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Uranium deposits of the Athabasca Basin, Saskatchewan (Field Trip 11)

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URANIUM DEPOSITS OF THE ATHABASCA BASIN, SASKATCHEWAN

[FIELD TRIP 11]

BY

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8TH IAGOD SYMPOSIUM

FIELD TRIP GUIDEBOOK

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INTRODUCTION

Northern Saskatchewan has been a uranium producer since the early 1950's with historic mines in the Uranium City area and since 1975 production from deposits in the Athabasca Basin, at Rabbit Lake - Collins Bay, Cluff Lake and Key Lake.

The early period of exploration in the 1940's and 1950's identified thousands of uranium showings in the vicinity of Uranium City. Some of these were eventually to become mines. The more important occurrences have been described by Beck (1969), who distinguished between syngenetic and epigenetic deposits.

The epigenetic, vein type, mineralization gives rise to deposits of economic significance with pitchblende being the chief ore mineral and thorium and rare earths typically absent. The veins have been variously interpreted as being of classical hydrothermal, metamorphic-hydrothermal and more recently supergene origin.

Exploration in the late 1960's identified another group of economic pitchblende deposits, which appear closely related, spatially, to the major regional unconformity separating the Helikian (Middle Proterozoic) Athabasca Group from the underlying Archean and Aphebian (Lower Proterozoic) crystalline basement. In view of this relationship these deposits have been described as being of 'unconformity-type'. They are typically of high grade and as such are attractive targets for exploration. The numerous significant discoveries of the last two decades have led to the emergence of the Athabasca Basin as the world's most important uranium district with 66% of Canadian output and 22% of western world output in 1988.

The origin of the unconformity deposits has been the subject of heated debate, with three major deposit models being advanced, respectively: near surface supergene, magmatic-metamorphic hydrothermal and diagenetic hydrothermal. The diagenetic-hydrothermal model, invoking the interaction of the crystalline basement and the Athabasca Group through the mixing of fluids of contrasting chemistry to produce mineralization has been favoured by recent deposit studies.

HISTORY OF URANIUM EXPLORATION AND PRODUCTION

Pitchblende was first discovered in Saskatchewan in 1935 at the Nicholson copper prospect on the north shore of Lake Athabasca (Fig. 1, locality 11). Note of this occurrence was made in Alcock's (1936) 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 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 and 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 16 main deposits and milling at 3 separate facilities (Table I, Fig. 1).

By 1958 it became clear that world demand for uranium would fall, by virtue of slow development of the nuclear power program in the United States and failure of that country to renew long term sales contracts. By 1964, Eldorado remained the only uranium producer in Saskatchewan, itself only surviving with the aid of a federal subsidy and stockpiling program and by reducing production capacity.

With the low ebb of mineral exploration the Saskatchewan Government introduced a financial assistance program to companies with approved exploration work schedules. In 1967, a consortium of companies, the Dynamic Group, taking advantage of this program decided to fly a systematic radiometric survey of the unexplored sandstones of the Athabasca Basin. Subsequent to the survey, the Group reached agreement with the British American Oil Company (Gulf Oil Company),

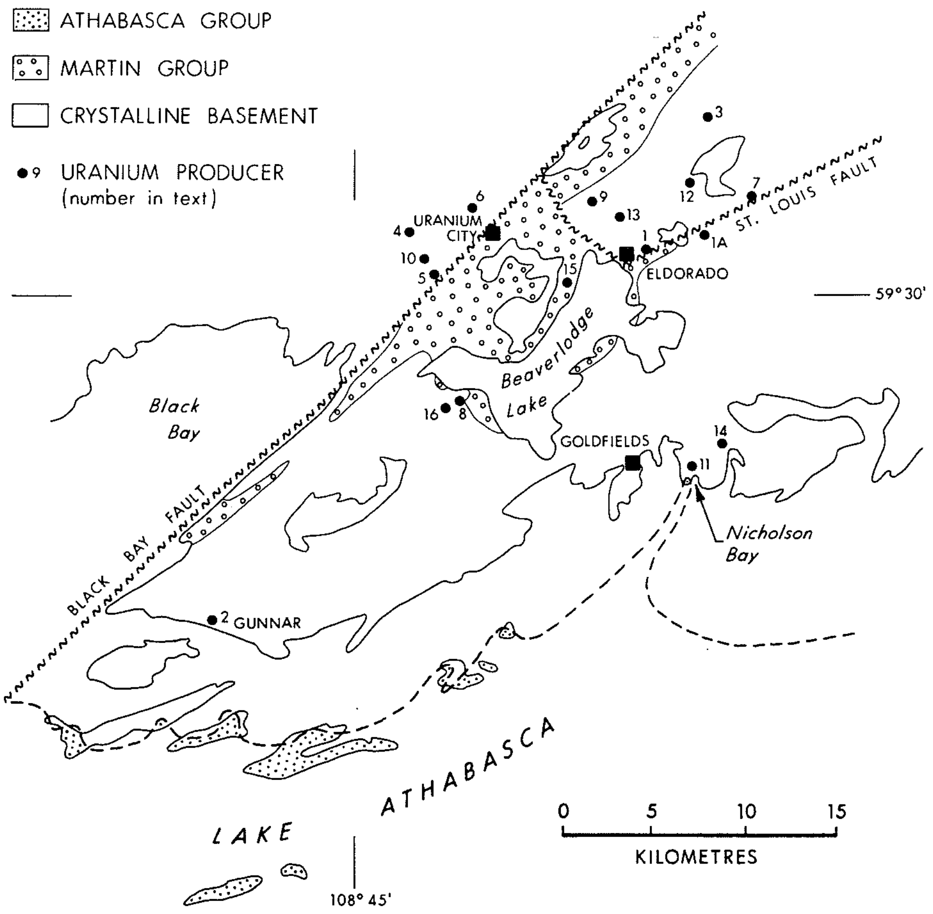

Figure 1 - Major uranium producers of the Beaverlodge District in relation to the outcrop of the Martin and Athabasca Groups. Numbers refer to Table I.

Figure 1. Major uranium producers of the Beaverlodge District in relation to outcrop of the Athabasca and Martin 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

whereby Gulf acquired five permits held by the Group covering high priority anomalies and took possession of the airborne survey data. In October 1968, as a result of following up airborne anomalies in the Wollaston Lake area, Gulf drilled the first hole into the Rabbit Lake deposit (Fig. 2, Table II locality 1). An exploration philosophy which had been designed to find sandstone hosted deposits led to an orebody in the underlying basement rocks.

The Rabbit Lake discovery, together with improving forecasts for uranium demand, precipitated a land staking rush unequalled in Canadian mineral exploration history. By early 1969, almost all of northern Saskatchewan had been claimed by mineral permits. Land was acquired in 'one shot' as permits covering thousands of square kilometres following the oil industry style. Traditional mining however moved slowly, unused to these techniques.

At the time Gulf acquired the Dynamic Group permits, Mokta (Canada) Ltd., a subsidiary of Compagnie de Mokta and now known as Amok Ltd., that had been exploring in Canada since 1963 and Saskatchewan since 1964, sent a team to investigate certain airborne radiometric anomalies in the Carswell Dome area. Initially attracted to the Beaverlodge area, Mokta soon turned their attention towards the Athabasca Basin undoubtedly prompted by their experience with sandstone hosted uranium deposits in Gabon, West Africa and the discovery, in 1967, of mineralized boulders of Athabasca Group sandstones at Fond-du-Lac. Investigations in the Cluff Lake area in 1969 resulted in discovery of the D orebody, which was of extremely high grade (6 percent U), and subsequently in the next few years to the N and Claude deposits.

By late 1972 the exploration flurry was over and exploration permits were dropped or reduced to mineral leases and claim blocks. While proving fruitless for many participants, work undertaken at this time provided clues that would later lead to other major uranium deposits, notably Midwest (Fig. 2, locality 7).

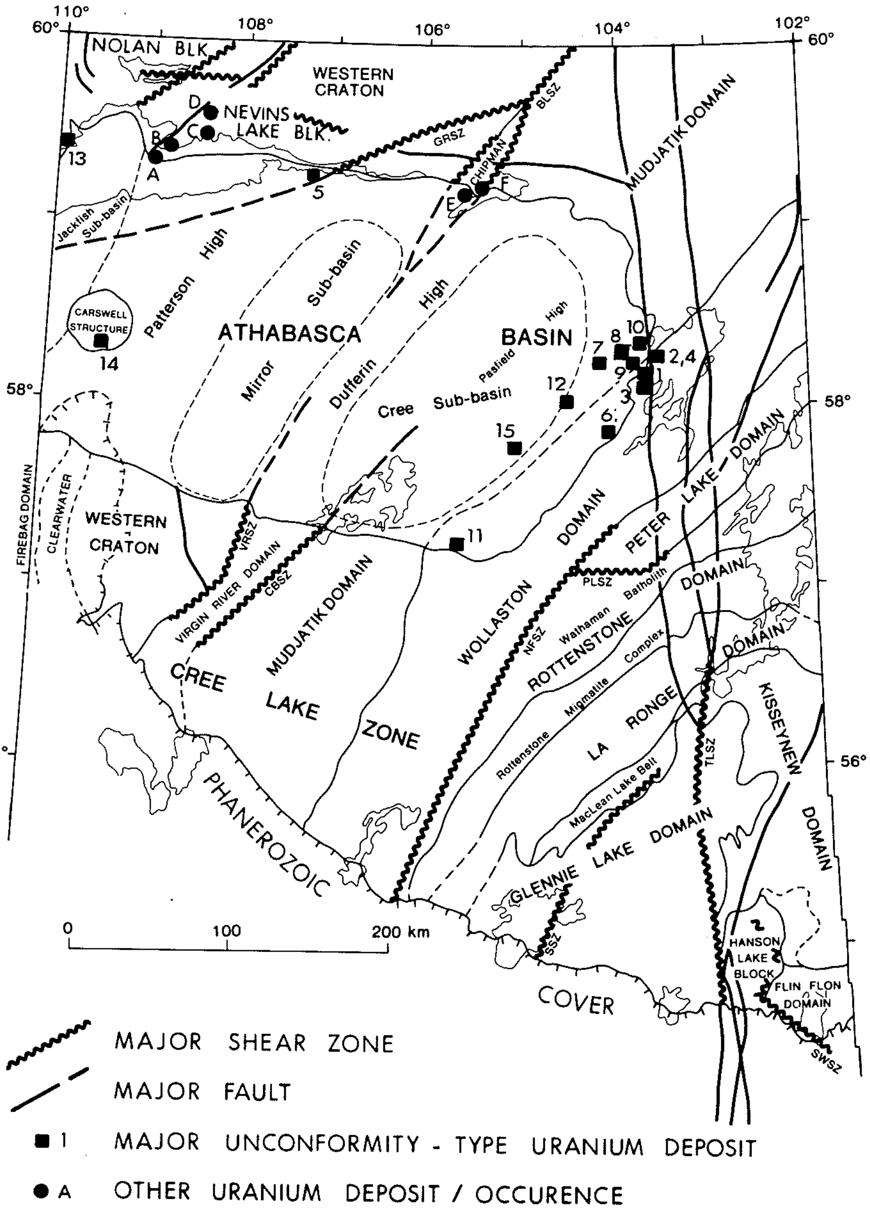

Figure 2. Major Athabasca Basin unconformity type uranium deposits and tectonic subdivisions of the Saskatchewan Shield. Numbers refer to Table II; other uranium deposits (A. Stewart Is., B. Gunnar, C. Nicholson, D. Ace-Fay-Verna, E. Middle Lake, F. Nisto). VRSZ-BLSZ, Virgin River-Black Lake Shear Zone; 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	Cameco - Uranerz Exploration and Mining Ltd.	1968	15 769*	0.27	Absent (eroded)	Meta-arkose, plagioclasite (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	4.83	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	15 750**	0.61	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	2 150	1.66	-	Pelitic graphitic gneiss, granite segregation pegmatite	-	Adjacent to Collins Bay thrust fault
3	Raven	"	1972	3 650	0.12	Absent (eroded)	Sillimanite quartzite, calcareous meta-arkose, semipelitic gneiss	0-300	Fracture controlled mineralization in altered basement
3A	Horseshoe	"	1974	1 550	0.14	Absent (eroded)	Sillimanite quartzite	60-300	Fracture controlled mineralization in altered basement
4A	Eagle Point South Zone	"	1980	28 850	1.39	Absent (eroded)	Pelitic-semipelitic gneiss (in part graphitic), quartzite, granite segregation pegmatite	0-460	In hanging wall of Collins Bay thrust fault. Structurally controlled in altered basement. Concordant lenses subcrop below drift
4B	Eagle Point North Zone	"	1980	22 300	1.76	Absent (eroded)	"	0-300	In hanging wall of Collins Bay Fault. Structurally controlled in altered basement. Discordant lenses.
5	Fond-du-Lac	Cameco	1967	400	0.2	30	Meta-arkose, pelitic gneiss (occasionally graphitic)	10-30	Mineralization in Athabasca Group. Subcrop below drift. Mineralized boulder train
6	Westbear	Cameco	1977	450	0.37	-	Pelitic graphitic gneiss	17-40	Mineralization occurs at unconformity
7	Midwest	Denison Mines Ltd. - Uranerz Exploration and Mining Ltd. - PNC - Bow Valley Industries Ltd.	1978	21 550	1.06	200	Pelitic graphitic gneiss locally with garnet, granite segregation pegmatite, bounded by granitoid gneiss; crosscutting diabase dykes	0-300	Dominantly at sub-Athabasca Group unconformity, mineralization extends more than 100 m below unconformity and to surface (source of mineralized boulder train)

8	Dawn Lake (11, 11A, 11B and 14 zones)	Cameco - Cogema (Canada) Ltd. - PNC - CEGB - Kepco	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.
9A	McClean Lake (North and South Zones)	Canadian Occidental Petroleums - Inco Metals Ltd. - Minatco Ltd.	North 1979 South 1980	5 500	1.5	150	Pelitic graphitic gneiss granite segregation pegmatite	115-190	Mineralization extends above and below sub-Athabasca Group unconformity. No surface expression.
9B	Sue Zones	"	1988	-	-	-	-	-	-
10	Jeb	"	1982	1 800	-	100	Pelitic graphitic gneiss	85-120	No surface expression
11	Key Lake	Cameco - Uranerz Exploration and Mining Limited - Eldor Resources Limited	1975	73 900**	2.0	0-60	Graphitic pelitic gneiss adjacent to granitiod 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
12	Cigar Lake	Cameco - Cogema (Canada) Ltd. - Idemitsu Uranium Exploration Canada Ltd. - Corona Grande - Kepco	1981	110 000 (38 500) additional estimated)	12.3 (4)	410-450	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
13	Maurice Bay	Cameco - 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
14A	Cluff Lake D	Amok Ltd. - Cameco	1969	4 170*	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.
14B	Cluff Lake (other)	"	1969-1980	18 850***	0.63	-	Pelitic to semipelitic gneiss (in part graphitic (Peter River Gneiss) quartzofeldspathic gneiss (Earl River Gneiss), granite pegmatite	0-300	Fracture controlled mineralization in altered basement
15	P2 North	Cameco - Agip Resources Ltd. - Cogema (Canada) Ltd. - Uranerz Exploration and Mining Ltd. - Interuranium Canada Ltd.	1989	-	-	460-590	Pelitic graphic gneiss-quartzite	± 550	Mineralization in Athabasca Group underlying overthrust basement wedge

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* Actual production, now mined out

** Original resources, now depleted by production

*** 1988 reserves (original reserves - production + discoveries)

In 1974 a joint venture group headed by Uranerz Exploration and Mining Ltd. approached the Saskatchewan Government proposing an exploration partnership. The offer was accepted and on June 1974, the Saskatchewan Mining and Development Corporation was born. Exploration by the group led to discovery in 1975, of the Key Lake Gaertner orebody and in 1976 the Deilmann orebody on strike with the former. The initial clue 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 fluvioglacial 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 (Ray, 1977). 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.

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 McMahon (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. Thus, by 1978, much of the open ground in the Athabasca Basin was staked and exploration expenditures rose, reaching a peak of around $100 million in 1980.

Several significant discoveries followed within the eastern part of the Basin, for example the Dawn Lake 11 and 14 zones (1978), McClean (1979), Cigar Lake (1981), Jeb deposit (1982), Sue zones (1988) and P2 zone (1989). These deposits lack any clear surface expression, such as mineralized boulders, which characterized the earlier discoveries. Recent work has shown that subtle geochemical variations reflecting the alteration haloe surrounding mineralization may however be identifiable at surface, in bedrock and derived drift (eg. Earle et al., 1990). The deposits were discovered by systematic drilling of electromagnetic conductors defined in airborne and ground follow up surveys.

The Athabasca Basin, with reserves estimated at about 325 000 tonnes of uranium in the lower cost categories (up to $150/kg U) contains some 10 percent of the reasonably assured low cost uranium reserves of non-communist world and approximately 75 percent of Canadian reserves. Most of the Athabasca Basin reserves are contained within two major deposits at Key Lake and Cigar Lake (Table II).

Discovery costs (in 1985 dollars) per kg U metal between 1971 and 1983 have been estimated at $1.53 in Saskatchewan compared with $13.58 in the remainder of Canada. A total of 383 800 t of U metal is identified as having been found during this period for an expenditure of $588 million (Cranstone and Whillans, 1989).

Development of existing and new production facilities has kept apace of the new discoveries with the current (1988) uranium production being approximately 8.2 million kg U, making Saskatchewan the non-communist world's leading uranium producer with 66% of Canadian production and 22% of non-communist world's production.

In October of 1975 Rabbit Lake came

on stream reaching planned annual production levels of around 2 million kg U in 1977. Production decreased in 1981 due to depletion of the higher grade portions of the ore zone and the body was mined out by May 1984, although processing continued until October 1985, yielding 15 750t U (41 million lbs U_3O_8) from 6 million tonnes of ore. The Rabbit Lake operation underwent transition in 1984 and 1985, due to phasing out of the Rabbit Lake open pit, development of the Collins Bay B zone open pit and extensive modification of the mill to accomodate the geochemically more complex ore of the B zone. The Collins Bay B zone achieved first production in November 1985 and continues to be mined with reserves capable of sustaining this effort until 1993. Mill capacity is around 2.5 million kg U per annum.

