

## Geology and Genesis of the Athabasca Basin Uranium Deposits

by T.I.I. Sibbald

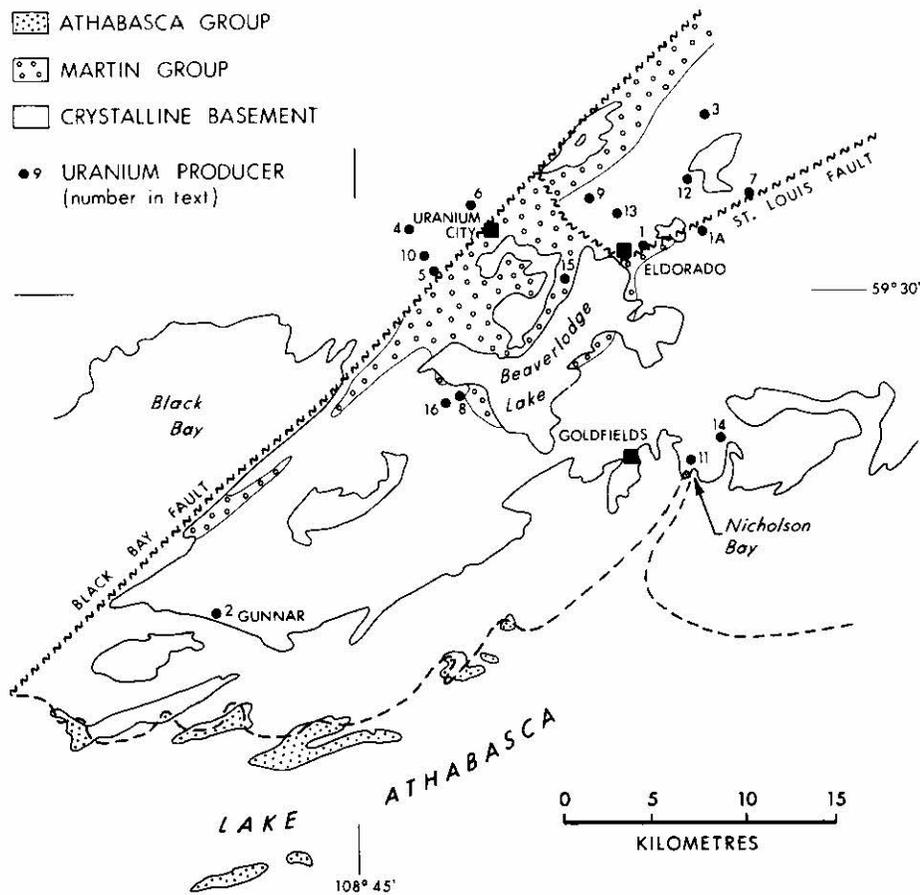
Sibbald, T.I.I. (1985): Geology and genesis of the Athabasca Basin uranium deposits; in Summary of Investigations 1985, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report 85-4.

Pitchblende was first discovered in Saskatchewan in 1935 at the Nicholson copper prospect on the north shore of Lake Athabasca (Fig. 1). Note of this occurrence was made in Alcock's (1) Geological Survey of Canada Memoir "The Geology of the Lake Athabasca Region".

Recognition of the military significance of uranium in the early forties led to an extensive uranium exploration effort by the Government of Canada through Eldorado, a Crown Corporation. This effort began at Nicholson, then one of three known occurrences of radioactive minerals in Canada. The others were Eldorado's, Port Radium, radium mine on Great Bear Lake, which was now being mined for uranium, and an unsubstantiated occurrence

on the north shore of Lake Superior which would subsequently lead to Elliot Lake.

In the 1945 field season, in what eventually became known as the Beaverlodge District, prospecting found over 1000 radioactive showings. In the following year the occurrences which would become Eldorado's Ace-Fay-Verna operation were discovered. Uranium production from Beaverlodge amounted to some 25 million kg U between 1953 and 1982, when Eldorado finally shut down. Over the years there was production from 17 main deposits and milling at 3 separate facilities (Table I, Fig. 1).



**Figure 1** - Major uranium producers of the Beaverlodge District in relation to the outcrop of the Martin and Athabasca Groups. Numbers refer to Table I.

**Table I - Major Uranium Producers, Beaverlodge District**

Uranium Mine	Production (t U)
1. Eldorado, Ace-Fay-Verna (1A)	16 035
2. Gunnar	6 892
3. Eldorado, Hab	763
4. Rix Smitty	436
5. Cinch Lake	285
6. Cayzor Athabasca	187
7. Eldorado, Dubyna	163
8. Lorado	89
9. Eldorado, Eagle	85
10. Rix Leonard	77
11. Nicholson	41
12. National Exploration	30
13. Nesbitt Labine	23
14. Eldorado, Fish-hook	15
15. Eldorado, Martin Lake	11
16. Uranium Ridge	10
	25 142

Exploration in the Athabasca Basin began in 1967, encouraged by the Government of Saskatchewan through a financial assistance program to companies with approved exploration work schedules. In 1968, following up airborne radiometric anomalies along the eastern edge of the Basin, the Gulf Oil Company discovered Rabbit Lake (Table II, Fig. 2). An exploration philosophy designed to find sandstone hosted deposits in the Athabasca Group identified an orebody in the underlying crystalline basement.

Also at this time, Mokta (Canada) Ltd. a subsidiary of Compagnie de Mokta that had been exploring in Saskatchewan since 1963, sent a team to investigate certain airborne radiometric anomalies in the Carswell Dome area. Initially attracted to Beaverlodge, the company was soon to turn its attention to the Athabasca Basin, undoubtedly prompted by experience with sandstone hosted uranium deposits in Gabon and the discovery, in 1967, of mineralized boulders of Athabasca Group sandstones at Fond-du-Lac. In 1969, ground trenching of the Carswell anomalies led to the discovery of pitchblende boulders in glacial overburden and thence to the D zone orebody, which was of extremely high grade (6 percent U).

The next significant find was at Key Lake, first the Gaertner orebody in 1975 and the Deilmann in 1976. The initial clue, which attracted Uranerz Exploration and Mining Ltd. geologists to the area, was a uranium in lake water anomaly identified in a previous exploration effort, in 1969, but not further pursued. On visiting the anomaly area in late 1971, high grade pitchblende boulders, now known to be derived by fluvio-glacial erosion from the Gaertner orebody, were found within a matter of hours.

At the time of the Key Lake discovery the Saskatchewan Geological Survey, financed under a Canada-Saskatchewan mineral exploration and development agreement was engaged in a major mapping program in

the Shield. In the 1976 field season work in the Key Lake area was instrumental in demonstrating the association between the deposits, graphitic pelitic gneisses forming the basal unit of the Aphebian Wollaston Group, and the sub-Athabasca Group unconformity. It became quickly apparent that a little known deposit, the Collins Bay A zone discovered by Gulf in 1971, occupied a geologically similar position. The role of 'graphitic basement units', recognizable as electromagnetic conductors, in controlling the locations of unconformity type uranium deposits became established as an idea.

Application of this idea led to re-evaluation of the Collins Bay A zone (1976), and discovery of the West Bear deposit (1977) and Collins Bay B zone (1977) by Gulf. Imperial Oil Ltd. (Esso Minerals Canada Ltd.) and joint venture partners had cause to review the significance of a mineralized boulder train found by prospectors in 1969 at Midwest Lake. The Athabasca Group boulders comprising the train overlay a possible basement conductive zone covered by Athabasca Group sediments estimated to be up to 300 m thick. Deep drilling in 1977 showed low grade mineralization at the Athabasca Group-basement unconformity and in 1978 an economic orebody was delimited.

The Midwest discovery illustrated that the deeper parts of the Basin could be explored, previous successes being confined to the margins. Additionally, it led to general acceptance and implementation of the Key Lake exploration model. Several significant discoveries followed within the Basin at depths of up to 440 m, for example at Dawn Lake (1978), McClean Lake (1979) and more recently Cigar Lake (1981). These deposits lack a guiding surface expression of mineralization, as boulders, and were outlined by systematic drilling of electromagnetic conductors defined in airborne and ground follow up surveys.

The supreme irony is that recent work (2, 3) has shown that the first discovery of uranium in Saskatchewan, at Nicholson, was of an Athabasca Basin unconformity type deposit. It took 33 years to find the first economic deposit of this type, at Rabbit Lake, although minor occurrences were discovered at Middle Lake (1952), Stewart Island (1955) and Fond-du-Lac (1967) (Fig. 2), and nearly 50 years to appreciate the significance of Nicholson. In the interim, the wholly different Beaverlodge uranium district was discovered, developed and mined, establishing Saskatchewan as a world uranium producer.

The Athabasca Basin contains some 14 percent of the reasonably assumed low cost uranium resources of the free world and around 70 percent of Canadian resources. Most of the Athabasca Basin resources are contained within two major deposits at Key Lake and Cigar Lake. Grades of mineralization are often extremely high, as at the Collins Bay A zone (9.7 percent U), Cigar Lake (12 percent U) and the lately mined Cluff Lake D zone (6 percent U) (Table II).

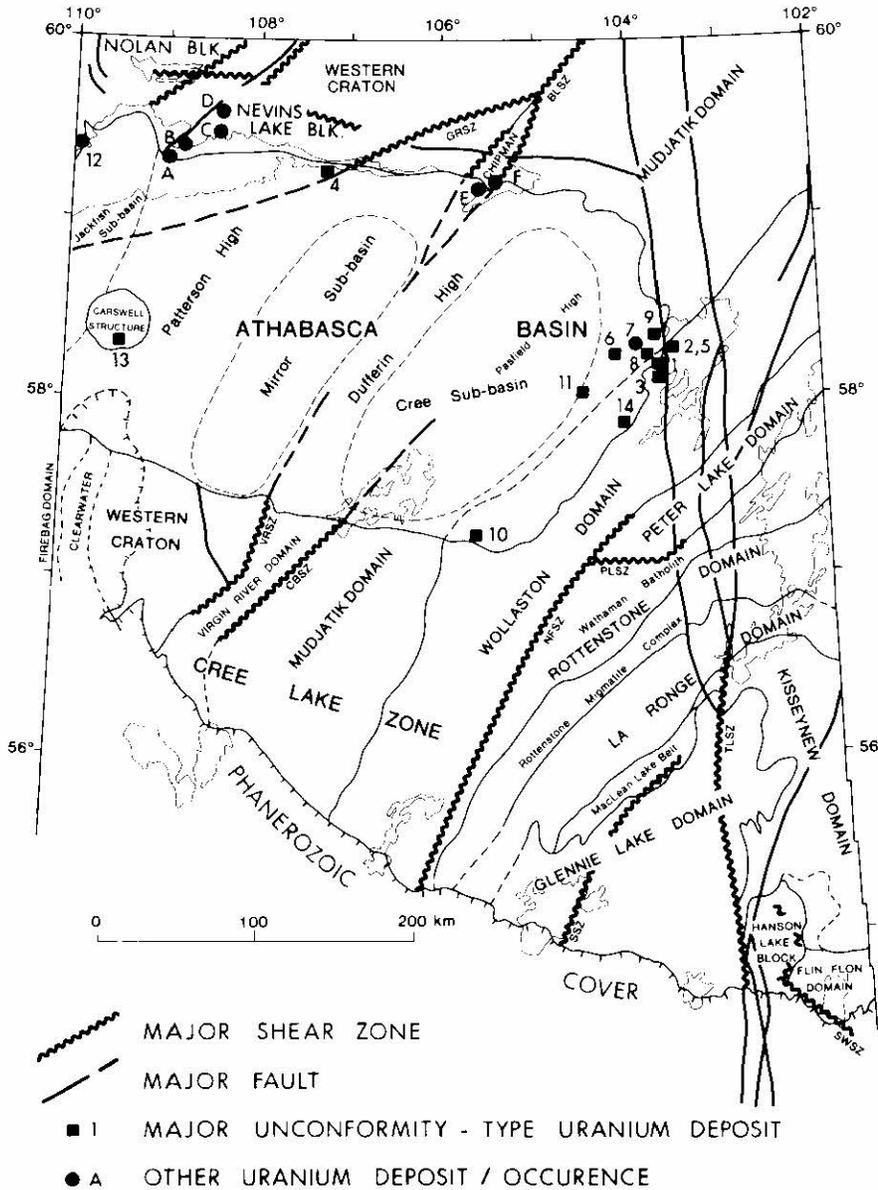
Currently developed deposits, representing the earlier discoveries, are located at the margin of the Basin in open pits (Rabbit Lake, Cluff Lake D zone, Key Lake, Collins Bay B zone) or in shallow underground operations (Cluff, other). The more recent discoveries have been made under an increasing thickness of Athabasca Group cover (up to 440 m at Cigar Lake) and will require underground extraction.

