A REVIEW OF UNCONFORMITY-TYPE URANIUM DEPOSITS

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Dissertation submitted in partial fulfilment of the requirements for the degree of Master of Science (Mineral Exploration) at Rhodes University.

JANUARY, 1980

This dissertation was prepared in accordance with specifications laid down by the University and was completed within a period of ten weeks full-time study.

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ABSTRACT

Intense interest in uranium in the past decade has led to the discovery of new kinds of deposits of which the so-called unconformity-type are economically the most important. Presently known occurrences are restricted to Australia and Canada where they are characterized chiefly by their spatial relationship to Lower-Middle Proterozoic unconformities. Other common features include similar host-rock assemblages, structural controls, alteration, mineralogy, age relationships and fluid-inclusion data. Similar characteristics in other vein-type deposits, including those of the Beaverlodge district in Canada, deposits in France and Portugal, and the Schwartzwalder mine in the United States, suggest that they may also be of the unconformity-type.

Various interpretations of the geological relationships of unconformity-type deposits have resulted in a number of genetic hypotheses, which require different exploration philosophies. Near-surface supergene processes are considered to be most important although other mechanisms may have played contributing roles in the concentration of uranium.

There is considerable potential for further discoveries of unconformity-type uranium deposits throughout the world. No such deposits are yet known in southern Africa although several favourable Precambrian unconformities are present.

INTRODUCTION

Intense interest in uranium in the past decade, arising mainly from the uncertainty of future energy supplies has promoted understanding of the geochemical behaviour of uranium, and resulted in the discovery of new types of economic and potentially economic uranium deposits. The most important new discoveries have been vein-type deposits in Australia and Canada. They are characterized by their spatial and perhaps genetic relationship to the Lower/Middle Proterozoic unconformity in both countries, hence their description as "unconformity-type" deposits. Because of their relatively high grades and the potential for further discoveries in various parts of the world, they should be considered as extremely attractive exploration targets wherever suitable geological environments are present. Although the most important unconformity-type deposits are associated with Proterozoic rocks, similar deposits are known in France, Portugal and other parts of Europe associated with rocks of Hercynian age (approximately 300 my). Vein-type deposits in other parts of the world may also be associated with unconformities of different ages, but in many cases they have not yet been recognized as such.

The main purpose of this dissertation is to examine the Australian and Canadian occurrences in some detail with a view to establishing a set of empirical criteria which may be significant in the exploration for these deposits. Some of the genetic theories for these deposits are reviewed and their influence on exploration compared. Although exploration methods are not described in detail, some important aspects of exploration for unconformity-type vein deposits arising from their particular geological associations are discussed. Other vein-type deposits in Canada, Europe and the United States are described briefly for comparative purposes.

Finally the potential of Southern Africa for unconformity-type uranium deposits is considered by comparing the favourable geological settings with their counterparts elsewhere.

GEOCHEMISTRY AND DISTRIBUTION OF URANIUM IN THE CRUST

Uranium is an extremely mobile element under certain conditions and as such is concentrated in a variety of geological environments by several different mechanisms. Since this variable behaviour is partly responsible for the variety of genetic theories which have been proposed for the unconformity-type uranium deposits, a brief review of geochemical and other factors controlling the distribution of uranium in the crust is presented in order to provide a basis for evaluating the theories.

Uranium is a lithophile and oxyphile element capable of existing in several valence states namely U^{2+}, U^{3+}, U^{4+}, U^{5+} and U^{6+}. Of these U^{4+} and U^{6+} are particularly important since the transition from U^{4+} to U^{6+} has a redox potential within the normal range for geologic environments (Krauskopf, 1967). The U^{2+} and U^{3+} valance states are such powerful reducing agents that they are readily oxidized to higher oxidation states. Although the U^{5+} valence state has previously been regarded as geologically unimportant (Krauskopf, 1967), Langmuir (1978) has shown that as the $(UO_2)^+$ ion it has an appreciable field of stability in reduced waters below pH = 7.

In the subsurface environment uranium occurs in the U^{4+} oxidation state and has an ionic radius of 1,08Å, which, in conjunction with its high charge has resulted in its classification as an incompatible element (Ringwood, 1975). As such uranium is excluded from normal rock-forming silicate minerals during magmatic crystallization and tends to be preferentially enriched in the late stage members of igneous differentiation series, especially in rocks of granitic composition. In these rocks uranium may occur as accessory uraninite (UO_2) but is also commonly contained in significant amounts in other accessory minerals such as thorianite, thorite, xenotime, zircon, monazite, sphene, allanite, epidote and apatite, in which uranium substitutes for such elements as zirconium, titanium, fluorine, thorium and phosphorus. Of particular importance is the diadochy between U^{4+} and Th^{4+} which is due to the identical charges and radii of these elements and results in their common association in igneous rocks. According to Rich et al. (1977) much of the uranium in rocks is only loosely held, occurring as films coating grains and cracks in rock-forming minerals. The tendency towards enrichment of uranium in more felsic rocks is clearly illustrated in Table 1.

	U
Igneous Rocks	
Ultramafic	0.003-0.1 ppm
Gabbro-basalt	0.1-1
Andesite	0.4-1.4
Granitic	
Alkalic Rocks	
Conway granite, U.S.A.	15 ppm *average*
Syenites, Russia	15-20
Colorado Front Range	44 (avg.) to 140
Sandstones	
Clean quartz sandstones	0.5-3 ppm
Volcanic (andesitic) sandstones	0.5-1.3
Arkoses	1.5 (est.)
Limestones	2.2
Shales	
Green, gray and red	2-4
Black Shales	
Marine (except geosynclinal)	20 ppm
All black shales	8 ppm
Chattanooga shale	80 (up to 350)
Alum shale (Sweden)	170

Source: Rogers and Adams, 1970.

TABLE 1 : Average content of uranium in crustal rocks. (From : Barasko, 1979)

The distribution of uranium in sedimentary rocks depends on the behaviour of uranium in solution in surface and groundwaters and on the depositional environment of the sedimentary rocks. Uranium is essentially mobile in its oxidized U^{6+} state and immobile in the reduced U^{4+} state. Studies by Langmuir (1978) have shown that the formation of complexes is most important in determining the mobility of uranium in natural waters. The most common complexes are carbonate, hydroxide, phosphate, fluoride, sulphate, and possibly silicate, as well as organic complexes, all of which increase the solubility of uranium minerals and hence the mobility of uranium in solution.

In reducing waters uranous (U^{4+}) complexes do form, but because of the extreme insolubility of primary minerals such as uraninite and coffinite under these conditions, they are rather unimportant. The relative importance of some uranous complexes are shown in Figure 1 which indicates that only the fluoride and rarely the hydroxyl complexes of U^{4+} can reach significant concentrations in groundwaters, and then only below pH = 3 for the fluoride complexes, and above pH = 8 for the $U(OH)_5^-$ complex. Since such conditions are for the most part outside the limits for natural groundwaters which possess pHs ranging from 4 to 9 (Levinson, 1974), uranium concentrations in reducing groundwaters are generally less than 0,01 ppb (Langmuir, 1978).

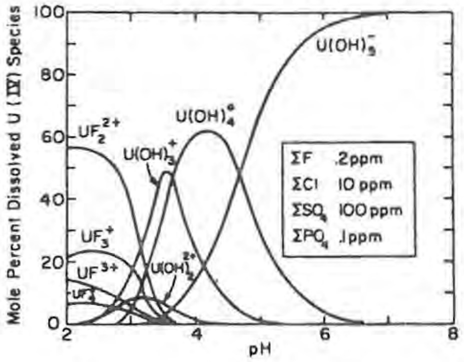


FIGURE 1 : Distribution of uranous complexes vs. pH for some typical ligands in ground water at 25°C. (From : Langmuir, 1978)

In oxidizing environments uraninite undergoes a solid state transformation to amorphous UO_3 which in oxygenated groundwaters readily dissociates to form the soluble uranyl $(UO_2)^{2+}$ ion (Qidwai and Jensen, 1979). The solubility of uranium minerals and the mobility of uranium in surface and groundwaters is greatly enhanced by the formation of uranyl complexes, which are considerably more important than uranous complexes. According to Langmuir (1978) the most important complexes are formed with fluoride, phosphate and carbonate ions, and are pH dependent. Therefore, in oxidized natural waters uranyl fluoride complexes predominate below pH = 5, uranyl phosphate complexes from pH = 4 - 7,5 and uranyl di- and tri-carbonate complexes at higher pHs. Sulphate complexes may be significant below pH = 7, whilst silica forms a somewhat weaker complex with the uranyl ion which is most important at pH = ±6. The relative importance of the various uranyl complexes as determined from typical groundwaters in the uraniferous Wind River Formation in the Shirley Basin of Wyoming is illustrated in Figure 2.

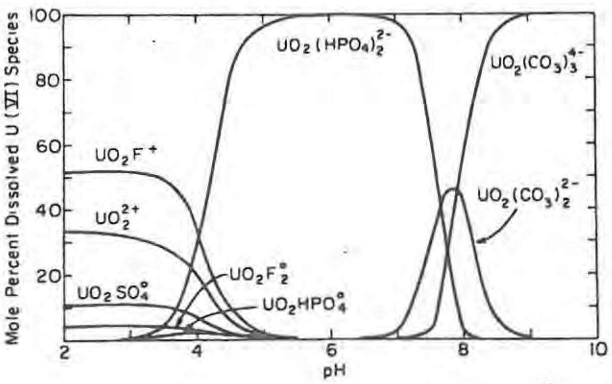


FIGURE 2 : Distribution of uranyl complexes vs. pH in typical groundwaters of the Wind River Formation at 25°C (From : Langmuir, 1978).

Uranium may be precipitated from solution by several processes, which include precipitation by unusual complexes, reduction and adsorption. In its U^{6+} form uranium may be precipitated from solution by a variety of complex anions, the most important of which are carbonate, vanadate and phosphate to form uranyl minerals such as carnotite and tyuyamunite (vanadates); autunite (phosphate); and uranophane (silicate). These most commonly form adjacent to uranium ore deposits by oxidation and leaching of primary uranium minerals such as uraninite and coffinite. Uranyl minerals are most common in arid climates where evapo-transpiration concentrates the uranium and precipitating ligands, and where CO_2 pressures in soils and groundwaters are relatively low because of the absence or scarcity of organic activity in the soil (Langmuir, 1978). Carnotite may also be precipitated as a primary mineral, as is the case in the Yeelirrie uranium deposit in the calcretes of Western Australia, where it is the most important ore mineral. The actual precipitation mechanism in this case is not well understood and up to eight different processes have been proposed (Mann, 1974; Carlisle et al., 1978).

Uranous minerals are considerably more important than uranyl minerals in uranium ore deposits, and the two most important minerals, uraninite (pitchblende) and coffinite are most commonly precipitated from uraniferous groundwater by the reduction of the mobile U^{6+} species to U^{4+} species by means of a variety of reducing agents. Examples of such reducing agents include carbon, iron, sulphur and hydrocarbons, all of which should be oxidized concurrently with the precipitation of uranium. Some oxidation reactions are : the oxidation of HS^- to SO_4^{2-}; Fe^{2+} to $Fe(OH)_3$; pyrite to Fe^{2+} and SO_4^{2-}; CH_4 to CO_2 and H_2 to H_2O. According to Langmuir (1978) the oxidation of Fe^{2+} to hematite, which is a common constituent of vein-type and many other types of uranium deposits, takes place at an oxidation potential below the H_2O (liquid) - H_2O (gas) boundary and is therefore theoretically impossible at normal temperatures (25^oC). Thus in such deposits as the sandstone uranium deposits of the Colorado Plateau hematite does not precipitate directly from groundwater but rather forms through time by the recrystallization of more soluble ferric hydroxides. However, at higher temperatures, oxidation of Fe^{2+} with direct crystallization can occur, and could lead to the co-precipitation of uraninite and hematite as observed in many vein-type uranium deposits.

Another process which may be instrumental in precipitating uranium from solution, is adsorption onto clay minerals. Giblin (1979) describes a postulated sequential process whereby $(UO_2)^{2+}$ or $(UO_2OH)^+$ is adsorbed by clays from an oxidizing solution containing less than 100 ppb uranium. In the process the adsorbed $(UO_2)^{2+}$ is subsequently reduced to UO_2 during a period of reduction, but remains adsorbed as such. During renewed oxidation the UO_2 is oxidized to a stable uranium mineral of such a stoichiometric composition that the surface charge is incompatible with that of the clay surface and decomposition occurs, thus leaving the clay free to repeat the cycle. Whilst this mechanism alone is not considered to be capable of producing ore-grade concentrations of uranium, Giblin (1979) proposes that the catalytic role played by adsorption, coupled with chemical changes initiated either by changes in the redox potential or changing temperatures could account for the intimate association observed between chlorite and uranium mineralization in vein-type deposits in the Alligator Rivers Uranium Field in the Northern Territory, Australia.

Poty et al. (1974) proposed, by deduction from fluid inclusion studies that pitchblende in French vein deposits may have been precipitated from highly carbonated solutions by a decrease in CO_2 content related to boiling. However Rich et al. (1977) doubt the validity of the proposal, suggesting that the effects of the process would be counteracted by other changes in the system related to CO_2 loss, such as increase in pH, or calcite precipitation. The former change would prevent further pitchblende precipitation whereas the expected calcite does not usually form simultaneously with pitchblende in uranium vein deposits.

In general precipitation of uraninite appears to be most dependent on redox conditions. Uranous minerals are most stable in low Eh environments at normal groundwater pHs, but at an intermediate Eh oxidation and leaching are greatly enhanced by the formation of complexes. Uranyl minerals are stable at a higher Eh and within a pH range of 5 - 8,5 (Langmuir, 1978).

The distribution of uranium in sedimentary rocks depends on the availability of suitable precipitants (assuming uranium is present in solution). Since reduction is apparently the dominant precipitation mechanism, the association of uranium with organic rich carbonaceous shales, (Table I) is to be expected. Where the shales are non-carbonaceous uranium contents are lower, the uranium either being adsorbed onto clays or contained within inclusions in the constituent minerals such as zircon in biotite for example. Clean sandstones are usually poor in uranium, probably due to the lack of reductants. The uranium in this case is largely concentrated in heavy accessory minerals. A notable exception to this generalization are the Witwatersrand-type detrital uranium deposits in which uraninite is the main ore mineral. These deposits are restricted to green and grey conglomerates and quartzites older than 2200 my and the ability of uraninite to exist in detrital form has been attributed by many authors (e.g. Robertson et al., 1978) to an oxygen deficient atmosphere in those times. Post 2000 my sandstones and conglomerates are typically red in colour and devoid of uraninite suggesting an oxygenated atmosphere. High concentrations of uranium in these rocks are only achieved where abundant organic material is present as is the case in the fluviatile sandstones of the Colorado Plateau. Rare concentrations of uranium occur in sandstones free of organic material, such as the deposits of the Texas Coastal Plains where mobile reducing agents related to petroleum occurrences have been invoked to precipitate the uranium (Adler, 1974). Pure limestones are generally uranium poor, whilst marine phosphorites may be sufficiently enriched in some cases to constitute potential ore deposits (Table I). In the latter case enrichment is due to the coprecipitation of uranium with apatite (Rich et al., 1977).

The uranium content of metamorphic rocks is variable but tends to reflect the uranium content of their protolith. However, some high-grade metamorphic rocks are apparently depleted in uranium relative to their lower grade and unmetamorphosed equivalents, suggesting that some mobilization of uranium might have occurred during metamorphism (Rich et al., 1977).

UNCONFORMITY-TYPE URANIUM VEIN DEPOSITS

CLASSIFICATION

Most classification schemes for uranium ore deposits, particularly if they are genetic, are complex because of the many environments and concentrating processes involved in the formation of economic deposits and also because many deposits are polygenetic due to the high mobility of uranium. In the last decade the classification of uranium deposits has been further complicated following the recognition of new types of uranium deposits, including the so-called unconformity - vein deposits and the calcrete deposits. The unconformity-type deposits are particularly difficult to classify genetically because their genesis is poorly understood.

Unconformity-type uranium deposits have been defined by Derry (1973, p. 1378) to be those uranium deposits "which have a veinlike or transgressive character and occur at an unconformity, generally between basement and a relatively unmetamorphosed cover rock". Although they are generally referred to as vein-type deposits, Derry (1977, p 58) has pointed out that the class also "includes on a much larger scale broad, shallow zones that may be basin-shaped or controlled by stratigraphy, and would not normally be classed or mined as veins". He distinguishes them as a class by their relationship to major unconformities following periods of extensive erosion, probably under semi-tropical conditions. This association with unconformities has led to considerable debate over the genesis of the unconformity-type deposits with many authors favouring a near surface supergene process of formation, in contrast to the previously generally accepted hydrothermal origin for all vein-type deposits.

The different treatment which vein-type uranium deposits have received in recent classification of uranium deposits is well illustrated by the genetic classifications of McMillan (1978) and Dahlkamp (1978a). In his classification McMillan distinguishes between what he has termed *classical* and *unconformity* veins, but classes them both as hydrogenic deposits, or deposits "formed by the precipitation from solution in water" (McMillan, 1978, p. 63), thus avoiding the genetic implication of such terms as supergene or hydrothermal, which are most commonly used. According to McMillan (1978) most vein deposits are similar in terms of their mineralogy and associated alteration products, whilst *all* are of low temperature origin, and *all* show close relationships to major unconformities. He distinguishes between unconformity-vein deposits and 'classical' vein deposits according to their mode of occurrence, regarding the former as deposits which are closely associated with stable peneplaned surfaces, whilst suggesting that the 'classical' vein deposits were emplaced during a tectonically active, late orogenic episode when there was considerable topographic relief. Neither type is thought to have magmatic affiliations, the uranium having been deposited from groundwaters in both cases. For the vein-deposits McMillan (1978) suggests that redistribution and deposition of uranium may have been promoted by retrogressive metamorphic alteration accompanying cataclasis, whilst the unconformity-vein deposits formed as a result of weathering processes acting on syngenetic concentrations of uranium in sediments below the unconformity. Thus the main difference between unconformity-vein and 'classical' vein deposits appears to be their different tectonic settings. Following this classification the vein deposits associated with the Athabasca Formation in northern Saskatchewan are unconformity-type deposits whereas the deposits of the Beaverlodge district are 'classical' vein deposits.

The classification of Dahlkamp (1978a) is presented in Figure 3 and shows a somewhat different interpretation of vein deposits which he clearly subdivides into *hydrothermal* and *veinlike* deposits. The latter are distinct from 'real veins in the classical sense' which 'are regarded as of magmatic hydrothermal origin' (Dahlkamp, 1978a), and are characterized by pitchblende in massive ore veins or bodies, and as impregnations in shear zones. Veinlike deposits are further subdivided (Dahlkamp, 1978b) into the Key Lake subtype which corresponds to McMillan's (1978) unconformity-vein deposits, and the Beaverlodge subtype which is represented by the peneconcordant vein-type mineralization of the Fay Mine and other deposits in the Beaverlodge district in Canada. The latter deposits are not considered to be genetically related to unconformities in contrast to McMillan's (1978) views. Broad but significant differences between the two classifications are illustrated in Table II by using examples of ore deposits. The most striking difference is in the genetic interpretation of the Schwartzwalder deposit in Colorado, U.S.A., which McMillan (1978) considers

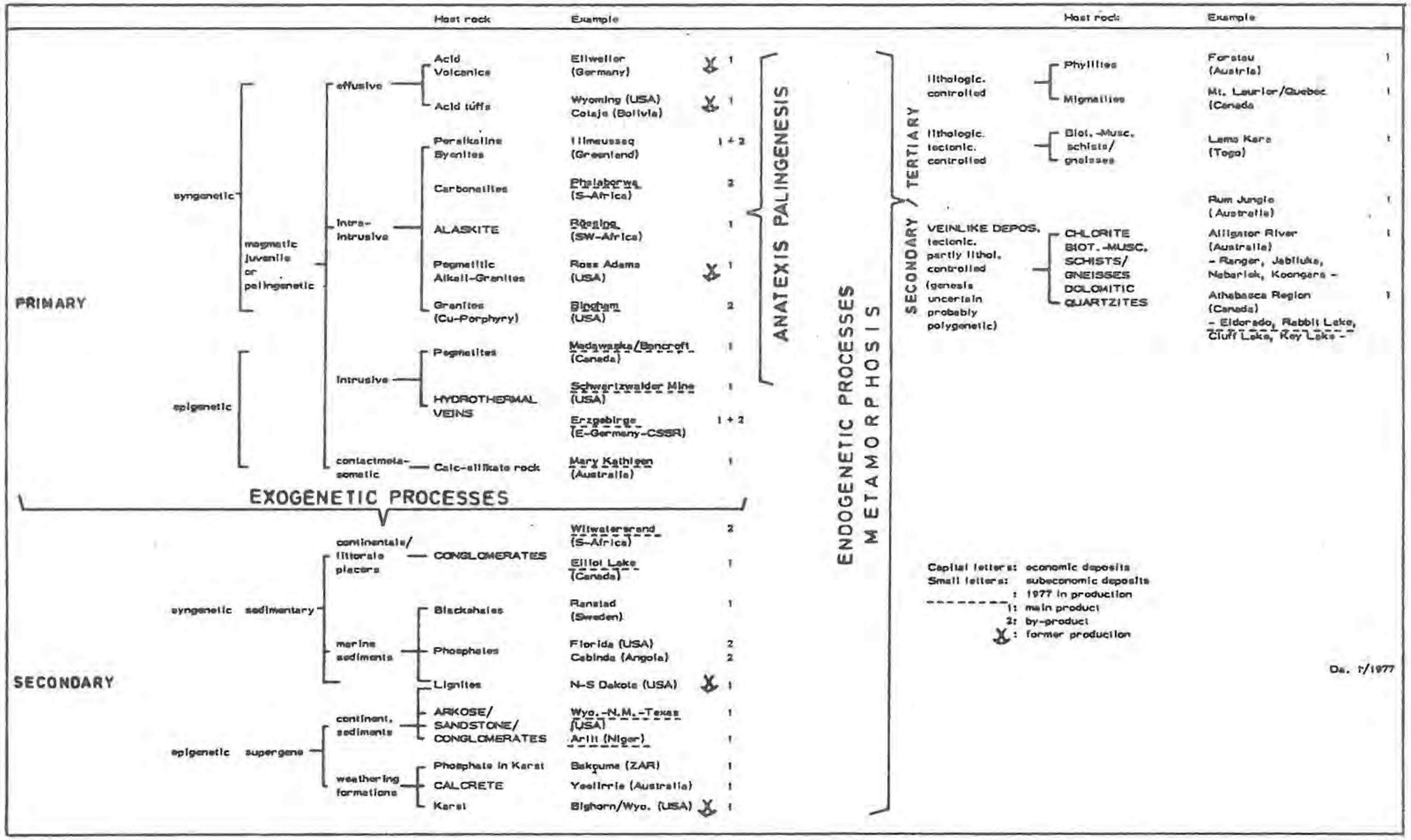


FIGURE 3 : *Classification of uranium deposits (From : Dahlkamp, 1978a)*

to be equivalent to the Beaverlodge deposits, whilst Dahlkamp (1978a) regards it as a hydrothermal deposit.

<table>
<tr><th colspan="3">DAHLKAMP (1978a,b)</th><th colspan="2">McMILLAN (1978)</th></tr>
<tr><td colspan="2">HYDROTHERMAL DEPOSITS</td><td>Schwartzwalder Mine</td><td rowspan="2">CLASSICAL VEINS</td><td>Schwartzwalder Mine</td></tr>
<tr><td rowspan="2">VEINLIKE DEPOSITS</td><td>Beaverlodge subtype</td><td>Beaverlodge District</td><td>Beaverlodge district</td></tr>
<tr><td>Key Lake subtype</td><td>Athabasca Basin deposits</td><td>UNCONFORMITY VEINS</td><td>Athabasca Basin deposits</td></tr>
</table>

TABLE II : A comparison of recent classifications of vein-type uranium deposits

The overlap between different classes in the two classifications as portrayed in Table II, and the different genetic interpretations, confirm that the genesis of vein-type uranium deposits is poorly understood and suggests that a genetic classification cannot really be justified at present. For these reasons unconformity-type deposits as defined in this dissertation are restricted to those deposits in the Northern Territory of Australia, and the Athabasca Basin in northern Saskatchewan, Canada, where the spatial relationship to a major unconformity is well established. Other vein-type deposits which may or may not be related to unconformities are described for comparative purposes.

It may well be that all these deposits are of vein type, and that the unconformity situations are only relevant in that they modify the veins in some cases by dispersing and/or upgrading the ores in the veins through groundwater or later hydrothermal activity. Alternatively, unconformity-type deposits may include the upgraded vein-deposits as well as other upgraded forms of uranium concentration such as syngenetic enrichments in sediments or granites.

ECONOMIC CHARACTERISTICS AND POTENTIAL

The most striking economic characteristic of the unconformity-type deposits is their high grade compared to most other types of uranium deposit. The available grade and tonnage figures for the most important Australian and Canadian deposits are presented in Table III which indicates that, whilst there is considerable variability both in grade and tonnage, even the smaller deposits possess substantial quantities of uranium. The Jabiluka deposit in Australia, with some

COUNTRY	DEPOSIT		% U_3O_8	TONNAGE	CONTAINED U_3O_8 TONNES
CANADA		Rabbit Lake	0,4	4 500 000	18 100
	CLUFF LAKE	D orebody	8,2	939 000	7 700
		N orebody	0,4	2 025 000	8 100
		C orebody	0,5	1 180 000	5 900
	KEY LAKE	Gaertner	2,84	841 549	23 900
		Deilmann	2,11	1 066 350	22 500
		Midwest Lake	3,4	1 291 176	43 900
AUSTRALIA		Jabiluka I	0,256	1 361 000	3 000
		Jabiluka II	0,397	52 000 000	204 400
		Ranger Ore	0,2007	41 000 000	100 350
		Koongurra	0,24	12 000 000	32 500
		Nabarlek	1,84	494 470	9 500

TABLE III : Compiled from Hegge (1977), Hegge and Rowntree (1978), Munday (1979) and Needham et al. (1979).

207 000 tonnes of contained uranium is the largest concentration of uranium in the world. Average grade and tonnage figures for all of the major types of uranium deposits (Table IV) show that the economic potential of unconformity-type deposits is greater than both sandstone-type and conglomerate-type uranium deposits which at present are the two main sources of uranium production. From an investment point of view the unconformity-type deposits are extremely attractive since their comparatively low tonnages for similar uranium contents to most other types of uranium deposit would result in a lower initial capital investment, lower operating costs because of smaller equipment requirements

TYPE OF DEPOSIT	SYMBOL	AVERAGE U-GRADE in %	TOTAL U-POTENTIAL (MINED + RESERVE) ≤ $ 15 p lb — Individual Deposit in t U	Uranium District up to max t U	MINED AS — Main Product	Secondary Product
CONGLOMERATE-TYPE	●	0,025-0,15	15000-100000	200000	1 U 2 Au	- U
SANDSTONE-TYPE		0.2	5000 - 25000	150000	U	Cu, V, Mo, Se
VEINLIKE TYPE	▼	0,2-2	10000-250000	450000	U	Ni
HYDROTHERMAL VEINS	▲	0,1-1	100 - 25000	50000	1 U 2 Co, Ni, Ag, Bi	U
INTRAINTRUSIVE TYPE	◆	0,04	10000 ≥ 100000	100000	1 U 2 Cu	U
CALCRETE-TYPE	◡	0,1-0,2	40000	40000	U	V
BLACK SHALE + PHOSPHORITE-TYPE	=	0,02-0,08	10000 - 70000	300000	1 U 2 P	U

TABLE IV : Uranium grade and potential of types of uranium deposits (From Dahlkamp, 1978a)

and fewer personnel, and consequently a quicker return on investment. Their attractiveness is enhanced by the fact that all of the presently known deposits are situated close to the surface, both in Canada and Australia, although this situation will probably change as exploration proceeds beneath thicker sections of sediment overlying the unconformities.

The contribution of unconformity-type deposits to the world's uranium reserves is difficult to establish accurately because it depends in the first instance on a firmly established classification of the various uranium deposits, which is not the case for the vein-type deposits. Furthermore accurate estimates of the percentage contribution of uranium provided by the various classes of deposit on a worldwide basis are difficult to make since they are dependent on the price assumed for uranium at any given time, and on whether reserves quoted are established or inferred (Derry, 1977). Fluctuating prices will alter the reserves for each type of deposit by different amounts, depending on the characteristics of the mineralization. It should therefore be stressed that information of this type is subjective and may vary considerably. Nevertheless some indications of the relative importance of the unconformity-type deposits is provided by the 1975 uranium production figures and reserve estimates presented in Figure 4.

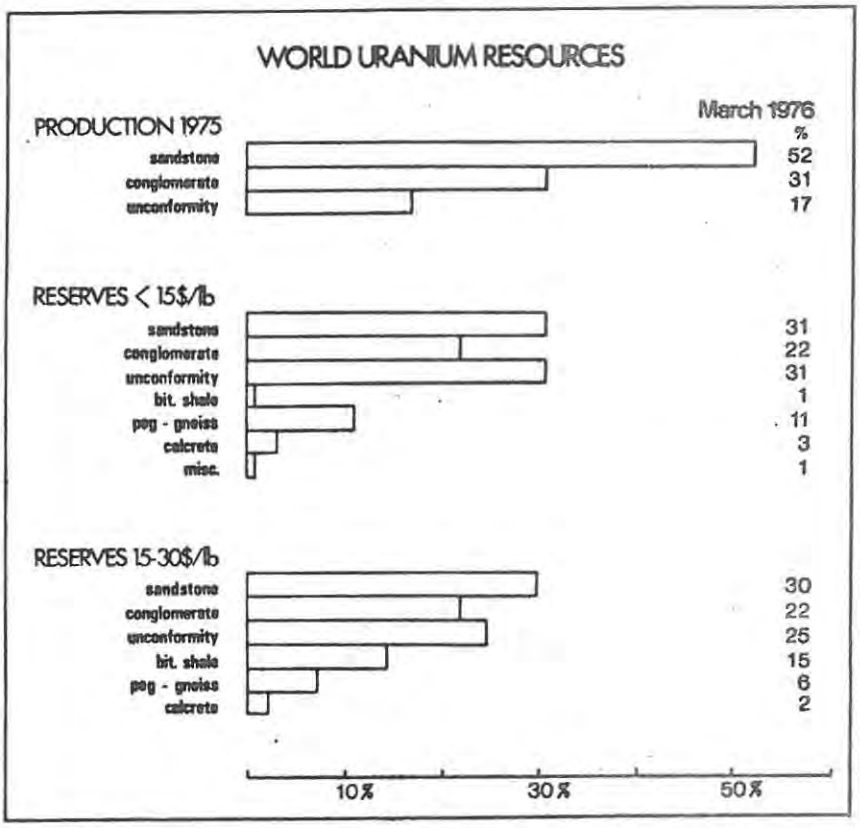


FIGURE 4 : The relative importance of types of uranium deposits (From : Derry, 1977)

According to more recent figures by Bowie (1979), all vein deposits comprise about 20% of the world reserves compared to 34% for sandstone-type deposits and 17% for uranium in conglomerates. Derry (1977) predicts that the unconformity-type deposits will increase in percentage of total non-communist world supply to such an extent that they will surpass all other types. His prediction is based on the premise that a large proportion of the uranium in the unconformity-type deposits is in ore containing between approximately 2 and 7 kg/t U_3O_8, which can be produced at a lower cost per kg than it can for any other class of uranium deposit. The relatively recent discovery of unconformity-type deposits compared to sandstone and conglomerate-type deposits, and the abundant favourable areas throughout the world, coupled with the intensity of present exploration, suggest that Derry's (1977) predictions may prove to be correct, and that unconformity-type deposits constitute the most attractive exploration targets in uranium exploration, given favourable geological environments.