Open pit production at Cluff Lake began from the small high grade D zone in the summer of 1980 and mining was completed by 1981, although milling continued until 1984. A second phase of underground and open pit mining and milling of basement hosted lower grade deposits, beginning with the Dominique-Peter and Claude zones, started up in the latter part of 1984. Production is currently somewhat less than 1 million kg U per year. Additional reserves have been identified since 1984 (approximately 5000t U). The company has also reprocessed Phase 1 tailings, which contained recoverable uranium and 7 800 troy ounces of gold.

The Key Lake Mining Corporation (now a part of a Canadian Mining and Energy Corporation (CAMECO)) commenced production, by open pit mining, from the Key Lake orebodies in 1983. The production rate of around 4.6 million kg U annually has made this mine the world's largest uranium producer. The Gaertner open pit was mined out by the end of 1986 and decommissioned. Mining of the larger Deilmann orebody is now in progress.

The massive Cigar Lake uranium deposit, and the Midwest deposit are the subject of test mining projects. The Cigar Lake Mining Corporation was established to manage the development of the giant Cigar Lake deposit with reserves estimated at 150,000 t U. The corporation is sinking a 510 m deep shaft and developing two levels from the shaft, one above and one below the orebody, to test various mining methods, the most favoured being raise boring. The operation is on schedule to begin test mining in 1990, with an anticipated completion date of late 1991, at which time the owners will review potential production scenarios. At the Midwest joint venture, operated by Denison Mines Ltd., sinking of a 185 m deep shaft, driving of a crosscut above the orebody, and drilling and recovery of cuttings from two, 1.2 m diameter blind bore holes has been completed. Reserves at Midwest are claimed to be 21 500t U at a grade of 1% U and plans for a mine/mill complex with a production capability of 1 350t U per year are being developed.

GENERAL GEOLOGY OF NORTHERN SASKATCHEWAN

The crystalline basement of northern Saskatchewan is part of the Trans-Hudson Orogen, which extends some 5 000 km from Greenland to the mid-continental United States (Lewry et al., 1985). 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 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 (Lewry and Sibbald, 1980). 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 (Camfield and Gough, 1977) with a geologically similar break in Wyoming (Hills and Armstrong, 1974). 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 respectively representing parts of the Rae and Hearne provinces of Hoffman (1988). These two units are further subdivided

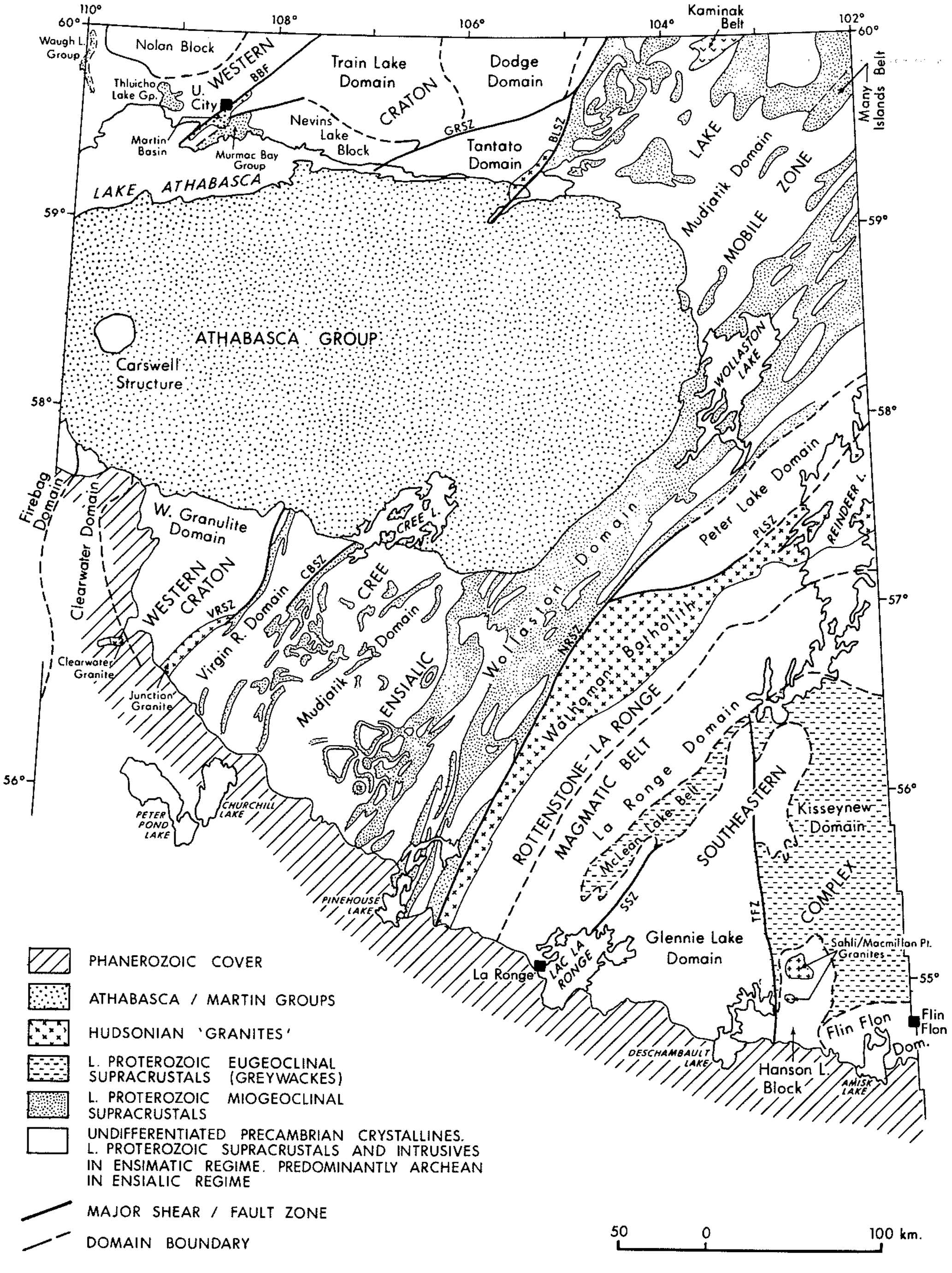

Figure 3 - General geology and major subdivisions of the Saskatchewan Shield.

into various lithostructural domains, or regimes of relative lithological, structural and metamorphic homogeneity (Lewry and Sibbald, 1977).

The Western Craton: Bounded in the east by the Virgin River - Black Lake Shear Zone, the Western Craton incorporates the Firebag, Western Granulite and Clearwater Domains and the region north of Lake Athabasca (Fig. 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 (Lewry and Sibbald, 1977). The Firebag Domain appears to have broadly similar character (Tremblay, 1961). The granulites yield Archean (2.6-2.9 Ga) Sm-Nd model ages. Complex zircon suites include Archean cores and clear zircon fractions. The latter yield virtually concordant ages of ca. 2.0 Ga, which are interpreted to mark the time of granulite facies metamorphism (Bickford et al., 1990).

The Clearwater Domain truncates abruptly magnetic and presumed structural trends, and forms a zone of low amplitude magnetic signature and low 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 the late tectonic, uranium enriched (ca. 8 ppm U) granite, Junction Granite (Parslow and Adamson, 1982), which yields a Sm-Nd model age of 2735 Ma and a U-Pb zircon age of 1820 ± 19 Ma (Bickford and Collerson, 1987). 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 (R.H. Wallis, personal communication).

The Western Granulite Domain and by analogy the Firebag Domain have been proposed (Lewry and Sibbald, 1977; 1980) as catazonal Archean crust, mildly overprinted by Hudsonian (sensu lato) thermotectonic processes coeval with those in the Cree Lake Zone to the east. While providing the simplest interpretation explanation of geological field relationships, this interpretation is at variance with Bickford et al.'s (1990) proposal of a 2.0 Ga age for granulite facies metamorphism in the Western Craton. The Clearwater Domain may represent a region of more extensive reworking within the cratonic complex (Lewry and Sibbald, 1977; 1980), although others (Wallis, 1970) have suggested that it represents an Aphebian structurally controlled sedimentary trough within the Archean basement. There are presently very limited age data available to evaluate the merits of these hypotheses.

North of Athabasa Basin, predominantly retrogressed granulite facies domains and blocks, similar to the Western Granulite Domain, are recognized - the Tantato Domain, the Nevins Lake Block and the Nolan Block. Intervening areas, again characterized by lower metamorphic grade, are diverse in character and form granitic migmatite complexes (Train Lake Hudsonian (sensu lato) refers to radiometric events within the time frame ca. 2200-1750 Ma, Hudsonian (sensu stricto) to the ca.1750 Ma event. Domain), Lower Proterozoic (?) supracrustal complexes invaded by granite plutons (Goldfields area) and zones of intense tectonism marked by extensive mylonite development and strong retrogression (Beaverlodge area and Grease River Shear Zone). Zircon and Rb-Sr dating of the granulites and surviving older components of the intervening zones yields ages ranging from 2500 to 3000 + Ma (Koster and Baadsgaard, 1970; Van Schmus et al., 1986, Bell and Blenkinsop, 1984; Tremblay et al., 1981). Plutons intrusive into the presumed Lower Proterozoic Murmac Bay Group in the Goldfields area are dated by the U-Pb zircon method at about 2000 and 2340 Ma (Van Schmus et al., 1986) and the Train Lake migmatite complex by the

Rb-Sr isochron method at around 2000 Ma (Bell and Blenkinsop, 1984).

Lower Proterozoic orogenesis has apparently influenced the Western Craton irregularly, leaving relatively untouched cratonic nuclei which are generally surrounded by restricted (often), linear zones of thermotectonism. This style contrasts markedly with the comparatively homogeneous tectonic and thermal character of the Cree Lake Mobile Zone. Age dating by various methods suggests a complex history of orogenesis within these zones with events at around 2350 Ma (Van Schmus et al., 1986) 2200 Ma (Beck, 1969; Tremblay et al., 1981; Van Schmus et al., 1986), 1850-2000 Ma (Baadsgaard and Godfrey, 1967; Beck, 1969; Koeppel, 1968; Sassano et al., 1972; Stevens et al., 1982; Bell and Blenkinsop, 1983) and 1750 Ma (Koeppel, 1968; Sassano et al., 1974). 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 (Bell and Macdonald, 1982), suggesting that Hudsonian (sensu lato) orogeny was diachronous and migrated with time from northwest to southeast.

The general structural character of the Craton is clearly seen on regional aeromagnetic maps. The cratonic nuclei conform with areas of high magnetic amplitude and intensity, the intervening zones of Lower Proterozoic thermotectonic reworking with areas of relatively lower magnetic amplitude and intensity. A major negative gravity feature is also noted to coincide with the Clearwater and Tantato reworking zones. It extends far into the Northwest Territories and into southeastern British Columbia. Darnley (1981) has pointed out that the gravity anomaly is marked by a belt of uranium enrichment, the Athabasca Axis, apparent from regional radiometric surveys and other work. The association between abnormally radioactive granitoids and negative gravity anomalies is well documented, for example in the Nova Scotia Batholith and in the Cornubian Batholith of southwest England - bodies which also contain tin and tungsten mineralization. Whether radioelement-enriched granites, such as the Clearwater and Junction Granites and granitoids north of Lake Athabasca, within the negative gravity belt in Saskatchewan have any potential for these elements is currently unknown. The belt is suggested by Darnley (1981) to have played a multifacetted 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 heatsource to drive hydrothermal mineralizing systems within these sedimentary basins.

<u>The Cree Lake (Mobile) Zone</u>: 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 metasediments with some interlayered volcanics. The supracrustals are most extensively developed in the Wollaston Domain as the Wollaston Group (Ray, 1977), a three to four kilometre thick sequence (Hoeve and Sibbald, 1978). Four main lithostratigraphic units are distinguished (Lewry and Sibbald, 1980) (Fig. 4):

1) A lower coarse clastic unit, of variable thickness, present 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. This unit 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 psammites, 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 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.

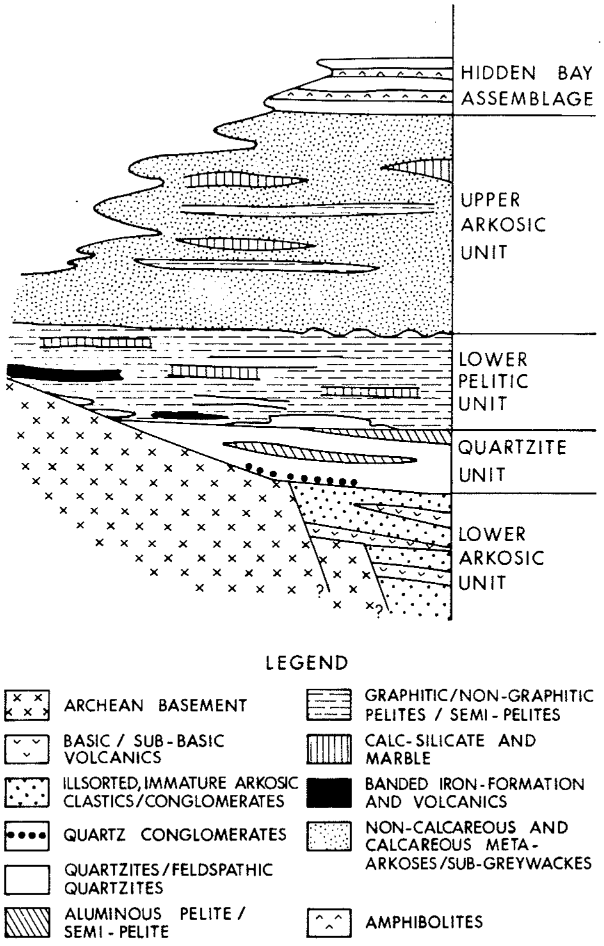

Figure 4. Generalized stratigraphic relations in the Wollaston Group. The right of the column is applicable to the eastern Wollaston Domain, the left to the western Wollaston and Mudjatik Domains (after Lewry and Sibbald, 1980).

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 (Wallis, 1971; Sibbald, 1983) 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) (Fig. 5). 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 Cree Lake (Mobile) Zone is interpreted as a region of miogeoclinal Aphebian sedimentation which has undergone Hudsonian (sensu lato) orogenesis, marked by high grade metamorphism and accompanying ductile interaction of the Archean cratonic basement and the Aphebian supracrustals. Age constraints on thermotectonism are provided by an 1840 Ma U-Pb zircon age from the post kinematic Horton Island Granite in the Wollaston Domain and an 1820 ± 19 Ma age from the late kinematic Junction Granite bounding the Virgin River Domain. K/Ar biotite ages are typically significantly younger (ca. < 1750 Ma) (Money, 1968; Ray and Wanless, 1980; Stevens et al.; 1982; Worden et al., 1985; Hoehndorf et al., 1989). Structural evolution is complicated and three main deformation events are recognised (Lewry and Sibbald, 1980). 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. 6). In the Wollaston Domain the domes comprise granitoid Archean cores dated at around 2.5 to 2.6 Ga (U-Pb, zircon method; Ray and Wanless, 1980; Krogh and Clark, 1987; Hoehndorf et al., 1989) enveloped by Aphebian supracrustals retaining their stratigraphic integrity. Subsequently, in the zone as a whole, longitudinal (D_2) and lateral (D_3) 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 (Kaminak Belt) suggests that the mobile infrastructure of the Cree Lake Zone

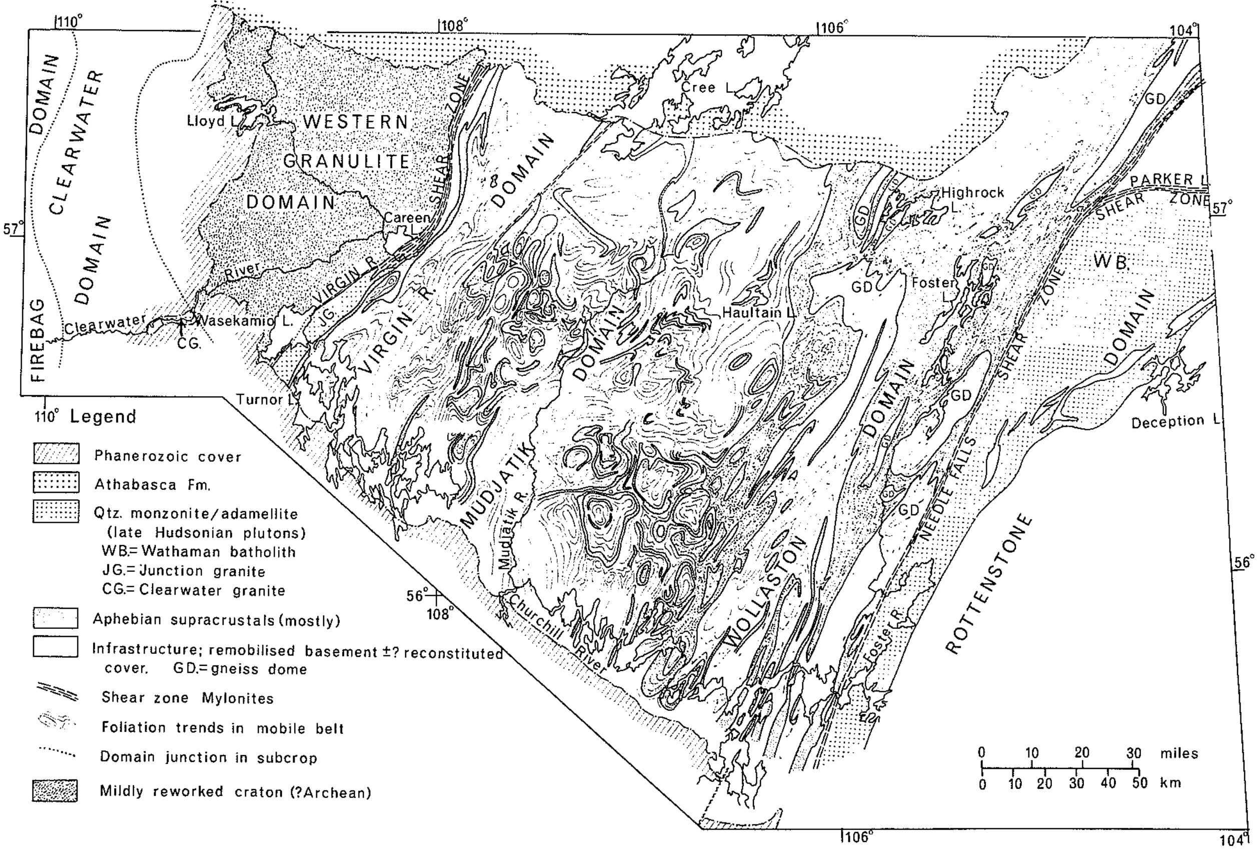

Figure 5. General geology of the southwestern Saskatchewan Shield (after Lewry and Sibbald, 1980).