**General Geology of Northern Saskatchewan**

The crystalline basement of northern Saskatchewan is part of the Trans-Hudson Orogen, which extends some

5000 km from Greenland to the mid-continental United States (4). It comprises Archean and Aphebian rocks variably influenced by Lower Proterozoic thermotectonic events (Fig. 3).

In northwestern Saskatchewan, around Uranium City, the crystalline basement is overlain by red beds of the late Aphebian Martin Group (Fig. 1). Further south the younger Paleohelikian Athabasca Group, also showing red bed character, forms the Athabasca Basin encompassing about one third of the Saskatchewan Shield area. The crystalline basement and overlying successions are cut by easterly and northwesterly



**Figure 2** - Major Athabasca Basin unconformity type uranium deposits and tectonic subdivisions of the Saskatchewan Shield. Numbers refer to Table II; other uranium deposits (A. Stewart Is., B. Gunnar, C. Nicholson, D. Ace-Fay-Verna, E. Middle Lake, F. Nisto). VRSZ-BLSZ, Virgin River-Black Lake Shear Zone, NFSZ. Needle Falls Shear Zone.

Table II - Major Athabasca Basin Unconformity-Type Uranium Deposits

Deposit	Ownership	Discovery date	Reserves tonnes U	Grade % U	Athabasca Gp. thickness (m)	Basement Rock Types	Depth of Mineralization (m)	Remarks	
1	Rabbit Lake	Eldor Mines Limited	1968	15,400	0.4	Absent (eroded)	Meta-arkose, plagioclase (in part graphitic), calcsilicate dolomitic marble, granite segregation pegmatite, microgranite	0-200	In hanging wall of Rabbit Lake thrust fault. Subcrop below drift. Mineralized boulder train. Mined out.
2A	Collins Bay A	"	1971	6,500	9.7	Absent (eroded)	Pelitic graphitic gneiss, granite segregation pegmatite in contact with granitoid gneiss	5-20	In clay zone at Athabasca Group unconformity in hanging wall of Collins Bay thrust fault. Subcrop below drift. Mineralized boulder train.
2B	Collins Bay B	"	1977	11,900	0.4	25	Pelitic graphitic gneiss, granite segregation pegmatite in contact with granitoid gneiss	5-30	Dominantly in Athabasca Group in footwall of Collins Bay thrust fault. Subcrop below drift
2C	Collins Bay D	"	1979	1,900	1.6	-	Pelitic graphitic gneiss, granite segregation pegmatite	-	Adjacent to Collins Bay thrust fault
3	Raven	"	1972	-	0.2	Absent (eroded)	Sillimanite quartzite, calcareous meta-arkose, semipelitic gneiss	0-300	-
3A	Horseshoe	"	1974	-	0.2	Absent (eroded)	Sillimanite quartzite	60-300	-
4	Fond-du-Lac	Eldorado Nuclear Limited	1967	400	0.2	30	Meta-arkose, pelitic gneiss (occasionally graphitic)	10-30	Mineralization in Athabasca Group. Subcrop below drift. Mineralized boulder train
5A	Eagle Point South Zone	Eldor Mines Limited	1980	7,000	0.5	Absent (eroded)	Pelitic-semipelitic gneiss (in part graphitic), quartzite, granite segregation pegmatite	0-300	In hanging wall of Collins Bay thrust fault. Stratabound in quartzite and fracture fillings. Subcrop below drift.
5B	Eagle Point North Zone	Eldor Mines Limited - Noranda - SMDC	1980	15,000	1.6	Absent (eroded)	"	"	"
6	Midwest Lake	Esso Canada Ltd. - Numac Oil and Gas - Bow Valley Industries and others	1978	13,500	3.0	200	Pelitic graphitic gneiss locally with garnet, granite segregation pegmatite, bounded by granitoid gneiss;	0-300	Dominantly at sub-Athabasca Group unconformity, mineralization extends more than 100 m below unconform-

							crosscutting diabase dykes		ity and to surface (source of mineralized boulder train)
7	Dawn Lake (11, 11A, 11B and 14 zones)	SMDC - Cogema Canada - PNC and others	1978	11,500	1.7	100	Pelitic graphitic gneiss, calc-silicate, granite segregation pegmatite	30-200	Mineralization extends 50m above and 100m below the Sub-Athabasca Group unconformity. No surface expression.
8	McClellan Lake (North and South Zones)	Canadian Occidental Petroleum - Inco Metals Ltd. - Minatco Ltd.	North 1979 South 1980	5,400	1.5	150	Pelitic graphitic gneiss granite segregation pegmatite	115-190	Mineralization extends above and below sub-Athabasca Group unconformity. No surface expression.
9	Jeb	*	1982	-	-	100	Pelitic graphitic gneiss	85-120	No surface expression
10	Key Lake	SMDC - Uranerz Exploration and Mining Limited - Eldor Resources Limited (Key Lake Mining Corp.)	1975	73,900	2.0	0-60	Graphitic pelitic gneiss adjacent to granitoid gneiss massif	50-150	Mineralization extends above and below sub-Athabasca Group unconformity but predominantly below within 20m of unconformity. Subcrop below drift. Mineralized fluvio-glacial boulder train
11	Waterbury (Cigar) Lake	SMDC - Cogema Canada - 1981 Idemitsu Uranium Exploration Canada Ltd. - Corona Grande (Cigar Lake Mining Corp.)		110,000 (38,000 additional estimated)	12.0 (4)	440	Graphitic pelitic gneiss, minor calc-silicate, granite segregation pegmatite	± 440	Mineralization predominantly in lens at sub-Athabasca Group unconformity. Some fracture controlled mineralization above and below unconformity. No surface expression
12	Maurice Bay	SMDC - Uranerz Exploration and Mining Ltd.	1977	600	0.5	0-130	Pelitic gneiss (in part graphitic), minor quartzite and amphibolite	0-150	Mineralization in three zones. Athabasca Group (B and Main) and basement (A). Subcrop below drift. Mineralized boulder train
13A	Cluff Lake D	Amok Ltd. - SMDC (Cluff Mining)	1969	5,400 (3,300 production)	6.0	-	Pelitic to semipelitic gneiss (in part graphitic) (Peter River Gneiss)	0-35	Mineralization in Athabasca Group sandstones and siltstones at thrust fault-inverted unconformity. Mineralized boulder train. Subcrop below drift. Mined out.
13B	Cluff Lake (other)	*	1969-1980	14,000	ca.0.5	-	Pelitic to semipelitic gneiss (in part graphitic) (Peter River Gneiss) quartzofeldspathic gneiss (Earl River Gneiss), granite pegmatite	0-300	Fracture controlled mineralization in basement
14	Westbear	Eldor Mines Limited	1977	400	0.5	-	Pelitic graphitic gneiss	-	-

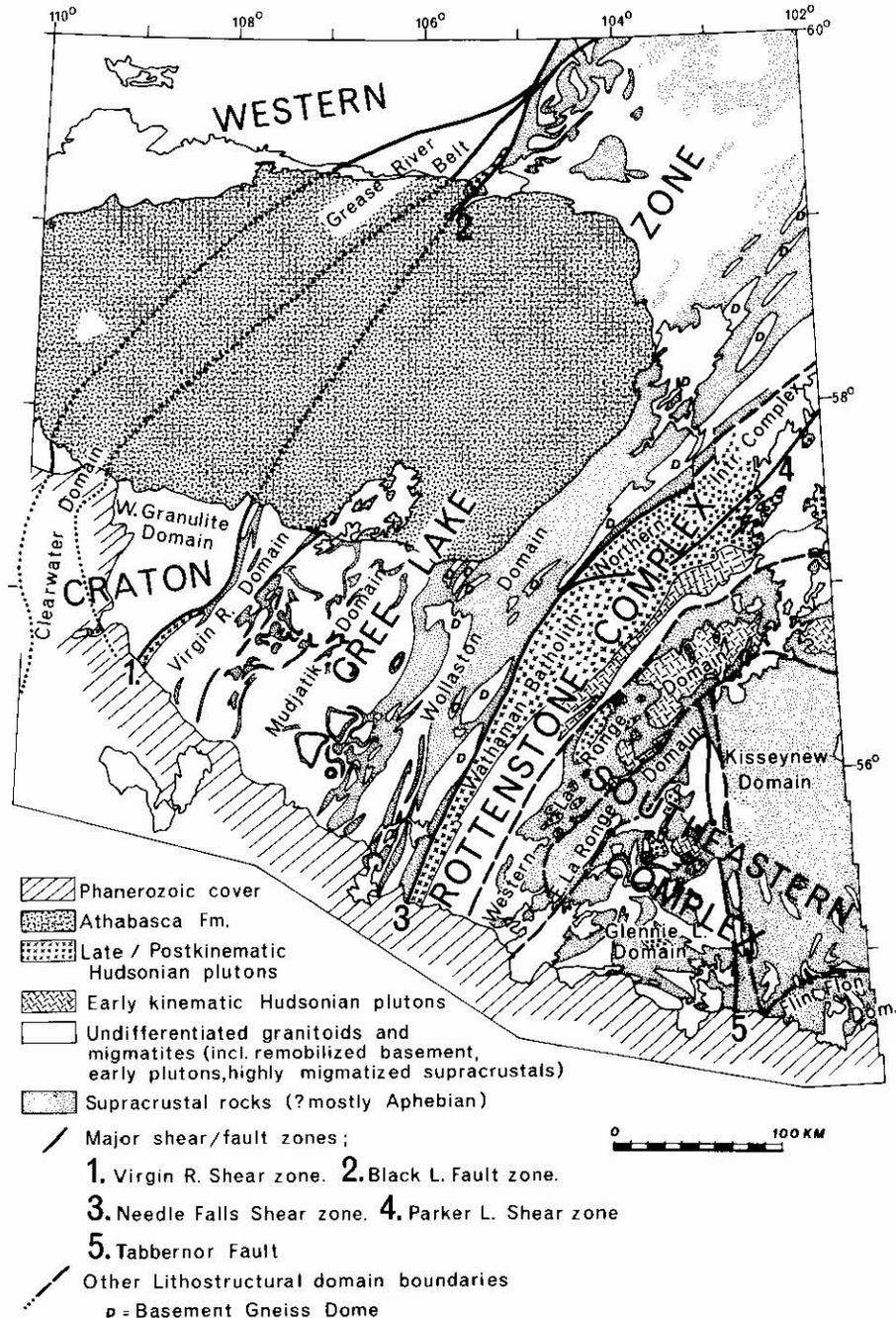
trending diabase dykes, probably emplaced in several generations.