In the following two chapters the regional setting, host lithologies, structural control, alteration and mineralogy of some Australian and Canadian deposits will be described and compared with a view to establishing an empirical model for unconformity-type deposits. Whilst such a model would be useful as an exploration guide, it is suggested that an understanding of the genesis of these complex ore deposits is essential for selecting exploration targets. Consequently some of the genetic theories will be reviewed in a subsequent chapter.

DEPOSITS IN THE NORTHERN TERRITORY, AUSTRALIA

All of the important uranium deposits in the Northern Territory, Australia occur in Lower Proterozoic sediments and metasediments of the Pine Creek Geosyncline. The uranium mineralization is concentrated in three areas : The Rum Jungle Field, the South Alligator River Field, and the Alligator Rivers Field (Fig. 5) which together constitute one of the largest uranium provinces in the world.

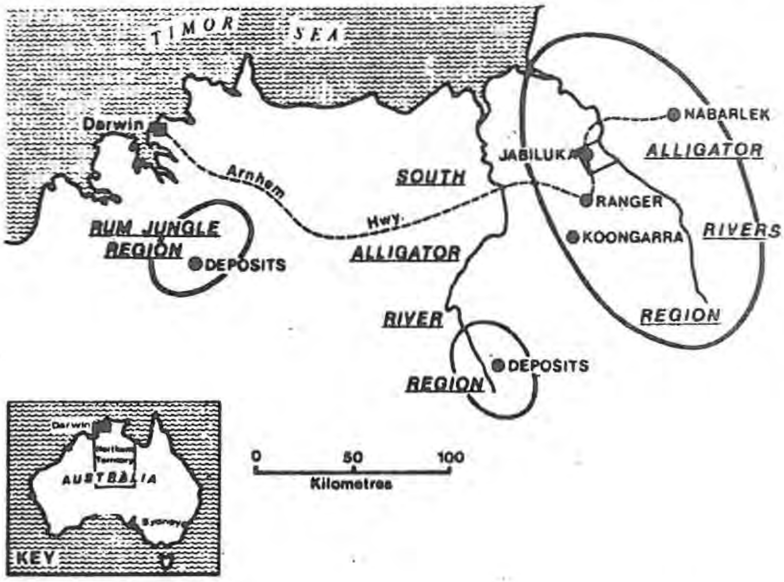


FIGURE 5 : The location of major uranium fields in the Northern Territory, Australia (From : Mosher and Rowntree, 1976)

The Alligator Rivers field alone contains 335 000 proven tonnes of U_3O_8 in four deposits which, according to Needham and Stuart-Smith (1976) constitutes about 25% of the western world's reasonably assured reserves of uranium recoverable "at less than $US 30-00 per lb". Although differences do exist in detail, the deposits show many similarities including similar host rocks, alteration and mineralogical assemblages, and structural controls of mineralization. In all of the fields the major deposits show a marked spatial relationship to the erosional margin of the Lower Proterozoic - Middle Proterozoic unconformity which is overlain by the Kombolgie Sandstone in the South Alligator and Alligator Rivers fields and by remnants of the Depot Creek Sandstone in the Rum Jungle field. No significant deposits have yet been discovered at any great distance from outcrops of these sandstones.

THE PINE CREEK GEOSYNCLINE

The Pine Creek Geosyncline (Fig. 6) consists of Lower Proterozoic metasediments with minor volcanics and concordant basic bodies overlying a basement of Archaean and in some instances Lower Proterozoic rocks, both of which have been subject to remobilization during a 1700 to 1800 my metamorphic event (Dodson et al., 1975). Up to 14 km of metasediments are preserved in the geosyncline, the sequence generally thinning out to the west. The western boundary is formed by the

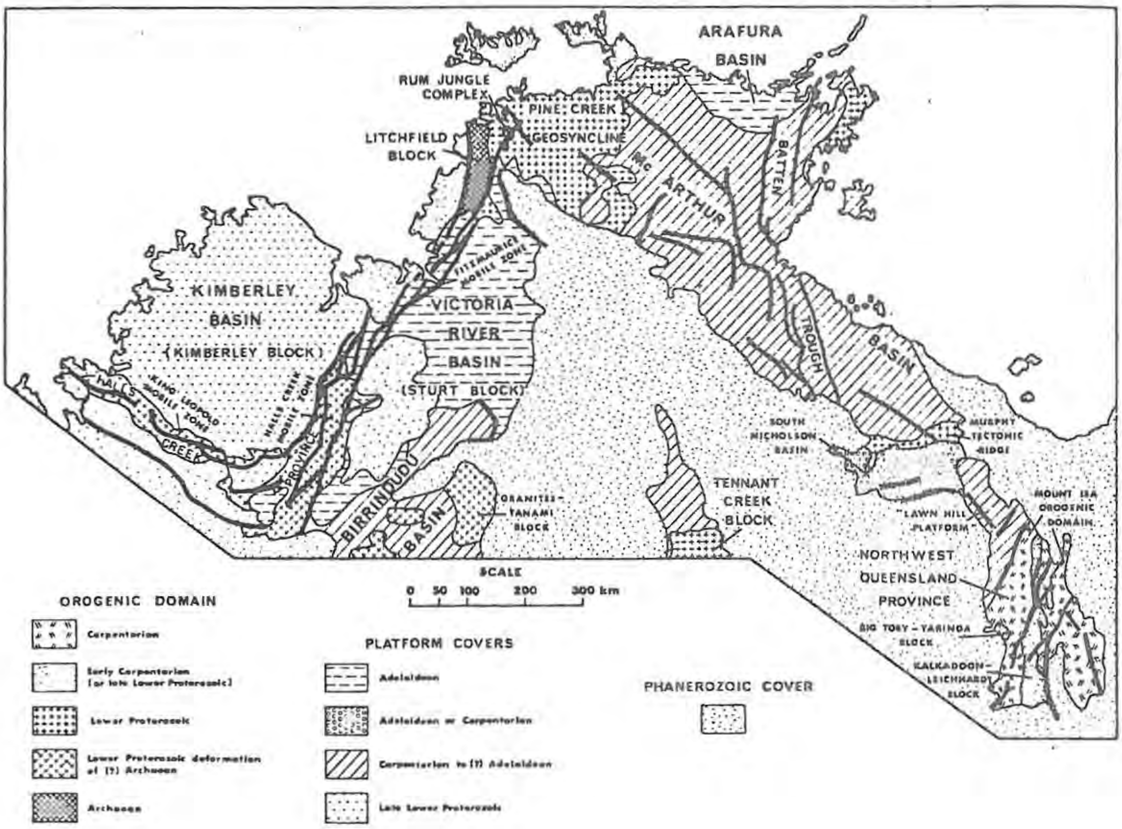


FIGURE 6 : Tectonic setting of the Pine Creek Geosyncline (From Plumb and Derrick, 1975)

Litchfield Complex, consisting of granitoids and metamorphic rocks of probable Archaean age (Walpole, 1968). In the eastern part of the geosyncline, in the South Alligator and Alligator rivers areas, the Lower Proterozoic rocks are unconformably overlain by Middle Proterozoic (Carpentarian) rocks of the McArthur Basin, and by the Upper Proterozoic (Adeladian) Victoria River Basin, and Palaeozoic Daly River Basin in the south. Much of the northwesterly trending geosyncline is thus obscured by younder sedimentary rocks (Fig. 6). The metasediments surround domes of Archaean to Lower Proterozoic granite, migmatite and metasediment exposed in the eastern and western parts of the geosyncline (Fig. 7). Metamorphism varies across the geosyncline from lower greenschist facies west of the South Alligator River, to amphibolite and locally granite facies in the east, accompanied by local anatexis

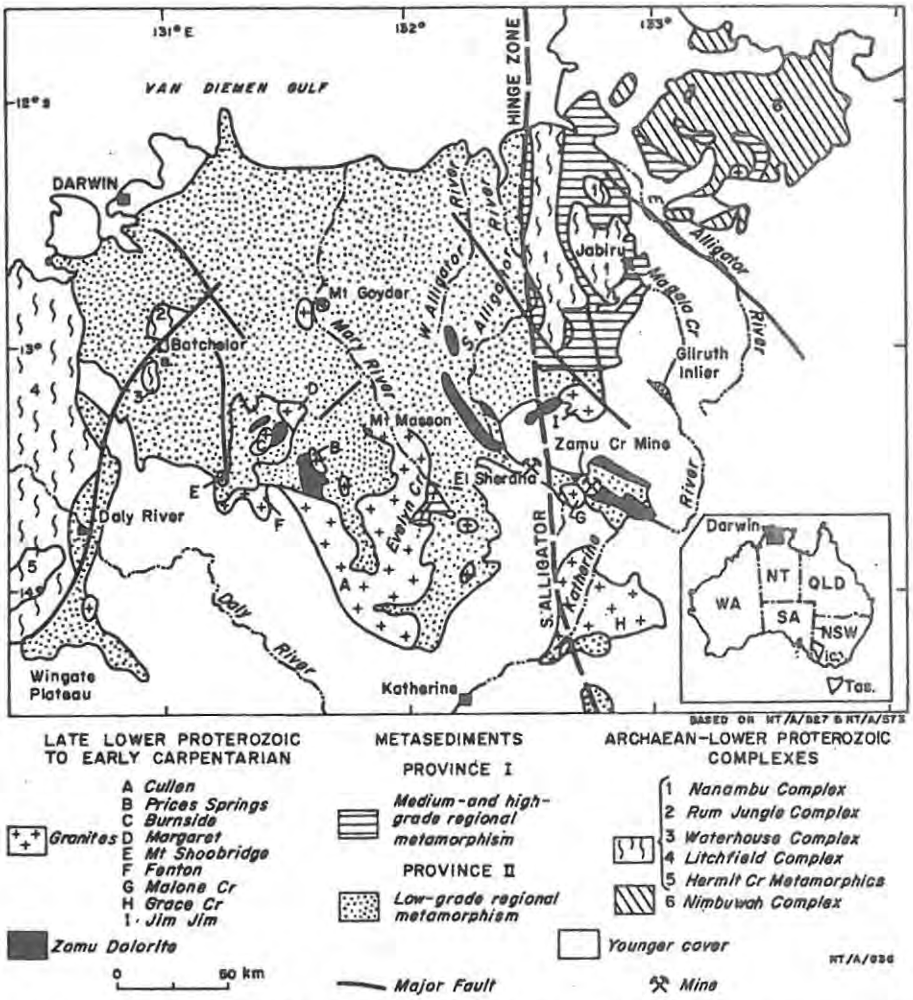


FIGURE 7 : Generalized geology of the Pine Creek Geosyncline (From : Ferguson, 1979)

in the lower part (Ryan, 1977). Similarly folding is generally moderate in the west but increases in intensity to the northeast where the strata are commonly overturned.

STRATIGRAPHIC RELATIONSHIPS IN THE PINE CREEK GEOSYNCLINE

The Basement Complexes (Archaean - Lower Proterozoic)

In the western part of the geosyncline (Fig. 7), the Rum Jungle and Waterhouse Complexes are of Archaean age and essentially composed of granite-gneiss, migmatites and metasediments, whilst in the east the Nauambu Complex consists of Archaean granites and gneisses which have been partly metamorphosed, together with accreted Lower Proterozoic leucogneiss, by an 1800 my. metamorphic event (Needham et al., 1979a). The latter complex is thus gradational into meta-arkoses of the basal Lower Proterozoic metasedimentary units and contains both

Archaean and 1800 my. old rocks. The Nimbuwah Complex in the extreme northeast was formerly considered to represent Archaean basement, but has been reinterpreted as anatexized Lower Proterozoic sediments (Needham et al., 1979a). In the extreme west of the geosyncline (Fig. 7) the Litchfield Complex and Hermit Creek Metamorphics are regarded by Walpole et al. (1968) as partly or wholly Archaean, although no isotopic work has yet been done to confirm this.

Lower Proterozoic Rocks

Since the discovery of the Rum Jungle Uranium Field in 1949 the Katherine-Darwin area (Fig. 7) has been remapped several times by the Bureau of Mineral Resources and private companies. This activity was stepped up dramatically in 1970 following the discovery of the Alligator Rivers Uranium Field. As a consequence of the more detailed mapping, basic concepts regarding the basin configuration during sedimentation, lithofacies relationships, correlations and petrological character of some units have substantially changed so that in most recent publications correlation of units and stratigraphic nomenclature differ considerably from earlier publications. For this reason the revised stratigraphy of the Pine Creek Geosyncline is tabulated in Appendix I, together with older nomenclature.

Walpole et al. (1968) regarded sedimentation in the Pine Creek Geosyncline as a greywacke-dominated sequence with lateral facies interfingering of units deposited in a central and eastern trough, separated by an Archaean Basement Ridge comprising the Stag Creek Volcanics which are exposed in the South Alligator River valley. In more recent work the Stag Creek Volcanics have been shown to be interlayered with the Lower Proterozoic metasediments (Foy and Miezitis, 1977), thus current interpretations suggest that sedimentation took place in one basin only, and that the metasedimentary units of the Pine Creek Geosyncline are mostly continuous with only minor facies variations across the basin of deposition (Needham et al., 1979). The most recently defined Lower Proterozoic stratigraphic relationships and nomenclature are illustrated in Figure 8, whilst the stratigraphic subdivisions and lithological variations across the geosyncline are summarized in Table V.

	WEST	CENTRAL
FINNIS RIVER GROUP	BURREL CREEK FORMATION siltstone, shale, greywacke, conglomerate	FISHER CREEK SILTSTONE siltstone, feldspathic sandstone, phyllites, greywacke, arkose
S. ALLIGATOR GROUP	KAPALAGA FORMATION carbonaceous siltstone, mudstones, ashstones, tuffaceous chert, carbonate, B.I.F.	
	GEROWIE TUFF argillite, ashstone, tuffaceous chert, andesite	
	KOOLPIN FORMATION * iron-rich pelites, dolomite, siltstone, carbonaceous shale, iron-rich chert	
Mt. PARTRIDGE GP.	WILDMAN SILTSTONE siltstone, shale, quartz, sandstone, quartz greywacke	
	ACACIA GAP SANDSTONE quartzite	
	MOUNT HOOPER SANDSTONE quartzite	MUNDOGIE SANDSTONE feldspathic, qzt., congl.
NAMOONA GROUP		STAG CREEK VOLCANICS basalt breccia, flows, tuff, shale
	MASSON FORMATION * pyritic, calcareous, carbonaceous shale, sandstone, siltstone, chert, ironstone	
	COOMALIE DOLOMITE algal dol., silicified dol., marl.	
BATCHELOR GROUP	CRATER FORMATION greywacke, congl., sandstone, siltstone	
	CELIA DOLOMITE algal dolomite, breccia	
	BEESTONS FORMATION arkose, conglomerate, shale	
	RUM JUNGLE/WATERHOUSE COMPLEXES	

*Uraniferous formations

	EAST	
	NOURLANGIE SCHIST quartz,mica schist	NIMBULWAH COMPLEX
	CAHILL FORMATION (Upper member) micaceous, feldsp. schist	
	CAHILL FORMATION (Lower member) carbonaceous schist, carbonate	
KAKADU GROUP	Mt.BASEDOW GNEISS, KUDJUMARNDI QZT. Mt. HOWSHIP GNEISS MUNMARLARY QTZ.	
	NANAMBU COMPLEX	

TABLE V : Stratigraphic succession and lithological variations in Lower Proterozoic rocks of Pine Creek Geosyncline

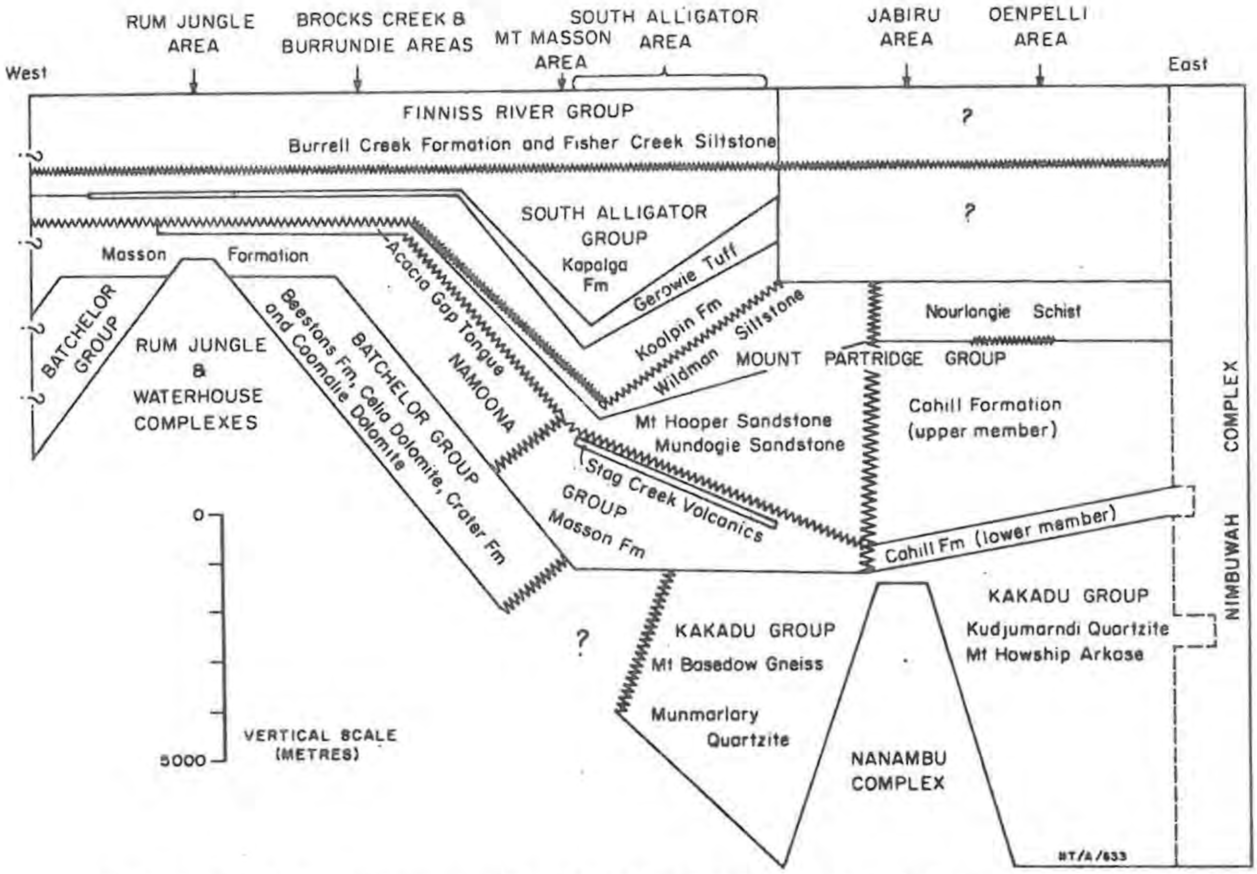


FIGURE 8 : Lower Proterozoic relationships of the Pine Creek Geosyncline (From : Needham et al., 1979)

Three formations are hosts of uranium mineralization in the Pine Creek Geosyncline, namely the Masson Formation, the Lower Cahill Formation and the Koolpin Formation.

The Masson Formation is the principal formation in the Namoona Group and extends from the Rum Jungle area almost to the South Alligator River. It contains all of the uranium and base metal deposits in the Rum Jungle area and consists mainly of pyritic calcareous carbonaceous shale, with minor sandstone, siltstone, chert and ironstone. Further east (Fig. 8) it is correlated with the *Lower Cahill Formation* which hosts the Alligator Rivers deposits and is a partly calcareous and carbonaceous sequence of micaceous quartzo-feldspathic schists with lenses of massive carbonate near its base (Needham and Stuart-Smith, 1976).

The South Alligator River deposits are hosted by the *Koolpin Formation* which is stratigraphically higher up in the sequence and contains pyritic carbonaceous shales, ferruginous siltstones with chert bands and nodules, algal carbonate and banded iron formation.

Middle Proterozoic

Middle Proterozoic rocks, which unconformably overlie the Lower Proterozoic rocks and are spatially related to the uranium deposits, include the Depot Creek Sandstone Member in the Rum Jungle area and the Kombolgie Formation in the eastern areas. The Depot Creek Member is composed essentially of quartz sandstone and minor pebble conglomerate beds. In the vicinity of the Rum Jungle deposits it is represented by the Hematite Quartz Breccia unit which outcrops as scattered basal remnants (Fraser, 1975). Southwest of the South Alligator River the Kombolgie Formation is made up of more than 1500m of sandstone, greywacke and volcanics, whilst to the northeast it contains less than 600m of sandstone. In the Alligator Rivers area the Kombolgie Formation contains massively bedded quartz sandstone, minor conglomerate and shale, and two interbedded mafic volcanic units (Needham & Stuart-Smith, 1979).

EVOLUTION OF THE PINE CREEK GEOSYNCLINE

An evolutionary model, which accounts for the sedimentation and subsequent deformation of the Pine Creek Geosyncline has been proposed by Stuart-Smith et al. (1979), who recognize seven major structural elements in the geocyncline, including the Chilling Platform, Western Fault Zone, Batchelor Shelf, South Alligator Trough, South Alligator Hinge Zone, Nanambu High, and Kakadu Shelf (Fig. 9). These features controlled sedimentation, tectonic development and location of uranium deposits within the geosyncline.

Stuart-Smith et al. (1979) recognize four main stages of development in the geosyncline, in which the Lower Proterozoic sediments were deposited in an intracratonic basin under alternating continental and shallow marine environmental conditions. Each stage reflects fundamental changes in environment and tectonics. The evolutionary sequence is diagrammatically illustrated in Figure 10.

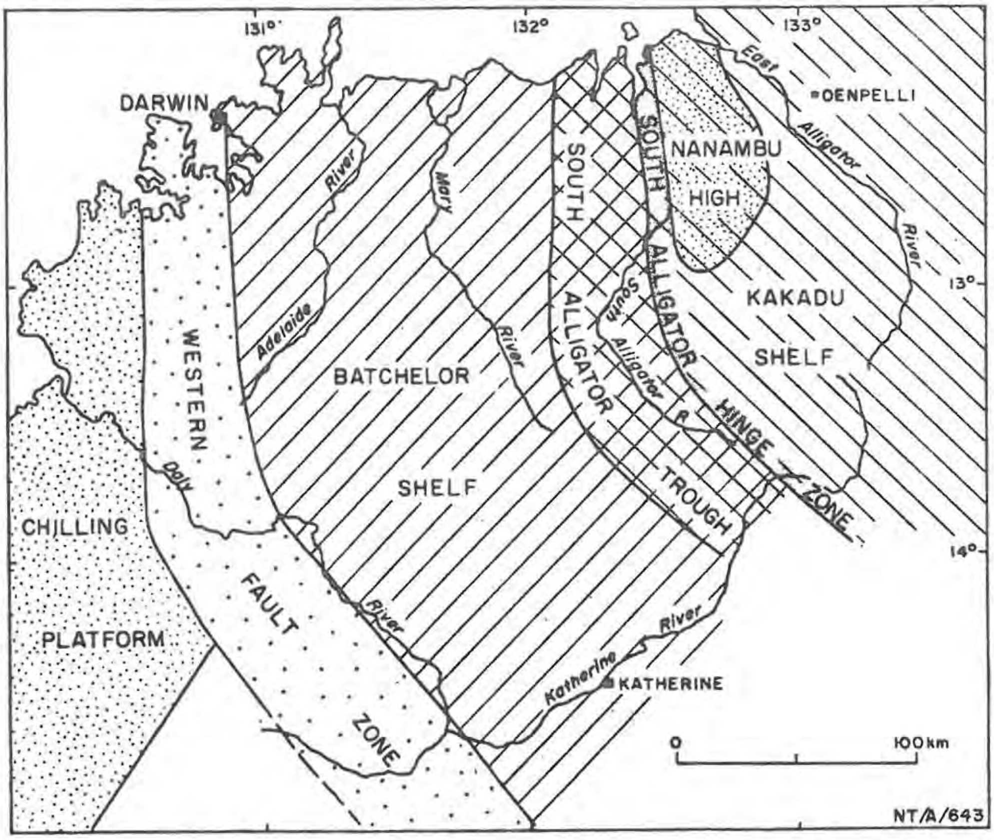


FIGURE 9 : Major structural elements of the Pine Creek Geosyncline (From : Stuart-Smith et al., 1979)

Stage 1 : Early Lower Proterozoic rifting produced the north-south trending South Alligator Trough and adjacent Batchelor and Kakadu shelves (Fig. 10). The alternating arenaceous and dolomitic marginal sediments of the Batchelor Group were deposited along the western margin of the Batchelor Shelf, whilst in the Alligator river area the Kakadu Group and part of the overlying Namoona Group were deposited adjacent to the Nanambu High. The main thickness of fine clastic and chemical sediments of the Namoona Group were deposited in and adjacent to the South Alligator Trough, the high pyrite and carbon content suggesting quiet anoxic conditions, whilst the minor sandstone and siltstone components suggest that the overall environment was one of fluctuating nearshore deposition. This initial stage terminated with the subaqueous basic to intermediate Stag Creek Volcanics, apparently confined to the South Alligator Trough.

Stage 2: Following the volcanic episode, basement uplift of the Nanambu High and an area to the north of the present geosyncline resulted in the deposition of the Mount Partridge Formation, which is essentially

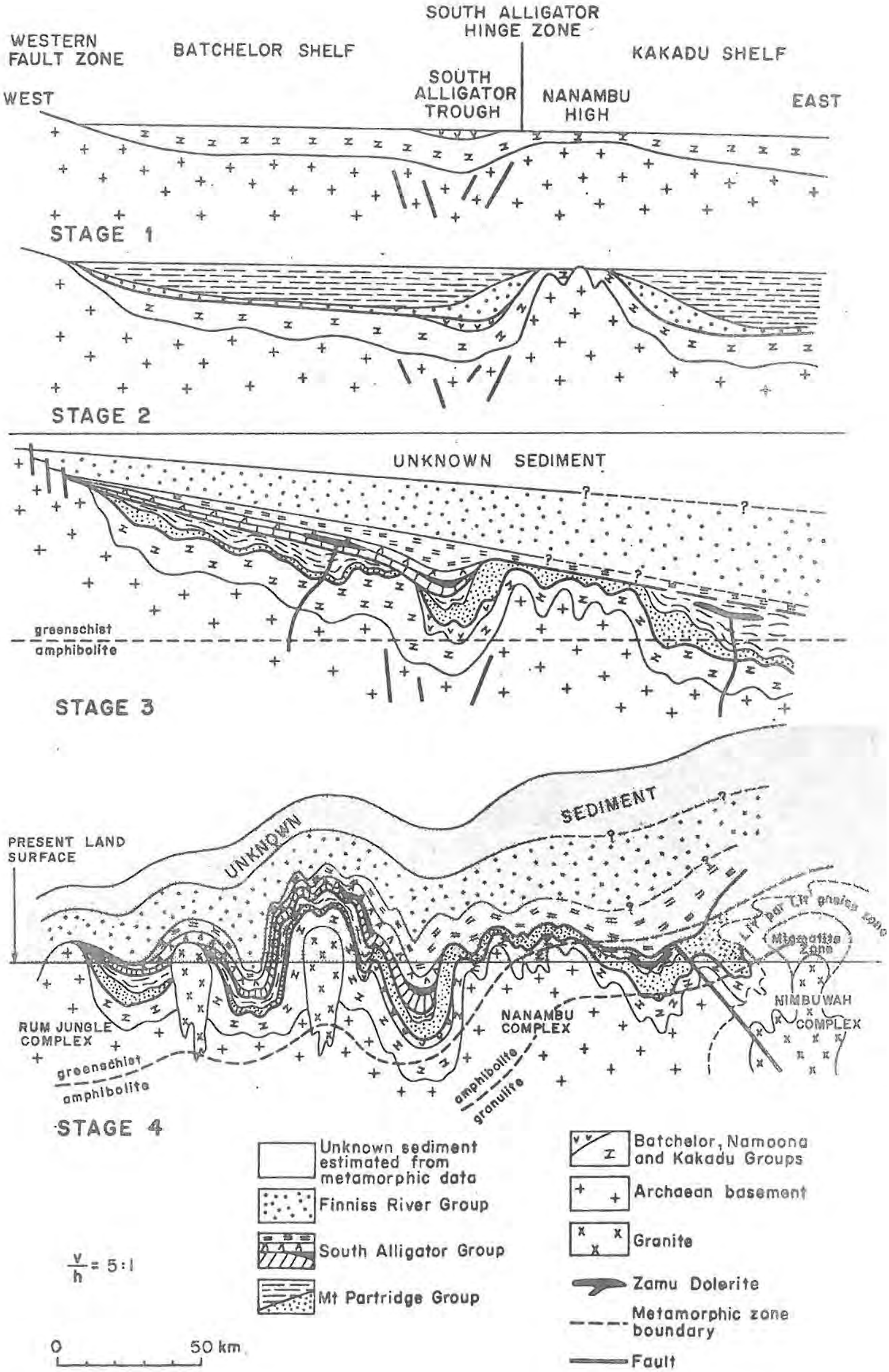


FIGURE 10 : Evolution of the Pine Creek Geosyncline
(From : Stuart-Smith et al., 1979)

a clastic wedge, being deposited in the trough and adjacent shelf areas. The sediments formed alluvial fans flanking uplifted areas and were subsequently overlain by transgressive littoral and subtidal deposits of laminated siltstone, shale and cross-bedded quartz sandstone.