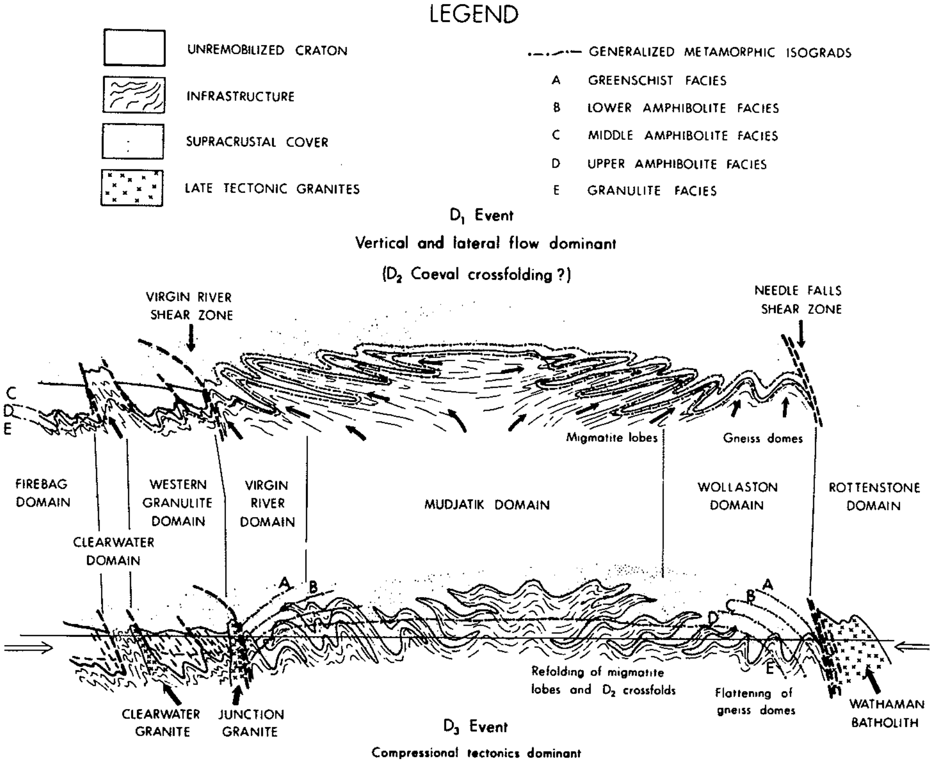

Figure 6. Schematic cross-section showing thermotectonic evolution of the southwestern Saskatchewan Shield and the relationship between different domains (after Lewry and Sibbald, 1980).

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, 3). It comprises a sequence of red beds which are folded on a large scale and faulted, but are unmetamorphosed. The Group outcrops in fault bounded basins. The largest of these, the Martin Lake Basin, contains from 8,000-10,000 m of immature sediments and basic volcanics and is intruded by gabbroic sills and dykes. Within it, the formations identified (Langford, 1981; Mazimhaka and Hendry, 1984, 1989 (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. Within this overall evolutionary sequence several discrete periods of basin reactivation marked by renewed deposition of coarse clastics are apparent. The sequence in general may reflect a reduction in elevation of the source area and/or scarp retreat and thence more distal sedimentation (Mazimhaka and Hendry, 1984).

The volcanics are alkaline basalts and trachybasalts (D.J. Thomas, personal communication) and are only present in the Martin Lake Basin. They have been dated by the K-Ar method at 1630 ± 180 Ma (Wanless et al., 1966), whereas the sills have yielded an age of 1410 ± 100 Ma (Wanless et al., 1965). It appears likely however, that the Martin may be significantly older, predating the earliest generation of epigenetic pitchblende mineralization at 1780 ± 20 Ma (Koeppel, 1968), but post-dating the latest orogenic events. Similar rocks of the Dubwant Group underlying the Thelon Formation in Northwest Territories yield ages around 1800 Ma (Frazer et al., 1970; Wanless and Loveridge, 1972; Lecheminant et al., 1979; 1981).

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°N is indicated by paleomagnetic studies (Evans and Bingham, 1973).

THE ATHABASCA GROUP

Following Hudsonian (sensu stricto) orogenesis and late stage crustal adjustments the crystalline basement was extensively weathered. The paleoweathering profile, or regolith, 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 (Hoeve, 1977; Hoeve and Sibbald, 1978; Macdonald, 1980). A mineralogical zoning, with kaolinite in the upper levels and illite and chlorite in the lower, is common. The regolith also displays a conspicuous colour zonation with the upper part being oxidized and coloured a pervasive red or purple by hematite pigment, whereas the lower part is reduced and predominantly greenish. The transition between these two zones defines a basin-wide redox boundary between oxidized Athabasca Group red bed sandstones and upper regolith and underlying lower regolith and reduced basement rocks. Superimposed alterations marked by the removal of hematite and emplacement of chlorite variably influence the weathering profile and represent post Athabasca Group hydrothermal effects.

Renewed instability, uplifts and subsidence along established Hudsonian NE-SW trending fault zones which separate major crustal units (Fig. 2, 3), led to deposition of a series of largely transgressive deposits whose remains form the Athabasca Group. The preserved portion of the Group covers some 100 000 km^2 and comprises a fining upward clastic succession capped by dolomite at least 2 300 m thick. Fluid inclusion (Pagel, 1975a,b) and clay mineral (Hoeve et al., 1981c) evidence suggests and original thickness of the sedimentary cover of approximately 5 km. A stratigraphy has been established by Ramaekers (1979a, 1980a, 1981, 1990) (Table IV), who recognises four marine transgressive sequences and one regressive fluvial wedge. Hoeve and Quirt (1984), however, interpret the Group as formed by a predominantly fluviatile sequence interspersed by two marine incursions.

Deposition occurred within three northeasterly trending sub-basins (Fig. 2, 7, 8, 9) initially outlined by seismic studies (Hobson and MacCaulay, 1969), whose development was likely controlled by the major ancient 'Hudsonian' faults in

Table III. Formations of the Martin Group (Martin Lake Basin).

Formation	Lithology	Thickness (m)
Melville Lake Fm.	Siltstones, minor interbedded conglomerates and sandstones rare stromatolites	800 (minimum)
Seaplane Base Fm.	Interbedded, well sorted conglomerates, sandstones and siltstones	1300-1800
Gillies Channel Fm.	Basal conglomerate, arkosic sandstones, mafic lava flows and sills	3900
Beaverlodge Fm.	Basal conglomerate/breccia arkosic sandstones and siltstones	1600-3000

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

	Depositional Environment	West		East	Source Area	Maximum Thickness (m)
		Jackfish Basin	Mirror Basin	Cree Basin		
Points Lake Subgroup	Marine	Carswell Fm.				1000?
	Marine	Douglas Fm.				185
William River Subgroup	Marine	Tuma Lake Fm.			NE?	80
			Unconformity			
	Marine	Otherside Fm.	Otherside Fm.			180
	Marine	Locker Lake Fm.	Locker Lake Fm.		S, E, NE	200
			Unconformity			
	Marine	Wolverine Point B	Wolverine Point B		S, E	250
	Marine	Wolverine Point A	Wolverine Point A	Wolverine Point A	S	300
	Marine		Lazenby Lake Fm.		S	120
			Unconformity			
	Nonmarine	Manitou Falls D	Manitou Falls D	Manitou Falls D	E, NE	700
	Nonmarine	Manitou Falls C	Manitou Falls C	Manitou Falls C	E, NE, S?	400
	Nonmarine			Manitou Falls B	E, NE, S (minor)	250
			Unconformity			
	Marine	Fair Point Fm.	Manitou Falls A (Marine in part)		local; S,E ?	400 (FP) 600 (MFA)
			Unconformity			
			Metamorphosed Basement			

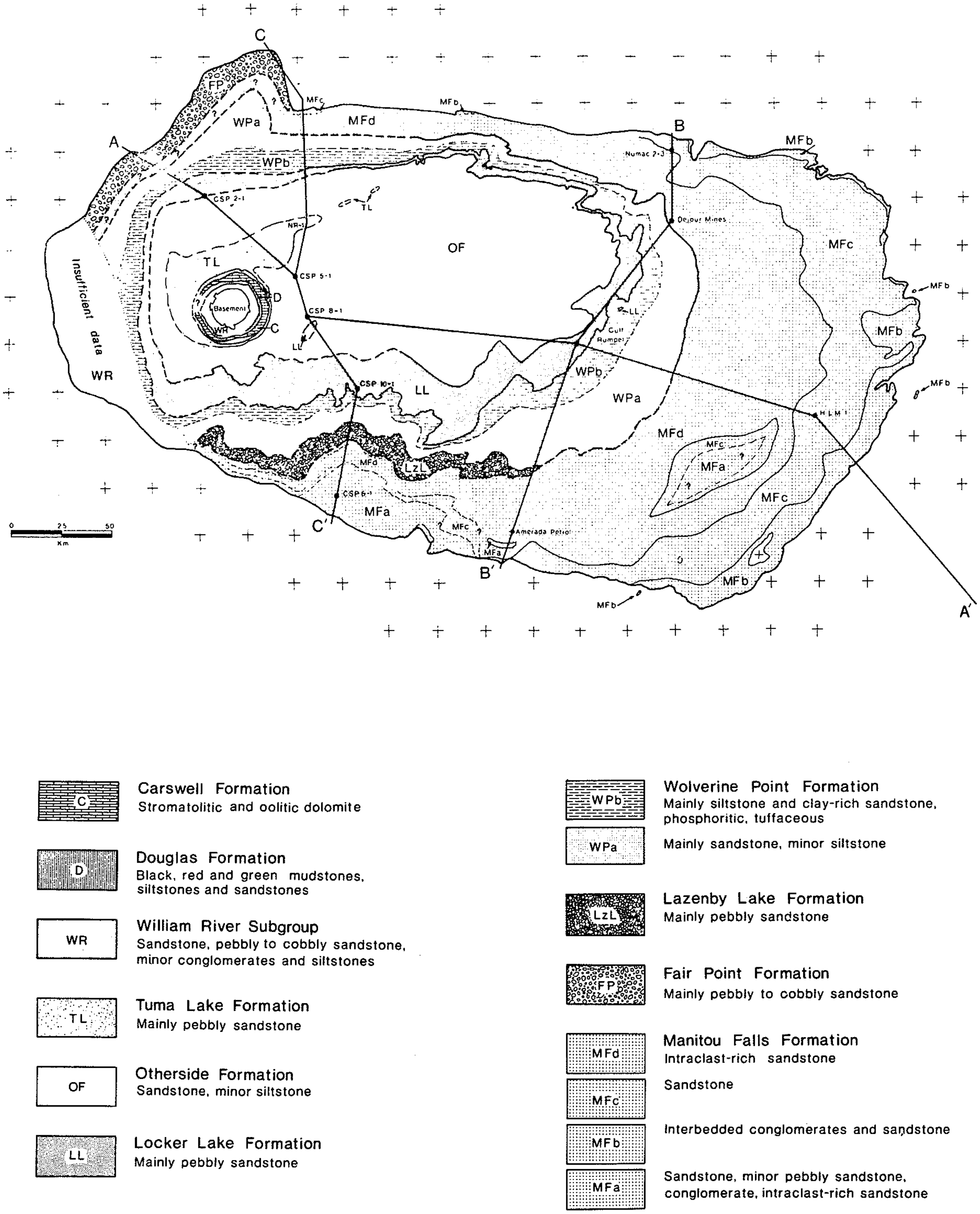

Figure 7. Geological Map of the Athabasca Basin. Locations of cross-sections (Fig. 8) also shown (after Ramaekers, 1981).

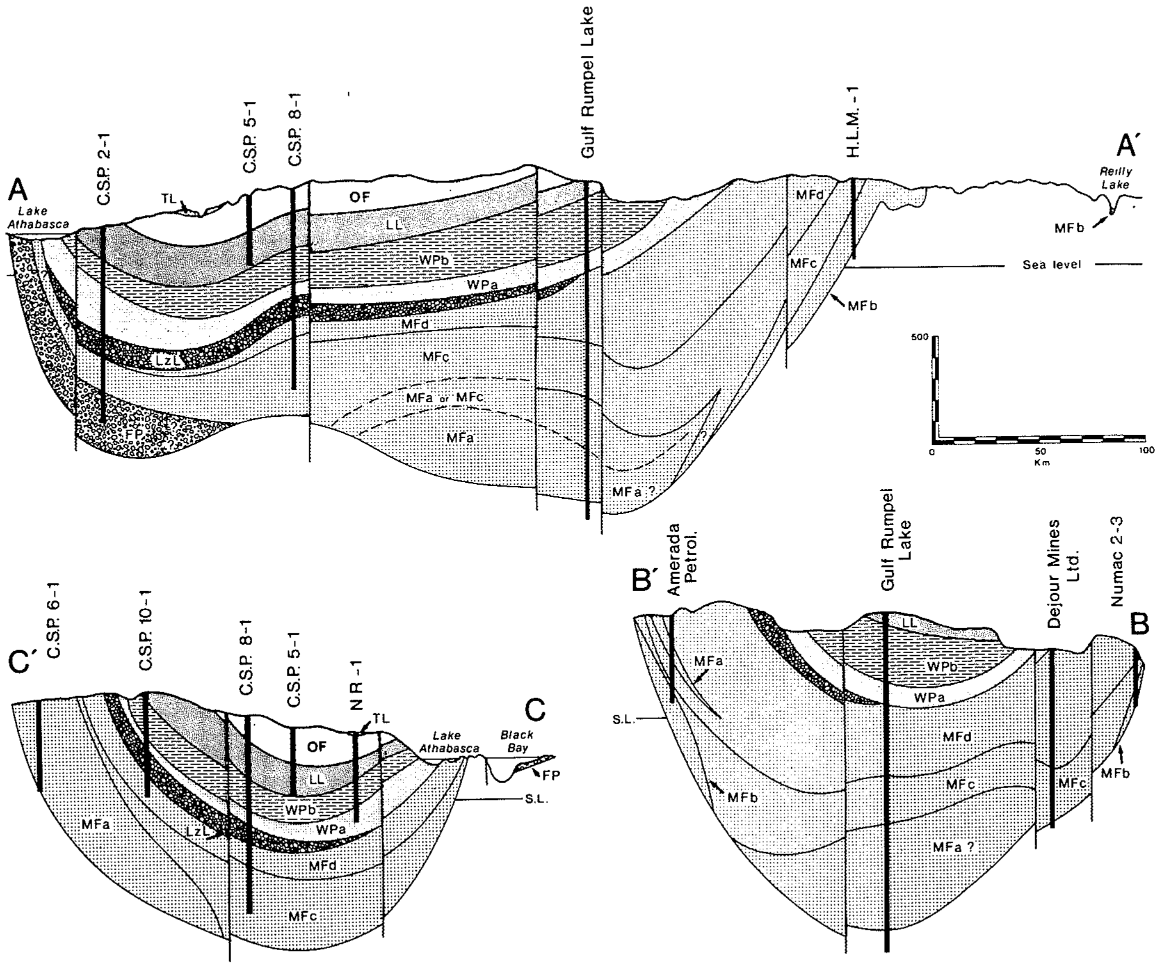

Figure 8. Cross-sections through the Athabasca Basin. Locations of sections and legend shown in Figure 7 (after Ramaekers, 1981).