**Crystalline Basement**

The basement comprises both ensialic and ensimatic portions of the Orogen, respectively developed to the west and east of the Needle Falls Shear Zone (5). The major change in crustal character, between early Aphebian continental-miogeoclinal and oceanic-eugeoclinal sedimentation regimes, has apparent continuity as a deep crustal conductivity anomaly below

the Canadian plains (6) with a geologically similar break in Wyoming (7). The Athabasca Basin lies wholly within the ensialic portion of the Orogen formed by two major crustal elements, the Western Craton and the Cree Lake (Mobile) Zone. These two units are further subdivided into various lithostructural domains, or regimes of relative lithological, structural and metamorphic homogeneity (8).

**The Western Craton:** Bounded in the east by the Virgin River - Black Lake Shear Zone, the Western Craton incorporates the Firebag, Western Granulite and



**Figure 3 - General geology and major subdivisions of the Churchill Province in northern Saskatchewan (after Lewy and Sibbald, 5]).**

Clearwater Domains and the region north of Lake Athabasca (Figs. 2, 3). It extends into Northwest Territories as far as the Macdonald Fault and Thelon Front, marking the edge of the Archean Slave Province.

South of the Athabasca Basin, the Western Granulite Domain comprises felsic to mafic gneisses and granulites, charnockites, anorthosites, gabbros and minor supracrustals. Blue quartz is characteristic of the felsic rocks. Metamorphic mineral textures and parageneses indicate static pyroxene granulite facies metamorphism overprinted by a lower amphibolite facies event, whose effects are progressively more strongly developed towards the Virgin River Shear Zone (8). The Firebag Domain appears to have broadly similar character (9).

The Clearwater Domain truncates abruptly magnetic and presumed structural trends, and forms a zone of low magnetic signature and gravity within the high amplitude magnetic and high gravity granulite facies terrain of the Western Granulite and Firebag Domains. It is virtually unexposed, however, the limited outcrop and drill hole data suggest a granitoid gneiss terrain similar to that forming the bulk of the Mudjatik Domain, but of somewhat lower, middle to upper amphibolite facies metamorphic grade.

The mylonitized granulites at the southern end of the Virgin River Shear Zone are intruded by a late tectonic, uranium enriched (ca. 8 ppm U) granite (Junction Granite) (10), dated at  $1720 \pm 45$  Ma (11). A similar body, the Clearwater Granite, occurs at the contact of the Clearwater and Western Granulite domains and is possibly more extensive beneath the Phanerozoic cover rocks to the north (12).

The Western Granulite Domain and by analogy the Firebag Domain are interpreted (5, 8) as catazonal Archean crust, mildly overprinted by Hudsonian (sensu lato) thermotectonic processes coeval with those in the Cree Lake Zone to the east. The Clearwater Domain may represent a region of more extensive reworking within the cratonic complex (5, 8), although others (13) have suggested that it represents an Aphebian structurally controlled sedimentary trough within the Archean basement. There are presently no age data to better evaluate the merit of these interpretations.

To the north of Lake Athabasca the Western Craton is geologically complex and comparatively poorly understood. It comprises distinct Archean elements and Aphebian supracrustal sequences, variously influenced by Hudsonian (sensu lato) thermotectonism. The Archean elements are identifiable, in part at least, as granulite facies terrains, for example, the Nolan Block north of Tazin Lake (14) and eastern segment of the Nevins Lake

Block east of Uranium City (15, 16) (Fig. 2). These have been dated respectively at  $2370 \pm 40$  Ma (biotite and hornblende, K-Ar method) (14) and  $2630 \pm 130$  Ma (Rb-Sr isochron method) (17). Other, as yet undated, granulite facies 'nuclei' are apparent from mapping and are noted by Lewry et al. (18).

Hudsonian (sensu lato) thermotectonism is marked by retrogression in the granulite facies terrains and by development of 'linear zones' of more intense deformation and greenschist to upper amphibolite (granulite ?) facies metamorphism (19), in which an Archean prehistory is less evident (20, 21, 22) and in which Aphebian supracrustals are locally identified. The 'linear zones' exhibit a variety of character, occurring as granitoid migmatite complexes, as supracrustal complexes intruded by granite plutons and as shear zones marked by strong tectonism (mylonite development) and retrogression. Age dating by various methods suggests a complex history of orogenesis within these zones with events at around 2200 Ma (19, 22), 1850-2000 Ma (19, 21, 23, 24, 25, 26) and 1750 Ma (23, 27). The latest event of Hudsonian (sensu stricto) age marks the time of initial emplacement of epigenetic pitchblende mineralization at Beaverlodge and likely occurred subsequent to deposition of the Martin Group. However, it is coeval with more major orogenic events in the Trans-Hudson Orogen to the southeast (11), suggesting that Hudsonian (sensu lato) orogeny was diachronous and migrated with time from northwest to southeast.

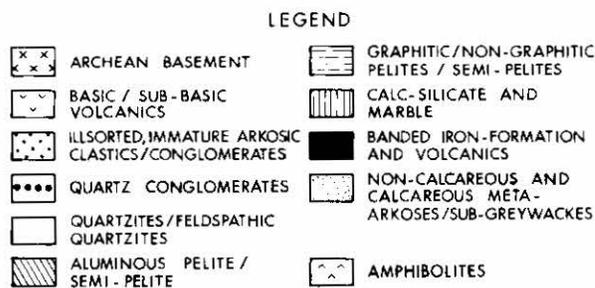
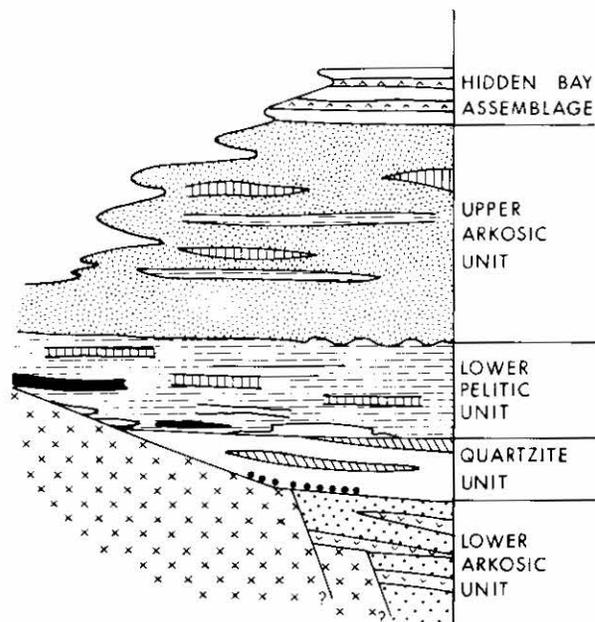
On a broad scale, both the Clearwater Domain, Virgin River Shear Zone and the eastern segment of the Western Craton north of Lake Athabasca fall within a belt of regional low gravity and high radiometric signature stretching from the Western Cordillera to Melville Peninsula (28). The high radiometric response has been recognized through regional airborne radiometric surveys, conducted by the federal government, in the shield area and through chemical analysis of basement cores, from beneath the Phanerozoic cover of the central plains (29). Darnley (28) has argued that the belt may represent a regime of incipient rifting into which uranium rich granites were emplaced in Hudsonian (sensu stricto) times. The general association of negative gravity and these granites is well known. The belt is suggested to have played a multifaceted role in the development of the Athabasca Basin uranium province and others (Thelon and Southeast B.C. provinces), which fall along it. Continued rifting in post-Hudsonian times may have provided the depressions in which the Athabasca Group and Thelon Formation were laid down, and the radiogenic granites, a long term heat source to drive hydrothermal mineralizing systems within these sedimentary basins.

**The Cree Lake (Mobile) Zone:** This Hudsonian (sensu lato) mobile zone is represented by the Virgin River, Mudjatik and Wollaston Domains and their extensions northeast of the Athabasca Basin (Fig. 3). It comprises granitoid gneisses and subordinate shelf-type

<sup>1</sup>Hudsonian (sensu lato) refers to radiometric events within the time frame ca. 2200 to 1750 Ma, Hudsonian (sensu stricto) to the ca. 1750 Ma event.

metasediments with some interlayered volcanics. The supracrustals are most extensively developed in the Wollaston Domain as the Wollaston Group (30), a three to four kilometre thick sequence (31). Four main lithostratigraphic units are distinguished (5) (Fig. 4):

- 1) A coarse clastic basal unit, of variable thickness, developed principally along the eastern margin of the Cree Lake Zone and comprising mature quartzitic to arkosic metasediments, locally developed basal conglomerate and semipelitic to pelitic muscovite and biotite schists. Locally it may itself be underlain, possibly unconformably, by a sequence of immature meta arkoses, arkosic metaconglomerates and interbedded basic meta-volcanics. To the west it is generally not identified or is seen only as a thin basal quartzite.
- 2) A dominantly pelitic unit, which is typically graphitic and contains interlayers of quartzitic psammities, calc-silicates and occasionally marble. The unit rests directly on Archean basement throughout most of the Wollaston and Mudjatik Domains. To the west, in parts



**Figure 4** - Generalized stratigraphic relations in the Wollaston Group. The right of the column is applicable to the eastern Wollaston Domain, the left to the western Wollaston and Mudjatik Domains (after Lewry and Sibbald, 5).

of the Mudjatik and Virgin River Domains, it appears to be associated with basic-ultrabasic intrusives and/or volcanics and oxide-silicate facies banded iron formation.

