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Ore Deposit Models #13. Unconformity-type Uranium Deposits

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Ore Deposit Models #13. Unconformity-type Uranium Deposits

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Introduction

Uranium is a relatively mobile, lithophile element occurring in nearly all major lithologies, and has an average crustal abundance of two to four ppm. As with many other metals, economic concentrations of uranium show a distinct time-bound relationship (Robertson *et al.*, 1978) (Figure 1). In the Precambrian, anomalous concentrations of uranium are found in two specific geological settings, separated in time by the oxygenation event of the earth's atmosphere at about 2600-2200 Ma. Prior to this event, paleoplacer uranium deposits hosted by quartz-pebble conglomerates, such as in the Witwatersrand Supergroup, South Africa, and in the Huronian Supergroup at Elliot Lake, Canada, were formed as a result of mechanical transportation of detrital uraninite grains. Subsequent to atmospheric oxygenation, however, uranium was dissolved and transported as hexavalent uranyl complexes in aqueous solutions. In the period between 1800 Ma to 1200 Ma, extensive concentrations of uranium, which are spatially, and most probably genetically, related to paleoweathering surfaces were formed and gave rise to a new type of deposits, generally referred to as the "Unconformity-type" uranium deposits. These Middle to Upper Proterozoic rocks host a significant component of the western world's uranium resources; for example, the Athabasca deposits, of northern Saskatchewan, Canada, constitute about 10% of the western world's low cost reserves (Sibbald and Quirt, 1987). To date, major deposits of this type are known in northern Saskatchewan and the Northwest Territories of Canada, the Northern Territory of Australia and parts of West Africa. Unlike the Early Proterozoic paleoplacers and the Phanerozoic sandstone-hosted roll-front deposits, the typical unconformity-type orebodies contain extremely high concentrations of uranium, which make them a more attractive mining proposition.

The discovery of a rich orebody at Rabbit Lake, Saskatchewan in 1968, and the increased world demand for uranium of the early to mid-1970s, triggered an avid search for this type of deposits. As a result, in Saskatchewan, numerous deposits such as the Cluff Lake D Zone (Lainé, 1986), Key Lake (de Carle, 1986), Midwest (Ayres *et al.*, 1983), McClean (Saracoglu *et al.*, 1983), Dawn Lake (Clarke and Fogwill, 1986), and Cigar Lake (Fouques *et al.*, 1986) were discovered between 1969 and 1981 (Figure 2). In Australia, world-class deposits such as Koongarra, Ranger, Nabarlek and Jabiluka were discovered in the 1970s (Nash, 1978)(Figure 3). A decline in uranium prices since the late 1970s has substantially slowed the exploration and exploitation rate of these deposits throughout the world.

The following is a summary of the main features of this group of deposits, based on descriptions of those in northern Saskatchewan, Canada, and the Northern Territory, Australia.

Regional Setting

Northern Saskatchewan, Canada. Part of the Churchill Province of the Canadian Shield, the Archean basement in this area consists of granitoid and gneissic terranes which are overlain by a sequence of Lower Proterozoic (Aphebian) metasediments. The crystalline basement has been divided into several lithostructural domains with different compositions, structures and metamorphic grades (Langford, 1986; Hoeve *et al.*, 1980; Lewry and Sibbald, 1979)(Figures 2 and 4). The most important uranium deposits are located within the Cree Lake Mobile Zone (bounded to the east by the Needle Falls Shear Zone) and the Western Craton, specifically where these terranes are covered by the Upper Proterozoic (Helikian) sediments of the Athabasca Basin.

The Cree Lake Mobile Zone, which is divided into Wollaston, Mudjatik and Virgin River domains, consists of granitoid and gneissic domes surrounded by Aphebian supracrustal rocks, all strongly deformed by Hudsonian tectonism and metamorphosed to upper amphibolite grade. Sibbald and Quirt (1987) and Lewry and Sibbald (1979) define four lithostratigraphic units within the supracrustal package (Wollaston Group) which is best developed in the Wollaston domain. The succession comprises a lower package of arkose, quartzite and pelite (only present at the eastern margin of the Cree Lake Mobile Zone) overlain by graphitic pelite (which serves an important role in EM surveys) interlayered with calc-silicate and minor marble. These rocks are in turn overlain by an upper meta-arkosic unit which includes calc-silicate and pelite and a final assemblage of amphibolite-quartzite. The arkosic and pelitic units have been metamorphosed to feldspathic gneisses and biotite-schists, respectively. In the Rabbit Lake area, the thickness of the Wollaston Group has been estimated to be at least 3-4 km (Hoeve and Sibbald, 1978). The depositional environment of the metasediments has been described (Nash *et al.*, 1981) as shallow water, marginal marine conditions. However, Hoeve and Sibbald (1978) note that the Hudsonian Orogeny has obscured many of the primary sedimentary features and suggest the presence of two distinct sedimentary environments: (1) deposition of pelite, quartzite and meta-arkose under stable tectonic conditions, as a westwardly transgressional, massive sequence over the Archean craton; and (2) meta-arkose, quartzite, amphibolite and coarse clastic sediments which were deposited under less stable conditions, possibly during uplift, to the east.

Many stages of deformation during the Hudsonian Orogeny are recorded in the

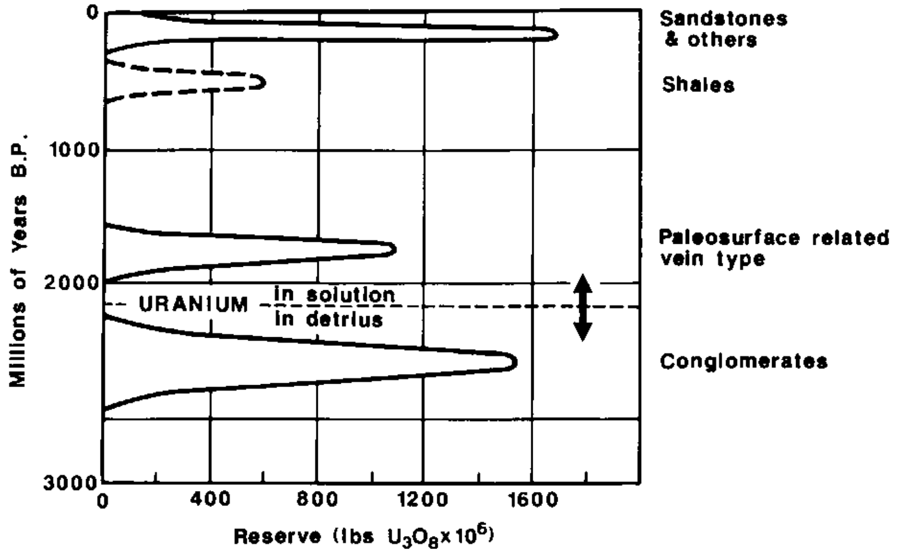

Figure 1 *Time-bound character of uranium deposits. After Robertson* et al. *(1978).*

Wollaston Group. An early foliation, commonly parallel to lithological contacts and compositional layering, is developed in both the Archean and Aphebian rocks. This penetrative fabric was subsequently folded about northeast-trending axial planes. Late-Hudsonian, left-lateral, strike-slip faults and post-Athabasca thrust faults terminated the structural history of the supracrustal rocks (Sibbald, 1983).

The metamorphosed Archean-Aphebian basement is unconformably overlain by the Athabasca Group (Helikian) which comprises four marine transgressive sequences and one fluvial regressive sequence (Ramaekers, 1983). The lithologies vary from "poorly sorted" to "well sorted", clay-rich sandstone, siltstone and mudstones, intercalated with conglomerate. The conglomerate is more prevalent at the base of the succession (Hoeve *et al.*, 1980). Ramaekers (1976, 1983) demonstrates that, within the basal conglomeratic members, paleocurrent directions indicate two prominent radiating fluvial fans, one deriving from the northeast and the other from the east; however, local exceptions are reported such as at the Collins Bay deposits where the current was to the north-northwest (Jones, 1980). Within the sandy sediments, Ramaekers (1983) points out that the paleocurrent indications direct to the west and suggests that the environment of deposition was an alluvial plain of a system of braided streams with intermittent lakes.