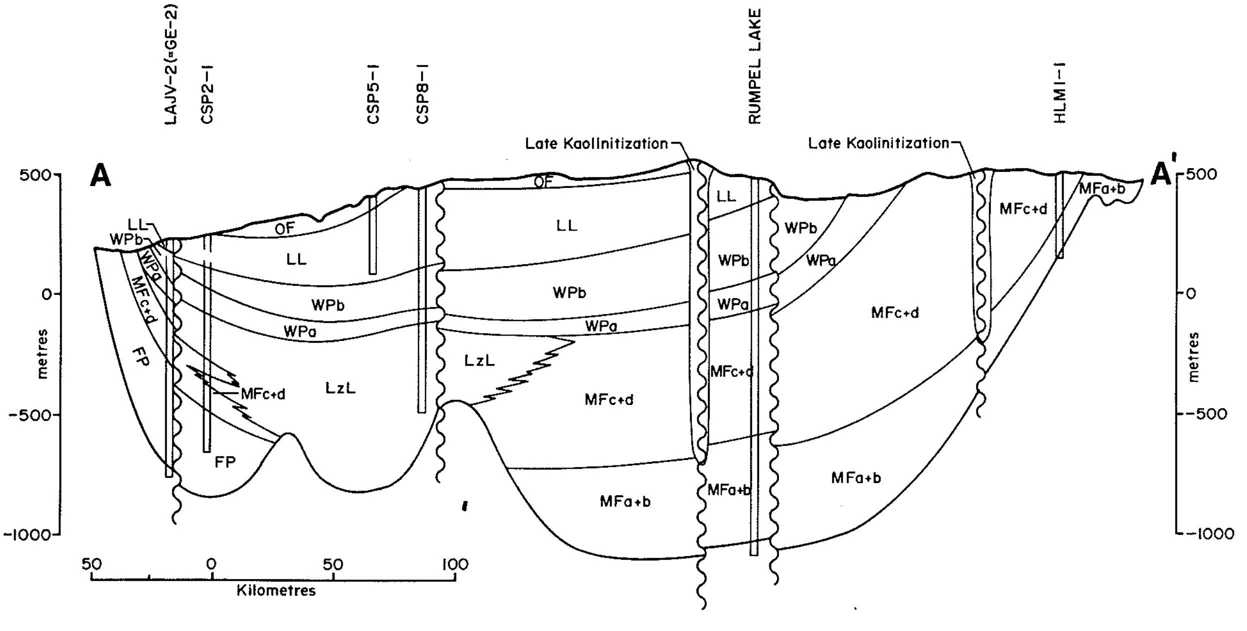

Figure 9. Interpreted clay mineral stratigraphy in section A-A′; late fault-controlled kaolinitization schematically indicated only; Legend as Figure 7 (after Hoeve and Quirt, 1984).

the metamorphic basement. Fluvial or marine cobbly to pebbly sandstones (Fair Point Fm.) were first laid down over debris flow deposits of local derivation in the most westerly lying Jackfish Basin, and fluvial sandstones, pebbly sandstones and conglomerates (Manitou Falls Fm. unit A) in the Mirror Basin. In the eastern half of the Jackfish Basin, Manitou Falls Fm. unit C overlies Fair Point Fm. rocks disconformably. 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 1 000 m thick. In the Mirror Basin, the Lazenby Lake Formation forms a third clastic wedge which is considered to be fluviatile and stratigraphically equivalent to the Fair Point and lower Manitou Falls Formation by Hoeve and Quirt (1984) (Fig. 9), although Ramaekers interpreted it as marine, transgressive and stratigraphically overlying (Fig. 8, Table IV). A marine incursion into the Mirror and Jackfish Basins is marked by pebbly sandstones of the lower Wolverine Point Formation (unit A) sands, silts and muds. The upper part of the Wolverine Point Fm. (unit B), most thickly developed in the Mirror Basin is finer grained and typified by thin phosphorites, and fine grained altered tuffs. The overlying Locker Lake, Otherside and Tuma Lake Formations comprise pebbly sandstones, sandstones and siltstones which are variously considered to be of marine (Ramaekers, 1981) or fluviatile (Wilson, 1985) origin. The Douglas and the Carswell Formations are the uppermost units of the exposed sequence and respectively comprise shallow marine sandstones, siltstones and carbonaceous mudstones, and oolitic and stromatolitic dolomites. These last two formations are preserved only in the Carswell structure which was possibly a result of meteorite impact in the Paleozoic (Bell, 1985).

Four main source areas are suggested to have supplied sediment to the Athabsca 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 occur in the conglomerates.

The tuffaceous unit of the Wolverine Point Formation has been dated at 1430 - 1450 Ma by the Rb-Sr isochron method (Bell and Macdonald, 1982; Armstrong and Ramaekers, 1985). However, fluorapatites from the Fair Point and Wolverine Point Formations have yielded U-Pb ages in the range 1650-1700 Ma (Cumming et al., 1987). The depositional age of the Athabasca Group could therefore be significantly older than previously envisaged, possibly ca. 1700 Ma, an age also suggesed by U-Pb apatite age data from the geologically similar Thelon Basin (Miller et al. 1989).

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 (1961) to argue that the sandstones are supermature multicycle sediments. Others (Hoeve et al., 1980; Ramaekers, 1981) have suggested that the clays and hematite are authigenic and that the sandstones once contained feldspars and mafic minerals which have been diagenetically altered. Rarely preserved relicts of the original detrital assemblage in early cemented zones, alterated mafic dykes and paleomagnetic data from hematized sandstone samples (Fahrig et al., 1978; Ramaekers, 1979b, 1980b) have been argued to favour this contention. Hoeve and Quirt (1984) assert, however, that virtually all clay derives from detrital kaolinite or a halloysitic precursor and that most of the dispersed hematite has been derived from colloidal limonite or other hematite precursors. These precursor materials were carried into the basin from the lateritic provenance area.

MAFIC DYKES

The Athabasca Group is cut by a series of northerly to northwesterly trending mafic dykes and in the eastern-central part of the basin at Moore Lake by a complex set of mafic intrusions. The northerly to northwesterly trend reflects tensional directions associated with left-lateral movements along the ancient 'Hudsonian' faults. Although poorly exposed, the dykes are often well defined as linear magnetic highs. Some dykes however are non-magnetic, or form negative anomalies, indicating that the frequency of dykes is greater than indicated. 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. Trace amounts of zircon and baddelleyite are also commonly present. Adjacent to dykes the sandstone is altered, by bleaching and silicification and locally exhibits columnar jointing (Ramaekers and Hartling, 1979; Ramaekers, 1990). The most reliable ages for emplacement are provided by Rb-Sr mineral isochrons from six individual dykes giving a weighted mean age of 1227 ± 11 Ma (Armstrong et al., 1988). K-Ar ages ranging between 1230 and 938 Ma (Burwash et al. 1962; Knipping, 1974; Wanless et al., 1979; Tremblay, 1978; Worden et al., 1985) have also been obtained.

DIAGENESIS AND BASINAL HISTORY OF THE ATHABASCA GROUP

Diagenesis has strongly affected the Athabasca Group sediments as most of the present day matrix minerals are authigenic or are alterations of detrital precursors. Kaolinite was the main detrital clay mineral carried into the basin as the provenance areas were underlain by a kaolinitic weathering profile similar to that preserved in the floor of the basin. It is preserved in intercalated kaolin-rich clay/silt layers and intraclasts in all formations, excepting the Upper Wolverine Point and the Douglas. The coarse clay fraction of the sandstones and conglomerates also consists largely of kaolinite. In contrast, a coherent clay mineral (illite-kaolinite-chlorite) stratigraphy which closely matches the lithostratigraphy is observed in the fine clay fraction of sandstones and conglomerates (Fig. 9). The illite of the present illite-kaolinite assemblages has been produced by conversion of kaolinite into illite with the proportions of illite and kaolinite in the fine clay fraction being governed by lithologically controlled potassium availability.

Detrital mica and feldspar may have provided a source of potassium during diagenesis as petrographic evidence indicates intensive post-depositional alteration. In general, as a significant proportion of kaolinite is still preserved in the majority of the Athabasca Group rocks, these detrital minerals made only an insignificant contribution towards illite formation owing to an insufficient reservoir of potassium for the conversion to proceed to completion. However, in some formations (Lazenby Lake and Manitou Falls D), the small quantity of clay minerals present has allowed portions of the sandstone to be completely illitized. In all units other than the Upper Wolverine Point and Douglas Formations, virtually all clay has been derived from detrital kaolinite or a halloyositic precursor which has been converted, to a variable degree into illite.

The marine Upper Wolverine Point and Douglas Formations differ from the other formations in that their clay mineral assemblage consists of illite and chlorite, pointing to a different sediment source. The detrital clay mineral assemblage of the Upper Wolverine Point Formation was likely dominated by smectites, mixed-layer minerals, poorly ordered illites and glauconite (Hoeve and Quirt, 1984) while the potassium and magnesium required to convert this assemblage into the present illite-chlorite assemblage may have been derived from detrital feldspar, ferromagnesian minerals and tuffaceous components.

The clay mineral characteristics of the sandstones indicate that the Athabasca Group rocks have been subjected to high-grade diagenesis (op. cit.). The apparent lower degree of diagenesis in the Upper Wolverine Point Formation (op. cit.) in spite of being subjected to the same conditions of deep burial and high-grade diagenesis may be attributed to lithological factors. The illites of this formation, containing up to 15% expandable layers, reflect a different diagenetic evolution as compared to the kaolinite-rich sandstones of the other formations. A low permeability during diagenesis due to abundant clay, silt, phosphate and tuff, may have been an important additional factor.

Two trends that reflect differences in original detrital mineralogy and sedimentary environment can be recognized in the prograde diagenetic history of the clay minerals in the Athabasca Group rocks (op. cit.). A marine trend is expressed in the Upper Wolverine Point and Douglas Formations where a detrital association of smectite, poorly ordered illite and smectite-illite mixed-layer minerals was transformed during burial into a diagenetic illite-chlorite assemblage. The remaining formations express a continental trend where detrital kaolinite was recrystallized during burial and variably converted into illite depending on lithologically controlled potassium availability.

In the development of the hematite pigment in the sandstones, as for the clay minerals, intrastratal oxidation of detrital ferromagnesian minerals has been of little importance. All units but the Manitou Falls Formation are typically red, red-purple or variegated in colour, and even the latter contains numerous, widespread, thick zones of reddish sandstone. Most of the dispersed hematite has been derived from colloidal limonite, or other hematite precursors, which were carried into the basin along with detrital quartz, kaolinite and accessory Fe-Ti oxides (op. cit.) from the lateritic provenance area. These yellow to brown iron hydroxides were converted to hematite upon diagenesis and imparted a red colour to the rocks.

The features discussed above concern mineralogical changes during prograde burial and diagenesis, however, retrograde diagenetic changes have also occurred. These changes are exemplified by late fault-controlled kaolinitization where the regular clay mineral stratigraphy of the sandstones and conglomerates is locally transected. Although a localized feature, this kaolinitization tends to be pervasive, leading to total obliteration of the normal diagenetic clay mineral assemblages. It is accompanied by a decrease in total clay content (from between 5% and 20% to about 1%), and by a loss of coherence, ultimately leading to the formation of an almost clay-free, loose sand. The kaolinitization represents a process of intensive leaching which destroyed most of the interstitial cement and transformed the remainder into kaolinite. On a smaller scale, fracture zones intersected in drill core are frequently flanked by kaolinite halos up to a few metres wide.

Similar late kaolinitization has been reported for other sedimentary basins where it has been interpreted as being related to uplift and unroofing, during which acidic surface waters percolating downwards along reactivated open fault zones, regained access to the deep aquifer (Dunoyer de Segonzac, 1969; 1970; Kish, 1983).

The Athabasca Basin constitutes a tectonically active sedimentary basin whose development is broadly similar to that of other intracratonic basins. Two fundamentally different stages are recognized in the evolution of many sedimentary basins: an early tectonic, rifting phase and an ensuing non-tectonic, thermal relaxation phase, although the history of a basin may be complicated by episodic tectonic reactivation (see Hoeve and Quirt, 1984, for references).

The early tectonic phase is marked by rapid subsidence and high rates of sedimentation and typically lasts for intervals of up to ten million years. The post-tectonic phase is characterized by the development of a broad platform-type basin, as a result of areal flexuring in response to sediment loading and thermal contraction over a prolonged period lasting in the order of 50-100 Ma or more.

Several stages of contrasting structural characteristics can be distinguished in the Athabasca Basin which correspond to the evolutionary stages of other sedimentary basins (Fig. 10). Radiometric evidence (Bell, 1981) suggests that during the interval 1550 to 1500 Ma, immediately preceding the formation of the basin, the region had undergone mild uplift of crustal segments, possibly accompanied by minor magmatic remobilization. The actual basin formation was initiated by an early tectonic phase, characterized by a tensional regime, which generated the Cree, Mirror and Jackfish sub-basins. This is consisent with Walcott's (1968) interpretation of the gravity study suggesting that the basin is underlain by northeasterly trending twin graben structures.

The early stratigraphic development was controlled by the three sub-basins respectively filled in with the lower Manitou Falls, Lazenby Lake and Fair Point Formations. The subsequent advance of the upper Manitou Falls Formation over almost the entire basin led to coalescence of the sub-basins, marking the transition to the ensuing non-tectonic phase. Towards the end of this period the sedimentary cover was approximately 1000 m thick. Burial

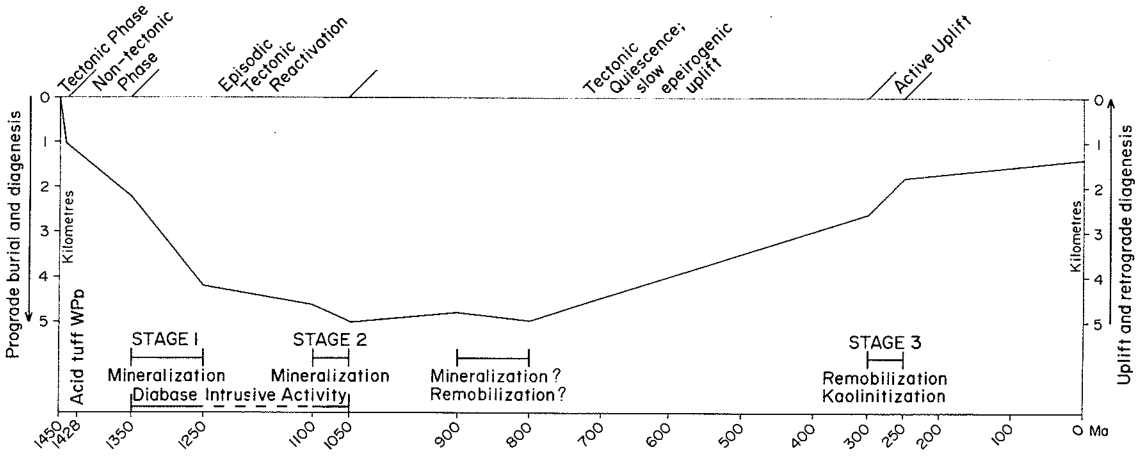

Figure 10. Schematic representation of geological evolution of the Athabasca basin (after Hoeve and Quirt, 1984).

compaction and diagenetic recrystallization may have begun during this phase, although no record is preserved in the clay mineral assemblages. Quartz overgrowths within the sandstones of the Lazenby Lake formation, however, formed during early diagenesis and shallow burial, before significant compaction had taken place.

The subsequent non-tectonic phase is marked by a uniform, basin-wide stratigraphic development reflecting a general downwarp of the area and a considerable broadening of the basin. The influence of the sub-basins is no longer apparent. Grain size analysis revealed that during sedimentation of the Wolverine Point, Locker Lake and Otherside Formations, in contrast to deposition of the Manitou Falls formation, the basin margin was situated well east of its present position (Ramaekers and Dunn, 1977). Depth of burial during this phase is unknown, but is likely to have exceeded the presently preserved stratigrapic thickness.

The non-tectonic phase was abruptly terminated by the intrusion of diabase dikes, starting at approximtely 1350 Ma, which marks the onset of a phase of renewed crustal instability and tectonic reactivation of the basin. Diabase intrusive activity took place over a 350 Ma period between about 1350 and 1000 Ma; however, uniform magmatic activity over such a long time span is unlikely, and the intrusion of the dikes may actually have been episodic in nature, even though currently available radiometric dates do not allow distinct magmatic pulses to be resolved. Some of the dikes are offset by these faults, attesting to post-intrusive tectonic activity.

By analogy with other sedimentary basins, episodes of diabase magmatism may represent periods of active deepening of the basin. The Athabasca Basin reached its deepest level of burial and peak diagenetic conditions during the phase of tectonic reactivation and diabase intrusive activity (Hoeve and Quirt, 1984).

The relatively low degree of diagenetic recrystallization in the upper Wolverine Point Formation as compared to underlying sandstones of the Manitou Falls, Lazenby Lake and Fair Point Formations is interpreted as being indicative of low permeability for this clay-silt-rich unit during diagenesis. This suggests that the upper Wolverine Point Formation may have formed a relatively impermeable seal, promoting the possible development of a geopressured zone in the underlying formations.

Following the termination of the phase of tectonic reactivation, no distinct major events are recognized in the Athabasca Basin until the episode of kaolinitization some 300 to 250 Ma. ago. This episode is interpreted as being a period of retrograde diagenesis related to uplift and erosion of the basin, when surface waters regained access to the deep aquifer. It was approximately during this episode that the Canadian Shield re-emerged above sea level following the Cambrian transgression (cf. palaeogeographic maps in Dott and Batten, 1971).

GEOCHEMISTRY OF THE ATHABASCA GROUP

Although all but the mudstones and carbonates are, at present, orthoquartzites by traditional definitions, the original compositions of these rocks varied. Chemically, the samples of sandy formations vary from arkose/subarkose to quartz arenite in composition (Quirt, 1985; Fig. 11) with the majority of sediments being classified as quartz arenites and sublithic arkoses. The Tuma Lake, Otherside, Locker Lake and Lazenby Lake Formations seem to have been deposited predominantly as quartz arenites as was the upper member of the Manitou Falls Formation (MFd). The balance of the Manitou Falls Formation as well as the lower Wolverine Point Formation were deposited as sublithic arkoses. The remaining formations, being less quartz rich and more clay rich were deposited as subarkoses (lower Fair Point and upper Wolverine Point Formations) and as lithic arenites (upper Fair Point Formation). Petrographic examination supports this interpretation.

In the sediments of the Athabasca Group, the presence of heavy minerals is not common except as hematite cement. Rare detrital grains of tourmaline, hematite and zircon are found, while heavy mineral bands are encountered in varying numbers. The paucity of heavy minerals is reflected in the relatively low values for all elements in the sandstone save silica and alumina (Tables V, VI).

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 Needle Falls 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 Mobile Zone. Yet another type, the most important economically, is seen in the younger Athabasca Basin uranium occurrences which straddle the unconformity at the base of the Athabasca Group.

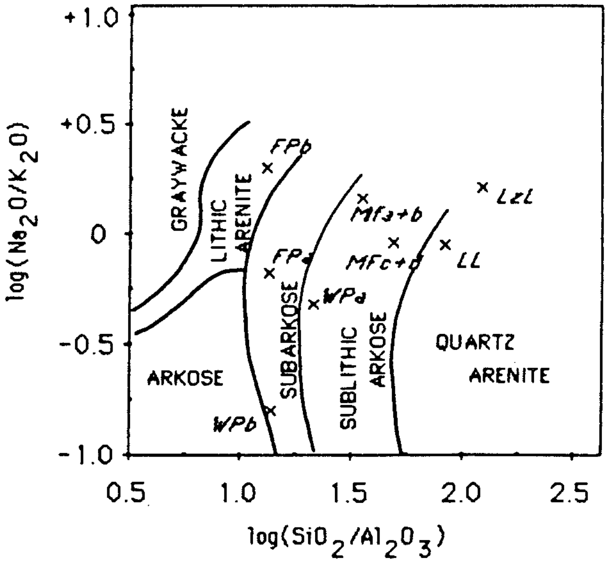

Figure 11. Chemical composition of Athabasca Group sandstones (after Quirt, 1985).