- 3) A thick unit of calcareous and non-calcareous meta-arkoses, which are interlayered with subordinate calc-silicates and thin pelite horizons.
- 4) An upper amphibolite-quartzite unit characterized by these two rock types and containing interlayered calcareous sediments and graphitic pelites. This unit is essentially synonymous with the Hidden Bay assemblage (32, 33) and is only known to outcrop in the Wollaston Lake area.

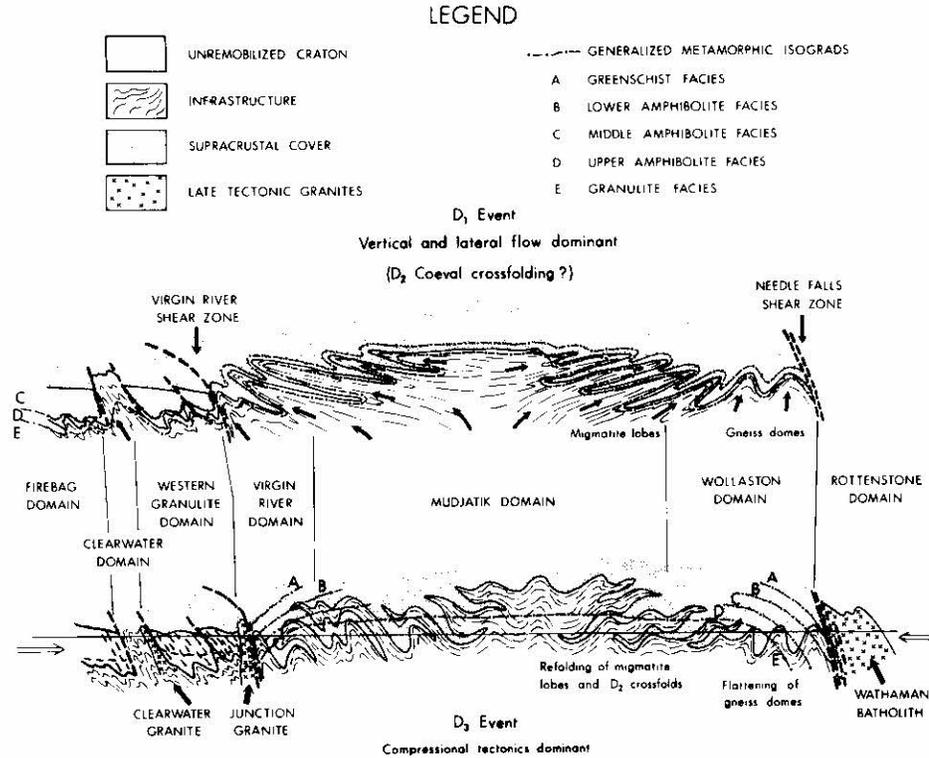
South of the Athabasca Basin the zone displays non-linear structural style in its core (Mudjatik Domain) and linear character marginally (Virgin River and Wollaston Domains). This symmetry is enhanced by development of major bounding shear zones (Needle Falls and Virgin River-Black Lake). Metamorphic grade is highest in the core of the zone, reaching hornblende granulite facies, and falls off rapidly only close to the shear zones.

The zone is interpreted as a region of miogeoclinal Aphebian sedimentation which has undergone intense Hudsonian (*sensu lato*) orogenesis, marked by high grade metamorphism and accompanying ductile interaction of the Archean cratonic basement and the Aphebian supracrustals. Structural evolution is complicated and three main deformation events are recognised (5, 6). The Mudjatik Domain representing the most mobile core of the zone developed flat-lying granitoid migmatite lobes (nappes) separated by screens of infolded supracrustals, whereas mantled gneiss domes formed in the cooler marginal Wollaston and Western Virgin River Domains (Fig. 5). In the Wollaston Domain the domes comprise granitoid Archean cores dated at around 2500 Ma (U-Pb, zircon method) (34) enveloped by Aphebian supracrustals retaining their stratigraphic integrity. Subsequently, in the zone as a whole, longitudinal (D<sub>2</sub>) and lateral (D<sub>3</sub>) compression resulted in dome and basin (non-linear) interference folding of the recumbent nappes in the core and flattening of upright gneiss domes into doubly plunging antiforms in the margins.

Northeast of the Athabasca Basin, along the Northwest Territories - Saskatchewan border, the existence of Aphebian supracrustals and Archean basement of low metamorphic grade suggests that the mobile infrastructure of the Cree Lake Zone plunges to deeper levels, well below the current erosional surface and Archean-Aphebian interface.

#### The Martin Group

The Martin Group unconformably overlies the metamorphic basement in the Uranium City and Tazin Lake areas (Fig. 1). It comprises a sequence of red beds which are folded on a large scale and faulted, but are



**Figure 5 - Schematic cross-section showing thermotectonic evolution of the southwestern Saskatchewan Shield and the relationship between different domains (after Lewry and Sibbald, 5)].**

unmetamorphosed. The Group outcrops in fault bounded basins. The largest of these, the Martin Lake Basin, contains around 5000 m of immature sediments and basic volcanics and is intruded by gabbroic sills and dykes. Within it, the formations identified (35, 36) (Table III) comprise a generally fining upward sequence, from coarse gravels and talus deposited adjacent to active faults at the base, to silts laid down in ephemeral lakes at the top. The sequence may reflect a reduction in elevation of the source area and/or scarp retreat and thence more distal sedimentation (36).

The volcanics are alkaline basalts and trachybasalts (37) and are only present in the Martin Lake Basin. They have

been dated by the K-Ar method at  $1630 \pm 180$  Ma (38), whereas the sills have yielded an age of  $1410 \pm 100$  Ma (39). It appears likely however, that the Martin may be significantly older, predating the earliest generation of epigenetic pitchblende mineralization at  $1780 \pm 20$  Ma (23) but post-dating the latest orogenic events at around 1850 Ma. Similar rocks underlying the Thelon Formation in Northwest Territories yield ages around 1800 Ma (40, 41, 42, 43).

Thus the Martin was deposited in the closing stages of Hudsonian (sensu lato) orogenesis marked by uplift, faulting and formation of successor basins. A low depositional latitude around  $16^\circ\text{N}$  is indicated by paleomagnetic studies (44).

**Table III - Formations of the Martin Group (Martin Lake Basin), Lithology and Thickness**

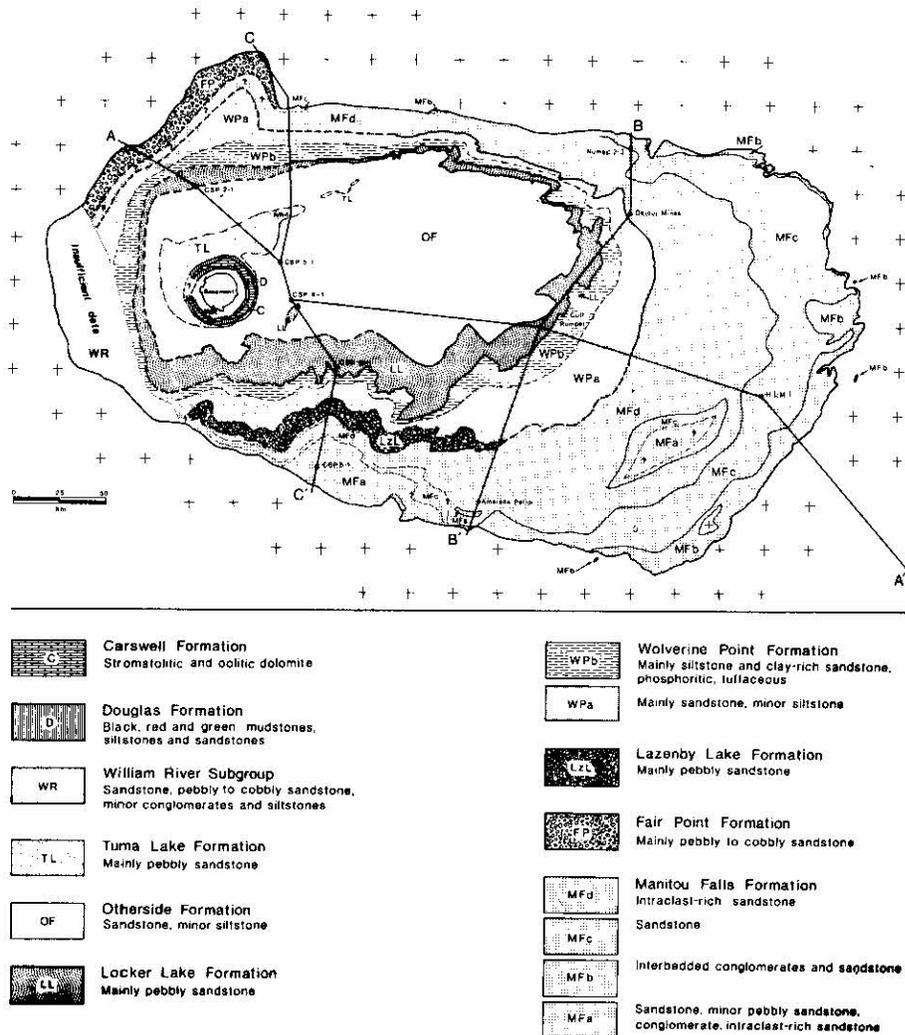
Formator.	Lithology	Thickness (m)
Melville Lake Fm.	Siltstones, minor interbedded conglomerates and sandstones rare stromatolites	80
Seaplane Base Fm.	Interbedded, well sorted conglomerates, sandstones and siltstones	1800
Gillies Channel Fm.	Basal conglomerate, arkosic sandstones, mafic lava flows and sills	2100-2900
Beaveridge Fm.	Basal conglomerate/breccia, arkosic sandstones and siltstones	1600

**The Athabasca Group**

Following Hudsonian (sensu stricto) orogenesis and late stage crustal adjustments the crystalline basement was extensively weathered. The paleoweathering profile, now preserved below the Athabasca Group, is typically around 50 m thick and has mineralogical and chemical characteristics similar to those of present day laterites (31, 45). A mineralogical zoning, with kaolinite in the upper levels and illite and chlorite in the lower, is common. Hematite is pervasive in the upper part of the profile. Superimposed alterations marked by the removal of hematite and emplacement of chlorite variably influence the weathering profile and represent post Athabasca Group hydrothermal effects.