Stage 3 : Mild tectonism caused uplift, folding and peneplanation of earlier sediments, followed by renewed chemical and organic sedimentation, during which the South Alligator Group was deposited by an eastward transgression of shallow-marine sedimentation, producing an eastwards thickening sequence of dolomite, pyritic carbonaceous siltstone containing bands, lenses and nodules of chert, and carbonaceous siltstone. During a sedimentary break subaerial volcanism produced the Gerowie Tuff unit, and may also have been the source of iron, gold and base metals which are commonly associated with the Gerowie Tuff/Koolpin sequence (Needham and Roarty, 1979; Goulevitch, 1979). Shift of tectonic activity to the east after the deposition of the South Alligator group produced faulting and volcanism along the Western Fault Zone accompanied by continued subsidence of the South Alligator Trough and Kakadu Shelf. Renewed basement uplift in the west accompanied by volcanism resulted in flysch-type sedimentation onto the Batchelor Shelf, forming the eastwards-thickening wedge of the Finniss River Group. At the close of sedimentation the Zamu dolerite was intruded into the Lower Proterozoic sediments mainly as sills in the South Alligator and Finniss River Groups.

Stage 4 : Continued subsidence in the geosyncline resulted in deformation and metamorphism, both of which increased towards the northeast. Sediments of the Batchelor Shelf and South Alligator Trough were metamorphosed to lower greenschist facies, whereas the Kakadu Shelf sediments reached amphibolite facies. Locally they were migmatized to form the outer schistose and gneissic parts of the Nimbuwah granitoid to form the Nimbuwah Complex itself. Granulitic facies was reached in some parts of the complex. Stuart-Smith et al. (1979) have suggested that the observed metamorphic grades could be accounted for by an additional wedge of overlying sediments (now removed) from 1 to 6 km thick from west to east. They account for the dramatic contrast in metamorphic grades across the South Alligator River (See Fig. 7) by suggesting that a 5-8 km upward displacement may have occurred east of the hinge zone, possibly associated with diapirism of the Nimbuwah and Nanambu Complexes.

Ferguson (1979), has suggested that tectonic conditions during the lower Proterozoic sedimentation were such that the accumulation of a total 20 km of sediment necessary to produce the high metamorphic grades east of the South Alligator River would have been unlikely, and therefore that the Cahill Formation may in fact be older than its present correlatives across the South Alligator River.

REGIONAL SETTING OF THE URANIUM DEPOSITS

The distribution of major uranium deposits in the Pine Creek Geosyncline with regard to its stratigraphy and tectonic history is relatively simple. On a regional scale only two stratigraphic levels appear to be significant. In the Alligator Rivers field the deposits are stratabound within the Lower Cahill Formation, whereas the South Alligator River deposits are all hosted by the Koolpin Formation on a higher stratigraphic level. In the Rum Jungle area the Masson Formation which is the correlative of the Lower Cahill Formation (Fig. 8) is host to uranium and other mineralization in the area. The three formations are characterized by the presence of carbonate and carbonaceous schist. The Masson Formation contains carbonaceous rocks with subordinate extensive carbonate sheets generally less than 1m thick. These lithologies predominate over minor terrigenous sediments. In the Koolpin Formation the carbonate occurs as lenses and beds ranging from 20m to over 300m in thickness. In the Cahill Formation carbonate is present mainly as sharply lenticular bodies up to 250m thick. Minor carbonaceous rocks occur, whilst terrigenous material is dominant (Needham and Stuart-Smith, 1976).

In the Rum Jungle and Alligator Rivers fields there is a clear spatial relationship between the uranium deposit and basement domes, the deposits occurring in the Lower Proterozoic metasediments surrounding the domes. Whether or not the domes were highs during Lower Proterozoic sedimentation is not clear. Rhodes (1965) established that the Rum Jungle and Waterhouse Complexes do not intrude the Lower Proterozoic sediments but are unconformably overlain by them. The doming of the Archaean basement and overlying metasediments has been attributed to polyphase interference folding resulting in the formation of a rim syncline around the Waterhouse Complex and the development of shearing along the basement-sediment contacts of both complexes. Rhodes (1965) compares the domes to mantled-gneiss domes of Eskola (1948). Stephansson and Johnson (1976) regard the complexes as solid-state diapirs which are thought to have been driven by the intrusion of younger underlying granitoids, and related to gravitational instability. It is possible, however, that the doming may represent the reactivation of original basement highs in the Rum Jungle area. Needham et al. (1979b, p 14), discussing the Rum Jungle and Waterhouse Complexes, state that "the Namoona and South Alligator Groups thin towards the basement highs and in places the Mount Partridge Group pinches out near them". Also, "during the ± 1800 my. orogeny the depositional dips around the Archaean basement highs were accentuated, and the Lower Proterozoic sequence folded along axes trending mostly north to north-northeast" (Needham et al., 1979b, p 14). Thus in the Rum Jungle area the proximity of the uranium deposits to predepositional basement highs may be very significant.

In the Alligator Rivers area the Jabiluka Ranger and Koongarra deposits are situated near the eastern limit of the Nanambu Complex (Fig. 11). The area is distinguished by medium to high metamorphic grades and intense folding. Basement reactivation is indicated by the accretion of Lower Proterozoic feldspathic and quartzitic gneiss and schist which are gradational into gneisses of the Kakadu Group. However some suggestion of basement highs existing prior to deposition of the Lower Proterozoic sediments is provided by the fact that the Cahill Formation overlaps the Kakudu Group in places to directly overlie Archaean granite of the Nanambu Complex (Needham and Stuart-Smith, 1976).

The Nabarlek deposit is situated on the western edge of the Nimbuwah Complex which was formed by the anatexis of Lower Proterozoic sediments, dated at 1800 my. (Ferguson et al., 1979) (Fig. 11).

The South Alligator Uranium Field is anomalous by comparison to the other uranium fields in that no Archaean basement is exposed in the vicinity. Stuart-Smith et al. (1979) consider that it occupies a basement low, which in this instance is the South Alligator Trough, probably formed by incipient rifting.

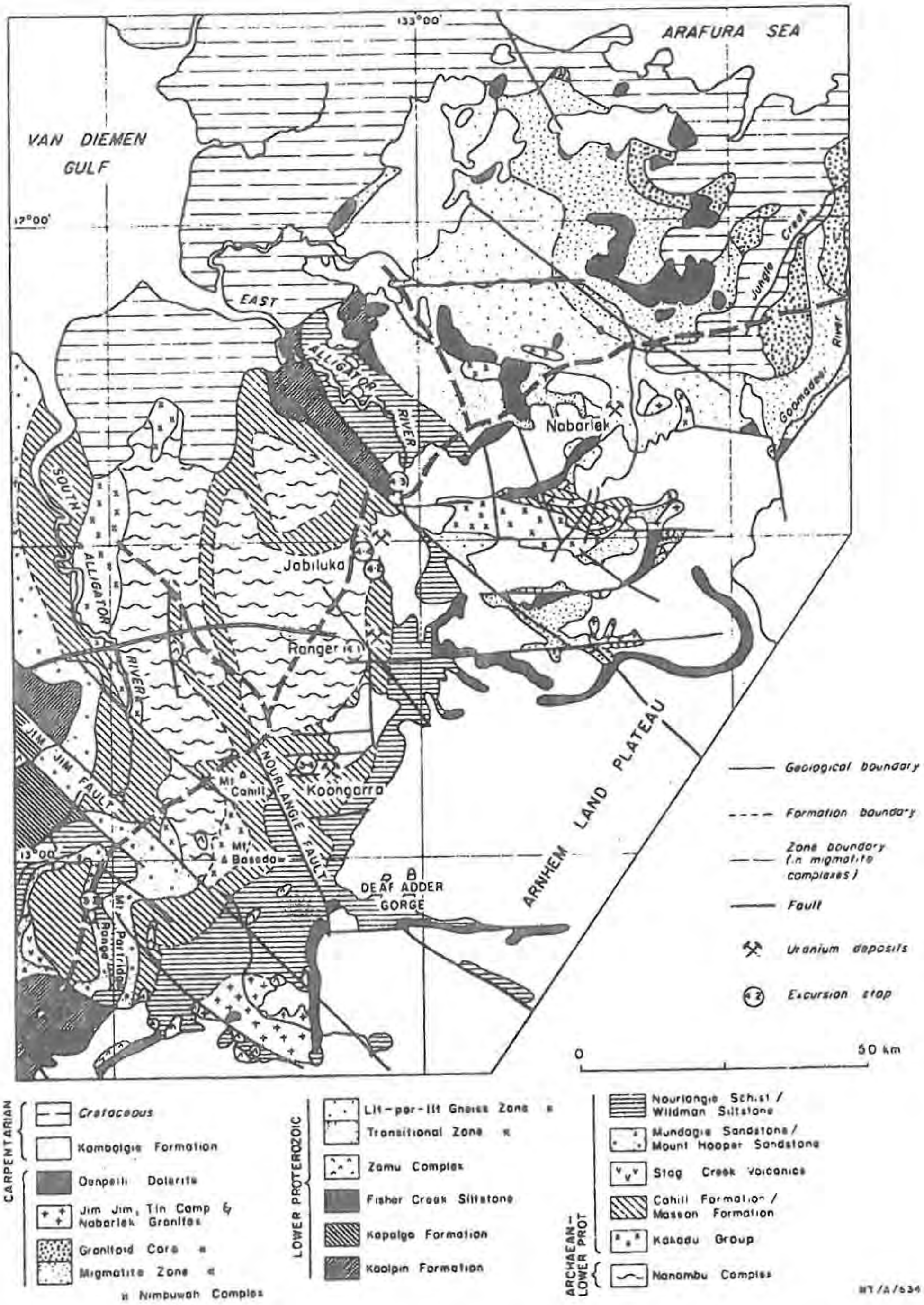


FIGURE 11 : Generalized geology of the Alligator Rivers Uranium Field (From : Needham and Stuart-Smith, 1979)

The most striking feature of the uranium deposits in the Pine Creek Geosyncline is their association with the unconformity between Middle and Lower Proterozoic rocks. In the Alligator Rivers and South Alligator Uranium Fields the Kombolgie Formation overlies the Lower Proterozoic metasediments with a marked angular unconformity. The area was subjected to partial peneplanation during Mezozoic and Tertiary times (Hegge and Rowntree, 1978) which lowered the present land surface over extensive areas to approximately the level of the Lower- Middle Proterozoic unconformity. Erosional remnants of the Kombolgie Formation form the Arnhem Land Plateau in the eastern part of the region (Fig. 11) and also occur as outliers separated from the plateau. According to Langford (1974) most of the uranium deposits occur within ± 16 km of the erosional margin of the unconformity, whilst the large deposits are considerably closer.

In the Rum Jungle area post-Proterozoic erosion is much more widespread. Evidence for the existence of an unconformity is provided by a hematite-quartzite breccia with intercalated mudstone and sandstone which occurs as scattered outcrops in the vicinity of the uranium deposits. This unit is interpreted to be the basal member of the Middle to Upper Proterozoic Depot Creek Formation (Fraser, 1979). The uranium deposits at Rum Jungle, as well as others at Adelaide River and George Creek are all near the present eastern limit of outcrop of the Depot Creek Sandstone Member and are at or immediately below the unconformity surface (Needham et al., 1979b).

From the relationships described it would appear that stratigraphy and proximity to the Middle-Lower Proterozoic unconformity are the two most important factors controlling the regional distribution of the uranium deposits. In the Rum Jungle and Alligator Rivers regions the relationship between the deposits and basement domes is significant. It is possible that the domes may have influenced sedimentation in these areas, thereby contributing in some way to the uranium enrichment of the sediments. On the other hand the function of the domes may merely have been to expose favourable host lithologies adjacent to them.

HOST ROCKS OF URANIUM MINERALIZATION

On a regional scale carbonate and carbonaceous schists are characteristic lithologies of the three uranium bearing formations which are the Lower Cahill Formation, the Koolpin Formation and the Masson Formation. Variations in detail are best illustrated by describing the host rocks of some of the individual uranium deposits.

The Alligator Rivers Field

This field contains the Jabiluka, Ranger, Koongarra and Nabarlek deposits (Fig. 11), all of which are hosted by the Lower Cahill Formation.

Jabiluka

At Jabiluka the Lower Cahill Formation is approximately 400m thick and has been subdivided into nine distinctive units known as the Jabiluka succession (Hegg 1977), listed as follows :

Upper Schist Series	*Muscovite-chlorite schist*
Upper Graphite Series	**Graphite schist; chlorite-graphite schist, dolomitic in part*
Hanging Wall Series	*Muscovite-chlorite schists*
Main Mine series	**Predominantly graphitic and chloritic schists with dolomitic and muscovite rich intercalations*
Footwall Series	*Muscovite-chlorite schists*
Lower Mine Series I	**Chlorite schists, feldspathic and graphitic in parts*
Lower Footwall Series I	*Muscovite-chlorite schists*
Lower Mine Series II.	**Chlorite schists; feldspathic, graphitic and dolomitic in parts*
Lower Footwall Series II	*Muscovite-chlorite schist, locally containing feldspar and biotite*

**Indicates ore bearing horizons*

Of these the Upper Graphite Series and the three Mine Series are the main hosts for the economic uranium mineralization (See Figure 15). Intervening units are lithologically similar, consisting essentially of chlorite-muscovite schists, and are poor host to uranium mineralization. The most favourable host lithology for both uranium and gold mineralization at Jabiluka One and Two orebodies is the Main Mine Series, which comprises a continuous and correlatable uppermost unit of pyritic, chloritic, graphitic schist, underlain by chlorite-muscovite feldspar schists, and chlorite-graphite schists. The lowermost unit is the inconsistent chlorite-schist breccia and chlorite-graphite schist. Dolomitic horizons, containing up to 40% magnetite are developed as wedge-shaped bodies up to 20m thick between the Jabiluka One and Two orebodies (See Figure 16), and are facies equivalents of schists in the orebodies. Chert is also present in the Main Mine Series, often as angular fragments in the chlorite breccia units. Hegge (1977) regards the chert as the end product of silicification of dolomite, and attributes the brecciation to collapse resulting from volume reduction incurred during silicification of the dolomite.

The Upper Graphite Series, composed of graphite and/or chlorite schists is host to uranium and local gold mineralization at Jabiluka Two. The Lower Mine Series (LMS) I and II, are unmineralized at Jabiluka One and the western part of Jabiluka Two. The LMS I is represented by thin chloritic and/or graphitic units whereas the LMS II consists of a dolomite-magnesite unit up to 10m thick with subordinate chlorite-schist and chlorite-graphite schist. Both units become more chloritic and brecciated in the eastern parts of Jabiluka II and are more intensely mineralized. Chlorite-feldspar-schist and chlorite-graphite schist are the most common assemblages. The former rock-type appears to be a strongly chloritized biotite-feldspar schist with variations in the proportion of quartz and sericite. The rocks with low muscovite content are more competent than the Hanging and Footwall Series chlorite-muscovite schists and have been readily fractured and brecciated.

Ranger I

At the Ranger I deposit the host rocks of the uranium mineralization have been subdivided into an Upper and Lower Mine Sequence. The *Upper Mine sequence* consists of evenly banded biotite-quartz-feldspar schists that have been subjected to varying degrees of chloritization (Eupene et al., 1975). Thin carbonaceous horizons are developed in places particularly at the base and a thin discontinuous dolomitic carbonate occurs at the top of the sequence. The *Lower Mine sequence* consists of dolomite which is fine-grained and chlorite-rich in the upper parts and recrystallized in the lower parts where the chlorite has segregated into large accumulations. A chlorite-sericite schist band (the Lenticle Schist) characterized by chlorite lenticles occurs within the carbonate unit and persists over much of the Ranger I deposit forming a useful marker horizon. The Lenticle Schist can be traced through the Lower Mine Series within the orebodies, whereas the carbonate horizon does not persist into the orebodies, resulting in a thinning of the Lower Mine Sequence in the ore zone, which, in addition to the schist, contains only chlorite and silica (Fig. 12). The latter, referred to as the Lower Mine Chert - appears to invade and replace the carbonate in the transition zone between the chert and the carbonate. This phenomenon in conjunction with the continuity of the Lenticle Schist is regarded by Eupene et al. (1975) as evidence for the control of mineralization in the number One orebody by a collapse zone resulting from the volume reduction in the Lower Mine Sequence caused by removal and silicification of carbonate. Although similar processes appear to have acted on the same stratigraphic level in the number 3 orebody they appear not to have been as important in localizing mineralization.

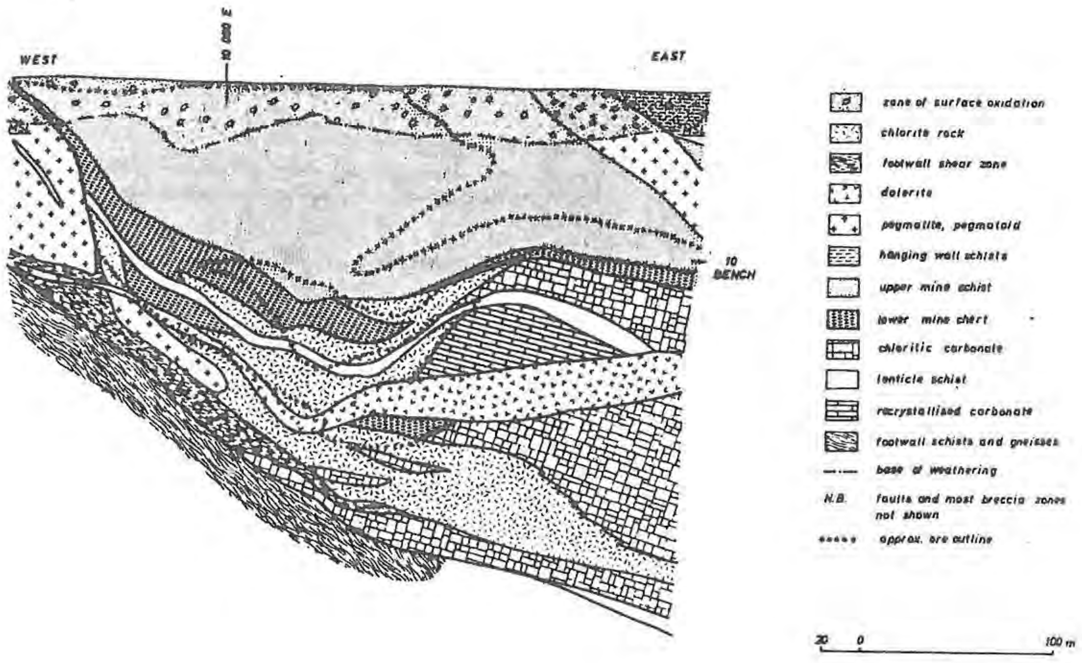


FIGURE 12 : Generalized geological section through Ranger I number One orebody. (From : Needham et al., 1979b)

In both the No.1 and No. 3 orebodies most of the mineralization occurs in the Upper Mine Sequence. The most consistent mineralization occurs in the main pyritic carbonaceous band at the base of the Upper Mine sequence although there is no broad relationship between the grade of uranium and pyrite or carbon concentrations. Extensive mineralization also occurs in non-carbonaceous rocks. Mineralization also extends below the schist and is present in chlorite veins underlying the silicified carbonate below the No. 1 orebody at the base of the Cahill Formation, and in chlorite veins in carbonate within the No. 3 orebody (Needham et al., 1979b). The hangingwall rocks are coarse mica-feldspar-quartz schists with frequent interbedded amphibolites, whilst the footwall consists of migmatites schists and gneisses of the Nanambu Complex. The Kombolgie Sandstone is not present at the orebody, its nearest exposure occurring approximately 2,5 km to the south.

Koongarra

The Lower Cahill Succession from top to bottom through the Koongarra deposit (Fig. 13) is as follows (Foy and Pederson, 1975) :

Quartz-muscovite schist - occasionally feldspathic

Quartz-chlorite schist with micaceous, garnetiferous, and pyritic bands

Graphitic quartz-chlorite schist, pyritic in places

Quartz-chlorite schist with well banded, often brecciated, lenticular siliceous units

The most intense uranium mineralization occurs immediately below the graphite-bearing horizon (Fig. 13) within the quartz chlorite schists. The latter rocks are evenly banded and slightly micaceous in parts.

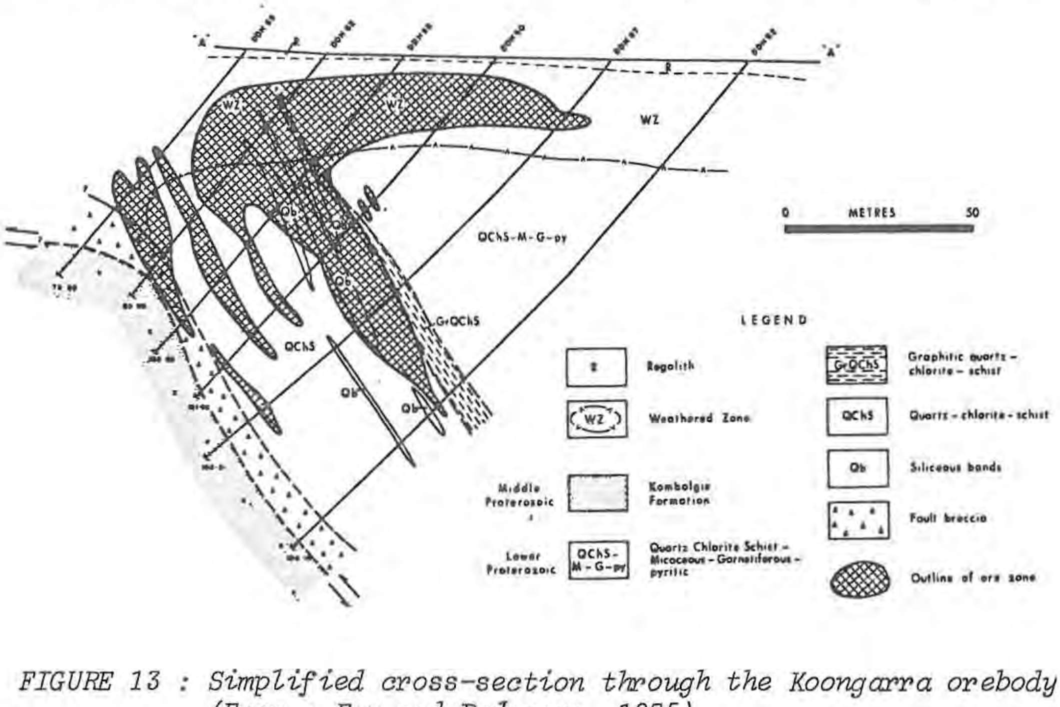


FIGURE 13 : Simplified cross-section through the Koongarra orebody (From : Foy and Pederson, 1975)

Dolomitic rocks which are an integral part of the schist sequence have been intersected by boreholes on both sides of the orebody (Foy and Pederson, 1975). No mineralization occurs in the Kombolgie Sandstone which, due to a reverse fault, is situated in the footwall of the orebody (Fig. 13).

Nabarlek

The host rocks of the uranium mineralization at the Nabarlek deposit are distinguished from the other Alligator Rivers orebodies by the absence of both carbonate and carbonaceous material in and adjacent to the mine area. The following succession has been established (Anthony, 1975) :

TOP : *Quartz-mica schists and quartz-schists*

Chlorite-mica schist, consisting >50% white mica made up of coarse muscovite and fine sericite

Chlorite-schist : this is the most abundant rocktype, composed of chlorite with minor sericite

Micaceous chlorite schist, composed mainly of chlorite and up to 25% white mica

Siliceous chlorite schist : this rocktype is generally poorly developed, occurring only in the southern area and is composed of chlorite with some quartz and feldspar.

According to Anthony (1975, p. 305)"the southern end of the orebody is marked by the rapid disappearance of the chlorite-mica schist, and the progressive disappearance of the micaceous chlorite schist". The mineralization at Nabarlek does not show the same stratigraphic control evident in the other Alligator Rivers deposits. It is transgressive and confined mainly to the chlorite- and micaceous-chlorite units, and is cut off at depth by a thick dolerite sill.

The South Alligator River Field

Thirteen small worked-out mines lie within the linear 14 km long north-west trending South Alligator Uranium Field (Fig. 14). Most of the primary uranium mineralization occurs in faulted or sheared carbonaceous shale, in places chloritic, of the Koolpin Formation, although Crick et al. (1979) suggest that the carbonaceous shale host rocks in the Sleisbeck mine (Fig. 14) may belong to the Masson Formation. In the Koolpin Formation the uranium mineralization occurs in pyritic carbonaceous shale and ferruginous chert-banded shale, and commonly

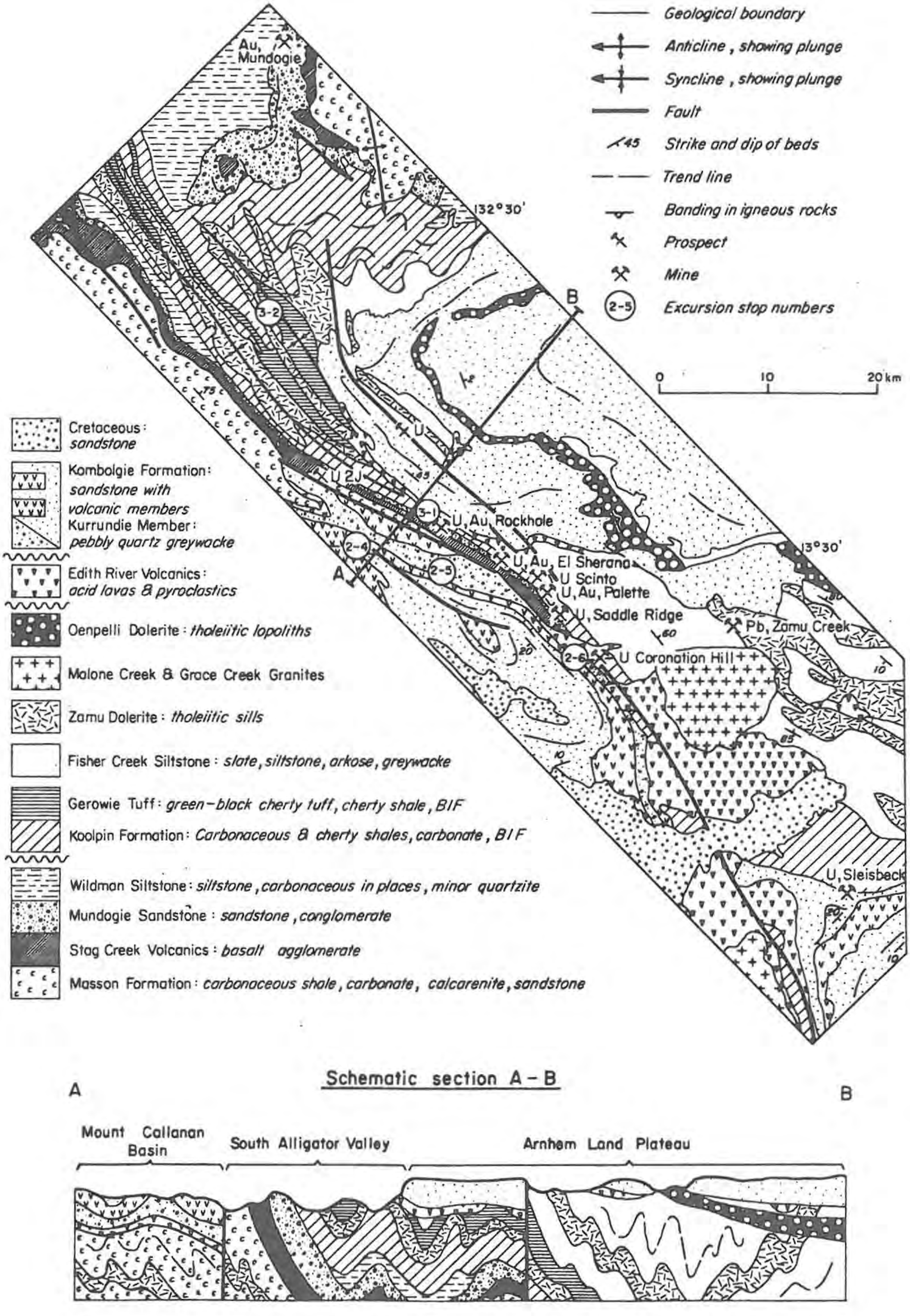


FIGURE 14 : Generalized geology and idealized cross-section of the South Alligator River Valley area. (From : Crick et al. 1979)

along the boundaries between these rock-types. Several orebodies are hosted by other rocktypes : the Coronation Hill deposit (Fig. 14) is situated in blocks of carbonaceous shale contained in a volcanic neck of the Middle Proterozoic Edith River Volcanics up to 100m above the Lower-Middle Proterozoic unconformity in the area. At the Saddle Ridge deposit tuffs of the Edith River Volcanics host the mineralization and Scinto VI the deposit occurs in syenite of the Zamu Complex (Foy, 1975). Secondary uranium mineralization is common in the Kombolgie Sandstone in many of the deposits.

The Rum Jungle Field

The Lower Proterozoic host rocks of uranium mineralization in the Rum Jungle area is the Masson Formation of the Namoona Group and also the Coomalie Dolomite of the underlying Batchelor Group. At the Dyson's Mine the orebody occurs in pyritic, dolomitic, graphitic slate and hematitic sericitic slate of the Masson Formation close to its contact with magnesian dolomite and magnesite of the Coomalic Dolomite (Needham et al., 1979b). Ore bearing rocks at White's deposit were dark grey and black sericitic and graphitic shales and lesser chloritie and hematitic shales (Fraser, 1975) of the Masson Formation. The Mount Fitch deposit occupies an identical position to the other deposits and is hosted by a grey shaly magnesite of the Coomalie Dolomite, and a black chloritic schist of the overlying Masson Formation (Berkman and Fraser, 1979).