In the Western Craton uranium mineralization appears most strongly in 'linear zones' of Hudsonian (sensu lato) thermotectonic reworking. Following Beck (1969), 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 rarely important in the pegmatites. U-Pb dating in the Beaverlodge area yields an age for the syngenetic deposits of 1930 ± 40 Ma (Koeppel, 1968).

Table V. Athabasca Group, Major Elements (Arithmetic Means)

Table Footnotes: Formation abbreviations as for Figure 7; FPb - Upper Fair Point Fm., FPa - Lower Fair Point Fm.; Fe_20_3 calc = Fe_20_3 total - 1.1113 Fe0; H_20 - by difference from LO1 and $C0_2$; $Si0_2$ - by difference; arithmetic mean ± 95% confidence level (%).

	FORMATION								
Oxide	LL	WPb	WPa	LzL	MF c+d	MF a+b	FPb	FPa	Athabasca
Al_2O_3	1.16 ± 0.28	6.44 ± 1.13	4.43 ± 1.92	0.79 ± 0.11	1.92 ± 0.62	2.66 ± 0.42	6.83 ± 0.86	6.69 ± 0.96	3.65
TiO_2	0.06 ± 0.03	0.11 ± 0.02	0.12 ± 0.06	0.03 ± 0.003	0.09 ± 0.02	0.11 ± 0.03	0.11 ± 0.02	0.16 ± 0.03	0.10
K_2O	0.10 ± 0.02	0.95 ± 0.27	0.23 ± 0.10	0.08 ± 0.01	0.13 ± 0.02	0.09 ± 0.02	0.06 ± 0.01	0.21 ± 0.08	0.26
Na_2O	0.09 ± 0.01	0.15 ± 0.03	0.11 ± 0.02	0.13 ± 0.04	0.12 ± 0.02	0.13 ± 0.02	0.12 ± 0.01	0.14 ± 0.03	0.13
MgO	0.05 ± 0.01	1.27 ± 0.23	0.05 ± 0.03	0.03 ± 0.01	0.03 ± 0.005	0.03 ± 0.01	0.02 ± 0.003	0.05 ± 0.02	0.24
CaO	0.04 ± 0.01	0.22 ± 0.22	0.02 ± 0.02	0.03 ± 0.01	0.03 ± 0.02	0.01 ± 0.002	0.05 ± 0.03	0.08 ± 0.05	0.06
FeO	0.81 ± 0.22	0.42 ± 0.03	0.45 ± 0.04	0.58 ± 0.07	0.54 ± 0.04	0.49 ± 0.03	0.34 ± 0.03	0.35 ± 0.05	0.50
Fe_2O_3 calc	0.27 ± 0.24	0.74 ± 0.17	0.46 ± 0.20	0.63 ± 0.53	0.78 ± 0.33	0.71 ± 0.36	1.37 ± 0.35	1.95 ± 0.52	0.78
P_2O_5	0.03 ± 0.01	0.04 ± 0.02	0.05 ± 0.02	0.03 ± 0.01	0.03 ± 0.01	0.04 ± 0.006	0.07 ± 0.01	0.09 ± 0.04	0.04
CO_2	0.43 ± 0.14	0.35 ± 0.13	0.28 ± 0.04	0.29 ± 0.06	0.30 ± 0.04	0.36 ± 0.04	0.21 ± 0.02	0.27 ± 0.05	0.32
LOI	0.47 ± 0.16	2.22 ± 0.43	1.25 ± 0.63	0.18 ± 0.05	0.59 ± 0.21	0.69 ± 0.14	2.47 ± 0.43	2.30 ± 0.33	1.19
H_2O	0.17 ± 0.12	1.89 ± 0.41	0.98 ± 0.62	0.04 ± 0.03	0.37 ± 0.20	0.49 ± 0.13	2.27 ± 0.42	2.04 ± 0.33	0.93
SiO_2	96.76 ± 0.67	87.30 ± 2.12	92.78 ± 2.78	97.33 ± 0.54	95.59 ± 0.92	94.83 ± 0.70	88.42 ± 1.26	87.83 ± 1.56	92.90
n	50	80	58	48	75	95	35	35	476

Table VI. Athabasca Group, Trace Elements (Arithmetic Means)

Table Footnotes: Formation abbreviations as for Figure 7; FPb - Upper Fair Point Fm., FPa - Lower Fair Point Fm.; Cr-values affected by grinding contamination; arithmetic mean ± 95% confidence level (ppm); Au values in ppb.

	FORMATION								
Element	LL	WPb	WPa	LzL	MF c+d	MF a+b	FPb	FPa	Athabasca
Mn	23.4 ± 4.5	45.7 ± 18.6	25.0 ± 4.7	30.8 ± 5.1	39.3 ± 14.9	32.2 ± 9.0	69.3 ± 17.5	67.3 ± 41.2	39.0
Cu	6.7 ± 1.0	5.1 ± 0.6	5.7 ± 1.1	4.3 ± 0.9	6.3 ± 0.7	10.0 ± 2.8	3.3 ± 0.5	4.5 ± 0.5	6.3
Zn	6.9 ± 2.1	7.3 ± 1.3	5.3 ± 1.7	4.9 ± 1.0	4.7 ± 0.8	13.8 ± 5.5	4.2 ± 0.6	8.2 ± 3.0	7.5
Pb	3.6 ± 0.7	3.2 ± 0.4	4.9 ± 1.0	3.5 ± 0.4	3.6 ± 0.6	3.7 ± 0.8	3.3 ± 0.9	3.5 ± 1.1	3.7
Ni	9.1 ± 0.9	10.2 ± 1.0	9.3 ± 0.7	10.6 ± 1.3	13.5 ± 1.2	9.9 ± 0.7	7.5 ± 0.8	12.1 ± 1.2	10.4
Cr	402.0 ± 29.9	278.2 ± 37.2	372.2 ± 39.6	412.4 ± 33.2	488.2 ± 45.5	404.6 ± 30.7	317.7 ± 21.2	330.2 ± 29.1	381.2
Li	16.9 ± 9.6	51.4 ± 7.6	60.2 ± 20.7	4.1 ± 1.6	25.2 ± 10.8	19.0 ± 4.9	41.4 ± 9.2	62.6 ± 12.7	33.6
Ba	23.5 ± 2.8	55.1 ± 10.1	36.3 ± 7.4	17.3 ± 2.3	16.9 ± 4.4	19.2 ± 4.1	37.8 ± 4.1	37.3 ± 6.3	29.9
Rb	2.4 ± 0.5	28.0 ± 8.0	6.0 ± 3.3	2.0 ± 0.3	3.2 ± 0.7	2.3 ± 0.6	1.9 ± 0.3	6.0 ± 2.1	7.4
Sr	104.9 ± 41.2	83.2 ± 11.5	225.7 ± 94.3	116.5 ± 34.4	172.9 ± 83.5	161.7 ± 27.5	235.5 ± 34.5	293.1 ± 81.9	163.0
V	6.9 ± 1.4	9.8 ± 1.3	7.9 ± 2.0	9.9 ± 7.5	10.9 ± 2.2	9.4 ± 2.2	12.4 ± 3.0	19.6 ± 4.5	10.3
Co	2.4 ± 0.4	2.4 ± 0.3	1.6 ± 0.4	1.8 ± 0.3	1.9 ± 0.4	2.0 ± 0.3	2.1 ± 0.4	2.0 ± 0.5	2.0
As	0.7 ± 0.2	1.1 ± 0.3	1.4 ± 0.3	1.3 ± 0.3	1.2 ± 0.3	1.8 ± 0.3	0.8 ± 0.2	1.1 ± 0.3	1.2
Ag	0.2 ± 0.03	0.2 ± 0.06	0.2 ± 0.06	0.2 ± 0.02	0.2 ± 0.08	0.2 ± 0.04	0.1 ± 0.02	0.2 ± 0.04	0.2
U	0.7 ± 0.2	2.6 ± 0.5	1.3 ± 0.4	0.9 ± 0.3	1.8 ± 0.5	1.1 ± 0.1	1.2 ± 0.2	1.9 ± 0.6	1.5
Mo	7.8 ± 1.1	6.5 ± 0.5	6.4 ± 0.7	5.3 ± 0.3	6.4 ± 0.6	5.4 ± 0.2	6.4 ± 0.7	6.1 ± 0.8	6.2
B	25.4 ± 5.6	160.3 ± 43.5	44.5 ± 16.6	17.3 ± 2.8	21.5 ± 5.6	13.9 ± 1.8	29.4 ± 4.7	38.3 ± 6.2	47.9
Th	3.8 ± 0.6	7.4 ± 1.1	7.5 ± 2.2	4.0 ± 0.4	7.3 ± 1.0	18.2 ± 5.6	14.1 ± 2.5	14.5 ± 4.1	9.8
Y	5.1 ± 1.5	22.2 ± 4.5	11.1 ± 4.6	3.5 ± 0.6	4.3 ± 0.8	3.4 ± 0.6	4.6 ± 0.7	5.9 ± 1.2	8.1
Zr	97.3 ± 52.1	155.9 ± 21.5	201.2 ±103.4	74.0 ± 13.2	200.8 ± 42.8	176.7 ± 32.8	88.4 ± 8.4	122.7 ± 24.4	150.8
Cd	1.4 ± 0.3	1.3 ± 0.2	1.4 ± 0.2	1.7 ± 0.5	1.5 ± 0.2	1.2 ± 0.1	1.2 ± 0.2	1.5 ± 0.3	1.4
Au	4.9 ± 1.4	8.9 ± 1.4	10.8 ± 1.5	5.1 ± 1.3	11.2 ± 0.8	10.1 ± 0.2	10.3 ± 1.3	10.6 ± 0.8	9.2
Be	1.2 ± 0.2	1.5 ± 0.2	1.0 ± 0.1	1.0 ± 0.06	1.0 ± 0.06	1.0 ± 0.09	1.0 ± 0.1	1.0 ± 0.1	1.1
La	14.0 ± 1.6	38.0 ± 3.6	22.9 ± 4.5	12.0 ± 2.3	11.1 ± 2.8	18.2 ± 2.9	22.6 ± 2.9	27.2 ± 9.4	20.9
n	50	80	58	48	75	95	35	35	476

The epigenetic mineralization is represented by fracture controlled, pitchblende vein deposits. These formed 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 (Robinson, 1955; Beck, 1969).

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, thucholite, 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±20 Ma, 1110±50 Ma, 270±20 Ma and 0-100 Ma (Koeppel, 1968).

Hoeve and Sibbald (1978) 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 found in the U-Pb age dates, obtained from deposits of both simple and complex type (Koeppel, 1968), and the recognition of a potential association between the Nicholson ore zones and the sub-Athabasca unconformity (Sibbald, 1982). Alteration and fluid inclusion characteristics are also indicative of unconformity origin 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 suffered earlier mylonitization during Hudsonian (sensu lato) orogenesis. Red hematitic alteration of wall rocks accompanied by albitization and development of chlorite and calcite (Dawson, 1951; Robinson, 1955) is typical adjacent to early pitchblende veins, though variable in intensity.

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. (1976) and Lewry and Sibbald (1979) distinghish 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 concentrations.

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 brittle-plastic 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 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 (Mobile) Zone and the Western Craton. The Cluff Lake, Maurice Bay and Fond-du-Lac 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 Aphebian (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 VII and below and illustrated by cross-sections of Rabbit Lake, Collins Bay B zone and Midwest (Figs. 12, 13, 14, 15). 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 Lake) 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, although not restricted to, the basal and lower parts of the Aphebian (Wollaston Group) supracrustal succession throughout the Cree Lake (Mobile) Zone. At their intersection with the sub-Athabasca Group unconformity these rocks may host or 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 (Hoeve and Sibbald, 1978) to a few tens of percent as at Key Lake (Dahlkamp, 1978). Accordingly these units may 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, (Hoeve and Sibbald, 1978; Dahlkamp, 1978; Jones, 1980) 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. 13, 15) (Hoeve and Sibbald, 1978; Dahlkamp, 1978; Jones, 1980), whereas at Midwest normal faulting is inferred (Fig. 12) (Ayres et al., 1983; Wray et al., 1985). These structures may occur singly, or in imbricate zones (Jones, 1980; Stoeterau, 1981) 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 the Collins Bay A and B zones (Jones 1980; Sibbald, 1983). In several deposits (McClean and Dawn Lake), there is no obvious displacement of the unconformity, although the basement below mineralization appears structurally disturbed (Wallis et al., 1983; Clarke and Fogwill, 1985).

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 (Wallis et al., 1983). Evidence for a pre-depositional origin is provided by the observation that basal conglomerate layers at Midwest, Dawn and Cigar Lakes wedge out against the ridges (Fig. 12) (Clarke and Fogwill, 1985; Bruneton, 1987). 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 (Combe, 1932).

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. 13) (Hoeve and Sibbald, 1978; Hoeve, 1978; Sibbald, 1978).

The Athabasca Group, when it

Table VII. 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, <u>but</u> 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 (@ 1400 Ma) postdates deposition of the Athabasca Group (@ 1450-1700 Ma)

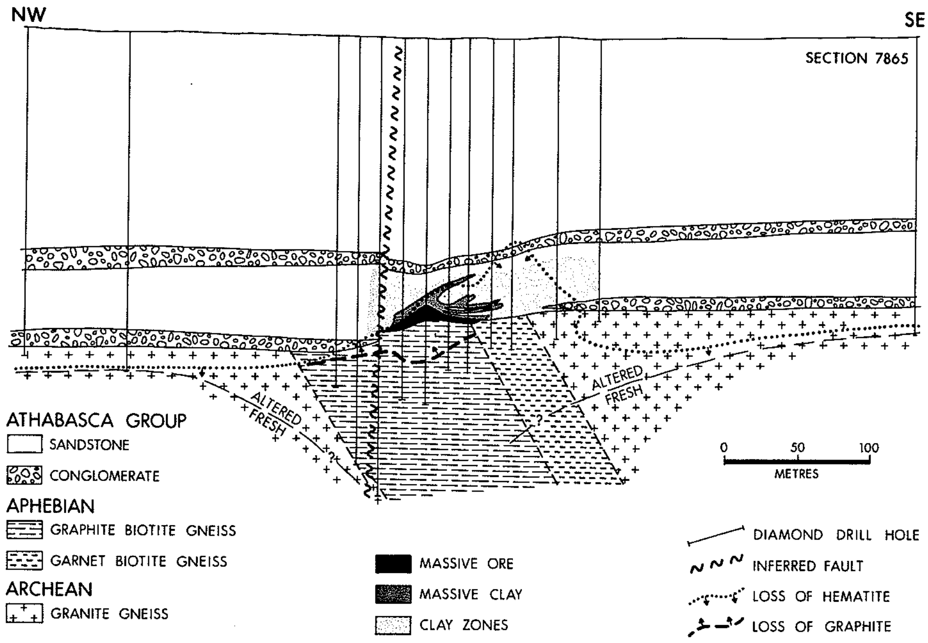

Figure 12. Geological cross-section of the Midwest deposit illustrating bleaching (loss of hematite) of the Athabasca Group and weathered basement and loss of graphite from the graphite biotite gneiss underlying the deposit (after Sibbald, 1985, 1988).

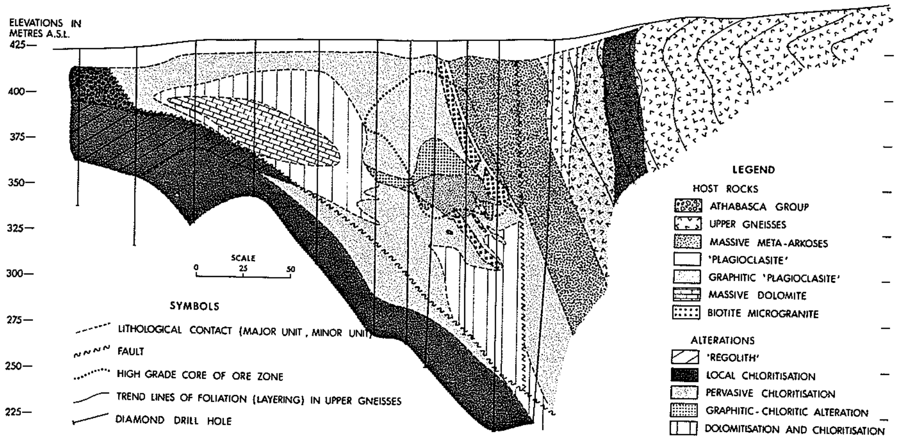

Figure 13. Geological cross-section of the Rabbit Lake deposit illustrating primary and alteration lithologies (after Sibbald, 1978).

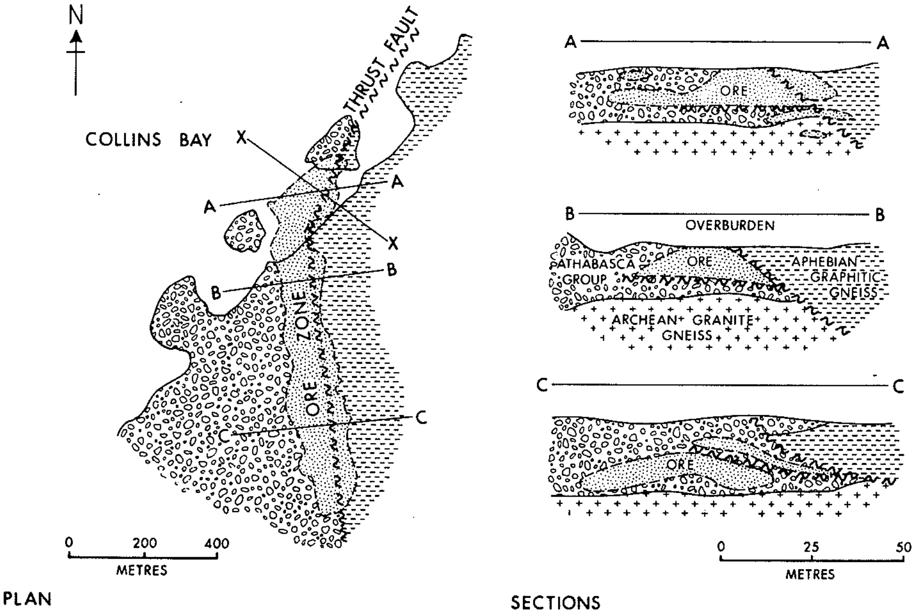

Figure 14. Schematic plan and cross-section of the Collins Bay B zone. Location of cross-section (Fig. 10) denoted XX (after Jones, 1980).