The Athabasca sediments are highly hematitic, with the hematite content generally between 1 and 2%, but locally as high as 30%. Hoeve *et al.* (1980) suggest a complex history of diagenesis for the sediments whereby oxidation and alteration, similar to processes active in recent red beds, started soon after deposition, and continued for a long time thereafter. This is witnessed by hematitization, kaolinitization and fracture-fillings by quartz and illite of a swarm of diabase dykes which cross-cut the Athabasca Group. The Athabasca sediments have been dated at 1484 ± 55 and 1459 ± 4 Ma by ^{40}Ar/^{39}Ar method (Bray *et al.*, 1987). Armstrong and Ramaekers (1985), using Rb/Sr method, have obtained similar ages for the sediments. They also report Rb/Sr ages of 1.31 ± 0.07 Ga and 1.16 ± 0.04 Ga for the diabase dykes.

The unconformity at the base of the Athabasca Basin is marked by a weathered paleosol profile averaging 20-40 m and in places reaching up to 100 m in thickness (Langford, 1986). Where complete, the regolith is zoned with a green chloritic zone in the lower parts of the soil profile grading to an overlying red and white zone consisting primarily of kaolinite and illite. Hematite staining is pervasive throughout the upper part of the profile (Hoeve *et al.*, 1980; Langford, 986). In most places, the regolith horizon has been well preserved by the Athabasca sediments, but in rare cases, such as the Rabbit Lake deposit, the paleo-weathered surface is absent from the upthrown block of the Rabbit Lake Fault, but present on the downthrown block (Hoeve and Sibbald, 1978). Macdonald (1981), in documenting the characteristics of the regolith, shows many similarities between this unit and present-day laterites, and attributes their differences to the lack of land vegetation in the pre-Helikian period. The regolith has been dated at 1482 ± 49 and 1453 ± 49 Ma (^{40}Ar/^{39}Ar) by Bray *et al.* (1987).

Northern Territory, Australia. The major uranium deposits of northern Australia are located in the East Alligator Rivers area within the Pine Creek Geosyncline (Figure 3). The Archean to Lower Proterozoic Nanambu Complex, which forms the basement, consists of a wide range of granitic and metamorphic lithologies. Needham and Stuart-Smith (1980), using radiometric ages (U-Pb of zircon and monazite, and whole rock Rb/Sr and K/Ar) published by Page *et al.* (1980), divided the Nanambu Complex into massive to foliated granites (2500-2400 Ma), grading to foliated gneisses (1980-1800 Ma), both surrounded by a sequence of younger (1800 Ma) gneisses, migmatites and metasediments which were derived from the Lower Proterozoic Kakadu Group. The basement rocks were metamorphosed to amphibolite grade, isoclinally folded and uplifted during an orogenic event at 1800 Ma (Needham and Stuart-Smith, 1980). The Cahill Formation, which is host to the majority of the uranium deposits, overlies the Nanambu Complex and the Kakadu Group. Nash and Frishman (1981) and Needham and Stuart-Smith (1980) divide the 3,000 m thick Cahill Formation into a lower member (200-500 m thick), consisting of Mg-rich marble, schist and gneisses and an upper member of carbonaceous pelite and impure sandstone, metamorphosed to quartz-biotite schist and gneiss.

The Kombolgie Formation (one of the major units of the Middle Proterozoic Carpentarian

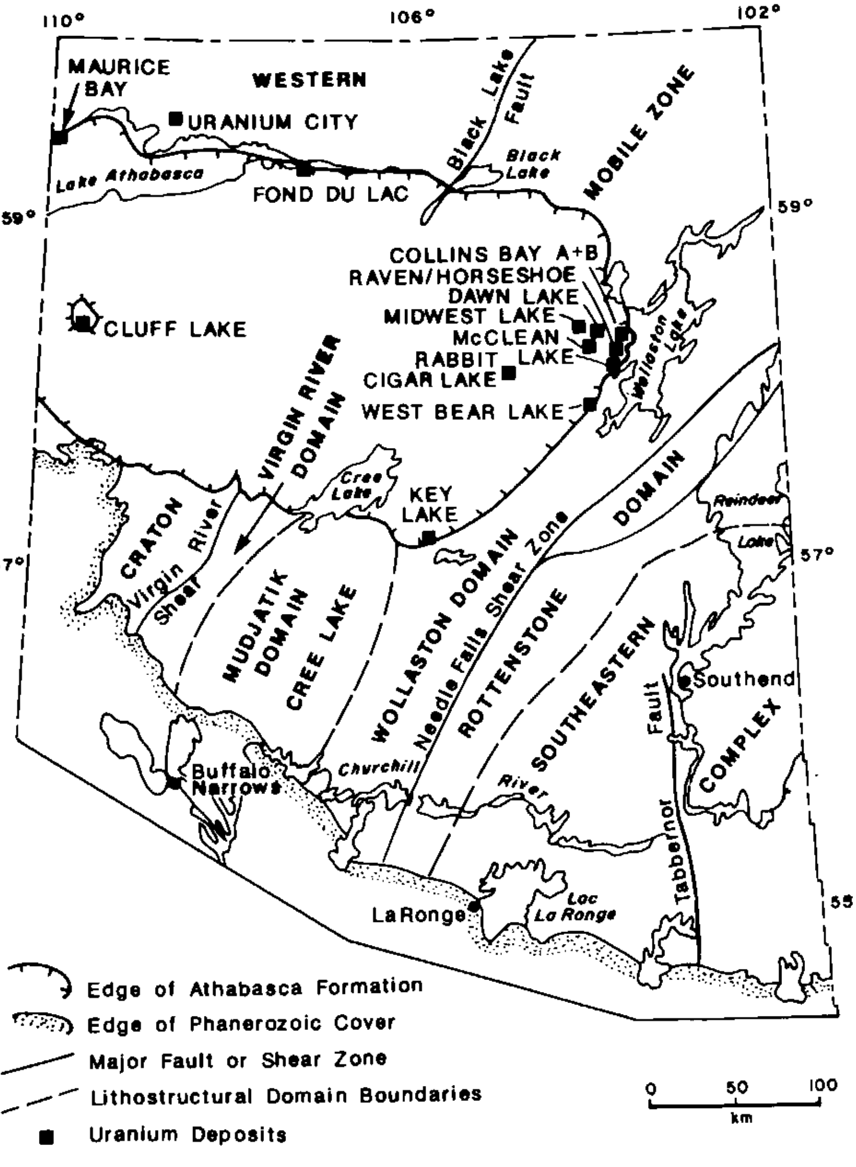

Figure 2 *Location of major uranium deposits in northern Saskatchewan. Modified after Hoeve* et al. *(1980).*

sediments) unconformably overlies the Archean and Lower Proterozoic rocks. It is similar to the Athabasca sediments in that it consists predominantly of a sequence of well-sorted fluviatile sandstones. Page *et al.* (1980) have dated volcanic units intercalated with the Kombolgie sandstone at 1648 ± 29 Ma (Rb/Sr).

Others districts. In addition to the two major uranium fields of northern Saskatchewan and the Northern Territory of Australia, a number of small discoveries and high potential occurrences have been reported in the Keewatin District of Canada (northeastern sub-arctic region). Curtis and Miller (1980), describe the regional setting of uranium showings associated with the Thelon, Baker Lake and Dubawnt basins. Similar to the larger uranium fields, these occurrences are hosted by Lower Proterozoic (Aphebian) shelf facies and Middle Proterozoic continental metasediments (Wright, 1967). The latter are intercalated with and overlain by alkalic and calc-alkalic volcanics and fluviatile metasediments. The metamorphosed and folded basement and the Aphebian rocks are unconformably overlain by mature sandstones (including a basal conglomeratic unit) of the Thelon, Dubawnt and Baker Lake basins.