**Table IV - Formations of the Athabasca Group: Distribution, Depositional Environment, Provenance and Thickness**

Depositional Environment	West			East		Source Area	Thickness (m)
	Jackfish Basin	Mirror Basin	Cree Basin				
Marine	Carswell Fm.						?
Marine	Douglas Fm.						?
Marine	Tuma Lake Fm.					NE ?	100
Marine	Otherside Fm.	Otherside Fm.					200
Marine	Locker Lake Fm.	Locker Lake Fm.				S, E, NE	75-200
Marine	Wolverine Point B	Wolverine Point B				S, E	100-300
Marine	Wolverine Point A	Wolverine Point A	Wolverine Point A			S	100-200
Marine		Lazenby Lake Fm.				S	100
Nonmarine	Manitou Falls D	Manitou Falls D	Manitou Falls D			E, NE	] 1000
Nonmarine	Manitou Falls C	Manitou Falls C	Manitou Falls C			E, NE, S?	
Nonmarine			Manitou Falls B			E, NE, S (minor)	
Marine	Fair Point Fm.	Manitou Falls A (Marine in part)				local; S,E ?	300 (FP) 400 (MFA)



**Figure 6 - Geological map of the Athabasca Basin. Locations of cross-sections (Fig. 7) also shown (after Ramaekers, 48).**

Renewed instability, uplifts and subsidence along established Hudsonian structures, led to deposition of a series of largely transgressive deposits whose remains form the Athabasca Group. The Group covers some 100 000 km<sup>2</sup> and comprises a 1400 m thick fining upward clastic succession capped by dolomite. A stratigraphy has been established by Ramaekers (46, 47, 48) (Table IV). Four marine transgressive sequences and one regressive fluvial wedge are recognised.

Deposition occurred within three northeasterly trending sub-basins (Figs. 2,6,7) initially outlined by seismic studies (49). Marine sandstones (Fair Point Fm.) were first laid down in the most westerly lying Jackfish Basin and fluvial and marine sandstones, pebbly sandstones and conglomerates (Manitou Falls Fm. unit A) in the Mirror Basin. Coarse alluvial fans (Manitou Falls Fm. Unit B) developed in the Cree Basin. These graded westward into more distal, progressively finer, braided stream deposits (Manitou Falls Fm. units C and D), giving rise to a fluvial wedge up to 1000 m thick. A second marine incursion into the Mirror Basin is marked by pebbly sandstones of the Locker Lake Formation and later overlapping Wolverine Point Formation sands, silts and muds. The upper part of the Wolverine Point Fm. (B unit) is finer grained and typified by phosphates, which rarely contain preserved tuffs. Later marine transgressions are represented by pebbly sandstones of the Locker Lake Formation and possibly also the Tuma Lake Formation. The Douglas and the Carswell Formations are the

uppermost units of the exposed sequence and respectively comprise shallow marine sandstones, siltstones and mudstones, and oolitic and stromatolitic dolomites.

Four main source areas are suggested to have supplied sediment to the Athabasca Basin. Initial deposition of the basal Fair Point Formation was dominated by local source material, whereas later formations derived detritus from the northeast, east and south (Table IV).

The marine clastics were laid down in shallow seas which were probably warm, as indicated by the dolomites of the Carswell Formation. The fluvial plains to the east were subject to aeolian action, as evidenced by well rounded sand grains and ventifacts in the conglomerates.

The tuffaceous unit of the Wolverine Point Formation has been dated at 1430 to 1450 Ma by the Rb-Sr isochron method and a depositional age around 1450 is indicated (11, 50).

The Athabasca Group clastics comprise predominant orthoquartzite characterized by a clay (kaolinite, illite) rich matrix and by a variable hematite content. Their purity caused Fahrig (51) to argue that the sandstones are supermature multicycle sediments. However, others (48, 52) have suggested that the clays and hematite are authigenic and that the sandstones once contained feldspars and mafic minerals which have been

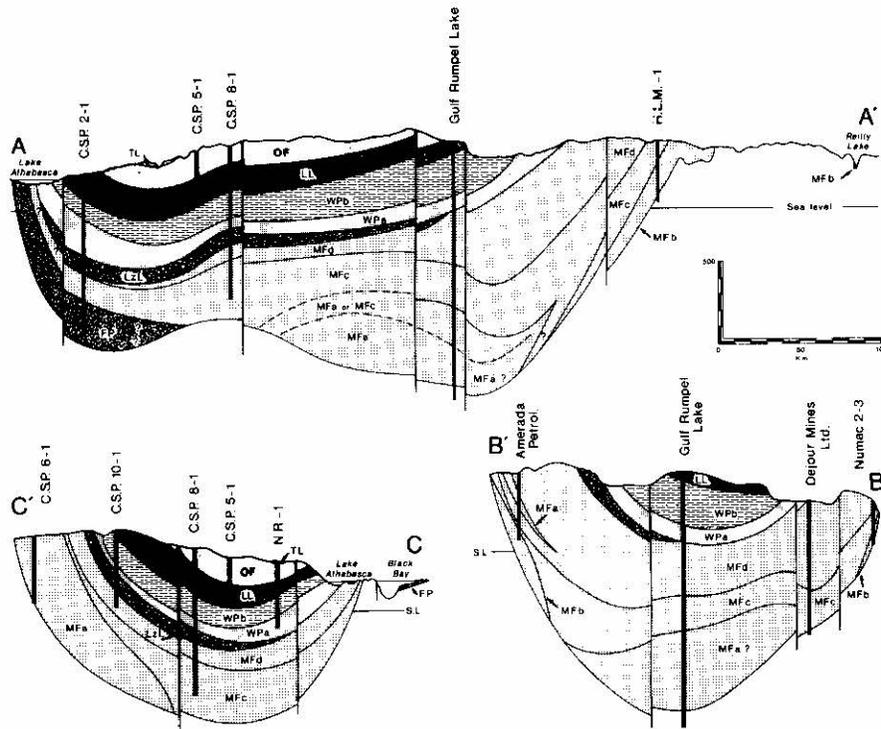


Figure 7 - Cross-sections through the Athabasca Basin. Locations, of sections and legend shown in Fig. 6 (after Ramaekers, 48)].

diagenetically altered. Rarely preserved relicts of the original detrital assemblage in early cemented zones, altered mafic dykes and paleomagnetic data from hematized sandstone samples (53, 54, 55) have been argued to favour this contention.

#### *Mafic dykes*

The Athabasca Group is cut by a series of northwesterly trending mafic dykes. Although poorly exposed, they are often well defined as linear magnetic highs. The intrusives range in size from a metre or less to several hundred metres wide and comprise ophitic textured, plagioclase-augite aggregates, with up to 15 percent magnetite and minor olivine, pigeonite apatite, orthoclase, quartz, biotite, chlorite and hornblende. Adjacent to dykes the sandstone is altered, by bleaching and silicification and locally exhibits columnar jointing (56). The most reliable ages for emplacement are provided by Rb-Sr mineral isochrons at  $1310 \pm 70$  Ma and  $1160 \pm 40$  Ma (50). K-Ar ages ranging between 1230 and 938 Ma (57, 58, 59, 60) have also been obtained.

#### **Uranium Mineralization in Northern Saskatchewan**

The majority of uranium occurrences, and all yet proven to be economic, lie to the west of the Needle Falls Shear Zone. This distribution is not considered fortuitous, rather it reflects the major differences in crustal evolution of the areas on either side.

To the east of the shear zone uranium mineralization is confined within granites and granite pegmatites of presumed Hudsonian (*sensu lato*) age, whereas to the west, a diversity of deposits and deposit ages is apparent. For example, differing types of uranium mineralization of Lower Proterozoic age are present in the Western Craton and in the Cree Lake Zone. Yet another type, the most important economically, is seen in the younger Athabasca Basin uranium deposits which straddle the unconformity at the base of the Athabasca Group.

In the Western Craton uranium mineralization appears most commonly in 'linear zones' of Hudsonian (*sensu lato*) thermotectonic reworking. Following Beck (19), both syngenetic and epigenetic types are recognized, the latter occurring as veins and unusually as disseminations.

The syngenetic mineralization manifests itself as disseminations of radioactive minerals in granite pegmatites and, less commonly, in country rocks. Uraninite, the typical ore mineral, is usually associated with monazite and thorite. Rare earth minerals are locally present, but are only important in the pegmatites. U-Pb dating yields an age for the syngenetic deposits in the Beaverlodge area of  $1930 \pm 40$  Ma (23).

The epigenetic mineralization occurs as fracture controlled, pitchblende vein deposits. These provided the source for uranium production from the Beaverlodge area (Fig. 1, Table I). The epigenetic deposits can be divided into two groups showing simple and complex mineralogy respectively (19, 61).

In the former, which are the more common and exemplified by Eldorado's Ace-Fay-Verna orebodies, pitchblende is accompanied by coffinite, brannerite, nolanite, pyrite, chalcopyrite and galena, whereas in the latter, illustrated by the Nicholson ore zones, pitchblende occurs with coffinite, thucolite, sulphides, arsenides and selenides of nickel, cobalt, copper, lead and zinc, and native gold and silver. U-Pb dating has identified four pitchblende forming or reworking events in these deposits at  $1780 \pm 20$  Ma,  $1110 \pm 50$  Ma,  $270 \pm 20$  Ma and 0-100 Ma (23).

Hoeve and Sibbald (31) emphasized the geochemical similarity between deposits of complex mineralogy, in the Beaverlodge area, and those of unconformity type, in the Athabasca Basin, and proposed two main episodes of epigenetic uranium mineralization. The first, at 1780 Ma, gave rise to the Beaverlodge deposits of simple mineralogy, whereas the second at 1100 Ma resulted in reworking of these deposits and in formation of new ores of complex mineralogy both at Beaverlodge and in the Athabasca Basin.

Evidence to support this hypothesis is provided by the U-Pb age dates, obtained from deposits of both simple and complex type (23), and the recognition of a potential association between the Nicholson ore zones and the sub-Athabasca unconformity (2). Alteration chemistry and fluid inclusion characteristics are also indicative of unconformity origin (3) for at least some deposits of complex mineralogy in the Beaverlodge area.

The early generation of epigenetic pitchblende exhibits a strong structural control, occurring in the fractured wall rocks of major faults, which themselves may cut rocks which have undergone earlier mylonitization during Hudsonian (*sensu lato*) orogenesis.

By contrast, the Cree Lake Zone is characterized by uranium mineralization which exhibits lithological and stratigraphic, rather than structural, controls. Some mineralization is present within granitic and pegmatitic anatectic fractions within the remobilized Archean basement, however, more commonly occurrences are located within the Aphebian, Wollaston Group, supracrustals (Fig. 4). On the basis of dominant host rock, Sibbald et al. (62) and Lewry and Sibbald (63) distinguish arkosic, pelite-pegmatite and calc-silicate types of deposits. Occurrences of the first two types are for the most part located near the base of the Aphebian succession, whereas those in calc-silicate rocks are encountered at several stratigraphic levels. These deposits are of sub-economic grade and are deemed to represent 'syngenetic' mineralizations which have been subjected to metamorphism and/or anatexis. Recent analogs might be sandstone type deposits and black shale and sabkha related uranium concentrations (64).

The absence of Hudsonian epigenetic vein type mineralization in the Cree Lake (Mobile) Zone is believed

to reflect its contrasting thermotectonic evolution relative to the Western Craton. The Zone was subjected to ductile, rather than plastic and brittle Hudsonian (*sensu lato*) deformation. The resultant absence of structural traps and the high grade metamorphic conditions precluded the development of Hudsonian fracture controlled vein type pitchblende deposits. The most easterly known occurrence of this type of mineralization is the Nisto showing (Fig. 2), located in the mylonites of the Black Lake Shear Zone, at the eastern margin of the Western Craton.