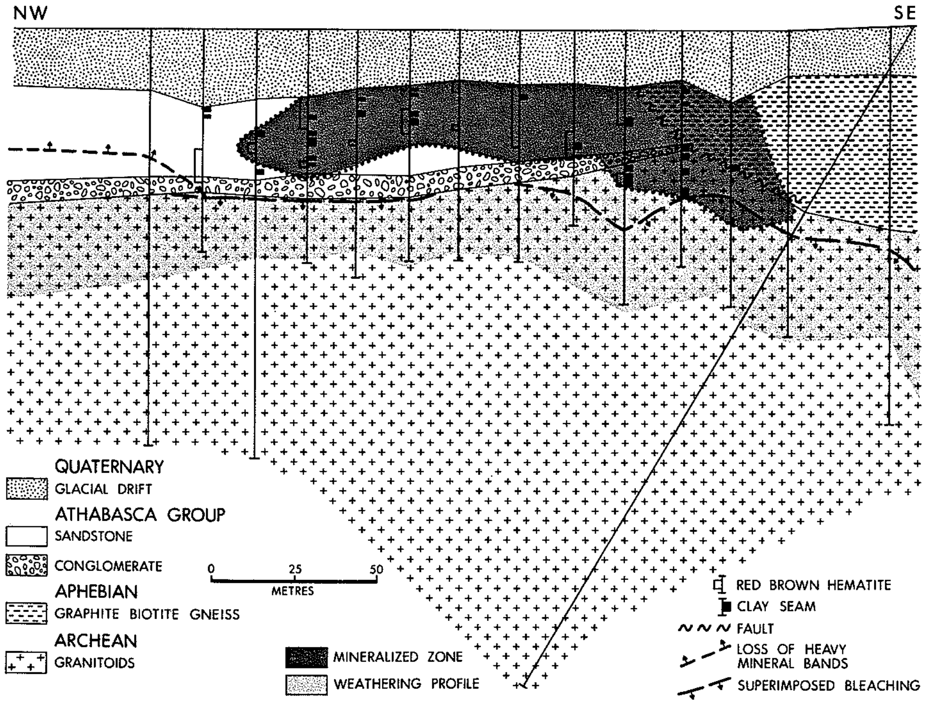

Figure 15. Geological cross-section of the Collins Bay B zone illustrating, red brown hematite and clay development, bleaching (loss of hematite) and destruction of heavy mineral banding in proximity to the mineralized zone (after Sibbald, 1981).

overlies or contains uranium mineralization invariably shows evidence of quartz grain corrosion. Sandstones become friable, clay enriched and transected by clay filled fractures (Wallis et al., 1983; Jones, 1981; Sibbald, 1981). On top of high grade pods, as at Midwest and Cigar Lake, massive clay caps are developed (Fig. 12). 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 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. 12). Similar relationships are observed above high grade pods at Dawn and McClean (Wallis et al., 1983; Clarke and Fogwill, 1985). 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 (Wallis et al., 1983).

The unconformity-type deposits are often of extremely high grade and characterized by a complex 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. Basement hosted mineralization in particular often also comprises significant secondary uranium minerals (Rabbit Lake, Eagle Point, Raven-Horseshoe). Gangue minerals comprise quartz, calcite, dolomite, ankerite, siderite, chlorite, sericite and adularia. A complex paragenesis is observed; typically early formed pitchblende is superseded by arsenides, sulpharsenides and sulphides, sometimes accompanied by pitchblende and/or coffinite. Superimposed on these 'early' mineralizations are later reworking events (Robinson, 1955; Hoeve and Sibbald, 1978; Bruneton, 1987; Ruhrmann and Von Pechmann, 1989). 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, Eagle Point, Raven-Horseshoe 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 contained significant selenium and gold (Amok, 1974). Midwest and Key, McClean, 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 (Dahlkamp, 1978; Jones, 1980; Wray et al., 1985; Wallis et al., 1983; Clarke and Fogwill, 1985). 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 (Dahlkamp, 1978). 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 (Jones, 1981). However, it is at McClean that mineralogical and geochemical variations are most clearly documented (Wallis et al., 1983; Golightly et al., 1983) 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 (Hoeve and Sibbald, 1978). The association of hydrocarbons with mineralized and altered rocks suggests a reducing agent capable of being precipitated as hydrocarbon in the ore forming process. In this respect, Pagel (1977) has reported carbon dioxide, methane and ethane as present in gangue quartz from Rabbit Lake. Other workers have argued against methane as a reductant on the basis of carbon isotope data obtained from basement graphite and from carbonaceous material (bitumen) associated with uranium mineralization (Kyser et al., 1989). Reduced iron in a basement derived fluid is emphasized as an alternative reductant.

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, kaolinitization, 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 ± siderite ± pyrite ± 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. 13) (Hoeve and Sibbald, 1978). 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 (Hoeve et al., 1981a). 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. 14) (Jones, 1981; Sibbald, 1981). Similarly, at Midwest, Sopuck et al. (1983), Hoeve (1984), Earle and Sopuck (1989) 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. 12). 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 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 the potential drilling target by a factor of 10 to 20 times (Hoeve, 1984).

At Key Lake kaolinitization of the Athabasca Group sandstones occurs for several hundred metres on either side of mineralization. An accompanying but less extensive zone of tourmalinization is present in the sandstones and also in the basement. The Key Lake kaolinite anomaly lies within a regional northwesterly trending zone of illite enrichment within the Athabasca Group which also encompasses the McArthur River uranium prospects (Earle & Sopuck, 1989). Stable and radiogenic isotopic studies of clay and associated minerals suggest that the kaolinite alteration, which is superimposed on the illitization, reflects an influx of meteoric water along faults and fractures during uplift of the basin beginning approximately 800 Ma ago (Kotzer and Kyser, 1990).

Within the alteration zones, whose character is shaped by the introduction/ removal of K, Mg, Fe and SiO_2, 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 Cigar and McClean Lakes 'chimneys' of uranium values of > 10 and 2-3 ppm U respectively occur in the Athabasca Group (background 1 ppm U) to the present erosion surface at 400-450 m and 150 m above mineralization, as does illitization (Wallis et al., 1983; Earle and Sopuck, 1989). At Midwest, uranium and boron and at Key Lake uranium, boron and lead are enhanced around mineralization, but not as widely as the major element alterations (Sopuck et al., 1983).

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 1.2 and 1.4 Ga (Wendt et al., 1978; Hoehndorf et al., 1985; Trocki et al., 1984; Carl et al., 1988; Ruhrmann and von Pechmann, 1989 (Key Lake); Cumming and Rimsaite, 1979; Hoeve et al., 1985 (Rabbit Lake); Worden et al., 1985; Baadsgaard et al., 1984 (Midwest); Fryer and Taylor, 1984 (Collins Bay B zone); Eldorado Resources Ltd., 1989; Andrade, 1989 (Eagle Point); Ruzicka and Lecheminant, 1986 (Cigar Lake)).

This age is recorded in illites from alteration zones adjacent to mineralization, using Ar-Ar (Wallis et al., 1983); Rb-Sr (Worden et al., 1985) and K-Ar (Stevens et al., 1982; Clauer et al., 1985; Wilson et al., 1987) dating methods. Kotzer and Kyser (1990) report a Rb-Sr isochron age of 1477 ± 57 Ma from illites from various locations within the Athabasca Basin. The age, which is somewhat older than that for initial uranium mineralization, is suggested to indicate the onset of hydrothermal activity which ultimately led to uranium deposit formation where interaction with basinal and basement fluids occurred.

Pitchblende and coffinite age data also indicate younger events equated with initial mineralization in some deposits and remobilization of pitchblende in others (Cumming and Rimsaite, 1979; Hoeve et al., 1985; Little, 1974) (Rabbit Lake); (Worden et al., 1985; Baadsgaard et al., 1984 (Midwest Lake); Gancartz, 1979; Bell, 1985 (Cluff Lake); Trocki, 1984; Hoehndorf et al.; 1985 (Key Lake). These data vary from one deposit to the next, so that definition of discrete basin-wide reworking events has not been possible. Additionally, the extent to which 'local' events as opposed to 'regional' events influence deposition and reworking is an unknown factor in interpretation of the data, as is the extent to which isotopic inhomogeneity is manifested in the ore samples and thereby influences the resultant ages.

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. (1980):

a) near surface supergene
b) magmatic hydrothermal
c) diagenetic hydrothermal
d) multicycle/process

Over time the diagenetic-hydrothermal model (Hoeve and Sibbald, 1978; Hoeve and Quirt, 1984, 1987) has found increasing acceptance among geologists as well as support from deposit studies. It has also been presented under a different name as the Reductant Plume Model (Wallis et al., 1983).

The model (Figs. 16, 17, 18) invokes the interaction of the crystalline basement and the Athabasca Group through the mixing of fluids of contrasting chemistry. Since the basin floor consists of high-grade metamorphic rocks with low fracture controlled porosity and permeability, all such interaction must have been restricted to fractures within the basement or to the immediate vicinity of the unconformity within highly permeable and porous Athabasca Group clastics and regolith. Oxidizing brines of the Athabasca Group aquifer entered the basement along fractures, reacted with the wall rocks and re-emerged with reduced character, containing hydrocarbons and carbon dioxide. 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. 14, 15).

Conditions of deposit formation suggesed by fluid inclusion studies (Pagel, 1975b; Pagel and Jaffrezic, 1977; Pagel et al., 1980) are: T 150-225°C, P 0.7-1.5 kb salinity ca. 30 percent NaCl, implying an elevated geothermal gradient in excess of 30°C/km. The reducing fluids emanating from the basement were probably charged with CO_2, CH_4, H_2S, 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 (Hoeve and Quirt, 1987).

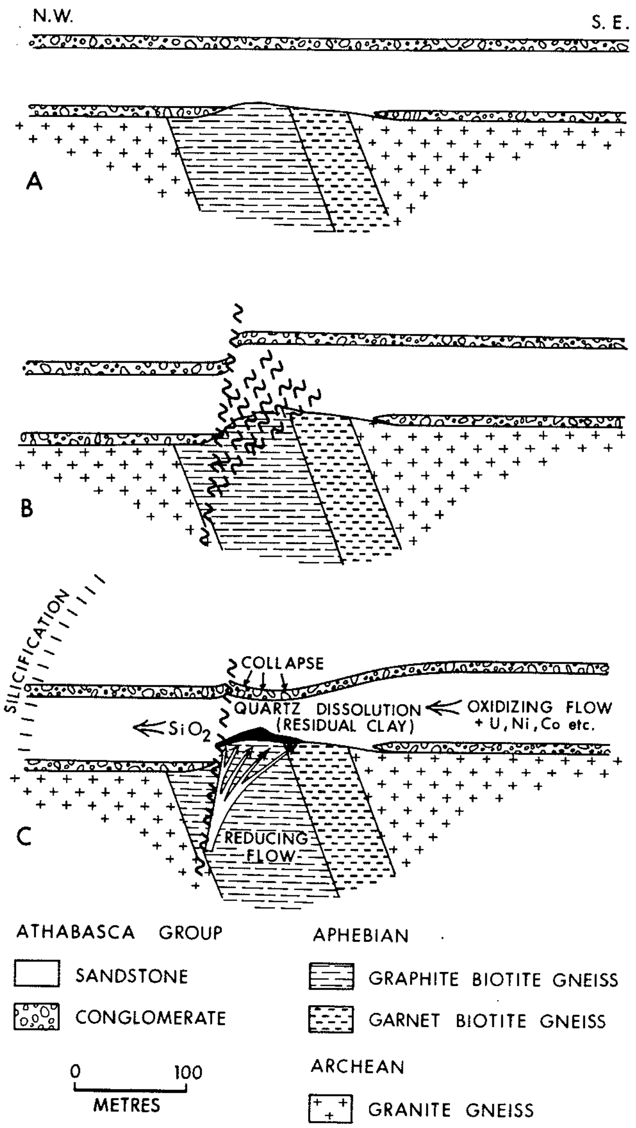

Figure 16. Model for evolution of the Midwest uranium deposit. A - non-deposition of basal conglomerate over pelitic basement ridge; B - faulting of basement pelite and Athabasca Group; C - interaction at fault of reduced basement fluids and Athabasca Group aquifer; quartz solutioning at basement outflow causes residual clay enrichment, collapse and by implication redeposition of silica (silicification) in the adjacent sandstones (after Sibbald, 1985, 1988).

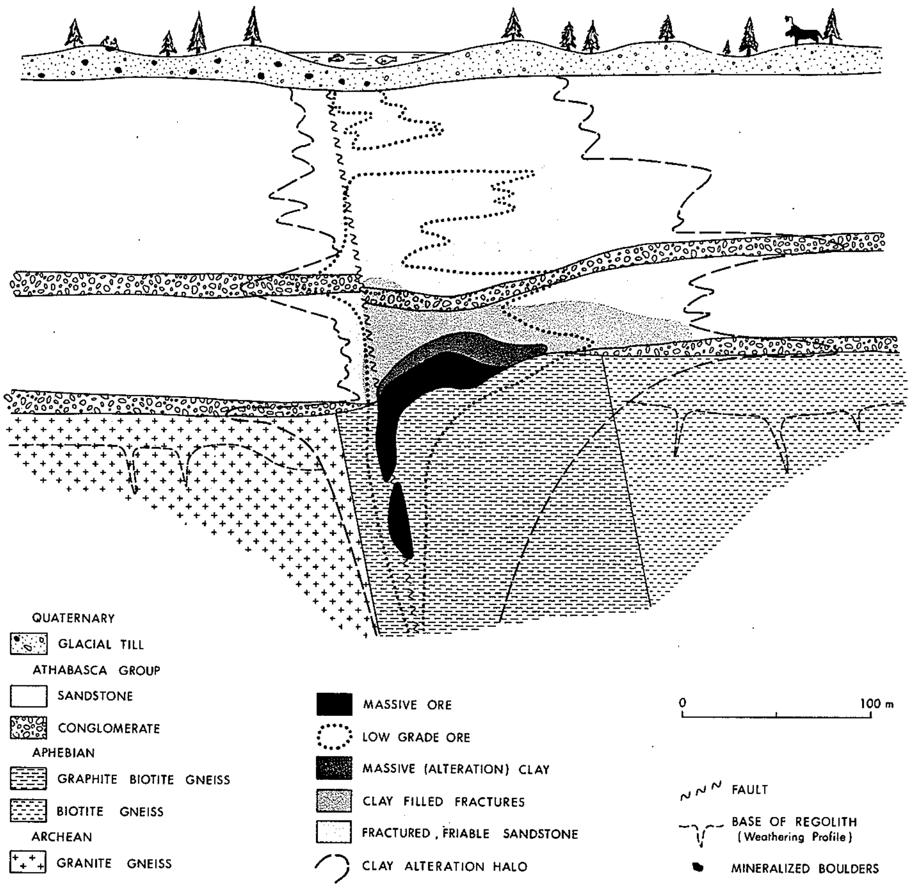

Figure 17. Idealized "model" Athabasca Basin unconformity-type uranium deposit (after Sibbald, 1985, 1988).

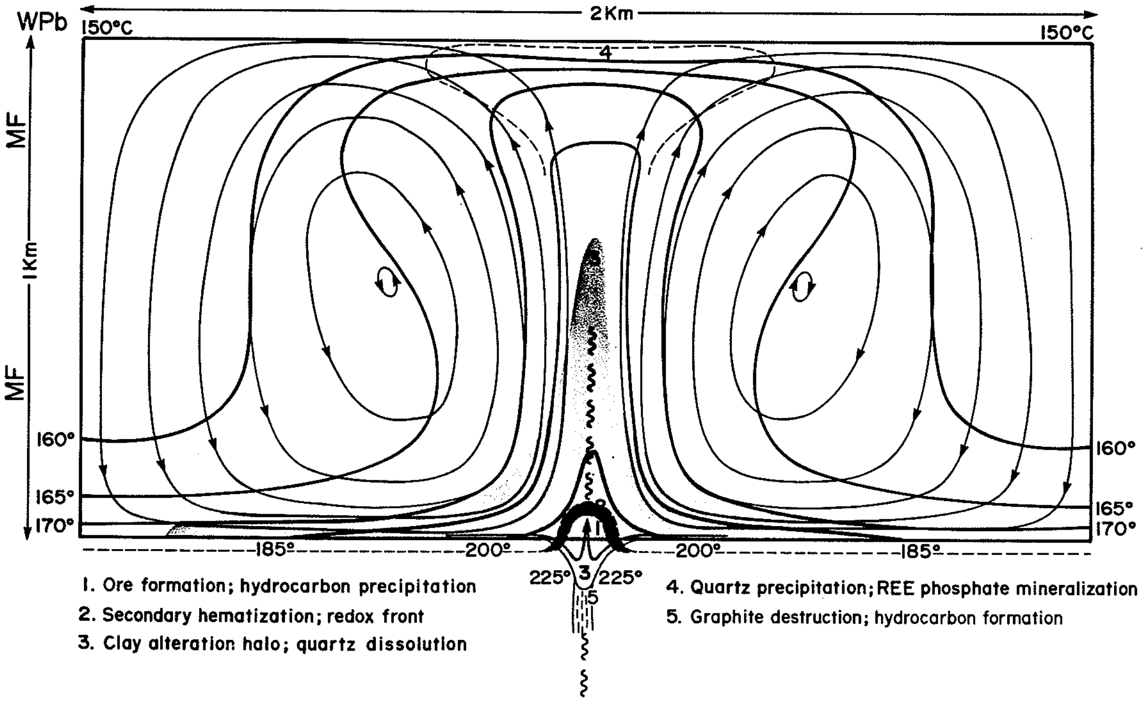

Figure 18. Schematic representation of diagenetic - hydrothermal connective system as inferred from formation of unconformity-type uranium deposits in the Athabasca Basin; configuration of isotherms and flow lines adopted from Parmentier and Spooner (1978) (after Hoeve and Quirt, 1984).