Deposit Characteristics

Stratigraphic position and host lithologies. Unconformity-type uranium deposits occupy a very specific stratigraphic location. Exploration leading to the early discoveries of this group of deposits, such as a number of large orebodies in the East Alligator Rivers of Northern Territory, was based on the model for the deposits of the Rum Jungle area, also in the Northern Territory, which were discovered in 1949 (Fraser, 1980). As a result, the initial search for the deposits was largely focussed on the Lower Proterozoic metasediments. In the Rabbit Lake deposit (Figure 2), the host lithologies consist of interlayers of calc-silicates and meta-arkoses with massive meta-arkose, segregation pegmatites, plagioclasite and biotite microgranite (Hoeve and Sibbald, 1978; Sibbald, 1983). Similarly, the A zone of the Collins Bay deposits (Jones, 1980), a portion of the Cigar Lake (Fouques *et al.*, 1986), the N Zone, Claude and Dominique deposits of Cluff Lake (Hoeve *et al.*, 1980), and the Midwest deposit (Wray *et al.*, 1981) are hosted by carbonaceous metasediments, calc-silicates, anatectic gneisses and granite-segregation pegmatites. Nash *et al.* (1981) indicate that most East Alligator Rivers deposits are hosted by, or are in close proximity to, the carbonaceous metasediments of the Cahill Formation.

Because of the close spatial association with carbonaceous and carbonate-bearing metasediments, Needham and Stuart-Smith (1980) concluded that these lithologies played an important role in inducing precipitation of uranium from fluids. However, discoveries of most of the Saskatchewan deposits showed that, in addition to the crystalline basement, the unconformably overlying fluvial sediments are prospective ground for substantial mineralization. Whereas deposits, such as Rabbit Lake, Collins Bay A Zone (Figure 2), Jabiluka I and II, Koongarra and Nabarlek (Figure 3), are entirely restricted to the Lower Proterozoic metasediments, deposits such as Midwest, Dawn Lake, McClean, Collins Bay B zone and Key Lake straddle the pre-Helikian unconformity (Figure 4). It should be pointed out, however, that in deposits such as Jabiluka I and Ranger the present-day exposure level coincides with the paleo-erosional surface and hence, if there was any mineralization in the overlying sub-aerial sediments it has been eroded. In fewer cases such as the D zone of the Cluff Lake deposits, with the exception of minor mineralization in basement fractures, all of the

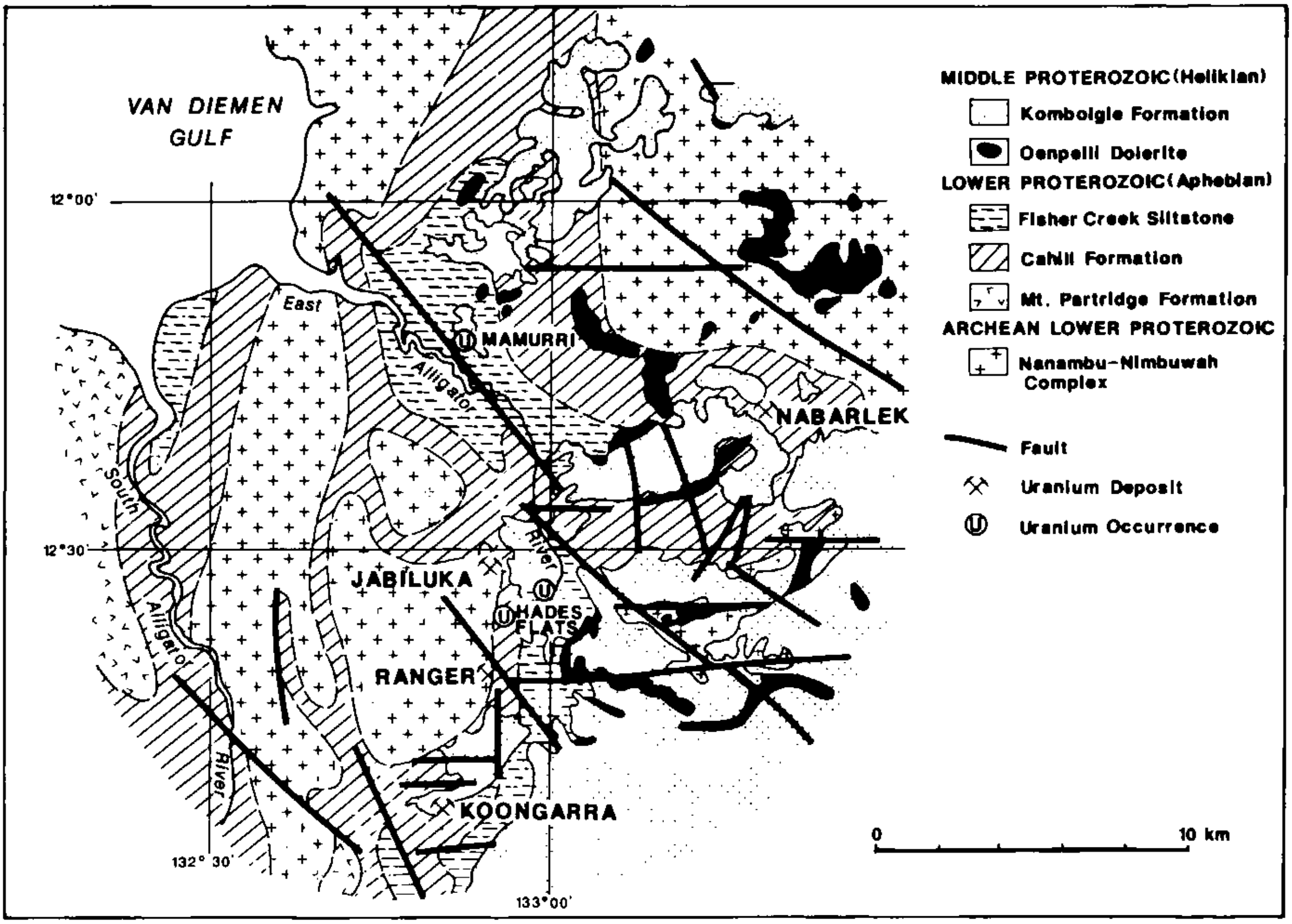

Figure 3 *General geology and major uranium deposits of the East Alligator Rivers area, Northern Territory, Australia. After Hegge and Rowntree (1978).*

mineralization occurs above the sub-Athabasca unconformity. It is apparent that this group of uranium deposits is spatially restricted to areas immediately above and below the unconformity. The extent of mineralization with respect to the paleo-erosional surface is variable. In cases such as the Rabbit Lake deposit, mineralization continues to a depth of 200 m below and, at Midwest, up to 200 m above the unconformity (Hoeve *et al.*, 1980; Sibbald, 1983). An average range of 70-100 m of mineralization on either side of the unconformity is fairly consistent in most deposits.

Hoeve *et al.* (1980) note that some of the NE-trending diabase dykes and sills cutting the Athabasca Basin may also be host to some mineralization.

Structural features and orebody form. In most unconformity-type deposits many episodes of pre-, syn- and post-mineralization deformation have been documented. Often, the siting of the deposits is either related to reverse faults or to normal faults (Sibbald, 1987; Hoeve *et al.*, 1980; Jones, 1980; Ayres *et al.*, 1983). For instance, at the Rabbit Lake deposit, NNE-trending faults have been cut off and reactivated by a set of low-angle, ENE-trending, reverse faults (Hoeve *et al.*, 1980). One of these faults, the Rabbit Lake Fault dips 30° SE and shows a vertical displacement of at least 75 m (Hoeve and Sibbald, 1978). The Rabbit Lake deposit is located in the upthrust block of this low-angle reverse fault (Hoeve and Sibbald, 1978; Nash *et al.*, 1981). Similarly, at the Koongarra deposit, reverse faulting has placed the Lower Proterozoic Cahill Formation above the Middle Proterozoic Kombolgie Formation. This reverse fault dips 60° SE and is filled with brecciated mineralized rocks (De Voto, 1978). At the B zone of the Collins Bay deposits, highly altered segments of sub-Athabasca rocks, having already been altered to sericite and kaolinite, were thrust onto or squeezed into the Athabasca sandstone as irregularly shaped dykes (Jones, 1980).

The best example of mineralization associated with normal faulting is at the Midwest deposit (Sibbald and Quirt, 1987).