The important unconformity-type deposits are confined to the Athabasca Basin which covers portions of both the Cree Lake and the Western Craton. The Cluff Lake deposits are located within the Western Craton, the other main deposits within the Cree Lake Zone. Mineralization seems to have been controlled by the presence of the sub-Athabasca unconformity, rather than by factors related to Apehbian (Lower Proterozoic) sedimentation or Hudsonian (*sensu lato*) structural and metamorphic evolution, because outside the Athabasca Basin no such mineralization is encountered.

### Athabasca Basin Unconformity-Type Deposits

The geological characteristics of these unconformity-type deposits are summarized in Table V and below and illustrated by cross-sections of Rabbit Lake, Collins Bay B zone and Midwest Lake (Figs. 8, 9, 10, 11). The deposits bear a clear cut relationship to the sub-Athabasca Group unconformity. The highest grade ore often straddles the unconformity, as at Midwest, McClean and Cigar Lakes, although mineralization may extend for hundreds of metres above (Midwest and Cigar Lakes) and below it (Rabbit Lake, Raven, Horseshoe and Eagle Point) (Table II). There is also an undeniable association with graphitic basement rocks which are characteristic of, though not restricted to, the basal and lower parts of the Apehbian (Wollaston Group) supracrustal succession throughout the Cree Lake Zone. At their intersection with the sub-Athabasca Group unconformity these rocks may host or

**Table V - Geological Characteristics of Athabasca Basin Unconformity-Type Uranium Deposits**

Proximity to the Sub-Athabasca Group unconformity	
Proximity to graphitic rocks in the crystalline basement	
Structural controls:	a) Post-Athabasca Group thrust faults b) Basement relief ('bumps') c) Solution collapse structures in basement (carbonates) and in Athabasca Group (quartz-sandstones)
High grade:	up to 12 percent U
Primary uranium minerals:	pitchblende and coffinite
Complex mineralogy and geochemistry, but variable concentrations of associated elements (U + Ni, Co, As, Cu, Mo, Pb, Zn, Fe, V, Ag, Au, Pt, Se, S)	
Glassy hydrocarbons present in the ore	
Extensive alteration envelopes: Mg - chloritization, Mg - tourmalinization, hematization, illitization, silicification and dolomitization	
Age of initial mineralization (@ 1300 Ma) postdates deposition of the Athabasca Group (@ 1450 Ma)	

underlie mineralization. As such there is an apparent basement stratigraphic control.

Graphite content within the basement gneisses, which are generally of pelitic composition, may vary from a few percent as at Rabbit Lake (31) to a few tens of percent as at Key Lake (64). Accordingly these units respond weakly, if at all, or strongly to electromagnetic survey methods. In detail, the spatial relationships between graphite and mineralization is less distinct, in that ore grade and graphite concentration are unrelated, (31, 64, 65) and the bulk of the mineralization is displaced and may occur in non-graphitic basement rocks or in the Athabasca Group.

In many deposits there are clear major structural controls. Mineralization can often be related to faults, which displace the sub-Athabasca Group unconformity by several tens of metres. At Rabbit Lake, Key Lake and the Collins Bay A and B zones reverse faults are characteristic (Figs. 8, 9, 10) (31, 64, 65), whereas at Midwest Lake normal faulting is inferred (Fig. 11) (66, 67). These structures may occur singly, or in imbricate zones (66, 68), and strike northerly to east-northeasterly, dipping moderately to steeply in either direction. Contacts between major units of graphitic pelitic and granitoid gneisses, which represent a major structural anisotropy, are preferred locations for these faults, as for example at Key Lake and the Collins Bay A and B zones (30, 33, 65). In several deposits (McClean and Dawn Lake), there is no obvious displacement of the unconformity, although the basement below mineralization appears structurally disturbed (69, 70).

A number of deposits occur on linear topographic basement highs showing a relief of a few metres (McClean, Midwest, Dawn and Cigar Lakes). These 'bumps' appear to have been features of the pre-Athabasca Group land surface, although there has been and continues to be debate as to their origin (69). Evidence for a pre-depositional origin is provided by the observation that basal conglomerate layers at Midwest and Dawn Lakes wedge out against the ridges (Fig. 11) (70). The development of pelitic ridges, while an irregularity to geologists familiar with temperate weathering environments, may be compatible with the tropical weathering lateritic conditions, which characterized the pre-Athabasca land surface. Under such conditions, relative to felsic rocks, those rich in phyllosilicates tend to weather resistently. A modern example is provided by the 'arena granites' of Uganda in which granite plutons form a depressed area rimmed by quartzites and argillaceous sediments (71).

Solution features have been recognized as adding to the structural complexity of deposits, both in the basement rocks and Athabasca Group. In the Rabbit Lake deposit secondary carbonate and quartz and alteration breccia occur within and around the ore zone. Repeated tectonic fracturing, solutioning of dolomitic marbles, collapse and mechanical infilling of open spaces have likely contributed to the lithologically and structurally chaotic alteration zone (Fig. 8) (31, 72, 73).

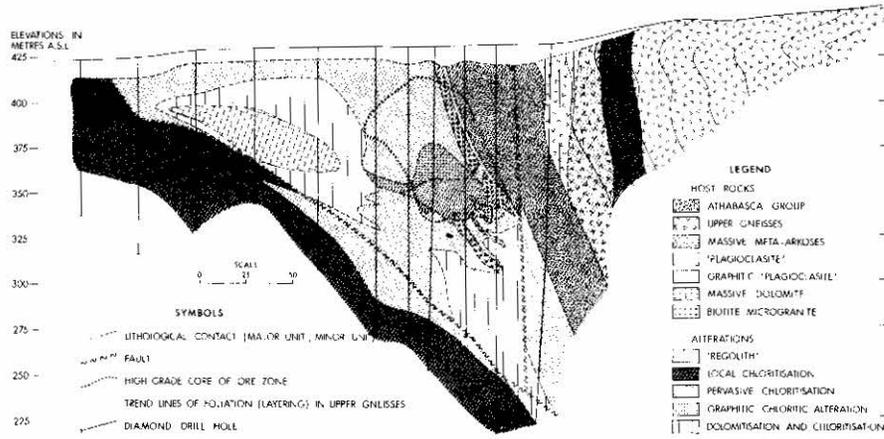


Figure 8 - Geological cross-section of the Rabbit Lake deposit illustrating primary and alteration lithologies (after Sibbald, 73]).

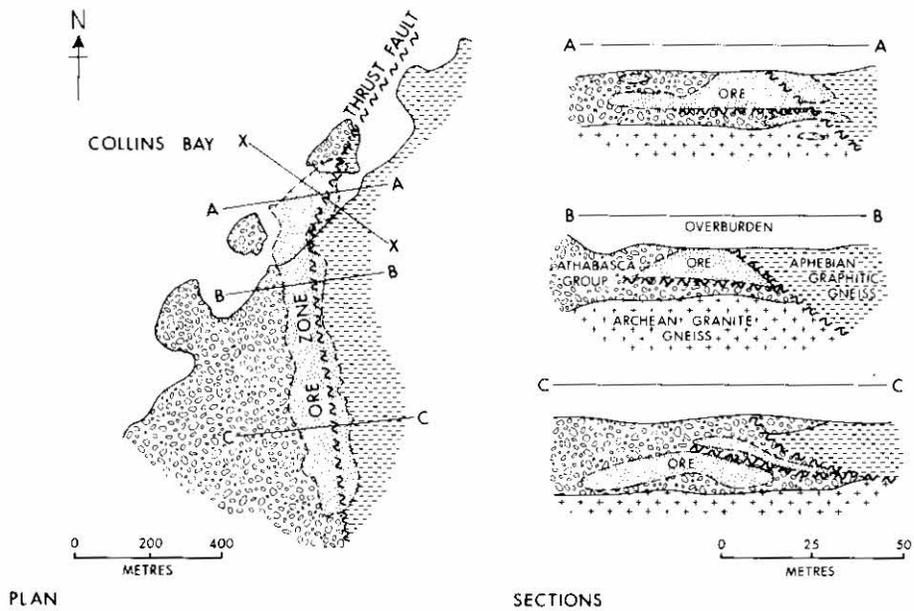


Figure 9 - Schematic plan and cross-sections of the Collins Bay B zone. Location of cross-section (Fig. 10) denoted XX (after Jones, 65]).

The Athabasca Group, when it overlies or contains uranium mineralization invariably shows evidence of quartz grain corrosion. Sandstones become friable, clay enriched and transected by clay filled fractures (69, 74, 75). On top of high grade pods, as at Midwest and Cigar Lakes, massive clay caps are developed (Fig. 11). If, as is suggested by these observations, the increased clay content, within and adjacent to mineralized zones, results from residual sandstone-matrix clay enrichment, then significant volume decrease must have occurred in the Athabasca Group. At Midwest Lake, in particular, there is evidence of accompanying collapse in that a conglomerate marker horizon overlying the high grade pod shows a downward 'sag' of over 20 m (Fig. 11). Similar relationships are observed above high grade pods at Dawn and McClean Lakes (69, 70). Extensive fracturing of the sandstones and, in some cases, zones of brecciation showing rotation of sandstone fragments may also be apparent. The intensity of fracturing is noted to correlate with the intensity of mineralization, but not with uranium grade (69).

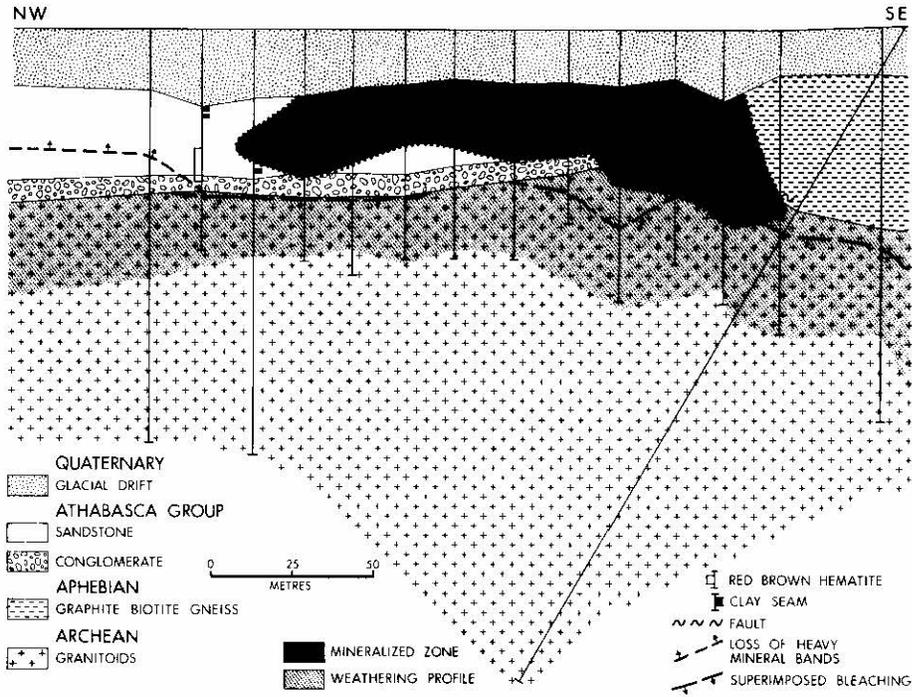
The unconformity-type deposits are often of extremely high grade and marked by a very diverse mineralogy and geochemistry. Intersections of tens of percent are relatively common. Pitchblende and coffinite, the primary uranium minerals, are accompanied by pararammelsbergite, rammelsbergite, niccolite, gersdorffite, millerite, carrollite, molybdenite, various copper sulphides, clausthalite, galena, sphalerite, hematite, goethite, psilomelane, native copper, gold and selenium, and others. Gangue minerals comprise quartz, calcite, dolomite, ankerite, siderite, chlorite, sericite and adularia. Geochemically uranium is accompanied by Ni, Co, Mo, Cu, Pb, Zn, Mn, Fe, V, Ag, Au, Pt-group elements, S, Se and As.