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 (Tilsley, 1980; Hoeve and Quirt, 1984).

Stable isotope data are argued to be incompatible with the single recirculating basinal fluid hypothesis. Rather, the existence of unrelated basinal and basement fluids with distinct isotopic signatures is advocated. In terms of influencing a mineral exploration model this distinction appears to have little significance, as the stable isotope data also clearly indicate that an oxidized basinal fluid accessed fractures in the basement and a reduced basinal fluid emerged from the basement into the Athabasca Group sandstone aquifer. Argument about whether the basinal fluid reacted with the basement and was recirculated, or displaced an existing basement fluid from another part of a basement fracture, is largely an exercise of semantics.

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 release of metals, and thence opportunity for basement interaction, the Athabasca Group must have been or become thoroughly oxidized. The lack of base metals in the unconformity ores is likely a reflection of the mineralogical maturity of the basin fill (Hoeve and Quirt, 1984). These conditions would be achieved most easily in basins containing clean and poorly stratified quartz sandstones, free of reducing plant-derived detritus (pre-Devonian) and subjected to diagenesis for a long time period (Robertson, et al., 1978). The flushed sandstone basins would be depleted in trace metals, as is 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 cycle through fractures in the basement to provide, through reaction with the wall rocks, a reduced fluid, and/or cause displacement of an existing reduced basement 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, Collins Bay B zone), possibly 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 fluid flow occurs across the basement interface. 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. It has been inferred (Hoeve and Quirt, 1984) (Fig. 18) that free convection within the sandstone may have been driven by increased regional heat flow associated with the diabase magmatic activity. The operation of convective flow in the Athabasca aquifer is a necessary component of the model in order to transport dispersed ore constituents to the site of mineralization. The initiation of convection and configuration of convection cells was likely strongly influenced by the presence of graphite in basement rock giving rise to 'hot spots' on the basin floor. Evidence for such 'hot spots' is provided by the quartz dissolution haloes which suggest that reduced fluids discharging from the basement were undersaturated with respect to quartz and probably warmer than the ambient temperature of the basal sandstone. Once initiated the cycle continued until local porosity became plugged, probably in response to residual clay build up. This condition would also aid deposit preservation. Episodic diabase magmatism, in response to tectonic reactivation and active deepening of the basin, gave rise to temporal variations in regional heat flow which may account for the extended duration of each of the main stages of hydrothermal activity.

6) The model entertains a single cycle of concentration and emphasizes process rather than source. Spectacular grades result from a stationary redox condition (Hoeve and Quirt, 1987), in contrast to sandstone hosted roll-front deposits which concentrate through migration. Overall, an unusually enriched source basement is neither advocated nor indicated by regional radiometric surveys (Darnley, 1981) and lithogeochemical studies (Dunning and Parslow, 1979; Parslow and Adamson, 1982), although locally some supracrustals and intrusive granites 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 (Ramaekers, 1980a; Hoeve et al., 1980; Hoeve and Quirt, 1984). The latter mechanism is preferred although this matter is still a contentious issue.

7) Host rock alteration features such as clay alteration, bleaching and quartz dissolution are diagnostic of the mineralization process and also constitute halos that extend well beyond the limits of the actual ore bodies. Host rock alteration is present along the full strike length of ore-bearing fault zones, though of varying intensity and extent, and major ore accumulations are associated with distinct alteration pipes that rise several hundred metres above the unconformity up to the level of the present bedrock surface. These are significant in that they allow host rock alteration to be applied in drill hole evaluation and thereby enlarge potential drill targets by a factor of 10-20. Information on the configuration of bleaching haloes can be obtained from systematic core logging; diagenetic clay mineral alteration is readily identified by means of automated quantitative XRD techniques, whereas quartz dissolution and residual clay enrichment can be quantified by simple gravimetric analysis of total clay content. Additional criteria for the recognition of diagnostic clay mineral alteration are provided by the illite (002)/(001) peak intensity ratio and by illite polytype. Alteration illites have a higher I(002)/I(001) ratio than diagenetic illites in the adjoining unaltered sandstones and, in addition, are characterized by the 3T and 2M polytypes as opposed to 2M and 1M polytypes in unaltered sandstones.

SELECTED DEPOSIT DESCRIPTIONS

CLUFF LAKE DEPOSITS (AMOK (CANADA) LTD., CAMECO)

The Cluff Lake deposits occur at or near the southern edge of an uplifted basement core within the western part of the Athabasca Basin, 60 km south of Lake Athabasca; 30 km east of the Alberta-Saskatchewan border. Uranium mineralization was first discovered in 1968 as a result of follow-up work to an airborne radiometric survey which had revealed several weak anomalies in the area. To date, several significant zones of mineralization, the D, N, OP, Dominique-Peter, Dominique-Janine, South Dominique-Janine and Claude zones, and numerous mineralized showings have been found. The zones outcrop or subcrop below glacial drift and give rise to geochemical dispersion haloes in the drift, which are detectable by ground and, in some cases, airborne prospecting.

The Cluff Lake deposits are estimated to comprise in excess of 20 million kg U, the grade of the ore varying substantially in different deposits. The Athabasca Group-hosted D zone for example had an average grade of 3.41 percent U, whereas the basement hosted zones grade around 0.5 percent U. Mining of the deposits has been in two phases commencing with the high grade D zone and continuing with the lower grade zones. At present, production is from the Dominique-Janine open pit and from the Dominique-Peter underground mine. Phase I open pit mining and milling of the D deposit began in May 1980 and continued to 1983. Uranium bearing gravimetric tails from this phase were processed between May 1983 and August 1984. Also in 1983 Phase II operations were initiated with the mining of the Claude deposit by open pit and of the OP deposit underground. Depletion of the OP orebody was followed by development of the Dominique-Peter orebody, also underground, and in 1989 of the Claude orebody by development of the Dominique-Janine (north) open pit. Gold residually concentrated in the leach tailings derived from Phase I processing of D zone ore gravimetric concentrate was extracted in 1987-88. Production was around 7 800 troy ounces.

The basement core forms one element of the Carswell circular structure, lithostructurally located within the Western Craton and considered by many to be of meteorite impact origin. It is surrounded by successive, 4 to 5 km wide, rings of deformed and fragmented Athabasca Group clastic sediments and Carswell Formation stromatolitic dolomite.

The basement rocks comprise granitoid and quartzofeldspathic gneisses (Earl River complex) and pelitic metasedimentary gneisses (Peter River gneiss) with minor iron formation and mafic and ultramafic rocks. The metasediments are typically invaded by sheets of pink leucocratic garnetiferous granite/granite pegmatite. Basement rocks give Rb-Sr whole rock and U-Pb zircon ages ranging from 2320 Ma to 1750 Ma. No Archean ages have yet been detected.

The Athabasca Group clastics immediately overlying the basement are generally conglomeratic, although fine to coarse sandstones and thin shale layers are interbedded locally, as are debris flows. As in other areas of the Athabasca Basin, the upper 30 to 40 m of basement is altered by paleoweathering and strongly hematized in the upper part of the alteration profile.

Uranium has been found in both basement gneisses and Athabasca Group cover rocks along the southern perimeter of the basement core. There are thought to be four mineralizing episodes in the area, which yield ages respectively at 1300 Ma, 1100 Ma, 850 Ma and 380 Ma similar to those obtained from deposits elsewhere in the Athabasca Basin

The D zone deposit which has been depleted, was located in an overthrust block at the inverted sub-Athabasca Group unconformity which dips moderately northwards. Graphitic Peter River gneisses overlie interbedded siltstones, conglomerates and sandstones. A high altered mylonite zone cuts the gneisses and extends into the Athabasca Group giving rise to a "zone a boules", within which rotated lenticular blocks of sandstone are enveloped by chloritic fault gouge. Massive ore occurred in the "zone a boules". Cross-faults intersecting the unconformity are mineralized in the basement rocks. The orebody is ellipsoidal, about 140 m long, up to 25 m wide and 7 m thick, with mineralization forming discontinuous lenses. It is surrounded by a bleached zone, both in the basement and Athabasca Group, from which hematite has been removed.

Pitchblende, uraninite and coffinite have been reported as uranium ore minerals. They were associated with native gold and gold tellurides, native selenium and selenides (predominantly clausthalite), bismuth, nickel and cobalt arsenides, jordisite, pyrite, and chalcopyrite. Hydrocarbon buttons and other carbonaceous material also occurred in the ore. Ore emplacement was accompanied by pervasive hydrothermal alteration, affecting both basement and cover rocks. The orebody was mined by open-pit in 1980 and 1981 yielding 4,370 tonnes U in ores grading 3.41% U.

The N zone is hosted by strongly altered quartzofeldspathic (Earl River) and cordierite-garnet-sillimanite and sometimes graphite-bearing pelitic metasedimentary (Peter River) gneisses, which are invaded by pink garnetiferous granite/granite pegmatite. Paleoweathered gneiss has been recognized illustrating the proximity of the sub-Athabasca unconformity. Mineralization is localized within shear and fracture zones trending northerly and northeasterly (N40°E) and dipping moderately to steeply westwards. Alteration, distinguished by hematization and chloritization/ argillization, is intimately associated with the mineralization, which is typically developed at the redox interface marked by hematized and pale green, bleached rock.

The mineralization comprises pitchblende and coffinite, with minor amounts of jordisite, galena, pyrite, marcasite, chalcopyrite, clausthalite, covellite and hydrocarbon buttons. Some 505,000t of ore grading 0.34% U are present in the zone.

The Claude deposit which has been depleted, occurred within Peter River gneisses, which are in part graphitic in character and interlayered with granitoids. For the most part, mineralization was localized within an easterly trending subvertical shear zone containing rotated fault blocks ("zone a boules"), although northeasterly trending faults were also mineralized. The deposit was around 600 m long, 200 m wide and had a maximum depth of 90 m. Mineralization and alteration characteristics were similar to those observed in the N zone. A decline was put down in 1979 and an experimental pit was opened in 1982. Mining by open pit took place between 1983 and 1989. Calculated tonnage for this orebody is given as 2097 times U in ores grading 0.36% U.

The OP deposit comprises fracture controlled mineralization in two settings. The O mineralization occurs at the intersection of two thrust faults which superimpose fresh Peter River gneisses over Athabasca Group and Athabasca regolith over other basement gneisses. The faults dip gently to the north and north-northwest respectively. Further east mineralization is present discontinuously in subvertical northerly trending fractures with vein quartz, which cut Peter River gneisses. It comprises uraninite with chalcopyrite, galena, clausthalite, and pyrite, all deposited on quartz crystals. Coffinite and Mg chlorite have been observed with mineralization and alteration zones around the veins are very narrow. The deposit was explored by decline in 1980 and 1981 and mined underground between 1983 and 1985. Some high-cost resources remain in the deposit.

The Dominique-Peter orebody was contained entirely within the basement in proximity to a mylonite zone marking the contact of the Peter River and Earl River gneisses. These gneisses are cut by three sets of faults, all of which displace the mylonite zone. Mineralization occurs as fracture fillings, veinlets and disseminations usually within tens of metres of the mylonite zone, mainly in the northerly and east- northeasterly faults cutting Peter River gneisses and mylonite. Two mineralization assemblages have been observed: a uraninite-polymetallic sulphide assemblage and a uraninite-dravite-simple sulphide assemblage. As of December 31, 1984 the Dominique-Peter orebody has been estimated to contain 11,587 tonnes U in ores grading 0.66% U.

The geological environment of the Dominique-Janine deposit resembles that of Dominique-Peter. The contact between the Peter River and Earl River gneisses is fault controlled and cross-cut by the subvertical northerly trending main ore structures. Mineralization occurs within these structures where they are intersected by steeply northwesterly dipping faults giving rise to a mineralized "zone a boules". Regolith and small blocks of Athabasca Group occur in the open pit illustrating the proximity of the sub-Athabasca Group unconformity. The deposit contains reserves of 874 tonnes U in ores grading 3.8% U.

South of the Dominique-Janine deposit, 1986 drilling indicated another deposit, confirmed by later drilling to be of higher grade and contain reserves estimated at 5.510 tonnes U in ores grading 5.8% U. The northern part of this deposit, now named "South Dominique Janine" is hosted by basement gneisses as the Dominique-Janine deposit itself, whereas the southern part is an unconformity-type mineralization, as the D zone deposit, of much higher grade.

References: Anonymous, 1974; Bell, 1985; Harper, 1977, 1978, 1980; Herring, 1976; Pagel, 1975a, b; Pagel et al., 1980; Ruzicka, 1975; Tapaninen, 1975, 1976; Laine et al., 1985.

KEY LAKE DEPOSITS (CAMECO, URANERZ EXPLORATION AND MINING LIMITED).

The Key Lake deposits lie at the southeast margin of the Athabasca Basin. They were discovered in 1975 and 1976 by a combination of exploration methods, including airborne radiometrics, mineralized boulder prospecting, surficial geology studies and geophysical and geochemical surveys. A fluvioglacial mineralized boulder train was traced to source and drilling in this general area eventually identified in situ mineralization. The deposits are characterized by conductivity anomalies, being underlain by graphitic gneisses, by low magnetic signature and by geochemical anomalies within a variety of sample media.

Diamond drilling of some 2400 holes totalling 266,000 m on a 20 x 10 m grid, with closer spacing in high grade sections, has indicated two major orebodies, the Gaertner and Deilmann and a zone of mineralized overburden. The grade of the ore is of the order of 2 % U, with substantial nickel, cobalt and arsenic associated with the uranium. Initially estimated reserves were 73 900 t U. A small proportion of these reserves (around 8%) occurs as "cobble ore" (glacial deposits in which mineralized boulders are sufficiently concentrated to form ore grading around 0.6% U). Mining began in 1983 by open pit methods at a production rate of around 4.6 million kg U. Operation of the Gaertner pit has now been completed and production from Deilmann pit has been ongoing since 1989.

The Key Lake area is underlain by Aphebian supracrustals of the Wollaston Group which mantle Archean granite gneiss domes. Both groups of rocks are overlain unconformably by the clastic sediments of the Athabasca Group, which comprise basal conglomerates grading upwards into sandstones. The upper part of the basement underlying the Athabasca Group exhibits a paleoweathering alteration profile.

The supracrustals are predominantly pelitic to semipelitic gneisses, typical of the basal Wollaston Group, and are often graphitic in character. They are cut by granitic sheets and lenses of anatectic segregation origin. In the vicinity of the orebodies the basement rocks dip moderately northwest and are cut by two sets of fault structures, respectively northeast and northwest trending. The northwest faults, which are subconcordant to basement lithology and displace the Athabasca Group unconformity both in a reverse and normal sense, are the more prominent structures.

The orebodies are long and narrow. The more northerly lying Deilmann exceeds 900 m in length, varies in width from 30 to 50 m and is about 40 m thick. It was covered by Athabasca Group sandstones and glacial overburden which together average 90 m in thickness. Ore shoots extend to 200 m below surface into the crystalline basement. The Gaertner is about 800 m long, from 10 to 50 m wide and up to 60 m thick. It subcrops below glacial drift (till, fluvioglacial outwash and eskerine deposits in part forming cobble ore) at its northeastern end and is overlain by Athabasca Group sandstones and drift in the southwest. The orebodies are separated by an approximately one kilometre 'gap', where glacial erosion has penetrated below the Athabasca Group unconformity into the underlying crystalline basement.

Mineralization occurs at the intersection of a northeasterly trending reverse fault showing a vertical displacement of 30 m and the sub-Athabasca Group unconformity. In the Gaertner deposit, the hanging wall of the fault comprises sillimanite-cordierite-graphite gneisses of the "main graphite" zone, which contain up to 30% graphite and 3% pyrite. Mineralization is hosted, as veins, massive nodules and disseminations, largely by downfaulted Athabasca Group sandstones which are extensively fractured, quartz corroded and clay altered. Some mineralization extends to a depth of 30 m into the underlying basement, formed by altered migmatitic quartz-feldspar-biotite gneisses which are reported to be in part mylonitized, folded and brecciated. Several periods of fracturing and alteration are apparent in the mineralized zone. Illitization is equated with main mineralization occurring possibly in several events between 1400 and 900 Ma ago. Kaolinite and redistribution of mineralization are linked to basin uplift and access of meteoric waters to the fault zone between 800 and 300 Ma ago. The Deilmann deposit is less well described by virtue of its later development. Fracture-controlled ore zones in the crystalline basement thicken upwards to the unconformity where massive ore occurs. The east-northeast trending basement fractures give rise to mineralized 'roots' extending over 100 m down dip within intermixed quartz-feldspar-biotite ± cordierite ± sillimanite ± graphite migmatites. Some mineralization occurs in the graphitic gneisses, however, ore shoots are characteristically in the adjacent rocks. Perched ore bodies occur in the Athabasca Group sandstones and disjointed satellite orebodies are present at the unconformity where it is intersected by cross-faults. The former are thought to result from remobilization.

The ore minerals comprise principally pitchblende and coffinite, accompanied by nickel arsenides, sulpharsenides and sulfides. Cobalt, molybdenum, lead, zinc, copper, gold and silver are present as minor constituents of the ore.

References: Dahlkamp, 1978; Dahlkamp and Tan, 1977; de Carle, 1986; Gatzweiler et al., 1979; Hoeve and Quirt, 1984; Kirchner et al., 1980; Ray, 1977; Tan, 1967; Watkinson et al., 1975; Wendt et al., 1978; Ruhrmann, 1987; Ruhrmann and von Pechmann, 1989.

RABBIT LAKE DEPOSIT (CAMECO, URANERZ EXPLORATION AND MINING LTD.)

The deposit was initially woned and developed by Gulf Minerals Canada Ltd. Gulf's properties, inclusive of the Collins Bay, Eagle Point and other deposits in the area, were acquired by Eldorado Nuclear Limited in 1982. Eldorado merged with Saskatchewan Mining Development Corporation to form Cameco - a Canadian Mining and Energy Corporation in 1988. A 33-1/3% interest in Cameco's Rabbit Lake - Collins Bay operation and surrounding properties was acquired in 1990 by Uranerz Exploration and Mining Ltd.