In some deposits, both normal and reverse faults have been reported; Nash and Frishman (1981) describe three distinct host structures from the Ranger orebody: (a) low-angle reverse or thrust faults; (b) high-angle normal faults; and (c) carbonate thinning and collapse breccias.

Both reverse and normal faults are often best developed along planes of weakness such as contacts of lithological units with differing competencies. Sibbald and Quirt (1987) give examples of this phenomenon from Key Lake and Collins Bay A and B zones where contacts between less competent graphitic pelites and more brittle granitoid gneisses have been the focus of high strain. Evidence of cataclasis, and intermittent brittle and ductile deformation, associated with mineralization are reported from many deposits. Hoeve *et al.* (1980) suggest that in many cases, structures hosting mineralization consist of veins, veinlets, open space-fillings and breccias. They emphasize that, as in the case of Rabbit Lake, although the breccia was initially tectonically induced, subsequent dissolution of carbonates generated a collapse breccia. Similarly, removal of carbonates by silicification, resulting in collapse breccias which host mineralization at the Ranger deposit, have been described by Hegge and Rowntree (1978). Ewers and Ferguson (1980) further emphasize the significance of continued re-brecciation at this deposit.

At the McClean deposits, Wallis *et al.* (1984) and Jagodits *et al.* (1986) report extensive fracturing, faulting and brecciation associated with orebodies. They note, however, that the zones of intense fracturing extend far beyond the mineralized zones, specifically within the rocks of the Athabasca Group, and draw attention to the fact that although intense brittle failure is significant and necessary to provide channelways, it is not a unique exploration guide, as in some cases the barren rocks may have a denser pattern of fractures than the deposit itself.

In addition to the structures related to brittle failure, features representing advanced stages of ductile deformation have been documented in many deposits. The most detailed description of such features is given by Dahlkamp (1978) for the Key Lake deposit (Figure 5) where the host lithologies are divided on the basis of their state of deformation. The Aphebian metasediments, where undeformed, consist of carbonaceous metapelite, biotite-plagioclase-cordierite gneiss and a coarse-grained anatectic gneiss/pegmatite. The deformed host rocks are described as various, highly altered mylonites. Dahlkamp (1978) points out that because of the intensity of deformation, with

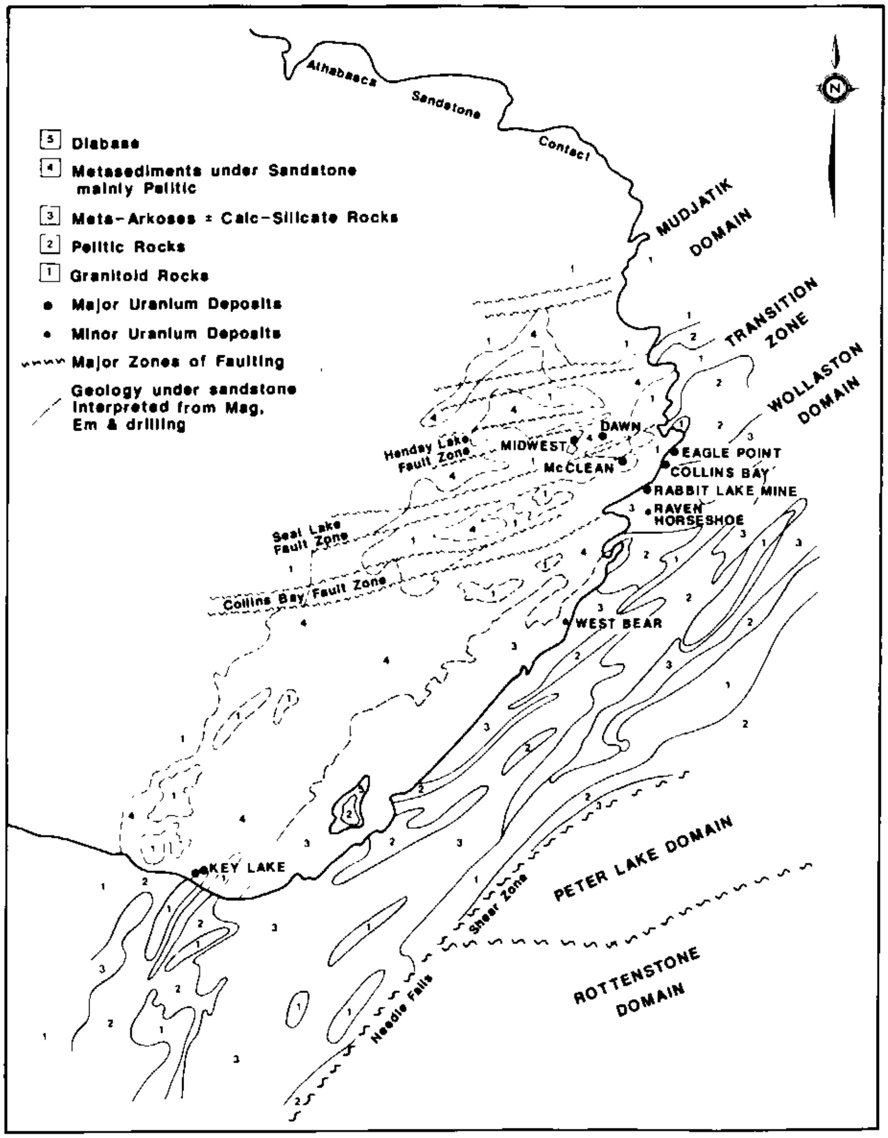

Figure 4 *Generalized geology of the eastern Athabasca uranium field. After Fogwill (1981).*

the exception of the biotite-plagioclase-cordierite gneiss which is the parent rock to a sericitic-chloritic mylonite, precursors to the other deformed host lithologies are not known. Von Pechmann (1981) also emphasizes the fine-grained nature of the rocks at Key Lake, as a result of tectonism. Wallis *et al.* (1984) make reference to some mylonitic textures, kink folds and crenulation that existed prior to the formation of the regolith, at the McClean deposit. From the Cigar Lake deposit, Fouques *et al.* (1986) describe blastomylonitic textures in a "quartz-eye" metapelite underlying the ore zone and Ayres *et al.* (1983) report ribbon-like textures in the porphyroblastic metapelites at the Midwest deposit.

At the McClean deposit, Wallis *et al.* (1986) show that many generations of channelways, which played an important role in focussing mineralizing fluids, were developed during the deformational history of the deposit. They propose a sequence as follows: (a) in the crystalline basement, numerous brittle structures formed after the Hudsonian Orogeny (1850-1750 Ma) and prior to the formation of the regolith (± 1600 Ma) and the Athabasca sediments. Some of these structures, however, have subsequently been reactivated; (b) in the Athabasca Group, structures consisted of joints, fractures, faults and the inherent porosity/permeability of bedding planes and conglomeratic strata; (c) mineralization-associated structures, superimposed on previous structures, comprised an early dilational-extensional phase and a later cavity collapse, partial corrosion and dissolution phase.