STRUCTURAL CONTROLS OF URANIUM MINERALIZATION

Apart from the major structural features which appear to have been responsible for the location of the uranium fields within the Pine Creek Geosyncline, other features of varying magnitudes are equally important in localizing individual deposits and controlling the mineralization within them, to such an extent that it is impossible to evaluate the relative importance of hostrock lithology and structure since these are never mutually exclusive in any deposit. Thus faults, fractures, joints, breccias and other permeable features have provided channelways for the mineralizing solutions, whilst favourable host rocks have provided the necessary precipitants for the uranium. In some instances folding has also played an important role in localizing the ore deposits.

Jabiluka

The Jabiluka orebodies occur in folded metasediments flanking the northeast part of the Nanambu Complex (see Figure 10), where they are localized in an open asymmetric flexure dipping south and striking east-southeast (Hegge, 1977, Fig. 14). Only the Jabiluka One orebody

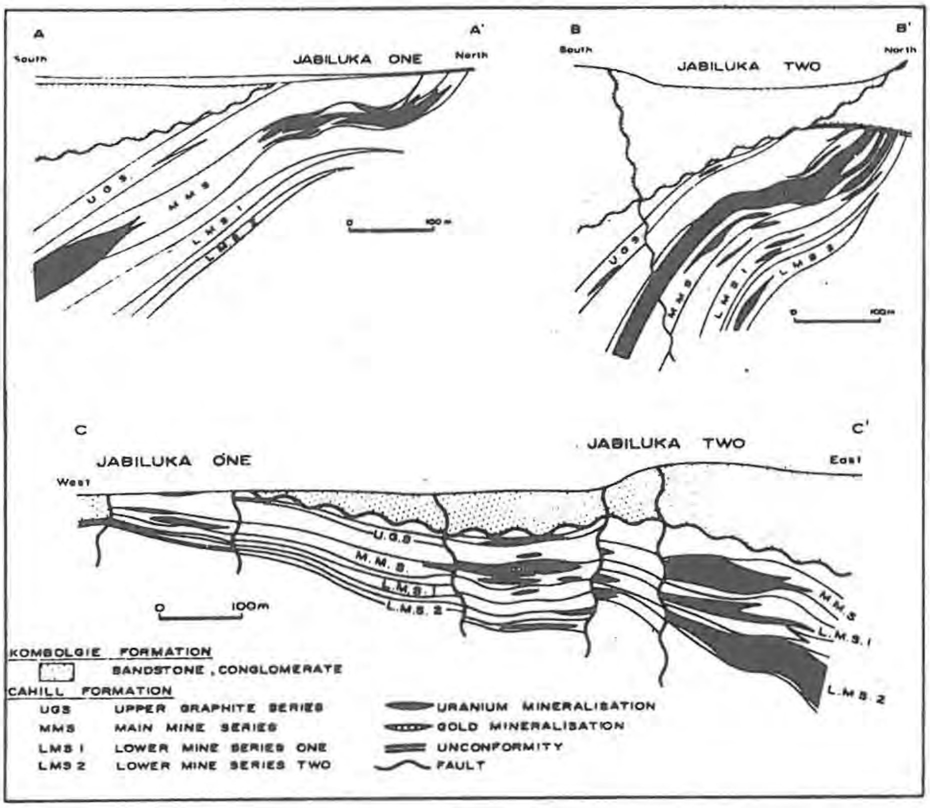


FIGURE 15 : Generalized cross sections of the Jabiluka One and Jabiluka Two orebodies (From : Hegge & Rowntree, 1978)

is exposed (subcropping) on the surface where it coincides with an erosional window bounded to the northeast by the overlying Kombolgie Formation, and to the south and west by normal faults which have downfaulted the Kombolgie (Fig. 16). The uranium concentrations at

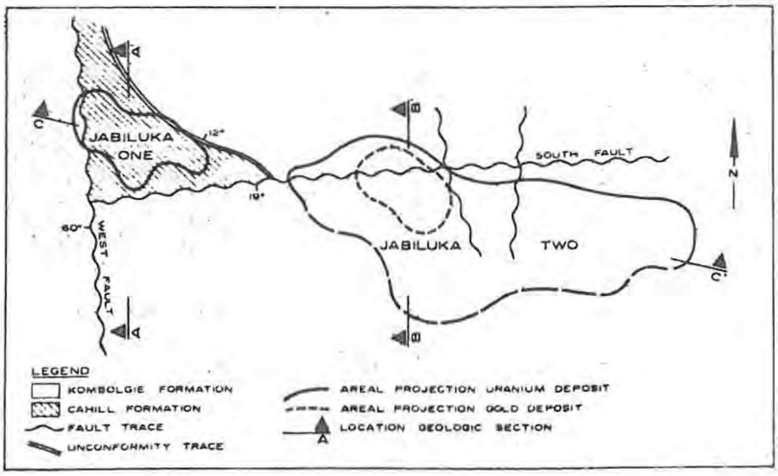


FIGURE 16 : Bedrock geological map over the Jabiluka One and Two deposits (From : Hegge and Rowntree, 1978)

Jabiluka occur in or near veins and breccia zones. Hegge (1977) has suggested a collapse mode of origin for the breccia bodies arising from silicification of dolomite, with the uranium filling open fractures and cavities. Binns et al. (1979) do not favour the latter model, instead suggesting a hydraulic fracturing mechanism, based on their opinion that most of the mineralized veins at Jabiluka are of replacement rather than dilational character. They consider the excessive fluid pressure necessary for hydraulic fracturing to be related either to a retrogressive metamorphic event which predates the mineralization, or to the earliest mineralizing event. Later dilational veins which are generally unmineralized cut across earlier veins and breccias at Jabiluka.

On a more regional scale, according to Hegge (1977), Jabiluka is situated at the intersection of lineaments trending 350^{o} and 073^{o}. The latter trend is reflected by the South Fault (Fig. 16) which is parallel to a major fault some 1500m south of Jabiluka. The 350^{o} trend coincides with the West Fault at Jabiluka One (Fig. 16) on which the dip-slip displacement is 40m and a right-lateral strike-slip movement, approximately 1600m.

Ranger I

The Ranger I orebodies are situated on the western flank of the Nanambu Complex where they occur just below the present land surface, which is almost coincident with the Lower Proterozoic - Middle Proterozoic unconformity. The Middle Proterozoic Kombolgie Formation forms the main mass of the Arnhem Land Plateau east of Ranger One, as well as two outliers to the north and south of the deposit (See Figure 11).

According to Eupene et al. (1975) no major structural features have been instrumental in localizing the deposit. Significant major faulting is absent whilst flexures in the regional strike are considered to have a local rather than tectonic origin, and can be related to thickness and lithological variations in the Lower Mine Sequence. However, within the orebodies there is a strong structural control of the mineralization, most of which occurs in fracture and breccia zones. The bulk of the ore is contained in the Upper Mine Schists which according to Eupene et al. (1975), were more susceptible to fracturing and brecciation than the other mica-rich lithologies. As at Jabiluka a collapse origin has been suggested for the brecciation related to silicification of dolomite in the underlying Lower Mine Sequence.

Koongarra

The Koongarra deposit is situated to the southeast of the Nanambu Complex and is also adjacent to an outlier of the Kombolgie Formation (See Figure 11). Mineralization occurs in two separate deposits and is indicated in at least three other prospects, all of which occur adjacent to a major northeast trending reverse fault which has thrusted the Lower Proterozoic rocks over the Kombolgie Formation Sandstone (See Figure 13) (Foy and Pederson, 1975). The fault has a 60° dip to the southeast and a throw of at least 200m. The contact zone is intensely brecciated and marks the footwall of the orebody. The fault breccia itself contains only minor mineralization. Strong shearing and minor brecciation parallel to the main fault persists into the overlying quartz-chlorite schist rocks which are the main ore hosts. The confinement of the ore below a sheared graphite unit (Figure 13) suggest that both chemical and structural controls were important in localizing the mineralization.

Nabarlek

The Nabarlek orebody is situated on the western edge of the Nimbuwah Complex close to outliers of the Arnhem Land Plateau (see Fig. 11). The ore deposit occurs close to the nose of a west-plunging synformal structure which outcrops immediately east of the orebody. Rocks in the area have been affected by several phases of deformation. An extensive recumbent phase produced tight drag folds in schistose quartzites as well as a pronounced subhorizontal schistosity (Anthony, 1975). The orebody is localised in a crush zone which transgresses the foliation of the Lower Cahill rocks, and is cut off at depth by a dolerite sill (Fig. 17).

The South Alligator River Field

The South Alligator River uranium deposits are situated along the northwest-trending fault-controlled South Alligator River valley which cuts through the Kombolgie sandstone of the Arnhem Land Plateau to expose tightly folded Lower Proterozoic metasediments along its floor.

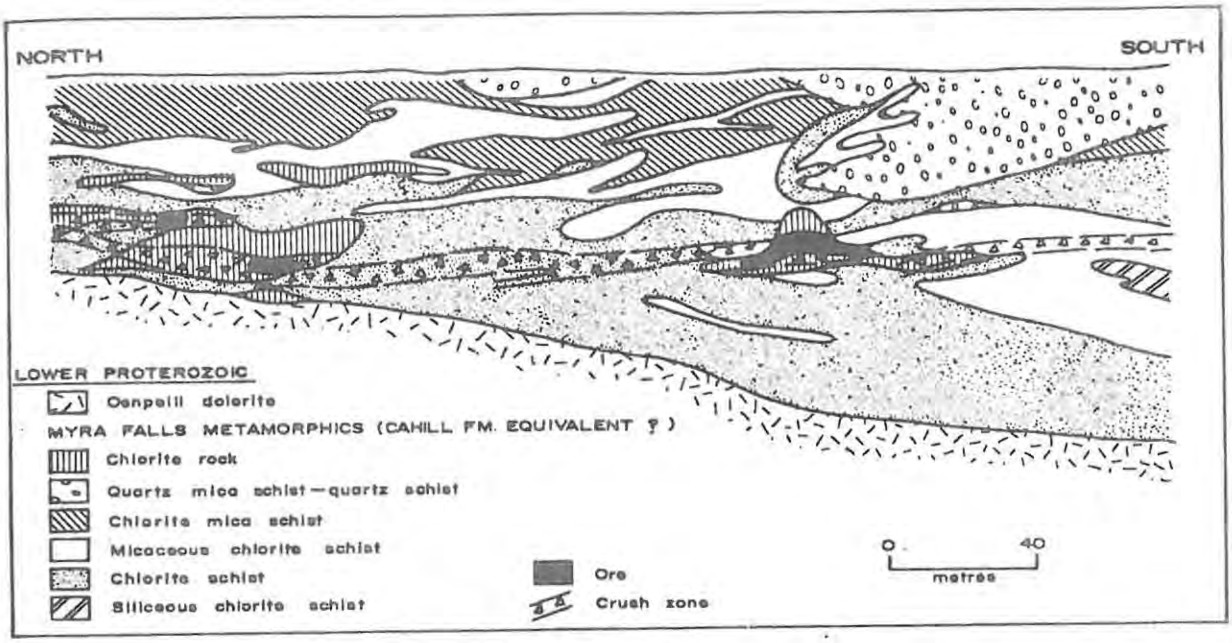


FIGURE 17 : Longitudinal geological section through the Nabarlek orebody (From : Hegge & Rowntree, 1978)

The ore deposits are mainly located in northwesterly trending faults, shears or fractures on, or close to the contact between Lower Proterozoic and Middle Proterozoic rocks (Crick et al., 1979).

The Rum Jungle Uranium Field

At Rum Jungle the uranium as well as base metal deposits occur close to the perimeter of the Rum Jungle Complex at or close to the contact between the Batchelor Group and the Masson Formation metasediments (Fig. 18). These have been folded to varying degrees by updoming of the Rum Jungle and Waterhouse Complexes after deposition of the Lower Proterozoic sediments, and faulted by the northeast trending Giant's Creek fault (Fig. 18). The largest concentration of ore deposits occurs in the so-called Embayment which is a laterally displaced wedge-shaped mass of folded Lower Proterozoic sediments forming an embayment in the southwestern part of the Rum Jungle Complex (Fig. 18). If the Giant's Reef fault is reconstructed, all of the deposits within the embayment are situated along the axis of a synclinal structure between the two complexes, in an arcuate line parallel to the Waterhouse Complex. The deposits are all associated with shearing and brecciation along the contact between the two Lower Proterozoic groups and are localized by flexures superimposed on the limbs of the syncline (Fraser, 1975).

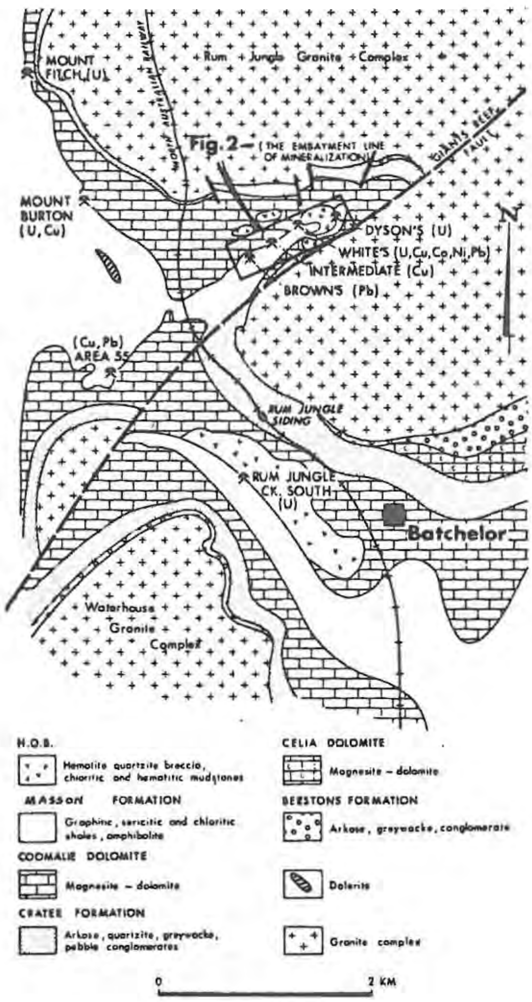


FIGURE 18 : Geological sketch map of the Rum Jungle Area (From : Fraser, 1975)

ALTERATION

A characteristic feature of the uranium deposits in the Pine Creek Geosyncline is their association with a pervasive retrogressive metamorphism to greenschist facies assemblages, which, particularly in the Alligator Rivers area, contrast heavily with the high grade regional metamorphic assemblages. This aspect of the deposits features prominently in most genetic and exploration models for the vein-type uranium deposits.

Jabiluka

Retrogressive metamorphism at Jabiluka is represented in the Lower Proterozoic rocks by the chloritization of biotite, garnet and possibly cordierite; by the replacement of sillimanite by white mica; and by the alteration of feldspars to very fine-grained chlorite-septechlorite-white mica aggregates (Binns et al., 1979). In carbonate horizons reactions involve the replacement of dolomite by magnesite, clearly indicating an introduction of magnesium. Since graphite and sulphides are preserved in the alteration zone the alteration fluids are assumed to have been reducing. The removal of Na, Ca and P appears to have accompanied the alteration at Jabiluka (Binns et al., 1979).

Matrix material in the overlying Kombolgie Sandstone as well as the 1-2m regolith which is developed beneath the unconformity have also been altered to greenschist facies assemblages, and the persistence of these assemblages across the unconformity suggests that the retrograde metamorphism of the Cahill Formation was coeval with burial metamorphism of the Kombolgie Formation, although the common presence of hematite in the latter suggests that the solutions were more oxidizing in the Kombolgie Formation.

Ranger I

The alteration halo at the Ranger deposit is similar to that at Jabiluka although it is more restricted and less intense (Ewers and Ferguson, 1979). The Hangingwall Sequence contains fresh garnet and K-feldspar, and unaltered hornblende and plagioclase occur in interbedded amphibolite. Minor K-feldspar, plagioclase, and hornblende have also been recorded in the ore-bearing Upper Mine Sequence. Generally the biotite-quartz-feldspar schist host in the latter sequence has been pervasively altered to a sericite-quartz-chlorite schist, by choritization of biotite as well as feldspar. The latter unusual reaction is observed both macroscopically and microscopically and is substantiated by chemical analyses which show an enrichment in Mg in altered rocks, and a depletion in K, Ca and Na (Eupene et al., 1975). Other evidences for Mg introduction is the fact that the usually dolomitic carbonate is commonly magnesite near the mineralized zone. In the carbonate-rich Lower Mine Sequence at Ranger I the most distinctive feature is the apparent replacement of carbonate by chert. In addition chlorite occurs as veins ranging in thickness from 1mm to 10m and is composed mainly of peninite with varying amounts of disseminated hematite, ilmenite, apatite, and pitchblende. Since this vein-type chlorite is similar to the replacement type in the Upper Mine Sequence, and contain most of the uranium mineralization, it is regarded as the dehydration product of the fluids which introduced the uranium mineralization (Binns et al., 1979). As at Jabiluka there is some evidence of chloritic alteration in the Kombolgie Formation.

Koongarra

At Koongarra the lease of the breccia zone associated with the reverse fault (see Figure 13) is intensely silicified and hematite-stained, in places containing massive hematite (Foy and Pederson, 1975). This zone generally contains little uranium. The overlying zone is a strongly brecciated and often very siliceous quartz-chlorite schist and a hematite stained massive dark green, chloritic rock. Within the ore zone massive chlorite is common as a fracture filling and as replacement rims surrounding muscovite, biotite, hornblende and garnet. The most intense uranium mineralization is confined to strongly chloritized rocks adjacent to the carbonaceous schist horizon which forms the hangingwall of the orebody.

Nabarlek

Alteration at Nabarlek appears to be different to that of the other uranium deposits in the Alligator Rivers Field, in that the ore-bearing rocks are affected by a later alteration not generally evident elsewhere (Anthony, 1975). The amphibolite facies rocks formed by an early regional metamorphic event were initially subjected to a retrograde metamorphic phase involving both chloritization and sericitization. Both the intrusive granite and the dolerite sill which underlie the Nabarlek deposit may have been partly responsible, since alteration adjacent to these features is more intense than further away, whilst neither intrusive is altered except along its margins. "In general the degree of alteration in the orebody is most intense in the metasediments above the dolerite, and tends to decrease at depth" (Anthony, 1975, p 306).

A later generation of replacive chlorite has a more restricted distribution and is intimately associated with the uranium mineralization in the crush zone at Naberlek (see Figure 17). The chlorite is fine-grained, dark green and massive, containing both sericite and hematite. Where uranium mineralization is present the colour ranges from dark green to black. Texturally it is massive and structureless, although mottled zones, relict banding and brecciation are present, as well as occasional flow structures, which suggest mobilization. Patches and blebs of hematite occur throughout the ore zone and within the chloritic rock. An orange or brick red variety is associated with the mineralization but does not occur elsewhere. Towards the high-grade centre of the orebody hematite commonly becomes a major constituent of the host rock and is associated with very fine-grained white sericite, and coarse pitchblende.

The South Alligator River Area

Widespread chloritization such as that occurring in the Alligator Rivers deposits has not been reported for the South Alligator River deposits. Ayers and Eadington (1975) report bleached carbonaceous shales in the Koolpin Formation but attribute the bleaching to recent and perhaps also early Proterozoic weathering, whilst others regard it as a product of hydrothermal alteration. Kaolinite, siderite, hematite and chlorite are locally important. Silica, chlorite and sericite also occur in minor amounts in the overlying Edith River Volcanics in some places.

Rum Jungle

Extensive chloritization is not reported from the Rum Jungle area, although chlorite and sericite are common constituents in some of the schists. Hematization is fairly widespread and is mainly associated with the Hematite Quartz Breccia, probably being related to palaeoweathering.

In general superimposed low-grade alteration would probably be difficult to recognize in the Rum Jungle area where regional greenschist meatmorphic grades prevail. However the same scale of alteration as that observed in the Alligator Rivers area is obviously not present, and it may possibly be significant that the Rum Jungle area deposits are of much smaller dimensions.

MINERALOGY

Uraninite is the most important uranium mineral in most deposits, filling a variety of open spaces and associated with chloritic and graphitic assemblages, indicating that both structural and chemical controls are important for its localization. This style of mineralization, together with the mineralogy of uranium and associated elements are important in both genetic and exploration models for unconformity-type deposits.

Jabiluka

At Jabiluka the uranium mineralization, consisting predominantly of uraninite and lesser amounts of coffinite and brannerite with rare thucholite, occurs in or near veins and breccia zones most commonly associated with, but not restricted to graphitic units in the sequence. Binns et al. (1979) recognize three main modes of occurrence for the uraninite :

(1) It occurs as selvedges and rarer internal layers or disseminations in veins which they consider to be of replacement origin, accompanied most commonly by a very distinctive gangue composed of a microcrystalline chlorite-septechlorite-quartz intergrowth (CSQ), and occasionally by subhedral quartz. Uraninite appears to have had a relatively late introduction since it replaces both CSQ and vein quartz, as well as retrograde phases in the immediately adjacent wall rocks. The uraninite is commonly zoned, usually with rims richer in oxygen, and is almost invariably bordered by a narrow zone of chlorite which is distinct from the other chlorite. Sulphides, including pyrite, chalcopyrite, chalcocite, sphalerite and galena are occasionally abundant within CSQ in the veins but are antipathetic with uraninite. Minor amounts of anhydrite may occur with CSQ.

(2) Uraninite occurs in disseminated form in the matrix of brecciated country rocks. The matrix consists of fine rock and mineral fragments, especially quartz, extensively replaced by CSQ. The uraninite is present mainly as isolated grains in CSQ, generally near quartz fragments and again surrounded by a narrow rim of chlorite. This mode of occurrence appears to be cogenetic with vein-type mineralization and shows a similar antipathetic relationship between uraninite and sulphides (Binns et al., 1979).

(3) Uraninite also occurs within narrow, irregular replacement zones of CSQ extending outwards from veins or breccias into adjacent schist. These zones commonly show replacement of quartz by coffinite and alteration of sphene or anatase to brannerite. As in the other types, uraninite occurs as a late stage replacement of CSQ, and decreases away from the vein or breccia body.

Binns et al. (1979) deduced from mineragraphic studies that the uraninite at Jabiluka formed at a comparatively late stage in the mineralization history, replacing CSQ and coffinite in particular.

Furthermore, since the CSQ intergrowth is often highly uraniferous, especially where uraninite is absent, they suggest that the uranium was first introduced to Jabiluka within CSQ replacements, from which the uraninite subsequently "exsolved". The fluids from which CSQ was precipitated must have been oxidizing since graphite is oxidized and syngenetic pyrite corroded in the vicinity of CSQ veins. The gradational relationship between CSQ patches and the retrogressive chlorite assemblages formed from more reducing fluids has been interpreted by Binns et al. (1979) to indicate that retrogressive metamorphism and creation of uraniferous CSQ were essentially contemporaneous. The more oxidizing fluids associated with the latter were probably introduced slightly later, after the creation of channelways which they suggest was achieved by hydraulic fracturing.

At Jabiluka Two and in the Kombolgie Sandstone later cross-cutting dilational quartz-dolomite-magnesite-chlorite veins are present, commonly carrying appreciable pyrite, and only isolated remnants of uraninite.

Gold is an important constituent at Jabiluka Two where 529 000 tonnes at an average grade of 15,3 g/t have been delineated (Hegge, 1977; Needham et al., 1979). It is normally present in native form but is occasionally accompanied by gold telluride. There appears to be no correlation between gold and uranium mineralization although gold is always present in uranium rich zones.

The most common gangue minerals in the Jabiluka orebodies are chlorite, quartz and sericite, with lesser calcite, and minor amounts of kaolinite, montmorillonite apatite, tourmaline, sphene, leucoxene and rutile. The latter two minerals are commonly intergrown with uraninite.

Ranger I

In the Ranger orebodies there is a clear relationship between uranium mineralization and magnesium metasomatism (Eupene et al., 1975). Uraninite (pitchblende) is the main primary mineral, occurring as veins as well as disseminations in the chlorite. Veins are generally less than 1 cm wide but nevertheless account for most of the high-grade patches of the orebody. Most of the uraninite is contained in hairline fractures where it coats foliation planes and joints. The disseminated form occurs as euhedral, subhedral and anhedral grains which may coalesce to form clusters, strings and massive uraninite. Uraninite cubes are normally found in progressive stages of replacement by chlorite (Ewers & Ferguson, 1979). Near surface secondary minerals include saleeite, sklodowskite and torbenite. Although the most consistent mineralization occurs in the main carbonaceous band at the base of the Upper Mine Sequence at Ranger One, there appears to be no broad relationship between uranium mineralization and pyrite or carbon content (Eupene et al., 1975).

Chlorite, quartz and pyrite are the most common gangue minerals whilst copper and lead sulphides and gold occur in trace amounts (Dodson et al., 1974).

Koongarra

The primary uranium mineral at Koongarra is uraninite which occurs in both crystalline and sooty amorphous forms. The crystalline variety both parallels and transgresses the schistosity, and also occurs as euhedral grains and botryoidal masses within a chloritic matrix in the breccia bodies. The sooty variety mainly coats fracture surfaces. The most intense mineralization is concentrated immediately below the graphite horizon which forms the hangingwall of the orebody (Foy and Pederson, 2975). Sklodowskite, kasolite and a number of secondary uranyl phosphates have been identified near surface downslope from the orebody, and in the fault zone (see Figure 13) (Hegge and Rowntree, 1978). Minor amounts of pyrite, chalcopyrite and galena, and trace amounts of gold are associated with high grade portions of the orebody. Quartz and chlorite are major gangue minerals whilst hematite is abundant in the fault zone forming the footwall of the orebody.

Nabarlek

At Nabarlek the uranium mineralization is contained within massive, structureless, fine-grained replacive chlorite, and consists of a high-grade core in which massive pitchblende predominates, surrounded by a lower grade envelope of more disseminated fine-grained mineralization (Anthony, 1975). There appears to be a sympathetic relationship between uranium grades and hematite which is most abundant in the high-grade core. This phenomenon is not observed in the other Alligator Rivers orebodies.

Disseminated sulphides in the orebody include galena and chalcopyrite, and trace amounts of bornite, chalcocite, covellite and marcasite. Secondary uranium minerals developed in the 15m thick weathered zone include sklodowskite, coffinite, curite, kasolite and rutherfordine.

The South Alligator River Deposits

In the essentially fault-controlled South Alligator River deposits both uranium and gold mineralization are most commonly associated with carbonaceous shales of the Koolpin Formation (Ayers and Eadington, 1975). Pitchblende is the dominant uranium mineral which occurs mainly as veins, but in places is disseminated in pyrite, carbonaceous shale, and ferruginous chert-banded shale, and also commonly along the boundaries between these rock-types (Crick et al., 1979). The pitchblende is accompanied by gold, minor iron and copper minerals, and in places by silver, niccolite, cobalt-nickel arsenites and galena. Secondary uranium minerals are common, and in some of the orebodies (e.g. Saddle Ridge and Scinto VI), are the only ore constituents.

The Rum Jungle Area

The ore deposits in the Rum Jungle area differ from those in the other Northern Territory uranium fields in that economic base-metal mineralization, notably copper and lead, and some cobalt, is associated with several of the uranium orebodies and also occurs independently of uranium mineralization in the same geological setting (Fig. 18). A broad mineral zonation has been recognized along the intergranite syncline in the Embayment, from predominantly base metal mineralization in the west to uranium in the east (Fraser, 1975), which corresponds to uranium being deposited nearest exposed basement, through copper to lead furthest from basement.

AGE RELATIONSHIPS

Hills and Richards (1976) have most recently reviewed the pitchblende and galena ages in the Pine Creek Geosyncline, together with the geochronology of the host rocks. The Lower Proterozoic rocks were laid down between 2400 and 1800 my. ago and metamorphosed at about 1800 my. resulting in the formation of the Nanambu and Nimbuwah Complexes. Granitic intrusions took place between 1830 and 1750 my.

Mineralization at Ranger One dates at about 1700 my, with a suggestion of remobilization at about 900 my. At Koongarra an 1850-1800 my. age was reported as well as a second 900-860 my. age for the mineralization. Jabiluka, Nabarlek and the South Alligator River deposits all fall within the 920-800 my. range, whilst a second 500-400 my. age is also present in the South Alligator River deposits. At Rum Jungle the deposits have been dated at about 1600 my. (Langford, 1974).

Ages for the Kombolgie formation range from about 1750 my. to 1400 my., suggesting that most of the uranium was deposited after deposition of the Kombolgie Formation.

SUMMARY - UNCONFORMITY-TYPE DEPOSITS IN THE PINE CREEK GEOSYNCLINE

Uranium accounts for 96,39% of the total metal value of recorded production and reserves in the Pine Creek Geosyncline (Needham et al., 1979c). The three most important uranium areas are the Alligator Rivers Field, the Rum Jungle Field, and the South Alligator River Field. Of these the Alligator River Field is by far the most important, accounting for 94% of the total value of metals (reserves and production) in the geosyncline. By comparison the Rum Jungle area accounts for 3,73% and the South Alligator River area for 0,28%. Thus whilst the characteristics of all of the deposits may be important in constructing conceptual models for exploration purposes it is obvious that the characteristics of deposits in the Alligator Rivers region are most important.