The Rabbit Lake deposit, on the eastern margin of the Athabasca Basin, was discovered in 1968 in ground follow up to a regional airborne radiometric survey. Ground checking of radiometric anomalies resulted in discovery of radioactive glacial overburden and delineation of a radiactive boulder train in the Rabbit Lake area. Subsequent work identified the deposit, which is characterized by a conductivity anomaly, by low magnetic, seismic velocity and gravity signatures and by lake bottom sediment geochemical anomalies.

Stripping began in 1974, following a development drilling program and the mill started up in 1975. Peak annual production reached 2 056t U from ore grading around 0.4% U. Mining was completed in 1984 and the pit turned into a depository for tails from milling of the remaining stockpiled Rabbit Lake ore and new Collins Bay B zone ore. Total production from Rabbit Lake was 15 769t U at an average of 0.27% U from initially estimated reserves of 17 300t U.

The deposit is hosted by Aphebian Wollaston Group supracrustals, comprising interlayered meta-arkoses and calc-silicates in the hanging wall (upper gneisses), massive meta-arkose and graphitic feldspar-rich granulite in the core of the ore zone and plagioclasite, calc-silicates and dolomitic marbles in the footwall. The hanging wall gneisses are cut by sub-concordant sheets of pink granite-granite pegmatite of anatectic segregation origin and the core of the ore zone by one or more sheets of grey microgranite.

The gneisses form a single southeasterly dipping, upright, homoclinal sequence in the south of the pit, but appear to become overturned and northerly to northwesterly dipping in the northeast, across the axis of a major northeasterly plunging reclined fold. Evidence of faulting is widespread and two major structures are recognized. The younger, the Rabbit Lake thrust fault, underlies the deposit, dips 30°SSE and downthrows the Athabasca Group sediments and underlying regolith to the northwest at least 75 m, against the crystalline basement. An older northeasterly trending, steeply dipping fault appears to bound the ore zone to the southeast.

The ore zone is elongated northeast-southwest and has the shape of a laterally flattened pipe, which is tilted to the northwest and is around 550 m long, up to 250 m wide and 200 m deep. A high grade core is surrounded by a lower grade envelope of mineralization.

Host rock alteration pervades and surrounds the orebody and is typified by Mg-chloritization, dolomitization, silification, tourmalinitization and hematization. Geochemically, the alteration is distinct from that which characterizes the paleoweathered (regolith) basement rocks under the Athabasca Group in the downthrown block of the Rabbit Lake Fault.

Mineralization comprises several different generations of pitchblende and coffinite, accompanied by a broad suite of minerals including euhedral quartz and dolomite, calcite, siderite, hematite, chlorite, adularia, sulphides, native copper and carbon buttons. Secondary uranium minerals, uranium minerals coatings and impregnations are also developed. On a large scale mineralization is geochemically simple comprising essentially uranium with only minor concentrations of Ni, As, Co, Se etc., which characterize many other unconformity type deposits.

References: Cumming and Rimsaite, 1979; Hoeve, 1977, 1978; Hoeve and Sibbald, 1977, 1978; Knipping, 1974; Little, 1974; Pagel, 1977; Pagel et al., 1980; Rimsaite, 1977, 1978a and b; Sibbald, 1976, 1977, 1978, Heine, 1985; Ward, 1989.

EAGLE POINT DEPOSITS (CAMECO, URANERZ EXPLORATION AND MINING LTD.)

The Eagle Point uranium deposits are located on the eastern margin of the Athabasca Basin about 12 km north-northeast of Rabbit Lake. There are two deposits, respectively called the Eagle North and South zones.

The deposits were discovered in 1980 by Gulf Minerals Canada Ltd. as a result of systematic drill testing of the Collins Bay Fault and of uranium-in-till anomalies. To date 245 holes totalling 47 260 m have been drilled on 15.2 m centres in the North zone and 288 holes totalling 77 200 m in the South zone. Drilling on the South zone is on 30.5 m centres except in proximity to the main ore lens, where it is on 15.2 m centres. Total identified reserves amount to 51 152t U grading 1.55% U, comprising 22 307t U grading 1.76% U in the North zone and 28,845t U grading 1.32% U in the South zone, at a cut-off grade of 0.42% U. The South zone remains open at depth and along strike.

The deposits are hosted by Aphebian supracrustals structurally and stratigraphically underlain to the northwest by granitoid gneisses of probable Archean age. The Archean-Aphebian contact dips moderately to the southeast parallel to regional foliation and lithological subdivisions in the overlying supracrustals. The contact is paralleled by the Collins Bay (thrust) Fault, which downthrows to the northwest the Athabasca Group unconformably overlying Archean granitoid gneisses. The deposits thus lie wholly in the hanging wall of the Collins Bay Fault in the Aphebian supracrustals.

The host supracrustal sequence is some 460 m thick. It comprises predominant pelitic to semipelitic biotite quartz-feldspar gneisses, in part divisible into garnet-, cordierite- and graphite-bearing subunits, psammitic gneisses locally containing sillimanite and garnet, which dominate the upper part of the sequence and minor quartzite, calc-silicate, marble and garnet-diopside-amphibole-cordierite rock (iron formation ?). Lenses of granitoid segregation 'pegmatites' comprise 15 to 20 percent of the Aphebian sequence in the deposit area. Some quartz-rich zones may also be of segregation rather than sedimentary origin.

Uranium mineralization is structurally controlled within zones, which are both concordant and discordant to stratigraphy. Within these zones mineralization is present in at least three sets of fault and breccia structures:

1) reverse structure (Collins Bay Fault and overlying parallel Eagle Point Fault)
2) subvertical structures

3) north-dipping structures.

At Eagle South there are five zones of mineralization, the two largest being concordant, tabular lenses, confined between the Collins Bay (footwall) and Eagle Point (hanging wall) reverse faults. The 144 zone contains around 70% of Eagle South reserves and forms a zone from 15 to 30 m wide, which has been traced to a depth of some 450 m. Eagle North has three zones, occurring in the hanging wall of the Eagle Point Fault and adjacent to it, which are weakly discordant and irregular in cross section. The 02 zone, containing 75% of the reserves, has a strike length of approximately 91 m, width of 61 m and vertical extent of 193m. The total strike length of mineralization is about 1 000 m and the vertical depth extension at least 457 m (about 600 m below the projected Athabasca Group unconformity eroded in the hanging wall of the Collins Bay Fault).

The mineralization is mineralogically and geochemically simple consisting of several generations of uraninite and pitchblende together with only trace amounts of boltwoodite, coffinite, pyrite, galena, chalcopyrite and native copper. Carbonaceous buttons are characteristically associated with patches of higher grade mineralization. The oldest U/Pb age obtained from mineralization is about 1400±25 Ma.

Alteration related to mineralization is characterized by chloritization and illitization of feldspars, hematization alteration of mafic minerals to clays. Illite dominates in the highest grade parts of the mineralized zones, whereas aluminous di-trioctahedral chlorite and illite in broadly equal proportions typify the lower grade areas. Loss of coherence and 'bleaching' of the host rock is ubiquitous. Silicification is locally important adjacent to mineralized quartzite units. In Eagle North alteration occurs in relatively restricted zones adjacent to mineralized faults and fractures and host rocks within a few metres are only weakly or unaltered. At Eagle South the alteration is more extensive because of an apparently greater fracture density. In general, however, the extent of alteration is far less than that which surrounds deposits such as the Collins Bay B zone in the Athabasca Group and does not serve to significantly enlarge the exploration target. Geochemically the alteration zones are characterized by anomalous concentrations of boron, magnesium and uranium.

References: Eldorado Resources Limited, 1987; Sopuck et al., 1983, Andrade, 1989; Quirt, 1989; Ward, 1989.

COLLINS BAY DEPOSITS (CAMECO, URANERZ EXPLORATION AND MINING LTD.)

The Collins Bay deposits are situated on the eastern margin of the Athabasca Basin some 10 km northeast of Rabbit Lake. Three principal zones of economic mineralization are recognized, the A, B and D along a mineralized trend which is approximately 3 km long. The A zone was found in 1971 as a result of ground checking of airborne electromagnetic anomalies. A mineralized boulder train was discovered, by prospectors and traced to source in Collins Bay. Subsequent drilling revealed a small zone of high grade uranium-nickel mineralization. In 1976, following the announcements at Key Lake and the recognition of possible ore controls, the A zone was re-evaluated and the strike extension of the underlying electromagnetic trend further explored. Drilling in 1977 led to the B zone, some 2 km south of the A. Systematic drilling of the mineralized trend between the A and B zones defined the D zone in 1979. Reserves are estimated at: A zone - 6 500t U grading 4.83% U, B zone - 15 769t U grading 0.61% U and D zone - 2 154t U grading 1.66% U. The B zone is currently being mined by open pit at a planned production rate of some 2 000t U per year. The A and D zones will also be mined by open pit and phased into production at some point in the future.

The Collins Bay area is underlain by Aphebian supracrustals, granitoid gneisses of probable Archean age and clastic sediments of the Athabasca Group. The Archean-Aphebian contact dips moderately to the southeast passing through Collins Bay, and juxtaposes pelitic-semipelitic graphitic supracrustal gneisses with lenses of granite-granite pegmatite of anatectic segregation origin to the southeast against granitoids to the northwest. The granitoid gneisses are overlain unconformably by Athabasca Group sediments downthrown by the Collins Bay (thrust) Fault along the contact of the two major basement units.

The A zone, drilled on 7.6 m grid pattern is 46 m long, 40 m wide and with a maximum thickness of 16 m. It is located in the hanging wall and footwall of the Collins Bay Fault in Aphebian metasediments and Athabasca Group sediments respectively. Economic uranium mineralization occurs within a lens of clay alteration, surrounded by a halo of nickel mineralization in adjacent Athabasca Group sediments. Ore minerals include pitchblende of two generations, rammelsbergite: pararammelsbergite, galena and pyrite and possibly niccolite, kasolite and coffinite. Some gold and silver is also associated with the mineralization.

The B zone is approximately 915 m long, 30 to 122 m wide and 30 m in average thickness. It is confined for the greater part in the footwall of the Collins Bay Fault, primarily within sandstones and conglomerates of the Athabasca Group which unconformably overlie Archean granitoid gneisses. Some mineralization occurs in the hanging wall formed by upthrown graphitic pelitic gneisses. The orebody comprises a lens or group of lenses of mineralization parallel to the strike of the fault, which is northerly except at the north end of the orebody, where it adopts the regional northeasterly trend. Imbrication characterizes the northerly trending segment of the fault.

In the sandstones mineralization occurs as intergranular fillings to quartz grains, as dustings on grain boundaries, as pods of massive replacement ore and as veins. Extremely high grade ore resembling that in the A zone is encountered in clays, interpreted by Jones (1981) as altered basement slices, but more likely representing zones either of concentration of sandstone matrix clay through quartz solutioning or of clay replacement.

Three types of ore are recognized: 1) green uranium-bearing sandstone, 2) grey uranium-nickel bearing sandstone and 3) uranium-nickel bearing clay. Ore is of grey sandstone type in the north of the orebody and of green sandstone type in the south. A clay hosted high grade pod of mineralization occurs in the north of the orebody and is surrounded by grey sandstone ore.

Ore and associated minerals include pitchblende in the green sandstone ore and a complex assemblage in the grey sandstone ore and clay hosted ore, comprising: pitchblende, coffinite, nicolite, rammelsbergite, gersdorffite, maucherite, bravoite, violarite, chalcopyrite and other copper sulphides. Locally pyrite, covellite, bornite, tennantite, millerite, polydimite and safflorite are present. Graphite and glassy carbonaceous material are characteristically associated with mineralization.

In the Athabasca Group the most visible alteration effect passing into the mineralized zone is an increase in clay content. The increase is marked by addition of matrix clays in zones up to several metres thick, and by the appearance of discrete, generally discordant layers of almost pure clay from a few centimetres to a metre thick.

The clays in the mineralized zone are pure illites and contrast with those from less altered and unaltered rocks, with normal matrix clay content, which are mixtures of illite and kaolinite. Quartz grains in the enriched clay zones are typically strongly corroded. Angular isolated quartz grains identified in some clay layers are possibly the last vestiges of corrosion. The margins of clay enriched zones may be gradational or sharp.

Hematization and bleaching are characteristic of both mineralized and unmineralized Athabasca Group sediments. Away from the ore zone hematization is dominant in the lower parts and bleaching in the upper parts of the Athabasca Group succession. Hematite is characteristicallypurple, and unusually brick red at the interface with bleached zones. Bleaching is superimposed on hematization. Hematite in the ore zone is mostly earthy red-brown in colour, although patches of purple and brick red hematite are also present. The red-brown hematite is probably younger than the purple hematite and it certainly predates bleaching.

Lateritic weathering of the basement prior to deposition of the Athabasca Group has also produced alteration. A typical, essentially unmodified, sub-Athabasca weathering profile is developed in the Archean granitoids underlying most of the Athabasca Group, even in places where the Group itself is extensively altered and mineralized. Below the unconformity, depths to which pervasive weathering occur range between 15 m and 70 m.

The D zone closely resembles the A zone in structural location, mineralogy and geochemistry. It occurs predominantly in strongly altered Athabasca Group sediments in the footwall of the Collins Bay Fault. Geochemically it is characterized by uranium, nickel and arsenic, but lacks the significant values of gold and silver which occur in the A zone. The southwestern tail of the deposit is relatively poor in nickel arsenides. The deposit has a strike length of 700 m, ranges from 8 to 40 m wide and in depth from 10 to 46 m.

References: Hoeve et al., 1981a; Jones, 1980, 1981; Sibbald, 1981; Ward, 1989.

CIGAR LAKE DEPOSIT (CAMECO, COGEMA (CANADA) LIMITED, IDEMITSU URANIUM EXPLORATION CANADA LIMITED, CORONA GRANDE, KOREA ELECTRIC POWER CORPORATION)

The Cigar Lake uranium deposit is located in the Athabasca Basin at the southwest end of Waterbury Lake approximately 50 km southwest of Rabbit Lake. It was discovered on May 9, 1981 by Seru Nuclear Canada Limited, now Cogema Canada Limited. In 1985, the joint venture formed the Cigar Lake Mining Corporation to develop the deposit for production. An underground test mining study is in progress and will be completed by mid 1991. A 510 m deep shaft is being sunk and two levels developed above and below the orebody for evaluation of various mining methods, the most favoured being raise boring.

The deposit was discovered by drilling of an electromagnetic conductor identified by airborne INPUT and ground DEEPEM surveys and located in the vicinity of a low amplitude uranium geochemical anomaly. As of July 1986, 170 diamond drill holes had been put down to delimit the orebody comprising 110 000t U at a grade of 12.3% U in the East zone and an additional 40 000t U at a grade of 4% U in the West zone. The East zone has been explored on a 50 m x 20 m grid (123 holes) and the west zone on a 200 m x 20 m grid (47 holes).

The deposit, located at a depth of 410 m to 450 m, forms a continuous flat elongated body 2 150 m long, 25 m to 100 m wide and up to 20 m thick. It occurs, immediately above the sub-Athabasca Group unconformity, although minor mineralization is present up to 300 m above the unconformity (perched mineralization) and in veins in the underlying basement.

In proximity to the deposit, the Athabasca Group (Manitou Falls Formation, Units B, C and D) is around 400 m thick and comprises predominant quartz sandstones with conglomerate layers locally developed, particularly at the base of the Group. The basal conglomerate, however, is absent at the deposit, wedging out against a 20 m high basement ridge on top of which the deposit is located.

The basement rocks comprise graphitic, pelitic, biotite-cordierite gneisses and diopsidic calc-silicate gneisses, cut by granitoid segregation 'pegmatites' derived from anatexis of the surrounding pelitic gneisses. These gneisses, where they underlie the orebody, are augen textured, the augen being formed by cordierite and K-feldspar crystals.

The deposit is surrounded by a significant alteration zone extending upwards about 300 m into the Athabasca Group sandstones and some 100 m into the basement. In the basement rocks the alteration zone is superimposed on a pre-existing lateritic weathering profile. The orebody capped by massive hematized clay, is surrounded successively by zones characterized by: a) clay alteration (quartz solutioning) and strong fracturing, b) euhedral quartz veining, c) grey alteration (disseminated iron sulphides and locally hydrocarbons) and d) bleaching. In the basement rocks, a zone of total argillization from one to three metres thick underlies the orebody. Within this zone original metamorphic textures are lacking as are sulphides and graphite. A zone of argillized rock in which original textures are preserved is underlying.

Clay minerals of the 'sandstone alteration zones' are essentially illite, except within the massive clay cap where mixed illite, Fe-rich illite, Mg-rich illite, Fe-chlorite and Mg-chlorite occur together with siderite and hydrocarbon buttons. Basement alteration clays are essentially Mg-chlorite and Mg-illite. Calcite, hydrocarbon buttons and dravite are locally important.

The orebody consists of a massive high grade core enveloped by clays containing lower grade mineralization. In addition, perched mineralization occurs in the overlying sandstones. It seldom exceeds a grade of one percent U and is mineralogically and geochemically simple, comprising pitchblende and coffinite with microdisseminated sulphides. Basement mineralization is of limited importance, occurs as vein and breccia ore and is characterized by pitchblende of various ages, coffinite and sulphides. The high grade ore is typified by pitchblende associated with Ni-Co arsenides, sulpharsenides and sulphides and hematite. In the high grade ore three stages of mineralization are recognized, the earlier two yielding the more reduced pitchblende-arsenide-sulphide facies, the latest the relatively oxidized pitchblende-hematite facies. U-Pb dating of the earliest stage of mineralization has provided an age of 1300 Ma, similar to that recorded for initial mineralization in other deposits. Geochemically uranium is associated with Ni, Co, Cu, Mo, Zn, Pb and As. F, Ag, Se, Th, Li, Sb, Be and Au are also locally anomalous in concentration.

There is no obvious structural control of mineralization as at many other deposits where faulting has clearly displaced the sub-Athabasca Group unconformity. The augen-textured pelites interpreted as blastomylonites, have been suggested to mark an ancient structural zone which may have undergone reactivation. On a detailed scale, various sets of fractures which exercise a control on mineralization appear to result from both tectonic and solution collapse processes.

References: Fouques et al., 1986; Bruneton, 1987.

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