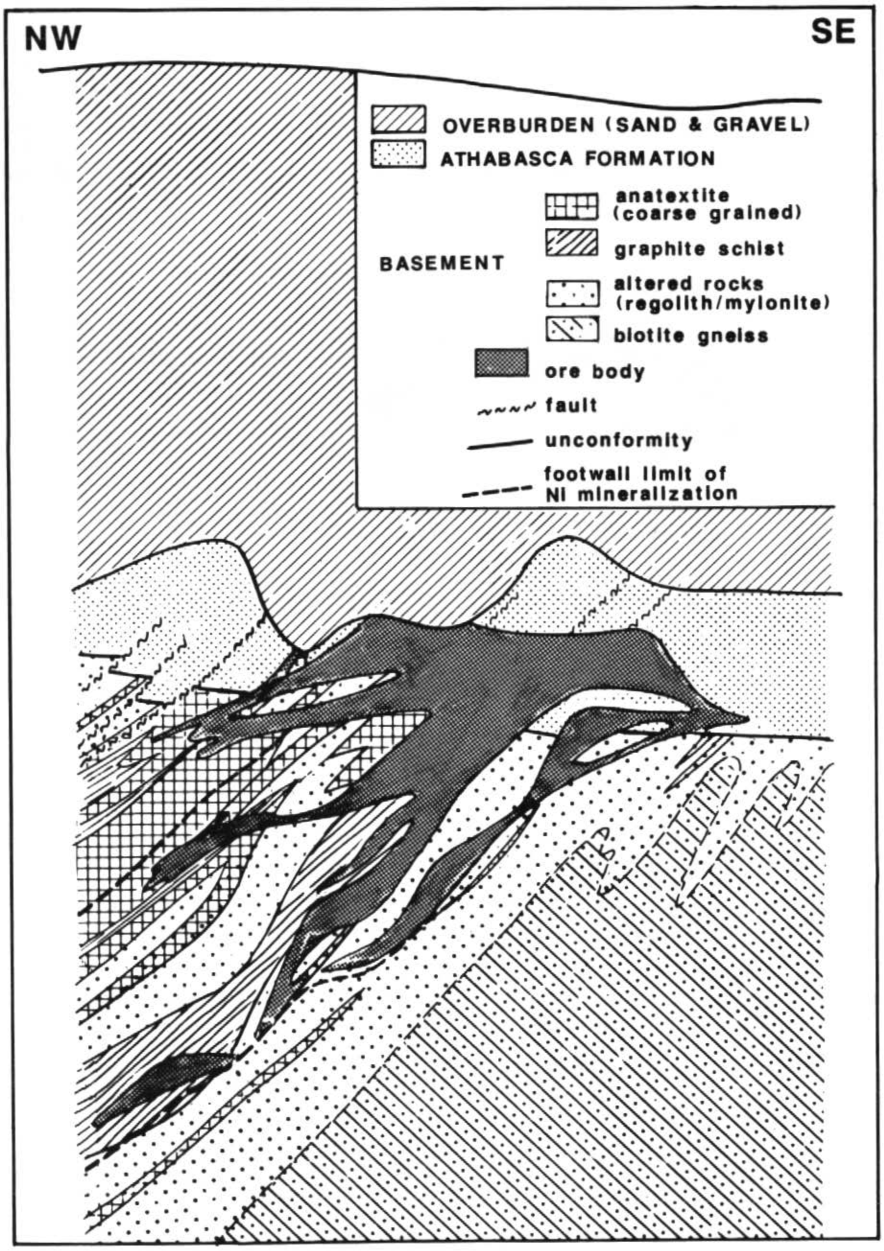

Figure 5 *Generalized geological cross-section of the Deilmann orebody, Key Lake deposit. After Dahlkamp (1978).*

The orebody forms have been described as wedge-shaped (Koongarra: Morton, 1977), tabular (McClean: Jagodits *et al.*, 1986), flattened and elongate (Midwest: Ayres *et al.*, 1983), half cylindrical (Key Lake, Collins Bay: Hoeve *et al.*, 1980), and amoeboidal in plan (Ranger: Morton, 1977). The Nabarlek orebody has been described as pods that occur at the intersection of a transcurrent cataclastic zone and horizons of chloritized rocks, and becomes more tabular with depth where the orebody is cut off by a diabase sill (Hegge and Rowntree, 1978).

In summary, it appears that unconformity-type uranium deposits show a strong structural control and consist of pods, lenses, veins, breccia fillings and disseminations.

Alteration. Three distinct alteration episodes and processes associated with unconformity-type uranium deposits have been recognized. In geochronological order, they are:

(a) "alteration related to retrogression" of the high-grade metamorphic assemblage, during the waning stages of the Hudsonian Orogeny. This is not extensive and has only been described from a few localities. Ayres *et al.* (1983) mention this type of alteration at the Midwest deposit where sericitization and chloritization of cordierite, biotite and feldspars have occurred;

(b) a major episode of **"alteration located at the sub-Athabasca"** level of erosion and weathering, where a paleo-weathering soil profile or regolith developed. This paleosol was preserved from later erosion by being capped by the Athabasca sediments. Wallis *et al.* (1984) give a detailed description of the regolithic horizons which developed during this weathering episode. Characteristically, the regolith shows a vertical zonation and is superimposed on the crystalline basement rocks. Wallis *et al.* (1984) describe an upper red division of the paleosol consisting of hematite capped by a thin (few centimetres) layer of bleached material. The lower half of the regolith is green and is gradational to the overlying red profile and to the underlying fresh bedrock. The zonation of the regolith may be better defined as kaolinite at the top and illite and chlorite at the bottom. Hematite is ubiquitous except at the very base of the profile (Hoeve *et al.*, 1980). At the McClean Lake deposit, the thickness of the regolith varies from 7 to 222 m, and is dependent on the underlying lithology, ranging from the thinnest (less than 21 m) over meta-arkose to the thickest (up to 106 m) over the carbonaceous metapelites (Wallis *et al.*, 1986). Clearly the depth of the regolith extends even further over fault zones and channelways.

The genesis of the regolith has been debated by various workers and is attributed to two fundamental processes: (1) the regolith represents a paleo-lateritic horizon which formed prior to the sedimentation of the Athabasca Formation, or (2) the regolith is a result of diagenesis after the basinal sedimentation.

Wallis *et al.* (1984) assume that the regolith is a paleo-laterite which is the source for quartz, clay and hematite in the Athabasca sediments. However, Ramaekers (1983) points out that the diagenesis and intense alteration of the Athabasca sediments continued several hundreds of million years after their deposition, if not in fact it is still continuing to date. Hoeve *et al.*, (1980) also emphasize that the red colouration of the Athabasca sediments is a consequence of oxidation and post-depositional leaching and, although there are hematite pebbles in the sandstone, the bulk of the hematite in the Athabasca sediments is diagenetically induced. Hematite, kaolinite and illite alteration of the post-Athabasca diabase dykes, as well as bleaching (reduction) of the oxidized regolith, also attest to the post-sedimentation alteration (Hoeve *et al.*, 1980).

It is therefore reasonable to assume that although the regolith was formed prior to the formation of the unconformity and deposition of the sandstone, it has been affected by later diagenesis.

Literature on the Australian deposits does not contain sufficient information on the extent and nature of the regolithic horizon; it may be that most of the regolith has been eroded or that it was only poorly developed.

(c) "the alteration directly associated with the mineralization" which overprints the regolith assemblage (Figure 6). In most instances, where mineralization-related alteration (referred to as hydrothermal alteration in the literature) is superimposed upon the basement rocks and the regolith, characterization of various types of alteration and their paragenesis is difficult or impossible. The best descriptions of this alteration have been given where it has affected the lithologically simpler Athabasca sandstone. One of the characteristic features of the hydrothermal alteration is that it is far more extensive than the mineralization and therefore provides an excellent exploration target. Fouques *et al.* (1986) point out that the alteration at the Cigar Lake deposit extends up to 100 m below and 200 m above the unconformity, but is limited laterally.

The dominant alteration types consist of chloritization, argillization, carbonatization (commonly dolomitization), silicification, sulphidation and tourmalinization. The intensity of the alteration increases with proximity to better mineralized sections. The present literature does not provide sufficient data on the nature of original textures of the primary lithologies which often have been obliterated by deformation and alteration, but in some cases, as has been documented by Fouques *et al.* (1986) from the Cigar Lake deposit, parts of the basement rocks altered to illite and chlorite have retained recognizable relict textures. In most deposits, an overall zonation may be defined and, depending on the dominant host lithology, one or several of the alteration assemblages predominate. At the Cigar Lake deposit, the central core of the mineralized zone comprises illite, sudoite (Mg-rich chlorite), dravite, and rare phosphates, such as goyazite; in addition, all the carbonaceous material has been removed from the upper basement and has been replaced by siderite and calcite (similar to the Rabbit Lake and the Collins Bay deposit, Hoeve *et al.*, 1980). In contrast to the inner core, 50-100 m below the unconformity, partial replacement by illite is practically the only product. At the Rabbit Lake deposit, Hoeve