In their regional setting the uranium deposits are characterized by three striking features :

(a) proximity to the Lower Proterozoic-Middle Proterozoic unconformity. All of the deposits occur in Lower Proterozoic metasediments immediately below the unconformity with only minor mineralization occurring in Middle Proterozoic rocks above the unconformity in the South Alligator River Field. In the Alligator Rivers Field all of the uranium deposits are situated close to exposures of the Middle-Proterozoic Kombolgie Sandstone which forms the Arnhem Land Plateau and several nearby outliers which survived the Mezozoic and Tertiary peneplanations. The locations of the deposits suggest that their discovery must be attributed to the approximate coincidence of the present land surface with the unconformity, which enabled the deposits to outcrop or suboutcrop close to surface. Similar deposits should be situated beneath the Arnhem Land Plateau or in other areas where the unconformity is still intact. In the South Alligator River area the unconformity is exposed in the river valley which has been incised into the Arnhem Land Plateau, exposing the Lower Proterozoic sediments;

(b) their association with carbonaceous and carbonate horizons, resulting in the confinement of the uranium deposits to the Lower Cahill Formation in the Alligator Rivers Area and its correlative the Masson Formation in the Rum Jungle area and to the Koolpin Formation in the South Alligator River area. The generally high uranium background of the carbonaceous rocks throughout the geosyncline has led to speculation that the ore deposits may represent remobilized syngenetically concentrated uranium. The Nabarlek deposit is exceptional in that neither graphite nor carbonate-rich rocks have been recognized in the vicinity of the mine. Interestingly the grade at Nabarlek is higher than any of the other deposits, and its tonnage lower (see Table III);

(c) proximity to basement complexes. The location of deposits in the Alligator Rivers and Rum Jungle areas on the flanks of basement domes is considered to be highly significant, regardless of whether the domes were palaeohighs during Lower-Proterozoic sedimentation or not. Both the Rum Jungle and Nanambu Complexes show some evidence of having been topographic highs during sedimentation, and it is conceivable that this may have had some effect on the localization of uranium in the marine sediments on their flanks. The basement complexes are considered to be the ultimate source of the uranium, and are enriched in uranium by 2 to 6 times world average abundances for granitoids (Ferguson et al., 1979). The South Alligator Rivers deposits do not seem to be spatially related to any basement domes.

The localization of mineralization in the individual deposits is primarily dependent on porosity features such as breccias, faults, fractures and shear zones. Breccias are particularly well developed at Ranger, Jabiluka and Koongarra and may be related to solution and silicification of dolomite at or near the unconformity. Nabarlek is again exceptional in that mineralization there is contained in a crush zone rather than a breccia body. Breccias are also important in the

Rum Jungle area where they have been related to folding and faulting associated with movement on the Giant's Reef Fault. Folding appears to have localized mineralization at Jabiluka and many of the deposits at Rum Jungle but is apparently unimportant in the other deposits. In the South Alligator River Field, mineralization is localized in faults, shears or fractures close to and on the contact (faulted in places) between Lower and Middle Proterozoic rocks.

Widespread chloritization is intimately associated with uranium mineralization in the Alligator Rivers region. At Nabarlek hematite also shows a sympathetic relationship with uranium grades, whilst at Koongarra the strongly hematized footwall fault is unmineralized. The chlorite at Koongarra is also hematite stained. Similar widespread chloritization is not associated with deposits in the other uranium fields. Hematite is common in the Rum Jungle deposits particularly associated with the Hematite Quartz Breccia. Chlorite and sericite are common constituents in some of the schists. In the South Alligator River area bleached carbonaceous shales are host of uranium mineralization and locally kaolinite, siderite, hematite and chlorite may be important. Minor silicification, chloritization and sericitization has taken place in rocks overlying the unconformity.

The most pronounced ages of uranium mineralization are 800-900 my., with a few older and younger ages also recorded. The bulk of the uraninite in the deposits formed after deposition of the Kombolgie Formation.

DEPOSITS IN THE ATHABASCA BASIN, NORTHERN SASKATCHEWAN, CANADA

Commencing with the discovery of the Rabbit Lake and Cluff Lake deposits in 1968 and 1969 respectively, ten discoveries of unconformity-type vein deposits have been made in the Athabasca Basin of Northern Saskatchewan (Fig.19) in little more than a decade. The other discoveries include Collins Bay A and B deposits, Raven and Horseshoe, Key Lake, West Bear Lake, Maurice Bay and Midwest Lake. The tonnage and grade characteristics of deposits where these have been established, are presented in Table III, which shows that by comparison with the Australian deposits Canadian examples are generally higher grade but smaller.

REGIONAL GEOLOGIC AND TECTONIC SETTING

The northern Saskatchewan uranium deposits are developed at or close to the unconformity between the unmetamorphosed Middle Proterozoic Athabsca Formation and underlying metamorphosed Archaean and Lower Proterozoic rocks which constitute part of the Canadian Shield. The latter has been subdivided into a number of structural provinces (Fig. 18) based mainly on overall differences in internal structural trends and style of folding, and supported by differences in dominant radiometric ages of their basement rocks. The boundaries are defined by the truncation of one trend by another, either along major unconformities or along organic fronts (Stockwell et al., 1970; King, 1976).

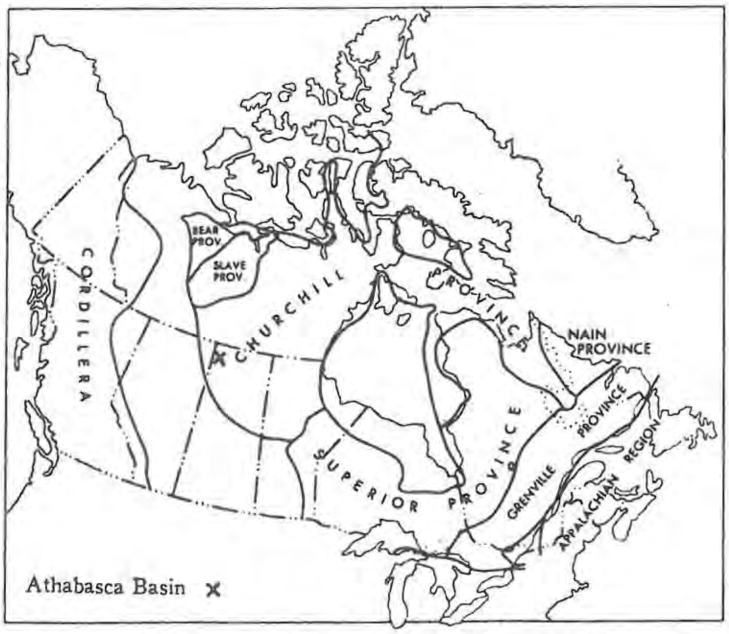


FIGURE 19 : Structural provinces of the Canadian Shield and location of the Athabasca Basin (Modified from Little, 1970)

The northern part of Saskatchewan falls within the Churchill structural province which is composed of granites, gneisses and belts of supra-crustal rock and is the type region for the Hudsonian orogeny, dated at 1820-1640 my. Based on lithological, structural and metamorphic characteristics, Lewry et al. (1977) subdivided the basement of the area into several northeast trending lithostructural domains (Fig. 20).

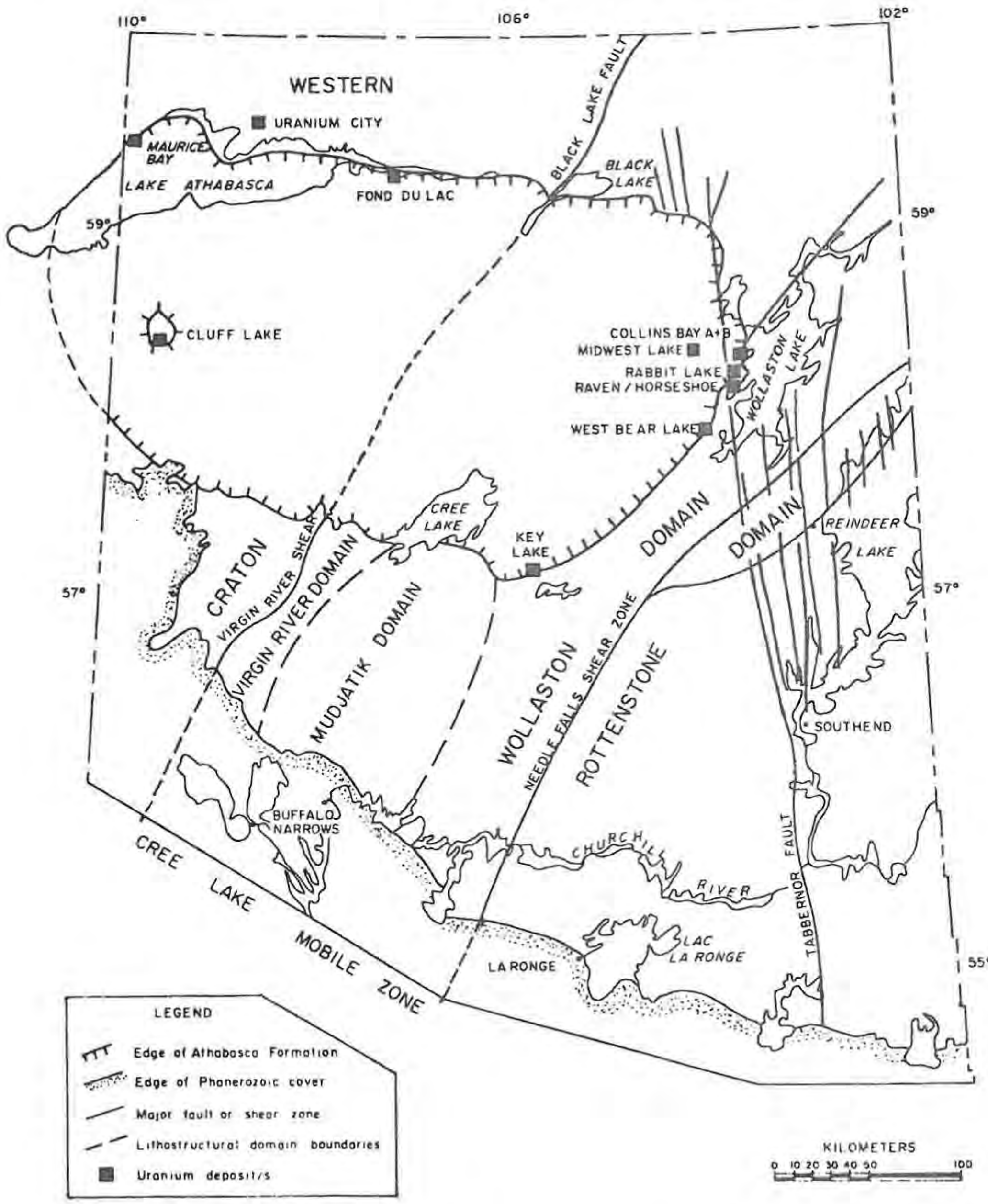


FIGURE 20 : Major lithostructural subdivision of the Churchill Province in northern Saskatchewan showing the location of uranium deposits (Modified from Hoeve and Sibbald (1978a) and Munday (1979)).

The dominant structural feature is the Cree Lake Mobile Zone in which lower Proterozoic metasediments are infolded with Archaean basement to varying degrees, producing the Mudjatik, Wollaston, and Virgin River domains. The latter two domains are similar, consisting predominantly of Lower Proterozoic supracrustal rocks overlying a remobilized Archaean basement. These are separated by the predominantly Archaean Mudjatik domain, which is characterized by a change in structural pattern and a higher metamorphic grade. The latter increases gradationally from upper greenschist to lower amphibolite facies in the adjacent domains to upper amphibolite/lower granulite facies in the Mudjatik domain (Gatzweiler et al., 1979). Lewry et al. (1977) have suggested that the pattern arises from an initial intense remobilization of the Mudjatik Archaean core, resulting in updoming and the formation of outward facing migmatite lobes, between which the lower Proterozoic supracrustal rocks became incorporated as nappe-like structures. In the cooler marginal sectors, represented by the Wollaston and Virgin River domains, less severe basement reactivation led merely to the formation of Archaean domes beneath a mantle of lower Proterozoic metamorphic rocks. A later period of compressive deformation resulted in arcuate and closed interference folding within the Mudjatik core, and a contemporaneous flattening of the mantled Archaean domes into elongated north east trending periclinal antiforms in the adjacent domains. Subsequent peneplanation resulted in the exposure of Archaean rocks in the core of some of the antiforms in the Wollaston and Virgin River domains whereas only remnants of lower Proterozoic rocks exist in the Mudjatik domain. The Needle Falls shear zone defines the eastern boundary of the Cree Lake mobile zone, east of which are migmatites of the Rottenstone domain. To the west, the mobile zone is separated from the Western granulite domain by the Virgin River Shear zone (Munday, 1979).

The majority of the unconformity-vein uranium deposits discovered to date occur in the Wollaston domain associated with lower Proterozoic metasediments (Fig. 20). In addition to the two previously mentioned phases of deformation, two later events also affected the lower Proterozoic Wollaston Group rocks during the Hudsonian orogeny. These were accompanied by greenschist facies metamorphism. In addition the rocks were affected by two generations of faulting. The earlier faults are sub-vertical, left-lateral, transcurrent faults which form part of the north-south trending

Tabbenor Lake fault system (Fig. 20). These were probably initiated during the Hudsonian orogeny, but may have been reactivated during the second phase of faulting which is of post-Athabasca, Grenvillian age (about 1000my.). The latter faults are low angle reverse faults (Hoeve and Sibbald, 1978a, 1978b).

STRATIGRAPHIC RELATIONSHIPS IN THE ATHABASCA BASIN

The stratigraphic succession in the Wollaston Lake area (Fig. 21) has been described by Hoeve and Sibbald (1978b).

Archaean Basement

These rocks are mainly of granitoid composition consisting essentially of felsic gneisses and minor mafic material, generally within the granulite metamorphic facies (Ray, 1977).

Lower Proterozoic Supracrustal Rocks

These consist of metasediments of the Wollaston Group, which has been subdivided into four units, namely a basal meta-arkose unit, a pelite unit, a meta-arkose unit, and an uppermost quartzite-amphibolite unit. The *basal meta-arkose unit* is thin and generally poorly developed. The overlying *pelite unit* is well developed and commonly graphitic. Where the meta-arkose unit is absent the pelite unit overlies basement directly. The *meta-arkose unit* consists of a montonous sequence of calcareous meta-arkoses interlayered with subordinate calc-silicate rocks and semi-pelitic metasediments. In parts of the succession the normally foliated meta-arkose, which comprises varying proportions of quartz, feldspar, biotite, clinopyroxene and amphibole, is transformed into massive unfoliated feldspar-rich granulites or "plagioclasites". Geochemical data indicate a sodium enrichment in these rocks manifested by a predominance of albite, and the presence of scapolite in interlayered calc-silicates. Elsewhere similar rocks have been interpreted as having been deposited in evaporitic environments (Weber et al., 1975). Massive carbonate lenses occur in the upper parts of the meta-arkose unit. The *quartzite-amphibolite unit* is characterized in its basal part by a well layered meta-arkose-calc-silicate-carbonate sequence. The remainder of the unit consists of pelitic gneisses with interdigitated sillimanite meta-arkoses, calcareous meta-arkoses to semi-pelitic

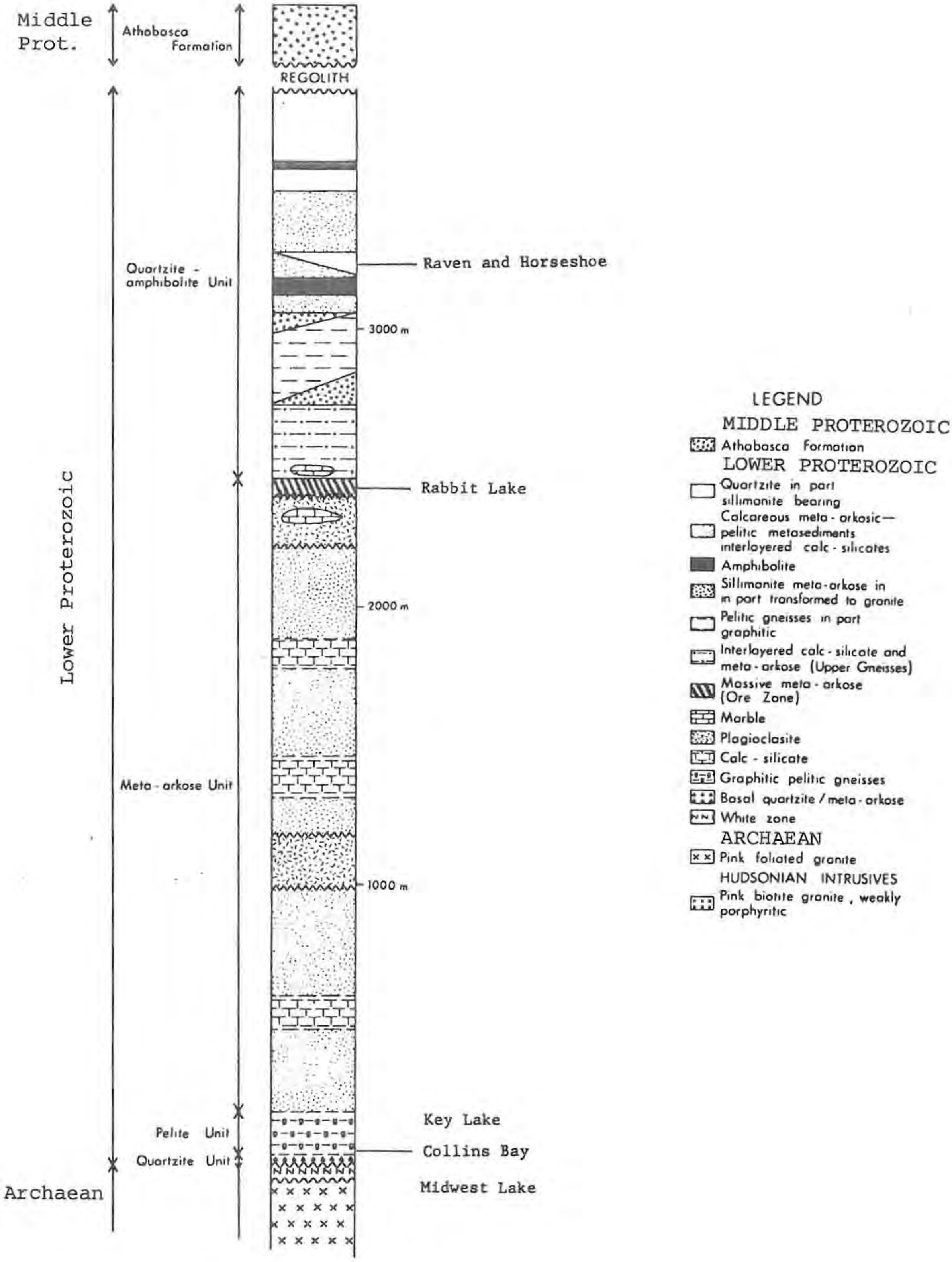


FIGURE 21 : Schematic stratigraphic succession for the Rabbit Lake area, showing the location of some unconformity-type uranium deposits (Modified from Hoeve and Sibbald, 1978b)

metasediments, amphibolites and quartzites. The pelitic gneisses and calcareous metasediments are locally graphitic.

Environmental interpretations are difficult in these rocks because primary sedimentary structures have been virtually obliterated by post-depositional metamorphism and deformation. Chandler (1978) has suggested that deposition occurred under tectonically quiet continental margin conditions, based on the association of pelites carbonates, quartzites and possible evaporites, and the general absence of coarse clastic sequences. Hoeve and Sibbald (1978b) consider the lowermost pelite unit to represent a westward marine transgression over a tectonically stable peneplaned Archaean craton, whereas they interpret the two upper units as having been deposited in a less stable environment under shallow water marine to fluviatile conditions from an eastern provenance area.

Where the lower Proterozoic and Archaean basement rocks have been truncated by the Sub-Athabasca unconformity they have been deeply weathered and hematized to form a regolith some 15-50m thick. The latter has mineralogical and chemical characteristics similar to present-day laterite, suggesting that humid subtropical conditions prevailed prior to the deposition of the overlying Anthabasca Formation. According to Hoeve and Sibbald (1978a) this weathering profile is consistent with the calculated palaeolatitude of 20° to 25°N for the region at that time, assuming a depositional age of 1350 $\pm$ 50 my. for the Athabasca Formation (Ramaekers and Dunn, 1977). In places, particularly in the vicinity of uranium mineralization, superimposed bleaching occurs in the regolith as patches and haloes around siderite-filled fractures. This bleaching is of regional significance and may be correlated with local chemical reduction observed at Rabbit Lake and other ore deposits, and also with bleaching phenomena in the Athabasca Formation (Hoeve and Sibbald, 1978a).

The Athabasca Formation

The Athabasca Formation comprises quartz sands with minor conglomerates, shales and greywackes reaching a thickness of 1750m. The conglomerates are concentrated towards the base of the formation. Earlier workers (Fahrig, 1961) described the Athabasca Formation as a homogeneous orthoquartzite probably deposited on a stable platform.

More recent work by Ramaekers (1979) has shown that a much more complex depositional history occurred. Ramaekers considers the Athabasca Formation to be a fault-controlled "pull-apart" basin deposit, consisting essentially of sediments deposited in a shallow-water braided-stream environment. According to Ramaekers (1979), the following sequence of events occurred during deposition of the Athabasca Formation : a series of elongate, deep, fault-bounded basins were formed in late Hudsonian times prior to deposition of the Athabasca Formation, possibly in response to a Hudsonian plate surture in eastern Saskatchewan. These were filled by mass-flow, alluvial fan and fluvial deposits, of which the Martin Formation (which is exposed to the north of the Athabasca Basin in the Beaverlodge area) is a remnant. Later less intense movements along the same fault zones produced several northeast trending basins which coalesced when infilled by the sediments of the Athabasca Formation. Palaeocurrent data indicate transport directions from the east and South. The sediments consisted of conglomerates and sandstones deposited along scarps in a series of fans. These graded upwards and basinwards into sandstones deposited by braided streams, culminating in a series of thin upward fining sequences of nearshore sands, silts and muds. Another similar cycle followed renewed uplift along the southeastern margin of the basin. The economic aspects of Ramaeker's (1979) interpretations will be discussed in a subsequent section.

The Athabasca Formation is characterized by extensive hematite staining associated with concentrations of iron in the coarse basal units (Hoeve and Sibbald, 1978a, 1978b). The presence of specularite in pore spaces indicates large scale post-depositional remobilization and redeposition of iron, suggesting that conditions during deposition and/or diagenesis must have been generally oxidizing. However widespread zones of bleaching similar to those in the underlying regolith occurs in fractures and permeable zones, pointing to subsequent reduction processes of basin wide importance, particularly in view of the common association of uranium deposits with zones of reduction.

Younger Formations

Younger formations conformably overlying the Athabasca Formation are preserved in a depressed ring surrounding the basement core of the Carawell circular structure (see Fig. 20). The latter has been interpreted both as a meteorite inpact crater and a crypto-volcanic explosion centre. The lower Douglas Formation comprises inter-bedded siltstones shales and fine-grained sandstones and is overlain by the Carswell Formation consisting of bedded dolomites of variable thicknesses which are locally stromatolitic, oolitic and brecciated (Harper, 1978). Both formations only occur in the immediate vicinity of the Carswell structure and are characteristically folded into arcuate,overturned isoclinal anticlines and synclines, the axial surfaces of which dip towards the centre of the structure.

All of the presently known unconformity-type deposits occur along or close to the margin of the Athabasca Sandstone. Mineralization occurs along the plane of unconformity at different stratigraphic levels in the basement rocks (see Figure 21) and in the overlying Athabasca Sandstone. The Key Lake deposits are located on the northwestern flank of a flattened periclinal basement dome, and the Cluff Lake deposits are situated within the Carswell structure. According to Bosschart (personal communication, 1979) the Midwest Lake deposit and several other uranium occurrences beneath the Athabasca Formation also occur adjacent to basement domes.

HOST ROCKS OF URANIUM MINERALIZATION

The predominantly host rock-type in northern Saskatchewan appears to be pelitic schists, but calcareous metasediments and quartzite are also hosts to important deposits.

Rabbit Lake

The hangingwall rocks at Rabbit Lake contain minor mineral-ization and consist of green calc-silicate layers composed predominantly of diopside, feldspar and biotite alternating with pink meta-arkose layers comprising varying proportions of feldspar, quartz, amphibole diopside and biotite. Carbonate is well developed in places and subconcordant pegmatitic metamorphic segregations are widespread. The high-grade core of the orebody is apparently confined to a massive meta-arkose unit, the major constituents of which are feldspar and subordinate quartz. Although generally massive, the meta-arkose unit sometimes shows a weak schistosity and also a crude layering due to concentrations of black tourmaline and dark green chlorite streaks. The dominant remaining rock-type in the Rabbit Lake pit is plagioclasite, comprising medium-grained granoblastic albite containing aggregates of porphyroblastic pyroxene and amphibolite. Included within the plagioclasite are weakly-to-unfoliated biotite-feldspar-clinopyroxene meta-arkose pods, probably representing parent material from which the plagioclasite was derived by metamorphic segregation and recrystallization (Hoeve and Sibbald, 1978b). Massive dolomite, impure layered carbonate, and diopside-biotite-calc-silicate rocks are interlayered with the plagioclasite in the west of the open pit.

Intermixed plagioclasite and calcareous meta-arkose form the footwall of the orebody below the Rabbit Lake fault. Hoeve and Sibbald (1978b) report that substantial amounts of graphite have been encountered during recent development drilling at Rabbit Lake, but do not elaborate on its mode of occurrence.

Key Lake

The uranium mineralization at Key Lake is hosted by Archaean/ Lower Proterozoic basement rocks as well as the overlying Athabasca Formation (Figure 22). Undisturbed and unaltered basement rocks consist of :

(a) *graphite-chlorite-sericite schist*, composed mainly of quartz, muscovite and aggregates of chlorite;

(b) *graphite schists*, composed of sericite, chlorite and 25-45% by volume of graphite, with garnets developed towards the base;

(c) *biotite-plagioclase-cordierite gneiss*. This is the most abundant rocktype composed mainly of biotite and plagioclase, quartz and cordierite. Also present are garnet-biotite gneisses, intercalations of metabasite (composed of biotite, hornblende and pyroxene), and coarse-grained pegmatoid anatectic gneiss.

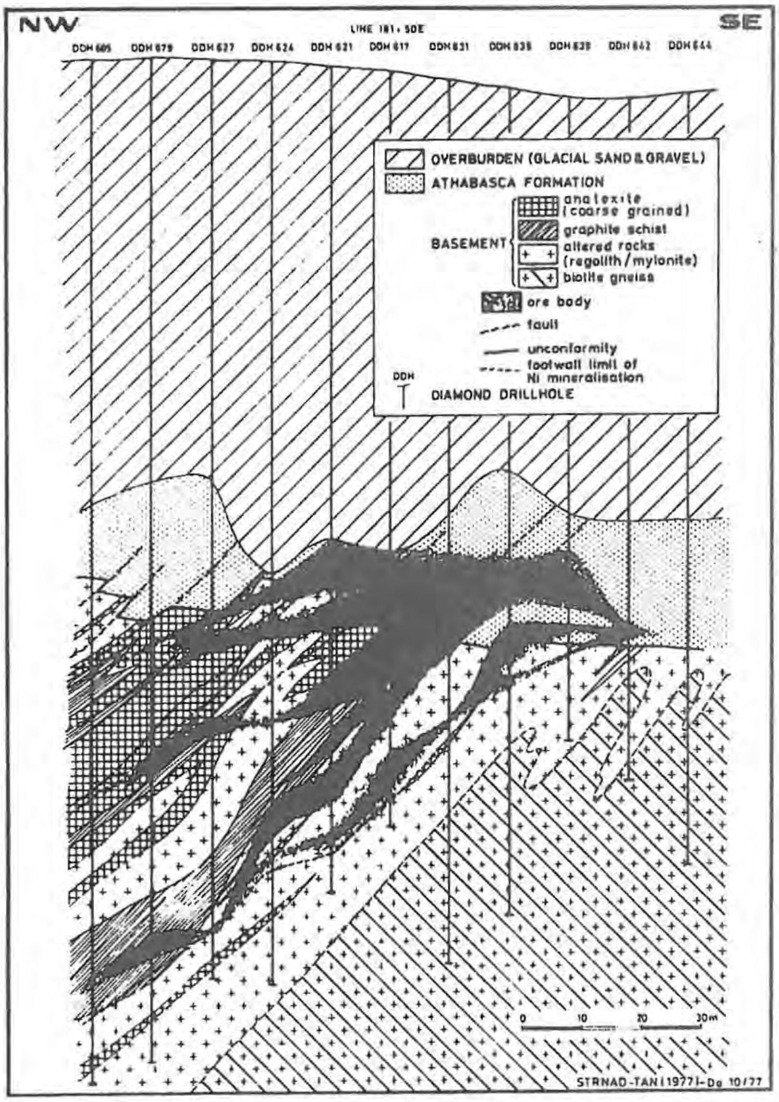


FIGURE 22 : Generalized geological cross section of the Deilmann orebody, Key Lake deposit (From : Dahlkamp, 1978b)

Above the unconformity the Athabasca Formation consists of a basal conglomerate in which some weathered basement pebbles are present. The quartzites generally consist of ± 95 modal % quartz, and where mineralized, they are characterized by a matrix of chlorite, kaolinite, sericite and carbonate. Accessory minerals include apatite, tourmaline, zircon and opaque minerals (Dahlkamp, 1978b; Gatzweiler et al., 1979).

Cluff Lake

At Cluff Lake three orebodies are present, two of which are situated entirely within basement rocks, the other occurring in both basement rocks and the Athabasca Sandstone. The following rock-types are represented in the basement core of the Carswell structure (Harper, 1978) :

(a) *Red granitoid gneisses.* These are granitic to dioritic in composition, locally containing abundant mafic rich remnants.

(b) *Quartzo-feldspathic gneisses,* comprising complexly interlayered quartzites, meta-arkoses and metapelites. Varients within the group consist of heavily limonite-stained, pyritic, graphitic, siliceous rocks, and amphibolite, and/or chloritic quartzo-feldspathic gneiss. Calc-silicates are locally developed.

(c) *Pelitic gneisses.* These are biotite-rich, with variable amounts of garnet, graphite and pyrite.

(d) *Iron formation,* consisting of banded magnetite quartzites and mafic gneisses.

(e) *Mafic gneisses,* occurring as thin bands or lenses within other rocktypes, or as discrete bodies.

(f) *Pegmatoid,* coarse-grained leucocratic rocks which have an apparent intrusive relationship with the basement gneisses.

The *D orebody* at Cluff Lake (Fig. 23) occurs at the inverted, unconformable contact between regolithic quartzo-feldspathic gneisses and the Athabasca formation. Most of the ore occurs in organic-rich pelites and, in disseminated form, in intercalated sandstones near the base of the Athabasca Formation, as well as in faults in the overlying quartzo-feldspathic basement gneiss.