In some deposits (Rabbit Lake and Cluff Lake - N and Claude zones) elements associated with uranium occur in trace amounts, whereas at others they are present in mineable quantities. For example, the D zone at Cluff Lake contains significant selenium and gold (76). Key, McClean, Midwest, Cigar and Dawn Lakes and the Collins Bay B zone have considerable nickel and arsenic and the Collins Bay A zone also silver and gold (64, 65, 67, 69, 70). Mineral and geochemical zonation occurs within deposits, as at the Key Lake Gaertner orebody where niccolite and massive lustrous pitchblende give way upward to sooty pitchblende and millerite (64). At the Collins Bay B zone, the bulk U/Ni ratio of the orebody increases from north to south in harmony with a change in sandstone colour from grey to green (74). However, it is at McClean Lake that mineralogical and geochemical variations are most clearly documented (69, 77) and ascribed primarily to Eh gradients within the ore zones. It is suggested that the U/Ni ratio can be used qualitatively as an indicator of paleo-redox potential, varying sympathetically with Eh, as can the transition from arsenide to sulphide to oxide dominated mineralogy. Similarly, the bulk variation between deposits can be explained as a function of bulk

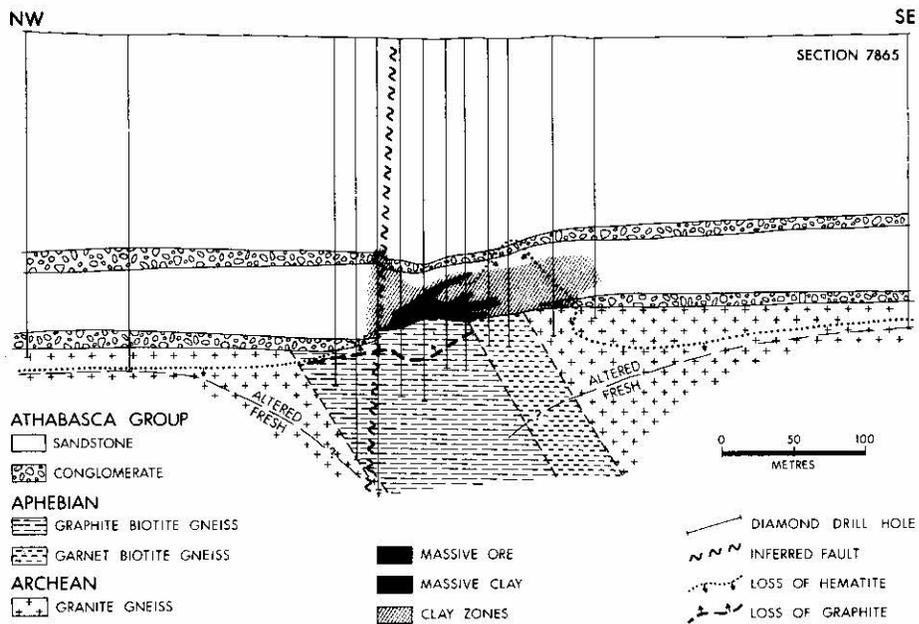
oxidation state, the geochemically most simple deposits being associated with a more oxidized environment.

Solid, glassy, amorphous hydrocarbons are present in most, if not all, deposits. They occur in mineralized rock, intimately associated with ore, as well as in unmineralized rocks of the alteration envelope. In some deposits, like the Collins Bay B zone and the D zone at Cluff Lake, they are present in appreciable amounts. At Rabbit Lake, hydrocarbon buttons are most abundant in high-grade ore, but also occur in vein fillings on top of euhedral quartz in the alteration envelope (31). The association of hydrocarbons with mineralized and altered rocks suggests a reducing agent capable of precipitating hydrocarbon in the ore forming process. In this respect, Pagel (78) has reported carbon dioxide, methane and ethane as present in gangue quartz from Rabbit Lake.

Deposits are surrounded by extensive alteration envelopes influencing both the Athabasca Group and crystalline basement. Alteration is distinct from that which characterizes the sub-Athabasca weathering profile and is variously marked by chloritization, tourmalinization, hematization (several episodes), illitization, silicification and dolomitization. Other processes operative within alteration zones are the destruction of graphite, corrosion of quartz and formation of residual clay seams and caps above mineralization in the Athabasca Group, bleaching (removal of hematite) and development of euhedral quartz  $\pm$  siderite  $\pm$  pyrite  $\pm$  hematite filled fractures. For example, at Rabbit Lake, where ore occurs wholly in basement rocks, Mg-chloritization and Mg-tourmalinization (dravite) are characteristic and reflect large scale introduction of magnesium and boron probably derived from solutioning of dolomitic marbles. Silicification and dolomitization are also locally important yielding irregular porous vuggy zones of secondary quartzite and carbonate. Graphite is visibly destroyed throughout part of the alteration zone (Fig. 8) (31). At the Collins Bay B zone, feldspars and mafic minerals in basement rocks adjacent to the Collins Bay thrust are replaced by illite and chlorite. In the Athabasca Group, approaching the ore zone, matrix clays of the sandstones represented by a broadly equally mixed illite/ kaolinite assemblage (background) are transformed to one dominated by illite (79). Development of an early generation of earthy red hematite, bleaching, quartz corrosion and formation of clay seams are other characteristics of the alteration zone (Fig. 8) (74, 75). Similarly, at Midwest Lake, Sopuck et al. (80) and Hoeve (81) have documented an illitization halo around the ore zone respectively by geochemical and XRD methods. Below the ore zone illitization and chloritization influence both fresh and lateritically weathered basement, as do bleaching quartz corrosion and graphite removal (Fig. 11). In the Athabasca Group illitization, bleaching, quartz corrosion, and formation of clay seams and a clay cap to mineralization are characteristic. In cross section, the alteration zones in the basement and Athabasca Group are funnel and inverted funnel shaped respectively and



**Figure 10** - Geological cross-section of the Collins Bay B zone illustrating, red brown hematite and clay development, bleaching (loss of hematite) and destruction of heavy mineral (hematite) banding in proximity to the mineralized zone (after Sibbald, 75).



**Figure 11** - Geological cross-section of the Midwest Lake deposit illustrating bleaching (loss of hematite) of the Athabasca Group and weathered basement and loss of graphite from the graphite-biotite gneiss underlying the deposit.

show their widest extension at the unconformity. Of particular interest to explorationists is the fact that they extend both vertically and laterally well beyond mineralization, and thereby enlarge potential drilling targets by a factor of 10 to 20 times (81).

Within the alteration zones, whose character is shaped by the introduction/removal of K, Mg, Fe and SiO<sub>2</sub>, trace metals generally show only limited dispersion around mineralization. For example, uranium values may vary from a few percent to a few ppm over metres. However, at McClean Lake a 'chimney' of uranium values of 2-3 ppm U occurs in the Athabasca Group (background 1 ppm U) to the present erosion surface, 150 m above mineralization, as does the illitization halo (69). At Midwest Lake, uranium and boron and at Key Lake uranium and lead are enhanced around mineralization, but not as widely as the major element alterations (80).

Age dating studies have yielded a wide range of numbers of varying quality for deposit formation. U-Pb, Pb-Pb and Sm-Nd data from pitchblende in several deposits serve to indicate that primary mineralization occurred around 1300 Ma. Samples identified as 'early' or 'first stage' pitchblendes commonly yield discordant ages defining various discordia intersecting concordia between 1250 and 1350 Ma (82, 83, 84 (Key Lake); 85, 86 (Rabbit Lake); 60, 87 (Midwest Lake); 88 (Collins Bay B zone)).

This age is recorded in illites from alteration zones adjacent to mineralization, using Ar-Ar (69); Rb-Sr (60) and K-Ar (25) dating methods.

The pitchblende data also indicate a second event, equated with initial mineralization in some deposits and remobilization of pitchblende in others, at around 1100 Ma (85, 86, 89 (Rabbit Lake); 60, 87 (Midwest Lake); 90 (Cluff Lake)). This event appears coeval with that identified by Koepfel (23), as a period of new pitchblende deposition or reworking (lead loss) in the Beaverlodge area (23). Koepfel also recognized younger periods of lead loss at around 300 Ma and between 100 Ma and the present day.

The more recent isotopic data from the Athabasca Basin deposits has confirmed these youngest events (84, 86, 87, 91). The former may represent a period of basin uplift. Ground waters gained access to mineralization causing redistribution of uranium in conjunction with kaolinitization, as, for example, at Key Lake (80, 86).

### Deposit Model

Several genetic models have been proposed for the Athabasca Basin unconformity type uranium deposits. They fall into four categories, discussed by Hoeve et al. (52):

- a) near surface supergene
- b) magmatic hydrothermal

- c) diagenetic hydrothermal
- d) multicycle/process

Over time the diagenetic-hydrothermal model (31) has found increasing acceptance among geologists as well as support from deposit studies. Recently it has been newly presented in a more elaborate form as the Reductant Plume Model (69).

The model (Figs. 12, 13) invokes the interaction of the crystalline basement and the Athabasca Group through the mixing of fluids of contrasting chemistry. Oxidizing brines of the Athabasca Group aquifer entered the basement along fractures, reacted with the wall rocks and re-emerged with reduced character. At, or in close proximity to the unconformity, they mixed with the aquifer creating a dynamic but essentially stationary redox front around a reductant plume displaced downstream by the flow of the aquifer (cf. Collins Bay B zone (Figs. 9, 10).