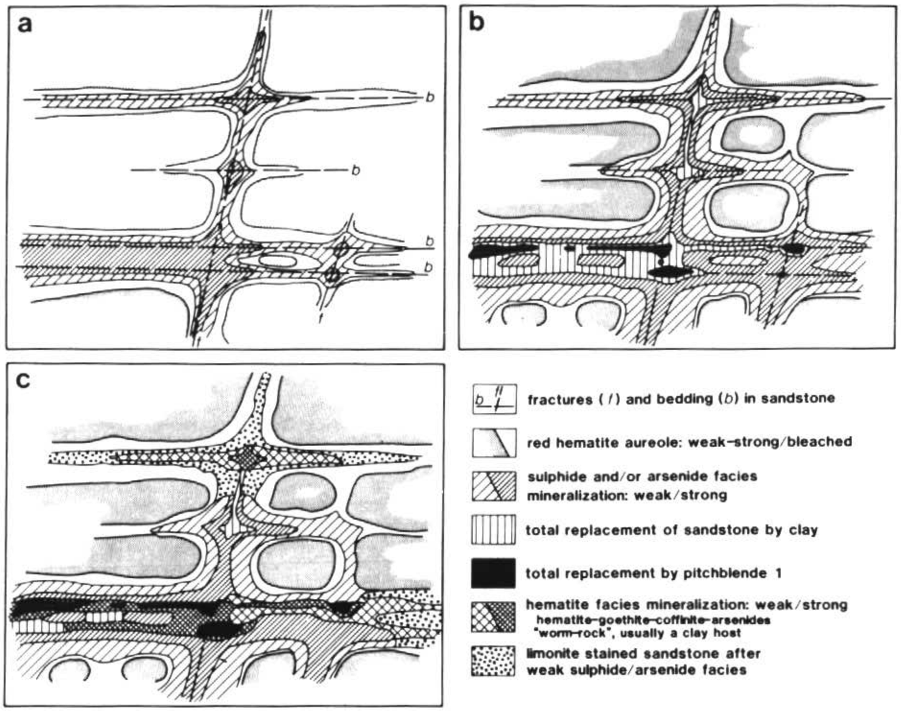

Figure 6 *Alteration and mineralization patterns at the McClean deposits. After Wallis* et al. *(1986).*

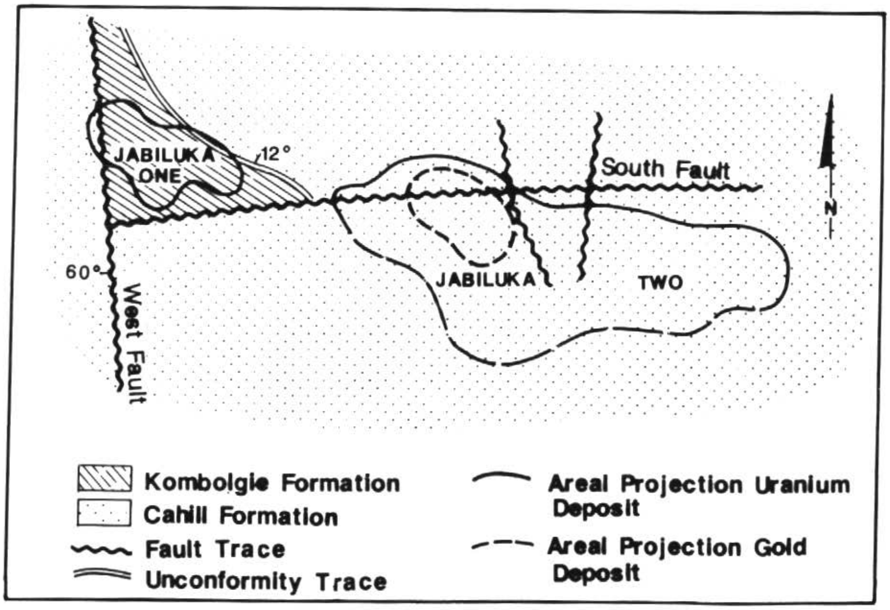

Figure 7 *Plan of Jabiluka I and II deposits; note the overlapping gold mineralization at Jabiluka II. After Hegge* et al. *(1980).*

and Sibbald (1978), describe three types of alteration. An early pre-mineralization type, which is restricted to the high-grade core of the mineralized zone, and consists of dark green Fe-rich chlorite and anatase. The two other types are synchronous with mineralization: a red halo which consists of Mg-rich chlorite, tourmaline (mostly dravite), quartz, anatase and hematite; and a pale green assemblage comprising an assemblage similar to the red halo but lacking the hematite and enriched in pyrite, chalcopyrite, chalcocite and galena. Hoeve and Sibbald (1978) mention that silicification and dolomitization are only locally significant.

A detailed description and paragenesis of the alteration minerals of the Ranger ore bodies is discussed by Nash and Frishman (1981). With the aid of x-ray diffraction and microprobe analyses, these workers show that the most extensive alteration is chloritization (which took place in several episodes), sericitization and argillization (whose distribution is not well known), dolomitization (mostly magnesite and dolomite with calcite totally absent) and formation of apatite and Ti-oxides. Similar assemblages have been reported from Nabarlek and Jabiluka deposits (Hegge and Rowntree, 1978; Binns *et al.*, 1980; Ewers and Ferguson, 1980). Wallis *et al.* (1984) define the alteration package of the McClean deposit based on kaolinite/illite/chlorite ratios. Illite, which is intergrown with various amounts of hematite, exhibits a spectrum of colours, and occurs up to 150 m above the core of the mineralized zone. These authors recognize at least five generations of hematite prior to, and some synchronous with, mineralization and note that it may be replaced by pyrite, siderite and subsequently by limonite. Wallis *et al.* (1984) demonstrate that, in contrast with a deposit such as Key Lake where Mg-rich chloritized rocks are barren and the ore is associated with the Fe-rich chloritic zones (Dahlkamp, 1978), at the McClean deposit, both Fe and Mg-rich chlorites co-exist. Bray *et al.* (1987) have dated illite from the alteration halo of the McClean deposit at 1319 ± 3Ma.

In summary, there are three distinct alteration assemblages in this group of deposits, reflecting metamorphic retrogression, a period of weathering and erosion, and mineralization. The mineralization-related alteration is extensive and overprints the two other assemblages.

Mineralization. One of the most important characteristics of this group of ore deposits is that, unlike other types of uranium deposits, the average grade of mineralization is very high. In most deposits, average grades reach several percents and in some deposits highest grades reach tens of percents of U_3O_8 (Hoeve *et al.*, 1980). In addition to U, the deposits may contain concentrations of Ni, Co, Ag, Mo, Cu, Pb, Zn, Bi, Se and As, and less frequently Au and PGE. In some cases, these elements attain economic grades. Examples include gold at Jabiluka II (Figure 7), gold and selenium in the D Zone of Cluff Lake, nickel and arsenic at Key Lake, Midwest, Cigar Lake and Dawn Lake, and gold and silver at Collins Bay A zone (Sibbald and Quirt, 1987). The genetic relationships among the metallic concentrations are not well understood. For example, Ewers and Ferguson (1980) find no positive correlation between U and Au in the East Alligator Rivers deposits.

An interesting chemical signature of the mineralization is the presence of many species of solid and gaseous hydrocarbons. Hoeve *et al.* (1980) report carbon dioxide, methane and ethane from Rabbit Lake, Cluff Lake and Collins Bay B zone.

The mineralization has three basic characteristics:

(a) There is a primary (hypogene) and a secondary (supergene) mineral assemblage. The main primary uranium minerals are uraninite and pitchblende (both oxides). The latter shows a variety of textures such as euhedral, subhedral, botryoidal, spherulitic, radial and colloform banding. Primary Ni minerals include rammelsbergite, pararammelsbergite, gersdorffite and millerite. Pyrite, arsenopyrite, galena, sphalerite, chalcopyrite and molybdenite are the usual sulphides.

The secondary (supergene) minerals result from *in situ* oxidation and alteration of primary uranium oxides by low-temperature ground waters (Snelling, 1980). At Nabarlek, Morton (1977) has shown that the depth of the supergene enrichment at Nabarlek is approximately 15 m (at the dry-season water level) and at Koongarra 25 m. In this case, a vast range of new minerals are formed, amongst which, the better known include uranophane and sklodowskite (silicate), torbernite and autunite (phosphate) and various vanadates and sulphates.