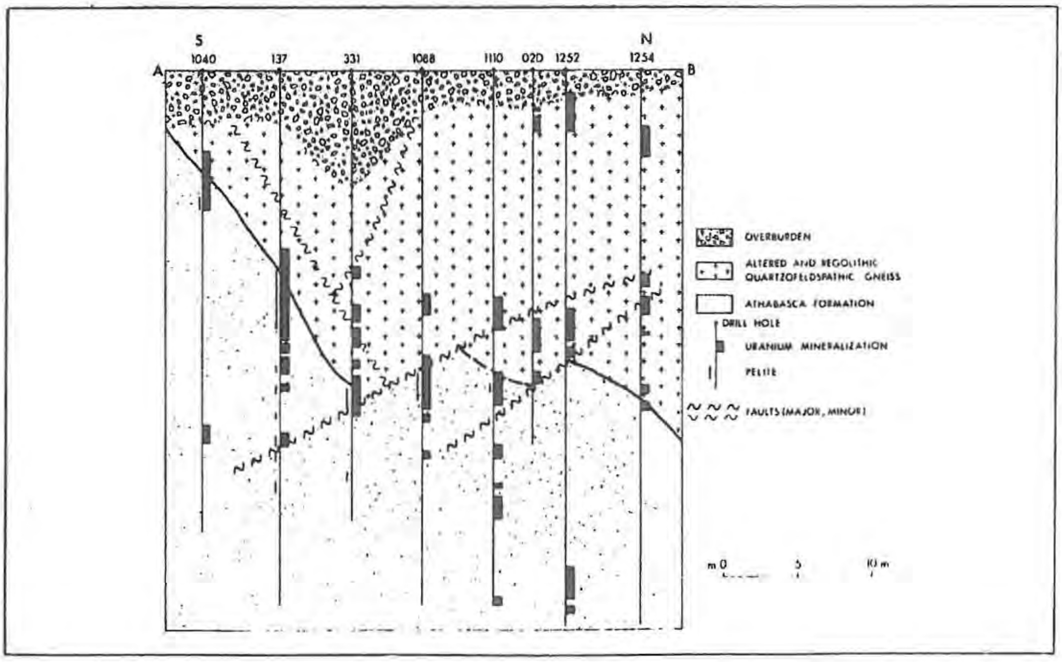


FIGURE 23 : Geological cross-section of the D orebody, Cluff Lake (From : Harper, 1978)

The *N orebody* occurs in, and adjacent to, a shear zone separating red granitoid gneisses in the west from a mixed sequence of generally amphibolitic quartzo-feldspathic gneisses and conformable garnetiferous pegmatoids.

The *Claude orebody* occurs entirely within quartzo-feldspathic basement rocks.

Other subeconomic uranium occurrences in the Cluff Lake area are situated in the Athabasca Sandstone, and one deposit, the M body, is situated in the red granitoid gneiss (Harper, 1978).

Of the remaining deposits the Collins Bay, West Bear, and Midwest Lake deposits in the Wollaston domain are all hosted by metapelites with quartzitic and graphitic beds (McMillan, 1979), whereas the Raven and Horseshoe deposits are hosted by quartzites of the quartzite-amphibolite unit (Hoeve and Sibbald, 1978) (Fig. 21). Much of the mineralization at Midwest Lake is hosted by the Athabasca Sandstone (Fish, 1979).

STRUCTURAL CONTROLS OF URANIUM MINERALIZATION

The textures of the uranium ore minerals indicate that most of the mineralization is of the open-space type (Langford, 1978), which accounts for the almost ubiquitous association of the unconformity-type deposits with structural features. These are generally represented by major faults and shear zones, along which brecciation is widespread.

At *Rabbit Lake* the ore deposit is located in the upthrown block of the Rabbit Lake fault, which is an east-northeast trending southerly dipping low angle reverse fault of post-Athabasca and also post-mineralization age. Widespread fracturing and brecciation accompany the fault, particularly in the basement rocks of the upthrown block, suggesting that several episodes of brittle deformation occurred and that the Rabbit Lake fault probably represents the reactivation of an older fault zone (Hoeve and Sibbald, 1978a). The high-grade core of the Rabbit Lake orebody is associated with the most intense fracturing and brecciation.

The two *Key Lake* orebodies are structurally controlled by the intersection of an east-northeast striking reverse fault zone and the sub-Athabasca unconformity. The fault-zone, which parallels the metamorphic foliation,is developed at the base of one of the graphite-gneiss units and extends through the plane of the unconformity into the Athabasca Sandstones. The orebodies are elongated and trend parallel to the trace of the intersection of the fault-zone and the unconformity. Offshoots from the main orebody also occur along and adjacent to the unconformity (see Figure 22). The ore shoots start in the lower basement as vein-like features conformable with the foliation, and within shear zones parallel to the foliation. Their thickness increases upwards and finally they develop into more irregular bodies. Within the Athabasca Sandstone the orebodies are mainly confined to shear zones and to complementary joint systems (Dahlkamp, 1978b, Gatzweiler et al., 1979).

At *Cluff Lake* the *D orebody* appears to have limited structural control over its mineralization, most of which is concentrated in a pelite lens within the Athabasca Formation (Munday, 1979), and in palaeoregolithic rocks along the unconformity. Some mineralization is contained in northwesterly trending faults in the overlying (inverted) gneisses. The *N orebody* is associated with a complexly faulted and sheared zone separating two main lithological units. The mineralization is localized within shear zones generally parallel to the metamorphic foliation and in the fault contact between the two groups of gneisses. Shear zones tend to be enriched where these intersect older faults and shears (Harper, 1978). The *Claude orebody* is outlined by,and is parallel to,north and north-northeast trending faults which are part of the radial system of the Carswell structure. Another east-west trending fault system cuts the ore zone into panels. Most of the uranium is concentrated within rather wide,horizontal, or gently dipping,cataclastic zones which are filled with layers of mylonite and Cluff breccia. The latter breccia is related to the formation of the Carswell structure and is much younger than the uranium mineralization. At Midwest Lake ore-bearing graphitic zones are sheared parallel to the foliation and are only locally brecciated. Fracturing and brecciation are better developed in the sandstone, particularly where there is a break in the palaeoslope of the Lower Proterozoic rocks (Fish, 1979).

ALTERATION

The uranium mineralization is always accompanied by some form of alteration of the host rocks, the most common products being chlorite and hematite, with lesser amounts of kaolinite and sericite. Silica and carbonate alteration occurs in some deposits.

Rabbit Lake

The most detailed study of alteration to date is that by Hoeve and Sibbald (1978a,b) on the Rabbit Lake deposit, in which they distinguish four different forms of alteration. These have been designated weathering, dark green chloritization, red alteration, and pale green alteration.

(a) *Weathering* : in the Rabbit Lake area the weathering profile is up to 50m thick and resembles that of present-day laterites. It is distinguished from top to bottom by a red, hematite-rich clay zone, a red hematized zone pseudomorphous after the parent rock, and a green zone which grades into fresh rock.

The red clay zone is structureless and is composed of kaolinite accompanied by small amounts of illite and some quartz. Parent rock textural elements increase with depth in the red pseudomorphous zone, and similarly illite replaces kaolinite as the dominant clay mineral, accompanied by some chlorite. The red pseudomorphous zone passes gradationally into the underlying green zone, characterized by chloritization of mafics and replacement of feldspars by illite. Pale green or creamy bleaching is superimposed on the hematized rocks in irregular patches and as haloes around fractures. The bleaching is accompanied by chloritization, and appears similar to the pale green alteration observed in the alteration envelope of the orebody.

(b) *Dark green chloritization* is the earliest alteration product, preceding mineralization and confined mainly to the brecciated high-grade core of the orebody. Mafic minerals are altered to aggregates of green chlorite associated with some anatase. Because of its dark green colour, Hoeve and Sibbald (1978b) suggest that the chlorite is an iron-rich variety.

(c) *Red alteration* involves the replacement of both mafic minerals and feldspars by an almost colourless magnesium-rich chlorite, accompanied by small amounts of epidote and relict quartz, apatite and tourmaline. The typical red colouration stems from finely divided hematite, which pervades both fragments and matrix of breccia zones. Mineralogical changes suggest that the alteration is accompanied by the introduction of iron, magnesium, water and boron, and the removal of silica, alkali metals and calcium oxide.

Red silicification and dolomitization are locally important, the former cementing chlorite and filling narrow fractures and small vugs, giving rise to diffuse impregnation zones, and occasionally to secondary quartzite. The dolomite also occurs as fracture fillings and diffuse impregnation zones, grading into massive dolomite.

(d) *Pale green alteration* is similar mineralogically to the red alteration, except that hematite is absent and small quantities of sulphides including pyrite, chalcopyrite, chalcocite and galena are often present instead. This alteration is superimposed on the red alteration and is so pervasive that the latter is only preserved as small remnant patches. In red coloured quartzite and dolomite, bleaching is accompanied by the removal of intergrain-boundary hematite. However, hematite pigment enclosed within quartz and dolomite crystals is not removed. In the median portion of the alteration zone local silicification occurs which, in contrast to the earlier silicification, is devoid of hematite, suggesting reducing conditions.

The superimposition of pale green alteration on red chloritization is characterized by the leaching of iron, with no other marked changes taking place. Where superimposed on regolith, however, introduction of magnesium occurs in addition to iron removal, thus accounting for the appearance of pale green chlorite.

Hoeve and Sibbald (1978b) have interpreted the mineralogical changes accompanying alteration to represent oscillations between oxidizing and reducing conditions which were intimately tied to intermittent brecciation. Precipitation of uranium took place after each of the oxidation episodes.

Key Lake

At Key Lake a distinction is also made between alteration due to palaeo-weathering and subsequently superimposed alteration (Dahlkamp and Tan, 1977; Dahlkamp, 1978; and Gatzweiler et al., 1979). Alteration associated with palaeoweathering extends for depths of up to 60m below the unconformity and decreases in intensity with depth. It is characterized by the replacement of hornblende, garnet, cordierite and biotite by chlorite; of plagioclase by zoisite; and of K-feldspar by sericite. Iron hydroxides and titanium oxides are distributed in a relict latticework derived from the complete alteration of biotite. According to Dahlkamp (1978) these features are indicative of a static weathering process.

Other alteration in the Key Lake deposits is associated with cataclastic deformation and has been subdivided on a mineralogical basis into kaolinite-mylonite, chlorite mylonite, and sericite-chlorite mylonite.

Kaolinite-mylonite is composed predominantly of kaolinite, coloured red in places by goethite. Apatite, epidote, quartz and zircon are accessories, and sericite and chlorite are characteristically absent. The kaolinite-mylonite is the main host of the uranium mineralization, which generally occurs along fissures and shears, although in some cases it is so intense that only islands of kaolinite are preserved in massive mineralization. This alteration is regarded as having been derived from intense tectonic deformation and subsequent hydrous alteration, resulting in the recrystallization of kaolinite.

In the *chlorite-mylonite zone* iron-rich chlorite is the major component. Other constituents include submicroscopic cataclastic primary quartz, and minor kaolinite. Limonite, siderite, and calcite occur in places in shears, cavities and fissures. The chlorite-mylonite is the second most important ore bearer, the mineralization again occurring along shears and as massive replacements. Recrystallization of chlorite indicates that a hydrous process was involved in the alteration.

Sericite-chlorite-mylonite : the main rock constituents are sericite, magnesium-rich chlorite and quartz. The rock is varyingly mylonitized and is generally unmineralized or only sparsely mineralized. Unlike the iron-rich chlorite, the magnesium-chlorite shows no evidence of hydrous alteration,and the formation of this rocktype has therefore been attributed to palaeoweathering of the basement followed by mylonitization, without the formation of new minerals (Dahlkamp, 1978b).

Cluff Lake

At Cluff Lake a 30-40m thick dark purple-to-maroon hematite-rich regolith is developed in the basement rocks. Dark green-to-black chloritic alteration is fairly widespread in the core of the Carswell structure and its status is uncertain. It occurs on fracture, joint, cleavage, and foliation surfaces, replaces amphiboles and pyroxenes, and is also associated with uranium mineralization in some places, e.g. the Dominique mineral showing (Harper, 1978). Dark green chloritic alteration may represent retrogressive metamorphism or an undefined hydrothermal event.

Pale green to white chloritic and sericitic alteration is superimposed on the hematitic alteration, and is associated with the uranium mineralization at the N and Claude orebodies, accompanied locally by dravite, suggesting that both magnesium and boron were introduced by the alteration fluids, in a similar fashion to the Rabbit Lake alteration process.

Midwest Lake

An extensive alteration envelope is present at Midwest Lake. According to Fish (1979) earliest alteration is represented by kaolinitization along the unconformity and in the shear and breccia zones in the Lower Proterozoic rocks, probably related to weathering. Chloritic and sericitic alteration is superimposed on the kaolinite in the Lower Proterozoic rocks and extends into the Athabasca Sandstone. The latter is also stained by hematite near its basal contact. Uranium mineralization accompanies kaolinitic, chloritic, and sericitic alteration.

MINERALIZATION

Rabbit Lake

The mineralization at Rabbit Lake is situated within the chloritic alteration envelope and comprises several generations of pitchblende and coffinite,and a broad suite of associated minerals, including secondary uranium minerals.

Earliest pitchblende mineralizations occurred in two stages, an earlier stage in which it forms colloform encrustations on wall-rock and breccia fragments, accompanied by euhedral quartz; followed by a later more massive variety, replacing early formed pitchblende, and accompanied by adularia, chlorite,hematite, calcite, and coffinite; the latter often in association with intergrown sulphides and arsenides, including galena, pyrite, arsenopyrite, chalcopyrite, bornite, chalcocite, covellite and others. From the paragenetic sequence for the early stages of pitchblende mineralization in Figure 24 it is evident that the two stages of pitchblende deposition were separated by a period of oxidation, during which hematite was precipitated.

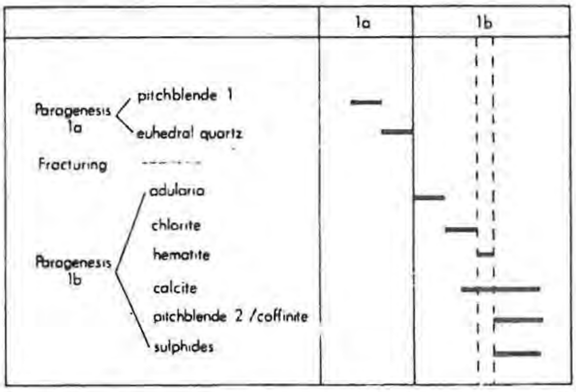


FIGURE 24 : Idealized paragenetic sequence for stage 1 mineralization at the Rabbit Lake deposit (From : Hoeve and Sibbald, 1978b)

A significant stage of mineralization is associated with the formation of euhedral quartz veins that separate the episodes of red and pale green alteration observed in the Rabbit Lake pit. Pitchblende is accompanied by a complex mineral assemblage including dravite, euhedral quartz, dolomite, calcite, hematite, siderite, goethite, chlorite,psilomelane, kaolinite, sulphides, native copper, and globular inclusions of amorphous carbon or hydrocarbon. All these minerals rarely occur together, most veins having a relatively simple mineralogy comprising dravite, euhedral quartz, hematite and a few others. An idealized paragenetic sequence for this stage of mineralization is presented in Figure 25. In general reducing conditions prevailed throughout the period, interrupted by oxidizing intervals marked by the crystallization of hematite and goethite.

A final period of uranium mineralization is represented by impregnations of sooty pitchblende and coffinite along fractures and joints in pale green altered rocks, and probably represents redeposition of uranium rather than a primary mineralizing event.

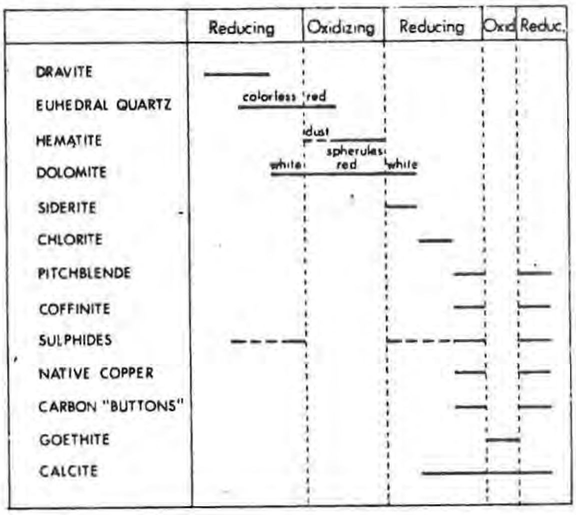


FIGURE 25 : Idealized paragenetic sequence for Stage 2 mineralization and euhedral quartz veins at the Rabbit Lake deposit (From : Hoeve & Sibbald, 1978b)

Key Lake

A somewhat different mineral assemblage is present at Key Lake, characterized principally by the association of economic quantities of nickel, in addition to uranium. Pitchblende and coffinite are the main ore minerals in both Key Lake orebodies. Type I pitchblende comprises euhedral and radially textured pitchblende and is restricted to the palaeoweathering zone and altered basement rocks, sometimes forming zonal intergrowths with gersdorffite. Type II, or sooty pitchblende is commonly intergrown with coffinite, both minerals apparently having been derived by oxidation of Type I pitchblende. Coffinite and Type II pitchblende predominate over Type I pitchblende in mineralized basement, whilst representing the only form of uranium mineralization in the overlying Athabasca Sandstone. The main nickel minerals are gersdorffite, millerite, niccolite and bravoite. Gersdorffite is most abundant, and is ubiquitous within the mineralized basement as well as the Athabasca Formation, whilst niccolite, which is less abundant, and characteristic of deeper ore zones, occurs only within basement rocks (Gatzweiler et al., 1979).

Radiogenic galena, which is absent in the Athabasca sandstone is the most abundant of the accessory sulphide minerals. Others are pyrite, sphalerite and chalcopyrite. Kaolinite, chlorite, quartz, siderite, calcite, sphene and epidote, all in minor quantities, form part of the introduced mineral assemblage (Dahlkamp, 1978b).

Cluff Lake

Of the three orebodies at Cluff Lake, the D orebody has been classified as complex, and the N and Claude as simple, based on their respective mineralogical compositions (Harper, 1978).

The D orebody : The principal ore minerals are pitchblende and uraninite. The most abundant accessories are native gold, and gold tellurides, native selenium, and lead, bismuth, nickel and cobalt selenides; and galena and chalcopyrite. Other constituents reported include clausthalite, calaverite, parammelsbergite and iron sulphides.

The N orebody : Uranium mineralization occurs as nodular pitchblende and coffinite, occurring with argillaceous alteration products, accompanied by graphite. Accessory minerals include pyrite and/or marcasite, and local development of chalcopyrite, galena and bituminous organic material similar to that present in the Rabbit Lake orebody. Secondary uranium and lead-bearing minerals occur in the oxidized zone. These include kasolite (lead-uranium hydrosilicate), and wulfenite (lead-molybdenum oxide). The lead is of radiogenic origin.

The Claude orebody : uraninite and coffinite are the principal uranium minerals with accessory graphite, pyrite, galena, molybdenum and organic material (Harper, 1978).

Midwest Lake

In the Midwest Lake deposit pitchblende occurs in fractures and in disseminated form in the Athabasca Sandstone, associated with zones of sericitization. In the Lower Proterozoic rocks pitchblende is accompanied by nickel-cobalt arsenides. Nodular to massive pitchblende and nickel-cobalt arsenides are also found in the altered contact zone, accompanied by galena, sphalerite, chalcocite and marcasite (Fish, 1979).

AGE RELATIONSHIPS

In general published ages of initial mineralization at the various deposits are fairly similar. Most ages at Rabbit Lake are around 1075 my. (Little, 1974) although several dates between 1200 and 1320 my. have been recorded (Knipping, 1974). Initial ages at Key Lake range from 1160 to 1230 my. (Dahlkamp, 1978b) with remobilization periods at 960 and 89 my. (Gatzweiler et al., 1979). The D orebody at Cluff Lake has been dated at about 1050 my. (Tapaninen, 1975). All of the ages are younger than the Athabasca Formation which has been dated at 1350 $\pm$ 50 my. (Ramaekers and Dunn, 1977).

SUMMARY - UNCONFORMITY-TYPE DEPOSITS IN THE ATHABASCA BASIN

The Canadian unconformity-type vein deposits show a definite spatial relationship to the Lower- Middle-Proterozoic unconformity in the Athabasca Basin of northern Saskatchewan. The Key Lake deposit and several other uranium occurrences are situated on the flanks of basement domes. Uranium mineralization occurs in Lower Proterozoic metasediments beneath the unconformity in all of the deposits, whilst at Key Lake, Cluff Lake and Midwest Lake the overlying Athabasca Formation also contains ore. Host rocks of uranium mineralization in the Lower Proterozoic metasediments are quite variable. At Rabbit Lake, and in the N and Claude orebodies at Cluff Lake, quartzo-feldspathic gneisses are the main hosts, whereas at Key Lake, Midwest Lake, Collins Bay, and West Bear Lake, graphitic horizons predominate. Quartzites are the host rocks at the Raven and Horseshoe deposits (Munday, 1979).

Structural control of mineralization is pronounced in all of the deposits but is less important in the D orebody at Cluff Lake. Fractures and breccias associated with major faults and shear zones are most commonly mineralized.

Chloritic alteration, often of several generations, is the most important alteration product at every deposit and may be accompanied by sericitization, hematization, and kaolinization. The alteration is due to palaeoweathering and retrograde metamorphism and precedes uranium mineralization.

Pitchblende, and to a lesser extent coffinite, are the most important uranium minerals. Economic nickel grades occur at Key and Midwest Lakes. Common accessory minerals include pyrite, marcasite, galena, chalcopyrite, bornite, chalcocite, arsenopyrite, molybdenite, sphalerite and others in varying amounts in the different deposits. In the complex D orebody at Cluff Lake native gold, gold tellurides; native selenium and lead, bismuth, nickel and cobalt selenides occur in addition to the more common sulphides. Amorphous carbon or hydrocarbon has also been recorded in most orebodies.

The most important mineralization age was around 1100 my. for most deposits. Younger ages have also been recorded for the Rabbit Lake and Key Lake deposits. All initial mineralization ages appear to be younger than the Athabasca Formation.

COMPARISON OF AUSTRALIAN AND CANADIAN DEPOSITS - AN EMPIRICAL MODEL FOR UNCONFORMITY-TYPE URANIUM VEIN DEPOSITS

Australian deposits of the Alligator Rivers area and Canadian unconformity-type deposits are similar in almost every respect. Most striking is their spatial relationship to the Lower- Middle Proterozoic unconformity, which in each case is underlain by metasedimentary assemblages and overlain by fluviatile red, arenaceous formations, suggesting similar tectonic settings for the uranium deposits. The deposits in the Alligator Rivers region are situated adjacent to basement domes and a similar setting exists at Key Lake in Canada. The Kombolgie Sandstone in Australia is rarely mineralized, in contrast to the Athabasca Sandstone in Canada, which is often ore bearing. However in neither country are the deposits situated far from outcrops of the sandstones. In both countries graphitic and chloritic schists are the most favourable host rocks, commonly accompanied by carbonate in Australia, but only at Rabbit Lake in Canada. Quartzo-feldspathic rocks are also important hosts, particularly in Canada, and it is noteworthy that in the latter country whenever these are hosts of orebodies, bituminous material has been recorded. Whilst the solution of carbonate and formation of collapse features in the Australian deposits may have created favourable openings for mineralizing solutions, faults, and a porous palaeoregolith appear to have been more important in Canada. Retrogressive chloritic alteration is characteristic of all the deposits, and is obviously genetically significant. Uraninite (pitchblende) is the most important ore mineral, often accompanied by coffinite and rarely brannerite. Gold is a coproduct at Jabiluka, and economic nickel grades are present at Key Lake and Midwest Lake in Canada. Accessory minerals include a wide variety of sulphides, sulpharsenides, selenides and others. These vary among the deposits and probably reflect compositional differences in the surrounding country rocks. Most deposits show evidence of redistribution of the uranium and this is reflected by variable ages for the mineralization. All of the published ages suggest that the mineralizing events occurred after deposition of the overlying sandstone.

SOME OTHER VEIN-TYPE DEPOSITS

In view of the unsatisfactory classification of vein-type deposits emphasized earlier, it is proposed here to briefly review, for comparitive purposes, some vein-type deposits which are not readily recognizeable as unconformity-type deposits, and which have generally been accepted as hydrothermal in origin.

VEIN-TYPE DEPOSITS IN THE BEAVERLODGE DISTRICT

The Beaverlodge district is situated immediately north of Lake Athabasca in the vicinity of Uranium City (see Figure 20). The area is underlain by rocks of the Archaean Tazin Group unconformably overlain in places by the earlier Middle Proterozoic Martin Formation (Fig. 26).

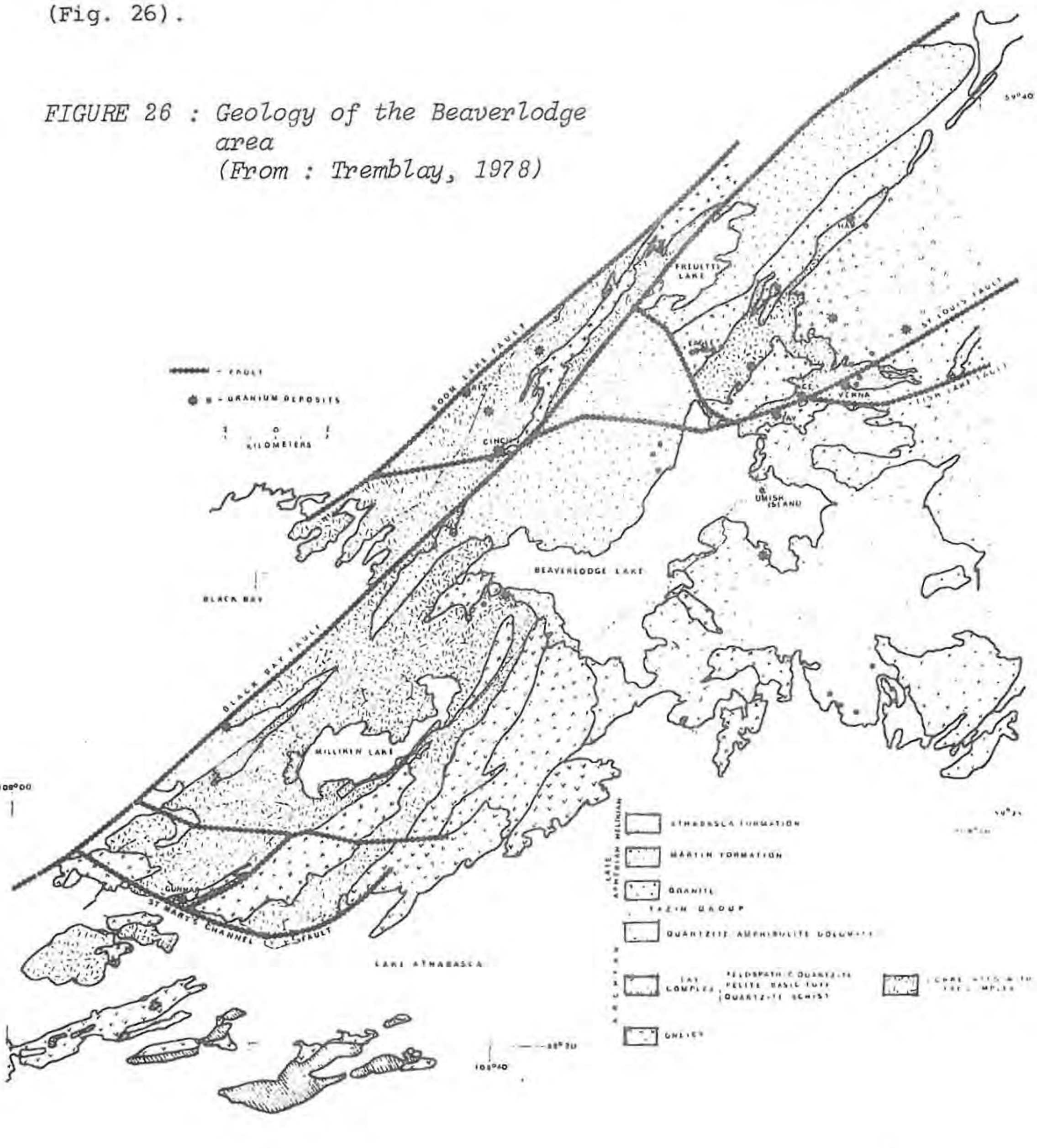


FIGURE 26 : Geology of the Beaverlodge area (From : Tremblay, 1978)

The Tazin Group is an amphibolite facies metamorphic assemblage consisting of quartzites, argillites, impure marbles, garnet-biotite schist, and quartz-feldspathic gneisses and schists. These have been intensely folded and faulted and are characterized by widespread brecciation, mylonitization, and alteration. Granitization, particularly of quartz-feldspar assemblages, is extensive (Rich et al., 1977). The unconformably overlying Martin Formation consists of a red succession of polymict conglomerates, arkoses, siltstones, shales, andesitic volcanic flows and gabbroic sills. These are unmetamorphosed and gently folded, and have been cut by several major faults (Fig. 26).

Vein-type deposits in the Beaverlodge district are exemplified by the Ace-Fay-Verna mine and have the following general characteristics (Tremblay, 1978; Hoeve, 1978; and Rich et al., 1977) :

(a) They are related to major faults which extend into the Martin Formation, and which are accompanied by wide zones of closely fractured mylonitized and brecciated rocks, suggesting that the faults were active over a long time.

(b) The uranium mineralization is generally located along subsidiary fractures within, and in brecciated parts of, the main fault zones, where it also replaces part of the brecciated matrix near fractures, and extends as disseminations into the breccia fragments.

(c) The lithological characteristics of the host rocks are generally obscured by granitization, cataclastic deformation, and alteration. However, most deposits are associated with feldspathic-quartzites, and to a lesser extent with highly altered metapelites and basic tuffs.

(d) Uranium is associated with red hematitic- and dark green chloritic alteration, accompanied by white carbonate. Feldspathization and silicification are common but not indicative of uranium mineralization. Argillic alteration is absent, or present in minor amounts in some deposits.