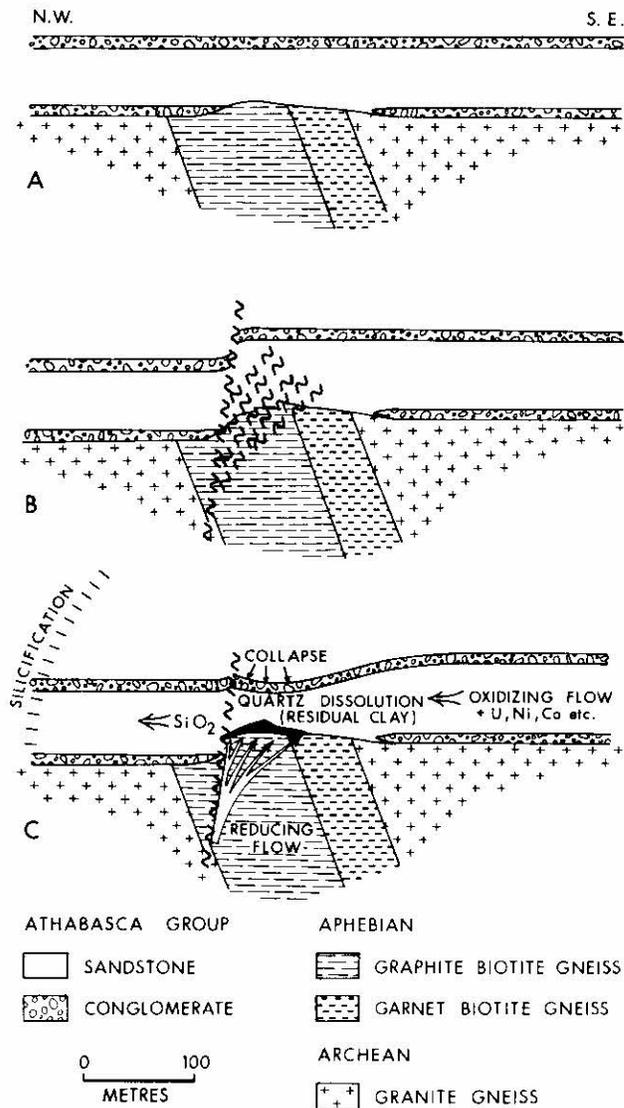
Conditions of deposit formation suggested by fluid inclusion studies (92, 93, 94) are: T 150-225°C, P 0.7-1.5 kb salinity ca. 30 per cent NaCl, implying an elevated geothermal gradient in excess of 30°C/km. The reducing fluids emanating from the basement were probably charged with CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>S, Fe, K and Mg, whereas the aquifer contained U, Ni, Co, As, Cu, Zn etc. Debate continues as to the relative contributions to the deposit of the reducing and oxidizing fluids (52, 69).

Quartz solutioning of the Athabasca Group sandstones must have been caused by basement fluids undersaturated with respect to silica, and thence hotter or more alkaline than the aquifer. The former appears more probable. In this respect the steeply dipping graphitic units may have formed linear hot spots in the Basin floor transporting heat from greater depth by virtue of their superior thermal conductivity (95).

### Discussion

The model has numerous implications from a mineral exploration viewpoint and on a broader scale for establishing parameters for recognition of a uranium province:

- 1) Deposit formation is dependent on the interaction of large volumes of fluids with dilute metal concentrations. Other factors aside, probability of mineralization increases with proximity to the fluid source, the formational brines of the Athabasca Group. To date, unconformity type mineralization has not been detected in excess of 1000 m vertically below the sub-Athabasca Group unconformity.
- 2) Deposits are formed by stripping of metals from the aquifer. For effective free circulation, and thence opportunity for basement interaction, the Athabasca Group must have been or become thoroughly oxidized. The unconformity deposits can be



**Figure 12 - Model for evolution of Midwest Lake uranium deposit.**  
 A - non-deposition of basal conglomerate over pelitic basement ridge. B - faulting of basement pelite and Athabasca Group. C - interaction at fault of reduced basement fluids and the Athabasca Group aquifer. Quartz solutioning at basement outflow causes residual clay enrichment, collapse and by implication redeposition of silica (silicification) in the adjacent sandstones.

considered as a class of sandstone type deposits occurring when a basin has been totally flushed. This condition would be achieved most easily in basins containing clean and poorly stratified quartz sandstones, free of plant derived detritus (pre-Devonian) and subjected to diagenesis for a long time period (96). The flushed sandstone basins would be depleted in trace metals, as the Athabasca Group and appear as negative geochemical anomalies. Hence their response to airborne radiometric surveys will be minimal.

- 3) Metalliferous waters of the Athabasca Group aquifer are cycled through fractures in the basement to

provide, through reaction with the wall rocks, a reducing fluid. There are thus two theoretical possibilities for deposit formation at the basement interface, at points of fluid ingress and egress.

Deposits interpreted to be of the former type (Eagle Point, Cluff Lake-Claude and N zones) are typically of lower grade (<1 percent U), geochemically simple and less reduced than those of the latter type (Key Lake, Midwest Lake, Collins Bay B zone), reflecting the different efficiencies of the fluid-solid, fluid-fluid deposit forming processes.

- 4) Outflow of reductant along fracture trends, by analogy with spring lines developed at the present land surface, likely concentrated in specific locations yielding a series of reductant plumes and thence pods of mineralization. Deposit morphology and complexity are governed by relative flow rates of the fluids and flow variations through time. Mineralization may encroach on the aquifer or vice versa leading to several reduction-oxidation cycles and complex mineral parageneses.

- 5) Activation of a mineralization cycle requires that brines of the Athabasca Group aquifer gain access to the basement along fractures. Mineralization is temporally sporadic and related to periods of tectonic instability of the basin manifested by faulting and mafic dyke emplacement. In this respect, the broad temporal correlation between deposit formation and the mafic dykes is well documented by age dating. Once initiated the cycle continues until local porosity becomes plugged, probably in response to residual clay build up. This condition would also aid deposit preservation.

- 6) The model entertains a single cycle of concentration and emphasizes process rather than source. Spectacular grades result from a stationary redox condition, in contrast to sandstone hosted roll deposits which concentrate through migration. Overall, an unusually enriched source basement is neither advocated nor indicated by regional radiometric surveys (28) and litho-geochemical studies (10, 97), although locally some supracrustals and intrusive granites, as noted earlier, do contain anomalously high uranium values. The Athabasca Group is entertained as the direct source of most metals, either through destruction of feldspars and mafic minerals by interstratal leaching and/or through release, during diagenesis, of metals adsorbed to iron hydroxides and clays (47, 52).

Simple calculations illustrate that the Athabasca Group when flushed must have liberated a significant quantity of metals. For example, 1 ppm U leached from 40 km<sup>3</sup> of sandstones would produce the 100 000 t of uranium concentrated at Key Lake. Similarly, Ramaekers (47) notes that the Athabasca Group as a whole might have contributed some four billion tonnes of uranium metal to the basinal brines, which if impounded would have

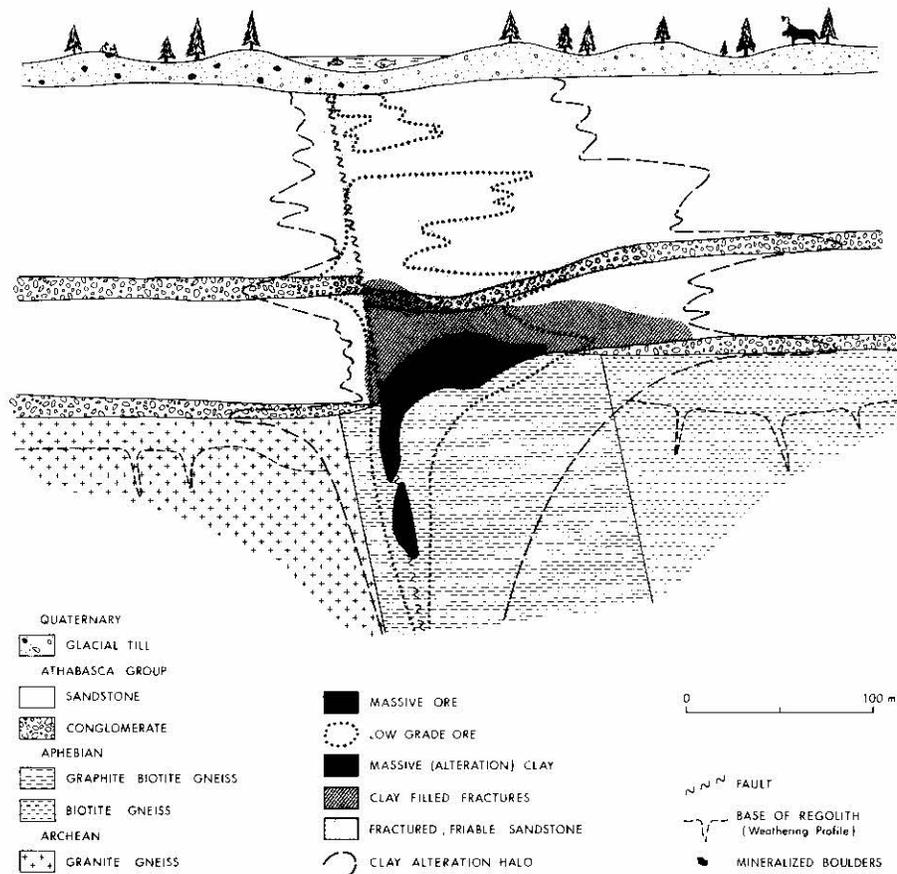


Figure 13 - Idealized "model" Athabasca Basin unconformity-type uranium deposit.

necessarily precipitated it somewhere. He suggests that any hypothesis that derives uranium exclusively from the basement subsequent to Athabasca Group deposition should also undertake to explain away this volume of metal.

## Conclusion

In retrospect the historical record suggests that the discovery of the Athabasca Basin uranium province was a comedy of errors, although human nature dictates that there are those who will claim remarkable intuition.

In 1945, the impetus for exploration in the Beaverlodge area arose because Nicholson was one of only three known occurrences of uranium minerals in Canada. Ironically, Nicholson, now recognized as an unconformity-type deposit, led to the discovery of a wholly different group of uranium deposits.

In the late sixties the objective was to examine a sandstone basin in a region with existing uranium production, using contemporary models for conglomerate and sandstone hosted deposits. Through prospecting of airborne radiometric anomalies, explorationists recognized a potential for mineralization in rocks underlying the sandstone basin. Despite models, the unconformity-type deposits were eventually discovered.

There are several lessons to be learnt from the above:

- 1) the search for mineralization has proven successful in regions where mineralization, however insignificant, has been observed before and is unexplained.
- 2) the exploration model, while providing a stimulus, may become a hinderance if it yields to dogma.
- 3) after discovery, deposit studies provide improved models for further exploration of the specific environment. However, as many factors are involved in

deposit formation, an incorrect emphasis on any one of these may lead to misdirection of effort.

- 4) The relevant model is one which has been rigorously and successfully applied, not one that has led to discovery through balancing the wrong approach with a large measure of luck.

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