(b) The mineral assemblage in the Athabasca host rocks differs from that in the basement lithologies. Von Pechmann (1981) shows that the uranium mineralization hosted by the Athabasca sediments consists primarily of sooty pitchblende and coffinite and the Ni occurs mainly as gersdorffite and millerite. In the basement rocks, however, uranium is present as both crystalline and sooty pitchblende and Ni and Co occur as various arsenides. Ayres *et al.* (1983) divide the ore at the Midwest deposit into three types according to their host lithology: (a) the basement ore, which is pitchblende and coffinite; (b) the unconformity ore, which consists of massive and colloform pitchblende; and, (c) the sandstone ore, which is primarily a sooty, fine-grained pitchblende. All three types of uranium ores are accompanied by high concentrations of various Ni-arsenides. At the Dawn Lake deposit, uranium occurs as sooty pitchblende, but in the deeper parts of the mineralized "pods", hosted by the Aphebian metasediments, the texture of the pitchblende becomes botryoidal (Clarke and Fogwill, 1986). This deposit is particularly rich in Co- and Ni-arsenides and chalcopyrite at depth. Hoeve *et al.* (1980) also contrast the lustrous colloform pitchblende in the Athabasca ore with the sooty pitchblende and coffinite in the Aphebian metasediments at the Key Lake deposit.

(c) Paragenesis and timing of mineralization. Lainé (1986) defines three phases of mineralization at Cluff Lake. Uraninite, brannerite and sulphides formed at 1150-1050 Ma, a second stage of uraninite and sulphides formed at 890-820 Ma and a last phase consisting of pitchblende and hematite formed at 380 Ma. Similarly, Dahlkamp (1978) demonstrates that, at the Key Lake deposit, crystalline pitchblende has been altered to sooty pitchblende and the latter has, in turn, been replaced by coffinite. Fouques *et al.* (1986) compare the paragenesis of the Cigar Lake orebody to Key Lake and Cluff Lake, but emphasize that volumetrically the most important phase was the first generation uraninite. Wallis *et al.* (1986) in subdividing the mineralization at the McClean deposit into three facies, note that early base metal sulphides and Ni-arsenides were contemporaneous with pitchblende, were overprinted by sericite and illite, and precede coffinite, colloform pitchblende and a second generation of Ni-arsenides, all of which are contemporaneous with oxides (Figure 6). Snelling (1980) provides another well-documented example of the paragenesis of the metallic minerals from the Koongarra deposit. In this instance, uraninite is divided into two types on the basis of its calcium and lead contents. The first type, with 1-2% CaO, shows many varieties of textures, whereas the second type, containing 3-5% CaO, has colloform banding and resembles low-temperature mineralogy typical of the sandstone-hosted roll-front type deposits. In this deposit, a vast array of secondary minerals constitute the bulk of the mineralization.

In general, there is consensus that the age of "initial" uranium mineralization, in the Saskatchewan deposits, is relatively consistent from one deposit to another. Hoeve *et al.* (1980) quote U-Pb dates such as 1281 Ma for Rabbit Lake, 1200 Ma for Key Lake, 1330 and 1050 Ma for the D Zone of Cluff Lake and Fryer and Taylor (1984) obtain a Sm/Nd age of 1281 ± 80 Ma for Collins Bay. Trocki *et al.* (1984) obtain an age of 1350 ± 4 Ma (U-Pb) for mineralization at Key Lake and suggest that although many younger ages have been reported from various deposits, no other "specific" time can be determined. Bray *et al.* (1987) obtain an alteration and mineralization age of 1319 ± 3 Ma ($^{40}Ar/^{39}Ar$).

In conclusion, the main features of the mineralization are: (i) a hypogene and a supergene assemblage; (ii) different mineralogy in basement and Athabasca host rocks; and, (iii) a multi-phase process with an initial uranium age some 100-150 m.y. younger than the Athabasca sediments.

Fluid inclusion and stable isotope data

The extent of data of this nature in the literature is inconsistent. Bray *et al.* (1982, 1984), Pagel *et al.* (1980), Donnelly and Ferguson (1980) and Ypma and Fuzikawa (1980) present data from some of the Saskatchewan and Australian deposits. Most of these workers obtain similar isotopic signatures, the summary of which follows.

Metamorphic fluids. Fluid inclusions from the Cahill metasediments suggest a metamorphic fluid with NaCl and high density CO_2 at 350°C (Ympa and Fuzikawa, 1980). Donnelly and Ferguson (1980) obtain $\delta^{34}S$ values of $+2.2‰$ for the metamorphic fluids of most of the Pine Creek Geosyncline deposits. Pagel *et al.* (1980) define the metamorphic fluids as carbonic (granulite facies).

Ore-related fluids. Data from samples of ore and alteration minerals show that the ore fluids had different characteristics from the metamorphic fluids. From the Australian deposits, Ympa and Fuzikawa (1980) obtain a very saline fluid with up to 20-30 wt.% $CaCl_2$, 5-10 wt.% $MgCl_2$, 10-20 wt.% NaCl and minor KCl and $FeCl_2$. They estimate a homogenization temperature of 160-110°C. Pagel *et al.* (1980), on the other hand, calculated temperatures ranging from 160-185°C from fluid inclusions from the Rabbit Lake deposit.

Isotopes. Carbon isotope values from the Cahill metapelites (either carbonates or carbonaceous minerals) indicate a sedimentary origin, and suggest an organic derivation (Donnelly and Ferguson, 1980). Bray *et al.* (1984) report that the oxygen isotope values obtained at the McClean deposits show no difference between the mineralized and unmineralized rocks. However, through the use of hydrogen isotope data, it is possible to distinguish the illite and chlorite associated with the ore zone from illite in the sandstone and the regolith. Ympa and Fuzikawa (1980), based on their oxygen isotope data from several Australian deposits, suggest a meteoric origin for the ore-forming fluids. Sulphur isotope information (Bray *et al.*, 1982) indicate similar signatures for the ore-related and barren sulphides.

In summary, ore fluids were highly saline (showing many salinity reversals), with an average temperature of 180-200°C. Pagel *et al.* (1980) and Bray *et al.* (1987) compare these fluids to diagenetic brines and point out that their characteristics are different from the earlier metamorphic fluids.

Genesis

As for any group of mineral deposits, debate over the genesis of unconformity-related uranium deposits has continued since the discovery of the first deposit of this type and their recognition as a class.

An examination of the progression of the genetic models developed for these deposits shows that early models, because of lack of sufficient geological and detailed laboratory data, are incomplete and therefore simplistic. Subsequently, when the complexity of the deposits was realized (by access to three-dimensional exposures and larger number of discoveries), the models that developed included all possible geological processes in an attempt to accommodate all features. It is only after many years of careful geological and laboratory documentation that models were produced which involved a single, dominant process capable of explaining most of the features of these deposits. The following is a brief account of this evolutionary path.

The "supergene model". The supergene model was originally proposed by Knipping (1974), and Ruzicka (1975), amongst others. In this case, it is assumed that uranium and other metals in the Lower Proterozoic rocks, were leached by ground and surface waters and were precipitated when and where they encountered a reducing environment such as the carbonaceous metasediments. The timing of this process is presumed to be pre-Athabasca, during the weathering and erosion that resulted in the formation of the regolith.

The supergene model was debated by workers, such as Hoeve and Sibbald (1976, 1978), who demonstrated the inconsistency of many geological observations with the proposed model. For instance, subsequent discoveries have shown that extensive amounts of mineralization occur within the Athabasca sediments and that both alteration and mineralization overprint the regolithic alteration. Also, later dating by various workers has proven that initial mineralization post-dates Athabasca sedimentation (Bray *et al.*, 1987; Armstrong and Ramaekers, 1985; Bell, 1981, 1985).