(e) The relationship between the Beaverlodge deposits and the Tazin - Martin unconformity has not been clearly established. According to Langford (1977) most of the deposits occur at or near the trace of the unconformity. Tremblay (1978) concedes that many of the deposits are situated close to surface, which locally coincides with the Tazin-

. Martin unconformity, but maintains that in the larger deposits of the district the latter may only have been a contributing element to the localization of mineralization, which was mainly controlled by major faults. Major ore zones extend to depths of 1500m which is considerably deeper than any of the unconformity-type deposits in the Athabasca Basin. Smith (1974) attempted to explain this phenomenon by suggesting that the St. Louis fault, along which the Ace-Fay-Verna mine is situated, approximately coincides with the plane of the Tazin-Martin unconformity, and therefore that mineralization in the Beaverlodge area is always found within 200m of the unconformity. His suggestion was based on the assumption that Martin Formation remnants were present in the fault plane at depth. However Tremblay (1978) considers the rocks in question to be of cataclastic origin and unrelated to the Martin Formation, hence the undefined relationship.

(f) Beaverlodge-type deposits have been subdivided into deposits of simple and complex mineralogy (Hoeve, 1978). In the former deposits pitchblende is accompanied by calcite, quartz, chlorite, minor sulphides and locally by nolanite, brannerite and/or coffinite. These constitute the majority of deposits. Deposits of complex mineralogy typically contain small quantities of native Au, Ag and Cu, arsenides, sulpharsenides and rare antimonides of Fe, Ni, Co, Cu, Pb, Zn and sometimes Hg (Hoeve, 1978).

(g) The deposits have uranium ages of 1780 $\pm$ 20 my and 1140 $\pm$ 50 my (Koeppel, 1968), the latter age corresponding closely with those obtained for unconformity-type deposits in the Athabasca region. These ages are younger than the Martin Formation, which was deposited between 1780 $\pm$ 20my. and 1930 $\pm$ 40my. (Koeppel, 1968).

Except for the age differences, large depths of some of the deposits, and the uncertain spatial relationship to the Tazin-Martin unconformity, the Beaverlodge vein-type deposits are very similar to unconformity-type deposits in the Athabasca Basin, and probably had a similar origin.

VEIN-TYPE DEPOSITS IN FRANCE

There are four major regions in France containing uranium vein deposits namely Morvan, Limousin, Forež and Vendée (Fig. 27). The three

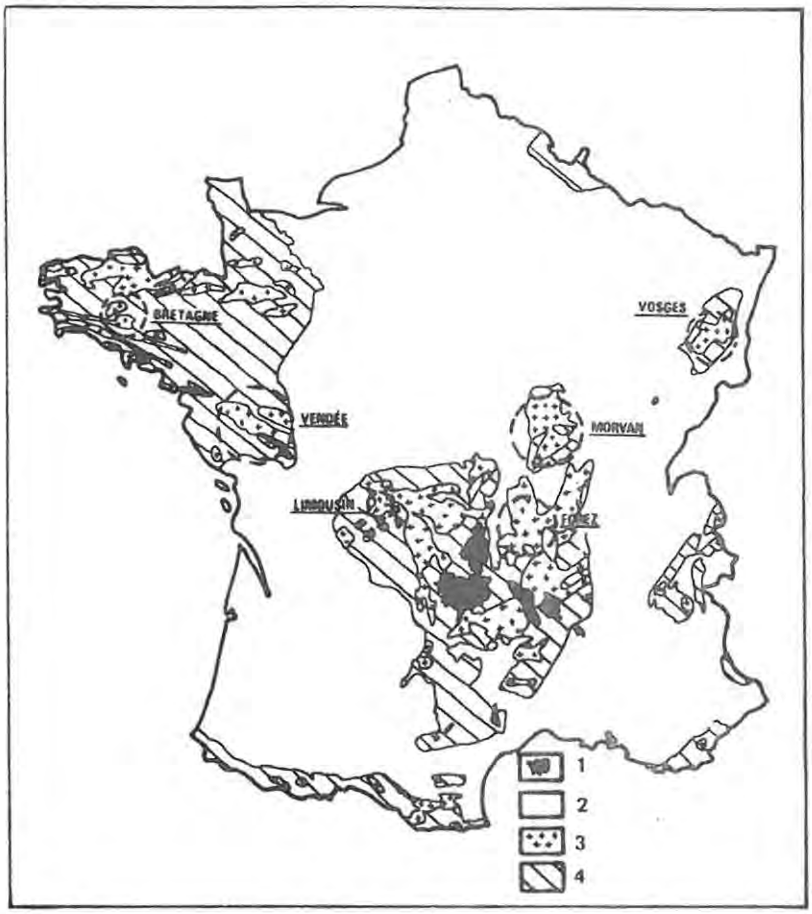


FIGURE 27 : Vein-type uranium deposits in France. 1 = Tertiary Volcanics; 2 = Post-Palaeozoic sedimentary rocks; 3 = granite; 4 = metamorphic and Palaeozoic sedimentary rocks. (From : Rich et al., 1977)

former areas form part of the Massif Centrale. In the major and other regions, all of the uranium deposits occur within, or immediately adjacent to, granites which were intruded during the 300 my. Hercynian Orogenesis. This is represented by an east-west trending mountain belt stretching from western Europe through to the Pacific Ocean (Verhoogen et al. 1970). During the orogenesis Precambrian and Caledonian metamorphic basement rocks were remobilized,and granites, ranging in size from isolated stocks to large batholithic bodies were intruded (Barbier, 1974). The uranium deposits are associated with two-mica granites which have an anomalously high uranium content (15-20 ppm). Up to 70% of the uranium is contained as disseminated accessory uraninite, whereas in biotite granites in the same area 70% of the uranium occurs in refractory accessory minerals such as zircon, monazite, and apatite (Rich et al., 1977). The two-mica granites are also Na-rich and are frequently accompanied by an aureole of tin-tungsten veins. The orebodies characteristically occur within 150-250m of the present land surface (Smith, 1974).

The dominant uranium mineral is pitchblende accompanied by minor coffinite. Associated minerals include pyrite, marcasite, galena, sphalerite, and chalcopyrite. Selenides are present in some assemblages, but Co-Ni-Ag-As-Bi-type mineralization, which is common in northern Saskatchewan, is notably absent in the important French deposits (Rich et al., 1977). Barbier (1974) has noted the importance of tectonic features, particularly fractures and faults, and also the apparent importance of Fe and Mg-rich rocks such as lamphrophyres and dolerites, in localizing uranium mineralization. Other important host rocks are pipelike episynenite bodies of essentially alkali metasomatized, carbonatized,and desilicified granites, which have become particularly porous. The bodies have a brecciated appearance which has been attributed to a possible collapse or settling process resulting from dissolution of quartz, which comprises 30% of the granite. Although the porous episyenite zones constitute favourable traps for mineralizing solutions, according to Barbier (1974) they are not necessarily genetically related to the uranium mineralization, since barren episyenites do exist. Hematitic alteration is common in most of the deposits, but is not always indicative of uranium mineralization. The hematite zones are frequently discoloured adjacent to pitchblende mineralization, where sulphides may be present.

The age relationships between the uranium deposits and the Mortagne and St. Sylvestre granites in the Vendée and Limousin regions respectively (Fig. 27) are shown in Table VI. Both granites were

Age (M.Y.)			Mortagne granite	Pitchblende veins	St. Sylvestre granite	Pitchblende veins
Middle	Saxonian	240		Le Chardon		Les Brugeauds Fanay
PERMIAN		250				
				L'Ecarpière		
Lower	Autunian	260	End of deuteric processes	La Commanderie		
		270				
	Stephanian	280				
CARBONI-FEROUS		290			End of deuteric processes	
	Westphalian	300	Intrusion		Intrusion	

TABLE VI : Chronology for some two-mica granites and related pitchblende Veins in France (Modified from Barbier, 1974) intruded about 300 my. ago and deuteric processes ceased somewhat later (Table VI). Of the deposits listed, all except La Commanderie show earliest pitchblende ages significantly younger than the granites, whilst most also yield younger ages ranging from 15-40 my., which, according to Barbier, militates against a hydrothermal origin for the deposits, in spite of some reported fluid inclusion temperatures as high at 400^{o}C. Instead Barbier (1974) advocates a continental weathering origin for the French deposits which will be elaborated on in a subsequent section.

Although mineralogically and structurally similar to the previously described vein deposits, the French deposits differ significantly in age and host-rock lithology, and lack chloritic alteration. It is significant that Middle Permian sedimentation, which was initiated immediately after the Hercynian orogenesis, consisted of a continental red-bed sequence. Present-day exposures of Middle Permian red beds are generally over 100km from the uranium deposits but were probably much closer immediately after their deposition. Thus the French deposits display the same relationship to unconformities as the Australian and Canadian unconformity-type deposits, and it is therefore suggested that they be classified as such.

VEIN-TYPE URANIUM DEPOSITS IN PORTUGAL

In their regional setting Portuguese vein deposits are similar to those in France. They occur in and adjacent to post-tectonic Hercynian granites which have intruded a basement composed of metasediments and metavolcanics (Fig. 28). After the Hercynian orogeny

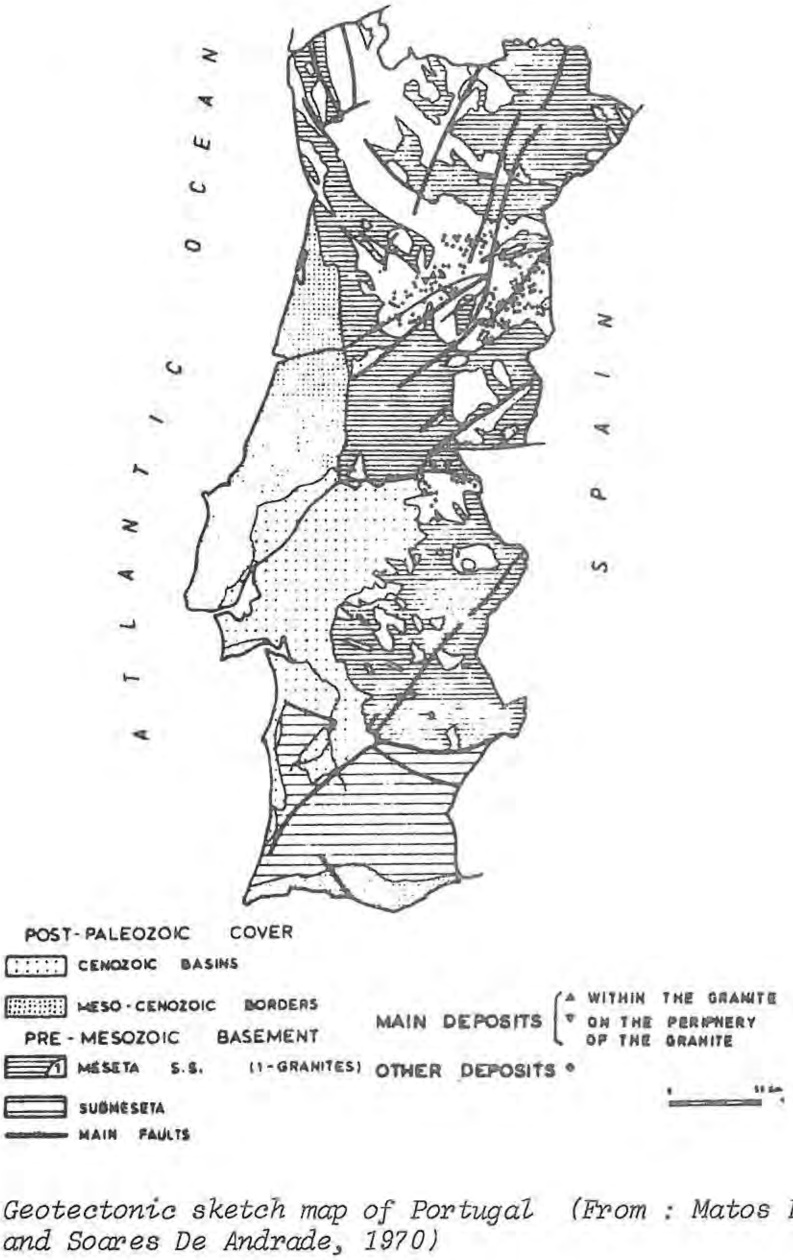


FIGURE 28 : Geotectonic sketch map of Portugal (From : Matos Dias and Soares De Andrade, 1970)

the area was subjected to intense Permo-Triassic peneplanation followed by detrital red-bed sediments of the Meso-Cenozoic Borders (Fig.28).

The uranium-bearing granites are often porphyritic, monzonitic, or biotite-muscovite rich. The uranium mineralization occurs in veins which vary from fractures several metres thick to submicroscopic in size, giving the impression of disseminated mineralization. Other mineralized features include quartz-limonite breccias and weathered basic rocks (Matos Dias and Soares Andrade, 1970).

The intragranitic deposits are characterized by :

1) the occurrence of deposits in clusters,
2) proximity to unconformities overlain by continental deposits,
3) preferential mineralization in intensely fractured and brecciated rocks adjacent to major faults,
4) mineralization at intersecting fractures or joints, and at the contact between zones of contrasting physical and chemical characteristics, and
5) the decrease of mineralization with depth.

The peripheral deposits occur both as isolated deposits in the surrounding rocks as well as transgressive bodies across the granite-metasediment contact. The bodies most frequently strike parallel to the foliation in the metasediments, and to the granite-metasediment contact. All of the peripheral deposits are confined to intensely fractured zones within a $\pm$ 3 km metamorphic aureole surrounding the granites, and seldom exceed depths of 50m below the present erosion surface.

In both types of deposit secondary minerals, principally autunite, predominate over pitchblende in most cases, and are often the only minerals present. The uranium is usually accompanied by moderate amounts of pyrite and/or marcasite, and occasionally by minor additional sulphides including chalcopyrite, galena, sphalerite and arsenopyrite. Calcite and siderite are rare.

Alteration is dominated by hematization, limonitization and sericitization. Other products include chlorite, kaolinite, colloidal silica, phosphates, tourmaline and discoloured biotites (Matos Dias and Soares De Andrade, 1970).

THE SCHWALTZWALDER MINE, COLORADO, U.S.A.

The Schwartzwalder mine is one of a number of uranium vein occurrences hosted by Proterozoic metamorphic rocks of the Front Range, Colorado, and whilst it has been traditionally regarded as a hydrothermal deposit, geological relationships suggest that other modes of formation mass by equally applicable.

The central part of the Front Range is dominated by Proterozoic metasediments and metavolcanics which were affected by three major Proterozoic intrusive events. Regional metamorphism (1690-1750 my.) was accompanied by folding and syntectonic intrusion of the *Boulder Creek* granodiorite and quartz monzonite. At about 1400-1600 my. ago acid-to-intermediate stocks and batholiths of the *Silver Plume* thermal event were intruded, and from 950-1040 million years the similar *Pikes Peak* intrusion took place. Subsequent tectonic activity involved mountain building of the Front Range by block faulting in Late Proterozoic and Late Cretacious-Tertiary times, peneplanation during Late Palaeozoic times, and the emplacement of porphyritic intrusions along the northeast trending Colorado Mineral Belt during the (56-70 my.) Laramide orogeny, followed in the mid-Tertiary by extensive intermediate volcanics. Stockwork molybdenum mineralization and gold-silver-base metal veins in Colorado are associated with these latter events (De Voto and Paschis, 1979).

The Schwartzwalder mine is one of several uraninite-adularia-jordisite-sulphide-carbonate vein systems which occur to the south of the Colorado Mineral Belt, confined mainly to the eastern edge of the Front Range near the unconformity with overlying Phanerozoic red sandstones (Fig. 29). The deposits are localized by structural dilation zones, intersecting fractures, fault deflections or branching, and occur mainly within, or at the contact of, certain preferred stratigraphic units. The principal host rocks are garnet-biotite gneiss, quartz-biotite schist, and quartzite, and to a minor extent pegmatites of Silver Plume age. At the Schwartzwalder mine the orebody occurs at the intersection of the Illinois vein with a synformal structure in the metasediments. Uranium mineralization is mainly confined to the steeply dipping Illinois vein and numerous shallower horsetail fractures, extending to a depth of at least 900m (De Voto and Paschis, 1979).

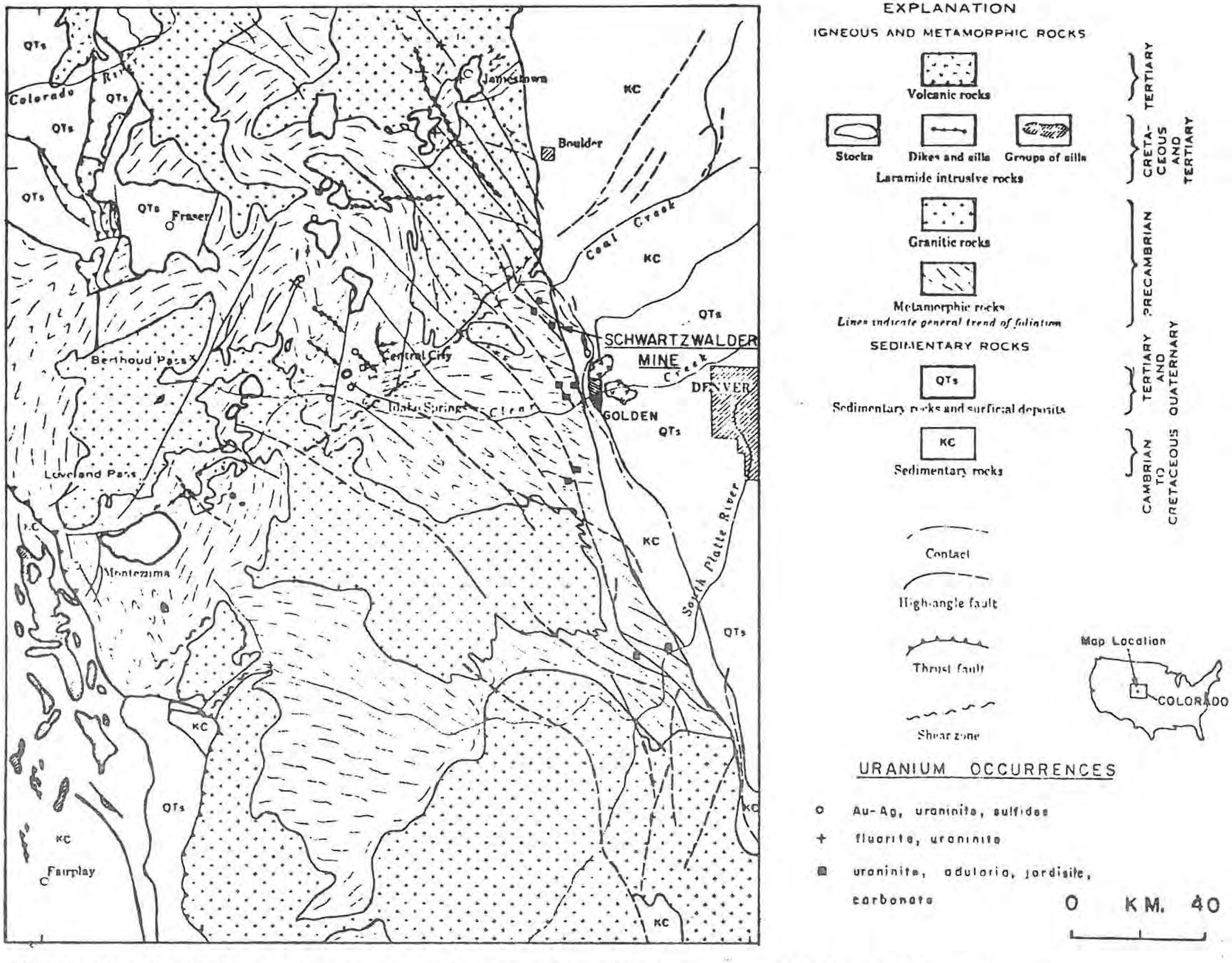


FIGURE 29 : Geologic setting of the Schwartzwalder mine (From : Devoto & Paschis, 1979)

The uranium occurs chiefly as uraninite filling open veins and breccias. Minor amounts of Cu, Pb, Zn as well as trace amounts of Co, Ni and Ag occur in the uranium ore. Hematite is the most common alteration product in the wall rocks, whilst breccia fragments are frequently altered to fine aggregates of hematite, ankerite, quartz and adularia.

The Schwartzwalder mine has always been presumed to be a Laramide (56-70 my.) hydrothermal deposit, particularly in view of its proximity to the Colorado Mineral Belt, which contains quartz monzonite and syenite intrusives with anomalous uranium contents (10-170 ppm). However, recent structural interpretations suggest that the Illinois vein was emplaced in a Proterozoic fault structure. Also, both Proterozoic and Laramide ages are recorded in the ore, suggesting that the deposit may have had a Proterozoic ancentry with later reworking. De Voto and Paschis (1979) consider the 1690-1750 million year metamorphic event to have been a major uranium concentrating event, with subsequent remobilization taking place during Proterozoic (Silver Plume and Pikes Peak), and Laramide intrusive events.

In general striking similarities exist between the Schwartzwalder deposit and unconformity-type deposits, particularly those in the Alligator Rivers region where mineralization is absent above the unconformity. Similarities include host rock assemblages, metamorphic events, controls of mineralization, mineralogy, alteration, and remobilization of the uranium. The main differences are that retrograde metamorphism and massive chloritization are absent at Schwartzwalder, and that the unconformity, which is exposed near the mine, is a a Late Palaeozoic, rather than Lower Proterozoic, erosion surface. Furthermore, when reconstructed, the unconformity lies some 800m above the surface of the Swchwartzwalder mine indicating that the present bottom of the mine is some 1700m below the unconformity. This is deeper than the recognized unconformity-type deposits, but similar to some of the Beaverlodge deposits. Inspite of these depths it is suggested that the unconformity and overlying red sandstones are spatially and genetically important in both areas.

EXPLORATION

GENETIC THEORIES AND THEIR INFLUENCE ON THE EXPLORATION FOR UNCONFORMITY-TYPE URANIUM DEPOSITS

In the exploration for most types of ore deposits a certain degree of success may be achieved by basing strategies on empirical relationships. This is particularly true during the first few years after a new type of discovery has been made. As exploration proceeds the more obvious orebodies are located and other favourable areas eventually eliminated. It is at this stage that most emphasis is placed on genetic concepts. In the case of unconformity-type deposits early exploration was successful in areas close to the erosional margin of the Lower-Middle Proterozoic Unconformity both in Australia and Canada. As exploration progresses away from the marginal areas genetic concepts become important not only for defining target areas but also for selecting exploration tools. Unfortunately different interpretations of the abundant characteristics of unconformity-type deposits has led to a variety of genetic hypotheses, which give rise to several alternative exploration approaches.

Genetic theories are influenced not only by geological relationships and characteristics of the orebodies, but also by age relationships and the temperature and composition of fluid inclusions in minerals associated with the uranium. Most of the deposits contain a variety of pitchblende ages. Oldest dates are usually considered to indicate the time of formation and later dates give ages of subsequent remobilization. Most of the initial ages for uranium mineralization in Australia and Canada are significantly younger than the Kombolgie or Athabasca sandstones respectively, but some earlier ages have been recorded at the Ranger I (1700), Koongarra (1850my.), Rabbit Lake (1230-1320my.) and the Beaverlodge district (1750my.) which may be about the same as the overlying rocks.

Fluid inclusions at Rabbit Lake by Pagel (1977) yielded temperatures ranging from 120°C to 160°C whilst Little (1974) obtained temperatures ranging from 180° to 225°C. Similar ranges have been recorded by Ypma and Fuzikawa (1979) in the Alligator Rivers Field, whilst temperatures of up to 400°C have been reported from the French deposits (Barbier, 1974) and the Beaverlodge deposits (Tremblay, 1978). High salinities and the presence of hydrocarbons characterize fluid inclusions at Rabbit Lake (Pagel, 1977) and at the Jabiluka and Nabarlek deposit (Ypma and Fuzikawa, 1979).

The genetic theories which have been proposed for the unconformity-type uranium deposits range from magmatic-hydrothermal through metamorphic hydrothermal, to diagenetic-hydrothermal, and near-surface-supergene processes for concentrating uranium. Each hypothesis emphasizes a different set of empirical observations. Whatever process is advocated, it is restricted by the geochemistry of uranium, which dictates that it is soluble under oxidizing conditions and precipitated in reduced environments, unless acid solutions are involved. Uranium may therefore be transported in solution and deposited to form an ore deposit provided suitable permeability features are present, and chemical conditions are favourable.

THE MAGMATIC HYDROTHERMAL MODEL

A magmatic-hydrothermal model for uranium veins requires an intrusive body, presumably of granitic origin, from which the mineralizing fluids may be derived. Beck (1969) regarded the Beaverlodge deposits as hydrothermal, suggesting that the pitchblende veins represented the end-product of the igneous and metamorphic activity that formed the basement complex in northern Saskatchewan. Although initial mineralization ages coincide more or less with the igneous activity during the Hudsonian orogenesis, the younger 1110, 270, and 100 my. mineralization ages (Koeppel, 1968) cannot be accounted for by this model. None of the unconformity-type deposits in Australia and Canada are spatially related to intrusive granites, and consequently the magmatic-hydrothermal model is not generally accepted.

METAMORPHIC-HYDROTHERMAL MODELS

Metamorphic-hydrothermal models were presumably devised initially to account for the absence of intrusive sources for magmatic hydrothermal deposits and also, particularly in Australia, to account for the stratigraphic control over the orebodies. The concepts were also influenced by the apparent relationship between the ages of ore deposits and those of major metamorphic events in both Canada and Australia.

Morton and Beck (1977) suggested that remobilization and concentration of pre-existing uranium in Proterozoic metamorphic or sedimentary suites, was effected by widespread hydrothermal pulses coeval with the Hudsonian (1800 my.) and Grenville (1000 my.) orogenies. The association of the deposits with unconformities is attributed to the existence of contrasting physico-chemical regimes at the interface of the unconformity, the precipitation mechanism involving such factors as abrupt decrease in temperatures and/or pressure. As Langford (1978) points out, the mechanism does not explain why the uranium is mostly deposited in the fractures rather than in the sandstone where such changes take place.

For the Alligator Rivers region Needham and Stuart-Smith (1976) suggest that the orebodies were formed partly syngenetically because of the well established association between uranium and carbon in the metasediments. They regard the pitchblende veins as the epigenetic enrichment of the syngenetic protore, and the uranium in the epigenetic fluids as having been derived from the Cahill Formation, or other Lower Proterozoic and Archaean rock units, during the 1800 my. metamorphic event, which they regard as the main concentrating period. Subsequent concentrations were low-temperature events. For the Nabarlek deposit, distinguished by its extremely high grade and the absence of a carbon association, Needham and Stuart-Smith (1976) envisage higher pressure and temperature conditions which they consider to be a function of the proximity of the deposit to the 1800 my. orogenic centre, represented by the Nimbuwah Complex. These resulted in the uranium being transported by hydrothermal solutions away from its original position, possibly associated with carbonaceous rocks, and re-deposited in the favourable crush-zone at Nabarlek.

Dodson et al. (1974) have stressed the association of Australian deposits with the basement complexes and suggest that the mineralization was related to the 1700-1800 my. orogenic activity which was responsible both for the rejuvenation of the Archaean

Complexes and the intrusion of granites throughout the Pine Creek Geosyncline. They regard the granites as heat sources rather than sources of the hydrothermal fluids. An essentially similar process has been advocated by Hegge (1977), and Hegge and Rowntree (1978), who recognize a post 1700 my. greenschist retrograde metamorphic event, accompanied by magnesium metasomatism, chloritization and the circulation of uranium scavenging brines, probably rich in carbon dioxide and chlorine. This event preceded the main 900my. redistribution of uranium. A less important 500 my. event also took place, and both events have been related to Hegge and Rowntree (1978, p. 1428) to "geophysically indicated continental tectonic features". They cite the South Alligator lineament and parallel block faulting of the Kombolgie Formation in the Alligator Rivers area, as evidence of these features.

The genetic models proposed by Needham and Stuart-Smith (1976), Dodson et al. (1974), Hegge (1977) and Hegge and Rowntree (1978) do not attach any genetic significance to the unconformity, other than the fact that where overlain by the Kombolgie Formation, it served to protect mineralized Lower Proterozoic rocks from oxidizing and remobilizing conditions. They imply that similar deposits could exist at depth in the Lower Proterozoic metasediments regardless of their proximity to the unconformity. Exploration for such deposits would entail locating areas of favourable Lower Proterozoic rocks (Lower Cahill Formation in this case) which have been structurally disturbed, and which were situated close to areas of high heat flow at some stage during geological history.

