T.*, *Australia*). I should like to congratulate Dr Dahlkamp on an excellent paper. It is interesting to see that he and Australian workers are approaching, by rather different routes, a consensus on the genesis and history of the Saskatchewan and Northern Territory deposits. I should like him to comment on the fact that, although the Ranger One and Jabiluka deposits are geologically almost identical, age dating so far has yielded results that indicate that Ranger One is about twice as old as Jabiluka.

F. J. DAHLKAMP. It is rather difficult to comment on the mentioned differing age datings without knowing (1) the sampling places within the deposits – fractured, altered or undisturbed zones – and (2) the exact ore mineralogy, paragenesis and alterations of the dated specimens. We found that pitchblende deposits often comprise several ore generations derived from each other. In places where strong alterations had transformed most of the primary generation into a second, third or later generation, consisting of sooty pitchblende and coffinite, it was often very difficult to find and to determine the oldest generation and thus extract it for age datings and other studies. With regard to the Alligator River deposits, I think that the geological settings of Jabiluka and Ranger and also of the other deposits resemble that of the Beaverlodge subtype of the vein-like type of deposit. If this comparison is correct (it still has to be proven by further mineralogical, crystallographic and minerochemical investigations), then I suspect that the parts of the deposits that were not altered by post-metamorphic alterations contain a 'primary' pitchblende generation of 1700–1800 Ma, i.e. time-equivalent to the regional metamorphism affecting the Pine Creek geosyncline.