The "hypogene model". The sources of the mineralizing structures for the hypogene model range from metamorphogenic/hydrothermal (Hegge and Rowntree, 1978; von Pechmann, 1981; Morton, 1977) to magmatic/hydrothermal (Binns *et al.*, 1980) to a combination of the two. In this model, the source of the fluids is considered to be deep-seated, generated during the metamorphic event that preceded the deposition of the Athabasca sediments. Hegge and Rowntree (1978) suggest that during the metamorphism of high-uranium granites (averaging 9.6 ppm U) and metasediments (average of 34 ppm U in the Cahill Formation), uraniferous fluids were generated, as a result of anatectic rejuvenation, migmatization and pegmatitic intrusion; later retrogression caused Mg-metasomatism and uranium deposition. Binns *et al.* (1980) hypothesize that a geological setting such as Jabiluka represents an upwelling centre where radiogenic heat generated from adjacent granites drove a convective cell of circulating metalliferous fluids. These authors suggest the same post-kinematic granitoids as the source for uranium. Fogwill (1981) even considers a mantle-derived source for the Ni-Co-As assemblage. One of the major drawbacks of this model is the fact that it does not satisfactorily explain the undeniable spatial association of the deposits with the pre-Helikian unconformity.

"Polygenetic, multiphase model". In order to accommodate all the features that are characteristic of the deposits, a number of workers have presented a multigenetic model. Dahlkamp (1978), Clarke and Fogwill (1986), McMillan (1977), Fouques *et al.* (1986) and Nash *et al.* (1981) present an involved

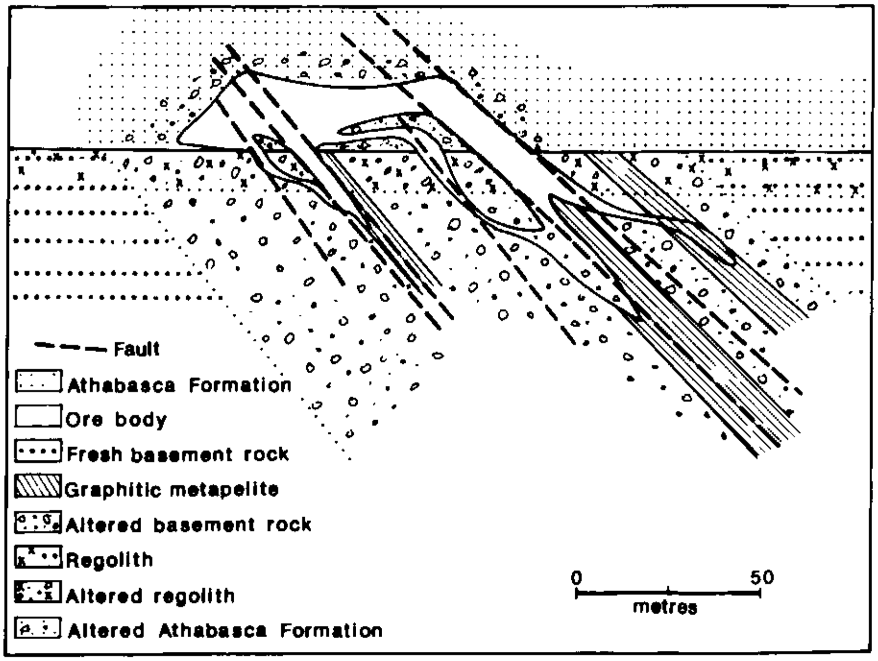

Figure 8 *Schematic cross-section of an orebody showing the general setting of unconformity-related deposits. After Hoeve and Sibbald (1978).*

and complex history of mineralization, which includes the following stages:
(a) Lower to Upper Proterozoic syn-sedimentary concentrations of uranium in carbonaceous sediments at 2200-1900 Ma;
(b) mobilization and further concentration of the uranium mineralization during the Hudsonian Orogeny at 1900-1800 Ma;
(c) formation of the regolith, whereby weathering and surface leaching removed some of the mineralization and redeposited a new generation of uranium minerals in fractures and faults of the basement rocks; this event took place at 1800-1350 Ma;
(d) deposition of the Athabasca Basin, generating diagenetic fluids and another generation of uranium minerals at 1350-1000 Ma; and, (e) finally, secondary mineralization during several episodes of uplift and erosion between 1000 and 200 Ma.

One of the major problems with this model is that syngenetic, economically significant deposits have never been identified in these environments (Nash *et al.*, 1981). Hegge and Rowntree (1978) report a background value of 34 ppm uranium in the Cahill Formation. However, Nash *et al.* (1981) remark that these values were not obtained from entirely barren rocks and represent a mixture of mineralized and unmineralized samples. Trocki *et al.* (1984), in discussing the Key Lake deposit, note that a concentration of at least 240 ppm U is necessary in the protore in order to reach the subsequent concentrations. The most problematic aspect of the polygenetic model is the timing of events. Bray *et al.* (1987), Armstrong and Ramaekers (1985), Baadsgaard *et al.* (1984) and Blenkinsop and Bell (1981) present many isotopic ages which clearly demonstrate that the timing of the first stage of mineralization postdates the deposition of the Athabasca sediments.

In summary, the following reasons suggest that evidence to prove the early stages of the model are insufficient: (i) lack of anomalous concentrations in the country rocks; (ii) absence of early mineralized veins; (iii) superposition of the alteration/mineralization assemblage upon the regolith; and, (iv) post-Athabasca, initial mineralization ages.

"Diagenetic model". Hoeve and Sibbald (1976, 1978), Hoeve *et al.* (1980) and Jones (1980), amongst others, are the advocates of the diagenetic model (Figure 8). Sibbald (1985) proposes that interaction of the basement and Athabasca rocks through the mixing of chemically contrasting fluids was responsible for precipitation of uranium. Hoeve *et al.* (1980) explain that after the deposition of the Athabasca sediments, intraformational fluids percolated through them to encounter a different physico-chemical environment upon reaching the unconformity and the basement contact. The oxidizing metalliferous fluids were heated during their descent along the geothermal gradient (T = 180-220°C and P = 700 bars from fluid inclusions, Pagel, 1975, 1977) and intersected a reducing environment at the base of the unconformity which could either be the carbonaceous metasediments or methane-bearing fluids ascending faults and fractures in the basement. At this redox front, which is described by Sibbald (1985) and Sibbald and Quirt (1987) as dynamic but basically stationary, metals were released from the fluids and precipitated in favourable structural sites such as the porous regolith, faults, fractures and breccias. Wallis *et al.* (1986) support the diagenetic model and propose a "two-fluid" system (the reductant plume model) to account for the redox variations. Hoeve *et al.* (1980) and Sibbald and Quirt (1987) consider the Athabasca sediments themselves as a possible source of metals, whereby breakdown of feldspars, mafic and heavy minerals could have released uranium and other metals which would have stayed in solution within the oxidizing environment of the sediments.

The strongest evidence in support of this genetic interpretation is the fact that it agrees with the paragenesis of the alteration and mineralization assemblages and the isotopic age data.

Summary and Discussion

The unconformity-related uranium deposits: (i) are hosted by varied lithologies located below, at, and above the unconformity between Lower and Middle Proterozoic rocks; (ii) occur as veins, breccias, and open-space fillings usually associated with reverse and normal faulting; (iii) are associated with three episodes of alteration related to the retrogression of the amphibolite metamorphic event, weathering and erosion, and later hydrothermal activity; (iv) are commonly polymetallic consisting of uranium, V and Mo oxides, Ni, Co, Cu, Zn and Pb sulphides and arsenides, and in some cases native Au; (v) have isotopic signatures which indicate a high salinity ore-forming fluid, ranging between 160 and 200°C (similar to diagenetic fluids); and, (vi) have initial mineralization ages between 1350-1200 Ma, which are 100-150 m.y. younger than the depositional age of the Middle Proterozoic sediments.

Most of the geological relationships, such as the paragenesis of the alteration and mineralization assemblages as well as the radiogenic and stable isotope data, suggest that, of the models presented, the "diagenetic" model accounts for the majority of the features of this class of deposits. The source of uranium and other metals is still not well established, and as proposed by Hoeve *et al.* (1980), the metals may have derived from the sedimentary basins or they may be from other origins. Hoeve *et al.* (1980) compare the unconformity-related deposits to younger uranium deposits which are hosted by sandstone beds and their siting is controlled by a redox front (roll-front type). In many respects, the mode of transportation, the site of deposition and the alteration associated with roll-front deposits are comparable with unconformity-type deposits emphasizing that similar ore-forming processes were active during various geological episodes.

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