Dahlkamp (1978a,b) has developed a model which is generalized to accomodate other Canadian orebodies, although specifically designed for the Key Lake deposits. It differs from the previous models in that considerable genetic importance is assigned to the sub-Athabasca unconformity, and to supergene processes, in addition to hydrothermal activity. The main features of the model are summarized diagrammatically in Fig. 30. *Stages I and II* are similar to the previous models, involving Lower Proterozoic syngenetic deposition of uranium together with pelitic and carbonaceous sediments, in marine or lagoonal basins adjacent to Archaean highlands, followed by further concentration during the 1800 my. Hudsonian orogeny. According to

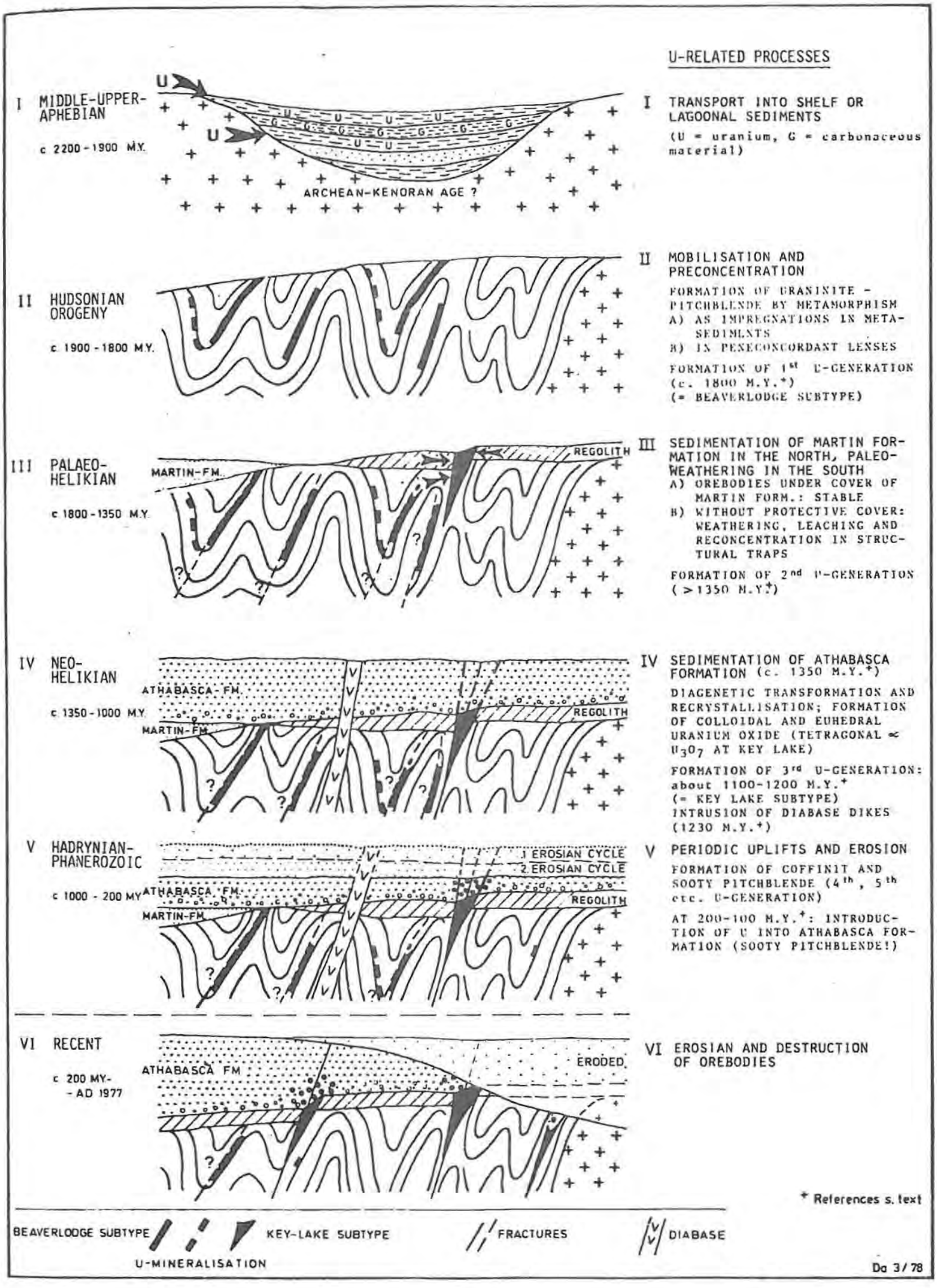


FIGURE 30 : Genetic model for vein-type uranium deposits in northern Saskatchewan (From : Dahlkamp, 1978b)

Dahlkamp (1978b), this activity accounts for the disseminated uraninite observed in the Lower Proterozoic rocks in the vicinity of Key Lake and also for the peneconcordant veins in the Beaverlodge area where uranium concentrated in the faults accompanying orogenisis. *Stage III* is important since it accounts for the differences between the Beaverlodge and Athabasca deposits by suggesting that the early Middle Proterozoic Martin Formation was deposited in the Beaverlodge area and protected the earlier formed uranium deposits from weathering, whilst in the Key Lake area the cover did not exist. Weathering produced a regolith and remobilized uranium into tectonic traps where it could have been precipitated by suitable reductants such as ferrous minerals, argillaceous and chloritic zones, or changes in permeability, pH, Eh, etc. The Athabasca Sandstone was subsequently deposited (*Stage IV)* at about 1350 my. Since the oldest uranium ages are younger than the Athabasca Formation, the supergene processes could not have accounted for uranium ages. Dahlkamp (1978b) considers the younger ages to be a result of diagenetic remobilization of the uranium and redeposition more or less in situ, thereby destroying the original radiogenic equilibrium,and simultaneously forming a new primary generation of uranium oxide with a rejuvenated age of 1160 to 1230 my. at Key Lake, and about 1100 my. at Rabbit Lake and Cluff Lake. The fluid inclusion temperatures of up to $200^{\circ}C$ at Rabbit Lake and Cluff Lake (Pagel, 1977) may also be accounted for by the diagenetic recrystallization beneath a thick Athabaca Sandstone sequence. The intrusion of diabase dykes at about the same time (1230 my.) may have influenced the diagenetic processes. Subsequent successive periods of uplift (Fig. 30 *Stage V)* resulted in erosion of the overlying cover rocks, thereby changing the hydrostatic equilibrium, which in turn resulted in limited redistribution of the uranium within the deposit, and the formation of new generations of sooty pitchblende, coffinite and Ni minerals. At this stage some mineralization also penetrated the overlying cover sediments along fractures.

Significant aspects of Dahlkamp's model are that it accounts for the proximity of deposits in the Athabasca Basin to the Sub-Athabasca unconformity, at the same time attributing uranium redistribution and enrichment to secondary processes acting along the unconformity. It is interesting to note that the model implies that similar processes did not take place beneath the Martin Formation, in spite of its deposition under very similar environmental conditions to the Athabasca Formation. This may be ascribed to a longer period of weathering prior to deposition of the younger Athabasca Formation, and could account for the lower average grade of the Beaverlodge deposits (0,25% U_3O_8; Hegge, 1977), compared to deposits in the Athabasca Basin (See Table III, p. 12).

From an exploration point of view Dahlkamp's (1978b) model suggests that lithologically favourable Lower Proterozoic metasediments would constitute good targets, but that priority should be given to areas which are close to the Lower/Middle Proterozoic unconformity or its trace. Beaverlodge-type veins could be expected at any depth below the unconformity in structurally favourable environments.

A DIAGENETIC-HYDROTHERMAL MODEL

Hoeve and Sibbald (1978a, 1978b) and Hoeve et al. (1979) have developed a diagenetic-hydrothermal genetic model based primarily on features observed at Rabbit Lake. The most important aspect of the model is that it advocates a source for the uranium in the overlying Athabasca Sandstone. According to Hoeve et al. (1979), sedimentological and petrographic studies suggest that the original Athabasca sediments were not oxidized, but acquired their red-bed characteristics through intense oxidation and leaching processes which may have been active for millions of years after deposition of the sediments. Such intrastratal weathering processes are thought to have released uranium, and a broad suite of other elements, including Ni, Co, As, Fe, Cu, Pb, Zn, Se, Se, S and others, by oxidation and destruction of feldspars, mafic and heavy minerals. As evidence for such a process Hoeve and Sibbald (1978b) cite the widespread hematization and the near absence of heavy minerals in the sandstones, even though these are abundant in all possible source rocks for the Athabasca Formation. The proposed model thus involves oxidizing groundwaters flowing into the permeable Athabasca Sandstone, being heated as they moved downward, finally reaching temperatures of around 200°C at the floor of the basin. Depending on the oxidation state of the sandstone, the latter either behaved as a passive acquifer or contributed uranium to the oxidizing solutions. At the unconformity the solutions encountered metamorphic basement rocks which were impermeable, except in fault and fracture zones, or where a palaeoregolith was developed.

Hoeve and Sibbald (1978a, b) envisage similar mechanisms for the precipitation of uranium to those proposed by Adler (1974) for roll-type sandstone uranium deposits. These involve either migration of oxidized ground waters into reduced sediments, or migration of mobile reductants into red beds containing uraniferous pore waters. The former writers favour a mobile reductant in spite of the common spatial association of the ore deposits with graphitic rocks. Their argument is that graphite could not have acted as a direct reductant, since in many cases mineralization occurs in adjacent non-graphitic rocks. Instead they propose that the reducing fluids were derived from the reaction of water and graphite at 200°C to produce carbon-dioxide and methane, based studies by French (1966), the presence of CO_2 and methane in fluid inclusions (Pagel, 1977), and the presence of glassy buttons of carbon and hydrocarbon in veins at Rabbit Lake, Key Lake and Cluff Lake. Uranium deposition resulted from the interaction between the mobile reducing solutions and oxidizing diagenetic solutions and were subject to such hydrogeological controls as porosity in the sandstones and the basement, fluid density differences, and hydrologic pressure. Variations in these could account for the distribution of uranium in the deposits and the oscillations between oxidizing and reducing conditions observed at Rabbit Lake.

Although the diagenetic-hydrothermal model is based essentially on the interaction between fluids which have become heated due to their depth of burial, Hoeve and Sibbald (1979) consider the coincidence of the 1000-1250 my. mineralization ages with the 900-1250 my. Grenville orogeny to be very significant. The steepening of the geothermal gradient which must have accompanied the initiation of Grenville mafic magmatism, could have induced the large-scale convection of diagenetic solutions required for the extraction of ore constituents to take place in the vicinity of the unconformity.

As such Hoeve and Sibbald's model accounts for (1) the spatial relationship to an unconformity which is specifically overlain by red sandstones, (2) mineralization in the Athabasca Formation, (3) fluid inclusion compositional and temperature data, and (4) ages of mineralization younger than the depositional age of the Athabasca Formation. An interesting aspect of the model is that it allows for the transportation of uranium in detrital form in contrast to the widely accepted views of Cloud (1976), who suggested that the post-2200 my. old atmosphere was oxidizing, and that minerals such as uraninite were only transported in solution in surface waters during that time. The model would influence exploration in the following ways : (1) the unconformity would only be significant if overlain by continental red beds, (2) the red beds should be related to a granitic source terrain with high uranium backgrounds, (3) rocks beneath the unconformity are important only as sources of reducing agents and to provide structural traps; but provided they are essentially impermeable they need not be of Lower Proterozoic age or metamorphic, (4) uranium ore deposits could exist at higher levels in the sandstone bodies possibly associated with faults and fractures or permeability barriers such as shale horizons.

NEAR-SURFACE SUPERGENE MODELS

Supergene processes of near-surface origin have been advocated among others by Barbier (1974, 1978), Langford (1974, 1977, 1978), Ferguson et al. (1979), Knipping (1974), and Tilsley and Hogg (1979). The concepts originated in France, where it was first noted by Moreau et al. (1966), that pitchblende vein deposits appeared to have formed contemparaneously with periods of continental erosion, and it was postulated that the veins were formed by downward percolation of uranium-rich surficial waters into porous fracture and shear zones, and weathered regolith in the granites.

Barbier (1974, 1978) related the distribution of vein deposits in France to different climatic conditions during periods of erosion. He noted that the uraniferous two-mica granites, which are the hosts of the French vein deposits, only contained pitchblende veins where these were exposed during the Middle Permian, and accounted for this with the following model : After the Hercynian orogeny the granite mountains were subjected to intense weathering under warm, wet climatic conditions, during the Lower Permian. Uranium was released from uraninite in the granites but, due to the abundant vegetation and well developed soils, was trapped in the soil profile by organic matter, colloids, iron hydroxides and various alteration products. Continued erosion resulted in the deposition of fine uraniferous organic rich sediments in low lying areas. During the Middle Permian climatic conditions became more arid, mechanical weathering predominated, and vegetation was reduced.

Because of its high mobility uranium was preferentially leached under these conditions, and in the absence of organic material, migrated downwards into fractures where its confinement led to the precipitation of pitchblende and accompanying sulphides. Reaction with the wall rocks caused hematization, whilst progressive alkalinization produced the characteristic hematite-calcite end phase. Barbier (1978) has also suggested that the pitchblende veins may be related to calcretes which were formed in drainage networks, often superimposed on fractures in the granitic regions during the Middle Permian; and proposed that the pitchblende veins may represent the roots of ancient uranium concentrations in calcretes, which have subsequently been eroded. The similar ages of calcrete and pitchblende veins in France reinforces Barbier's proposal that formation of the latter may be climatically controlled.

The most important feature of the model is that it implies that the formation of pitchblende and deposition of red beds are intimately related, and as such suggests that the occurrence of red beds is an important exploration guide, especially where these overlie, or are adjacent to, uraniferous basement rocks.

Ferguson et al. (1979), dealing specifically with the Jabiluka, Ranger and Koongarra deposits, have placed emphasis on the proximity of these ore deposits to massive bedded carbonates, which are absent in the ore zones, but present along strike in the same stratigraphic horizons (Eupene et al., 1975; Foy and Pederson, 1975; Hegge, 1977). Although they recognize the syngenetic concentration of uranium in the Lower Proterozoic rocks, they do not believe that such a process, or subsequent metamorphic remobilization could have formed the ore deposits. According to Ferguson et al. (1979), development of the brecciated ore zones in the three deposits took place after metamorphism and peneplanation of the Lower Proterozoic sediments, but before deposition of the Kombolgie Formation, by solution of the carbonate rocks, producing a karst topography characterized by collapse structures or large caverns containing fragments and insoluble residues such as mica, chlorite, clays and graphite. The collapse structures may have been open or overlain by a thin cover of fractured rocks. The main mineralizing event was a low temperature phenomenon which took place at the plane of unconformity. Prior to deposition of the Kombolgie Formation Mg-rich clays (and/or chlorite), and possibly decaying organic matter were washed into the collapse structures and created an anaeorobic environment in which CH_4 and CO_2 may have been present at a pH between 5 and 7. Simultaneously low temperature, CO_2-rich, neutral-to-slightly alkaline groundwater, carrying uranium as uranyl carbonate complexes, percolated through the structures. Uranium precipitation, mainly by adsorption onto clay particles, was enhanced by a pH reduction when the solutions encountered the reducing environment in the collapse structures. Also, the reduction of uranyl complexes may have been facilitated by oxidation of Fe^{2+} in clay and/or chlorite. The deposits were effectively sealed by infill and alluvium around 1700 my. and all subsequently recorded events represent in situ reworking of the uranium. Ferguson et al. (1979) consider the 1700 my. uraninite age from the Ranger deposit to be related to heating of the pre-existing deposit by the Oenpelli Dolerite suite, which intruded at about 1688 $\pm$ 13 my. (Page et al., 1979). The dolerites also account for the fluid inclusion temperature of $266 \pm 40^{o}C$. Ympa and Fuzikawa (1979) have suggested that hydrocarbon-rich fluid inclusions examined by them may represent original mineralizing groundwaters, whereas other highly saline inclusions could have resulted from intrusion of the Oenpelli Dolerite. Ferguson et al. (1979) have related the 800-900 my. ages of mineralization in the Alligator Rivers Field to epeirogenesis and development of Adelaidean (Upper Proterozoic) sedimentation to the south of the Pine Creek Geosyncline. For the Nabarlek deposit, which lacks both carbonate and carbonaceous material, they suggest that the crush zone may have acted as a structural trap for washed-in clays, and/or chlorite, and hydrated iron oxides, which were subsequently dehydrated to form hematite.

The model would confine exploration to rocks immediately below a major unconformity, particularly where it truncates carbonate-rich, uraniferous Lower Proterozoic lithologies. Structural features such as faults, fractures and joints would be important for two reasons. Firstly, where these trends intersected carbonate beds solution of the latter would be facilitated, and secondly if of sufficient magnitude, such features could themselves trap the uranium-bearing solutions, as at Nabarlek .

Other supergene models are essentially similar to Barbier's (1974) model. Langford (1977) pointed out the similarities in composition, mineralogy and environment of Colorado Plateau sandstone-type deposits and vein-type deposits, suggesting a similar origin, and stressing the association of both types with fluvial sediments. In order to explain fluid inclusion temperatures which are too high for such near-surface processes, Langford (1978) calls upon later diagenetic readjustments related to burial. He explains mineralization ages younger than the overlying sandstones by quoting less publicized ages between 1200 and 1320 my. for the Rabbit Lake deposit (Knipping, 1974), compared to about 1350 my. for the Athabasca sandstone; and the 1700 my. age for the Ranger deposit (Hills and Richards, 1976), compared to about 1750 my. for the Kombolgie Formation, as evidence that uranium was introduced by surficial processes. The alteration phenomena are attributed to surficial weathering and later diagenetic reactions involving pore fluids; and the Mg metasomatism to karst-type weathering. Langford (1978) points out that magnesian chlorites occur in those deposits that have limestone or marble in the country rocks, whereas iron-rich chlorites predominate in deposits in other rocks. Mineralization in the overlying sandstones is explained by the escape of previously confined pore fluids into newly created permeability features, particularly fractures, caused by unroofing of the deposits.

Target selection based on Langford's (1978) model would be restricted to impermeable rocks immediately below a major unconformity which is overlain by continental red beds of fluvial origin.

Tilsley (1979) proposed a model whereby syngenetically concentrated uranium in folded Lower Proterozoic metasediments was released during continental weathering, and reconcentrated in suitable physical-chemical traps along the unconformity. Precipitation of the uranium depends on the existence of an electric field set up between a relatively oxidizing near-surface environment, and a relatively reducing environment at depth, with electrolytic continuity provided by conductive, sheared, graphitic zones. The model proposes that uranium and other positively charged ions in solution will migrate under the influence of the potential gradient and be precipitated at the negatively charged reducing end of the natural electrode by a plating cell action (Fig. 31). Tilsley (1979) accounts for the later redistribution of uranium by proposing that the thermal energy required is provided by the radioactive decay of uranium in the ores, or by thermal anomalies associated with graphitic zones that extend to depth below the unconformity.

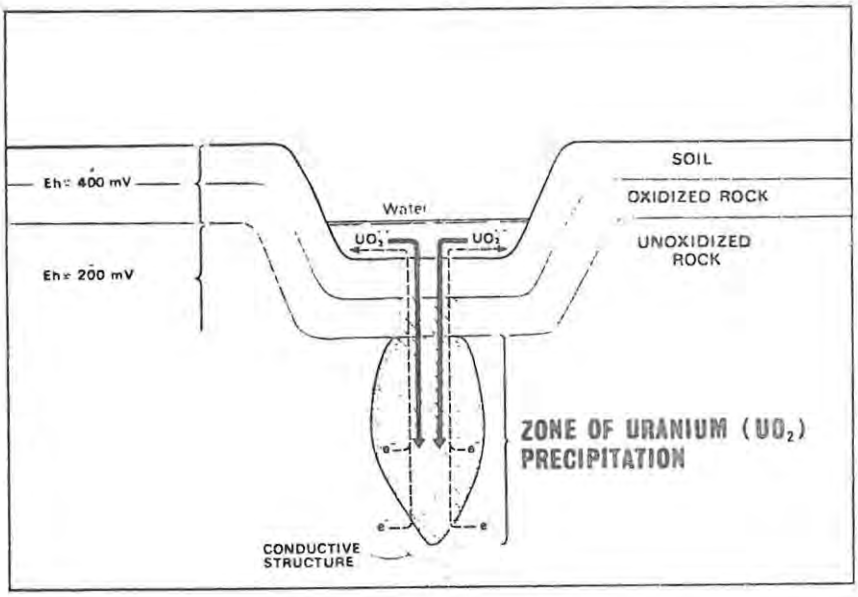


FIGURE 31 : Diagram of plating cell mechanism (From Robertson et al., 1978)

DISCUSSION

The variety of genetic hypotheses indicates that the genesis of unconformity-type uranium vein deposits is poorly understood. Most genetic models emphasize certain aspects of the deposits whilst neglecting others. No single model accounts for all of the observed features, particularly if the European intragranitic vein deposits are considered to be of similar origin to those in the Lower Proterozoic of Australia and Canada, as is suggested here. It is also suggested that the two most important features of unconformity-type deposits, which should be accounted for in any genetic model, are their spatial relation to unconformities, and to red-bed sequences overlying the unconformities.

Magmatic-hydrothermal models are considered inadequate for several reasons. Apart from not explaining the above-mentioned relationships, the deposits in Australia and Canada cannot be related either spatially or temporally to intrusive bodies. Furthermore, the uranium ages in the French deposits are younger than the intrusive granites in which they are hosted, and the same granites only contain pitchblende veins where they were exposed to erosion during the Permian.

All of the metamorphic-hydrothermal models advocate the remobilization of uranium which was deposited syngenetically with the Lower Proterozoic sediments. Hegge (1977) and Needham and Stuart-Smith (1976) attach no genetic significance to the unconformity or the red beds. Morton and Beck (1977), and Dahlkamp (1978b), recognize the genetic importance of the unconformity, but for different reasons. The former writers regard the unconformity as a trap, whereas Dahlkamp suggests that weathering along the unconformity surface upgraded pre-existing vein-deposits. Neither of the models consider the fluvial, red-bed nature of the overlying sandstones to be significant. The fact that French deposits do not occur in metamorphic rocks suggests that metamorphic remobilization of uranium is not essential for the formation of vein-type deposit. Whilst uranium remobilization is to be expected during regional metamorphism, it is suggested that dispersion of the uranium is more likely to occur, particularly in an open system such as that which exists during regional metamorphism. The association of deposits with metamorphic rocks may be a function of age, and the folded and faulted nature of the host rocks.

Models which advocate surficial processes are similarly divided. Ferguson et al. (1979), Tilsley (1979) and Dahlkamp (1978b) favour a process of upgrading of syngenetically concentrated uranium in Lower Proterozoic metasediments by circulating groundwaters, but do not consider the overlying rock-types to be significant. Only the hypotheses of Barbier (1974), Langford (1974, 1977, 1978) and Hoeve and Sibbald (1978a, 1978b) emphasize the genetic importance of the overlying red beds. Barbier regards the latter as indicators of favourable climatic conditions for the preferential leaching of uranium in the absence of vegetation, and its deposition in structural features within, or close to, the granites from which it was derived. The other two models stress the fluvial processes which were responsible for deposition of the sandstones overlying the unconformities. However, whilst both models consider the uranium to have been derived from a distal granitic source, Langford (1978) suggests that the uranium was in solution in groundwaters below the river systems, whereas Hoeve and Sibbald (1978b) suggest that it was originally transported and deposited in detrital form, and subsequently mobilized by, and redeposited from, oxygenated diagenetic solutions. The latter model is rejected for two reasons. Firstly, as Langford (1974) points out, there is no evidence of the passage of uranium through the thick sandstone sequences, and secondly, evidence in the geological record suggests that oxygenated atmospheric conditions have prevailed on the earth since about 2200 my., and therefore that uranium should have been transported in solution in surficial environments.

In this writer's opinion the recognized unconformity-type deposits in Canada and Australia are not fundementally different from the other vein-type deposits that have been described, and it is suggested that their common characteristic features are best explained by near-surface supergene processes of formation, although other processes may have contributed to the concentration of uranium in some cases.

EXPLORATION CRITERIA

The following criteria are suggested as being most important in the exploration for unconformity-type uranium deposits, based on empirical geological relationships, and the assumption that near-surface processes are most important in concentrating the uranium :

(a) *Unconformities :* deposits should be situated immediately below, along, or above major unconformities which are overlain specifically by continental red beds, or which are situated close to deposits of continental red beds. The size of deposit should decrease away from the erosional margin of the unconformity, where it has been truncated by the present land surface. Erosional or faulted remnants within the peneplain would also constitute favourable target areas. Proponents of metamorphic-hydrothermal genetic concepts suggest that similar deposits should exist at deeper levels below the unconformity. There is at present no published evidence to support the theory, and in any event it is considered unlikely that such processes could account for high grade deposits without being upgraded by weathering processes, as suggested by Dahlkamp (1978b). It is also suggested that favourable open structures, in which uranium could be trapped, would be confined to higher levels of the crust, so that a low priority rating should be given to areas at depth below the unconformity.

The Lower-Middle Proterozoic unconformity is considered to be the best target since it contains most of the deposits, and is developed world-wide. However the situation of the Schwartzwalder mine close to a Late Palaeozoic erosion surface, and the French deposits below a Middle Permian erosion surface, suggests that any substantial unconformity overlain by red beds would be favourable. This suggestion is supported by the Yeelirrie calcrete uranium deposit in Australia and the deposits in calcreted gravels and red sands in South West Africa, which may be regarded as forming on present day unconformities, significantly in arid environments.

(b) *Host rocks :* The most important host rocks are shallow marine, pyritic, carbonaceous, and calcareous shales, and quartz-feldspar sandstones that have been metamorphosed. Although these are favourable source rocks in the Proterozoic of Australia and Canada, their reducing and adsorptive capabilities are also important for fixing the uranium, and may be partly responsible for the larger size and higher grades of Proterozoic deposits compared to those in France, where reductants in the granites are scarce, and precipitation is thought to have occurred mainly as a result of biochemical activity in stagnant waters, accompanied by dehydration (Barbier, 1974). Carbonates and other soluble rock-types such as evaporites, are important in exploration because karst topography, solution cavities, and breccia bodies develop in them below the unconformity, thereby providing passageways and traps for mineralizing solutions. In general rocks beneath the unconformity should be impermeable, so that the mineralizing fluids are restricted to structural and other porous features.

(c) *Structural Controls :* In Australia and Canada areas surrounding *basement domes* are regarded as prime target areas. Although the location of some major deposits on the flanks of basement domes may purely be a function of exposure of suitable host rocks by updoming of the basement, it is also possible that Lower Proterozoic sediments are enriched in uranium adjacent to palaeohighs in the basement. In general tilted, folded, and faulted areas in the basement would be prefereble to flat lying areas because favourable host rocks would be repeatedly exposed.

On a more local scale *faults, fractures, shears* and *zones of brecciation* in rocks below the unconformity are most important for localizing the uranium deposits. Thus priority should be given to areas in which favourable source or host rocks are intersected by such features. Faults, fractures, and joints in carbonate rocks or marbles would facilitate their solution, thereby enhancing karstification and the development of collapse breccias and other porous features. Other favourable traps would be provided by *zones of weathering (palaeo-regoliths), palaeochannels and other depressions, as well as barriers, on the unconformity surface.*

(a) *Intrusives :* The coincidence of uranium mineralization ages and intrusive events at Key Lake, Ranger I, and the Schwartzwalder mine; and the close relationship between the Midwest Lake orebody and basic intrusives (Sullivan, 1979), suggest that the situation of favourable areas in relation to young intrusives may be important in exploration. On a broad scale, Sullivan (1979) has noted a relationship between the development of intracratonic basins and basic intrusions, and has suggested that the latter are indicative of favourable conditions for volcanic activity which could have introduced uranium mineralization into basins such as Athabasca and Kombolgie basins.

SOME EXPLORATION METHODS

Based on geological relationships and proposed genetic concepts for unconformity-type deposits, favourable exploration environments can be subdivided into two areas, namely a marginal area, where the overlying sandstones have been removed; and an internal area where targets are buried beneath the sandstones. Different techniques would be employed in the two sub-environments.

Geological mapping would be most applicable to exposed areas and would involve careful lithological and structural mapping on regional and local scales. In areas remote from sandstone outcrops, structural and geomorphological data would be vital for determining the depth of the present erosion surface below the unconformity. In sandstone-covered areas most geological work would be confined to interpreting geophysical data, although structural mapping would be important for locating faults, and sedimentological studies could provided limited information on basement topography, channel directions, and source areas of the sandstones.

Geophysical methods have wide application in uranium exploration, and can essentially be subdivided into direct and indirect methods.

The former utilise the physical and chemical properties of uranium such as its radioactive decay series, mobility in oxidizing environments and fixation in reducing environments, whereas indirect methods utilise geological characteristics such as host lithologies and structural settings of the various types of deposits. Thus indirect methods vary for the different types of deposit in contrast to direct methods which have universal application in uranium exploration.

Radiometric techniques are the most widely used direct method and have been successful in discovering most of the Australian unconformity-type deposits in the Alligator Rivers area, as well as the Cluff Lake and Rabbit Lake deposits in Canada. In a less direct capacity radiometrics were also responsible for the discovery of the Key Lake and Midwest Lake deposits which resulted from the tracing of radioactive, glacially derived boulders to their sources (Armstrong and Brewster, 1979; Gatzweiler et al., 1979). However, radiometric techniques are limited to orebodies having surface radiometric expressions because gamma radiation, which is the measured parameter, is completely attenuated by overlying rocks and soil. Therefore in sandstone-covered areas the application of radiometric methods is limited to rare situations where mineralization may have penetrated to surface through the sandstones along fractures.

Another direct method is the Track Etch method which also relies upon the uranium radioactive decay series. In this case alpha radiation from the radon gas daughter product is measured. The method has been advocated for detecting hidden orebodies, based on the assumption that radon gas can migrate to surface through soils, porous rocks, and fractures. Pederson et al. (1979) recorded a substantial Track Etch anomaly over the Koongarra deposit which is overlain by sandy alluvium and contained a weak radiometric anomaly. On the other hand the Jabiluka Two orebody, which is overlain by a minimum of 20m of Kombolgie sandstone, contained no radiometric anomaly and was not detected by the Track Etch method, in spite of fractures and faults which penetrate through the sandstone to surface (Rowntree and Mosher, 1976) (see Figure 15). On this basis it is suggested that the method would have limited, if any, applicability to deposits covered by a few hundred metres of sandstone. Geochemical methods are similarly limited in areas overlain by sandstone cover, although in Canada, where fault-bounded lakes within the Athabasca Formation are abundant, lake-sediment geochemistry is extensively used in exploration.

Several characteristics of the unconformity-type uranium deposits lend themselves to indirect geophysical exploration methods. The association of deposits with basement domes has led to the widespread use of airborne magnetics for distinguishing between domes and favourable flanking areas beneath the Athabasca Formation in Canada. Magnetics are also useful for locating basic intrusives, particularly dykes, which, apart from their possible genetic significance, may indicate favourable fault zones. High sensitivity magnetics, using downward continuation processing techniques can also be used for measuring the depth to basement and constructing basement topographic maps (Bosschart, personal communication, 1979). These can be used for delineating palaeovalleys and other irregularities on the unconformity surface, which could have localized uranium. A knowledge of basement depth is also important for planning drilling programmes.

The graphitic properties of host rocks are utilised in electromagnetic surveys to delineate conductors below the sandstones, and these are regarded as significant if they parallel the regional strike and coincide with magnetic lows. One problem in using electromagnetic methods is that too many anomalies are normally obtained because of the abundance of barren graphitic rocks. Thus careful geological interpretation is necessary for the selection of suitable targets for follow-up by ground geophysical methods and drilling. The West Bear deposits were discovered by such methods below several hundred feet of the Athabasca Sandstone (Armstrong and Brewster, 1979)

The density contrast between basement and overlying sandstones permits the use of Seismic methods for defining basement topography and particularly for locating faults which have been active from basement times until after deposition of the unconformable sandstones. These growth faults would be indicated by thickening of sediments in graben structures, for example, and would constitute favourable exploration targets particularly where they intersect favourable source or host rocks. Faults can also be located on surface by aerial photography and satellite imagery, and projected down to basement.

The success of all exploration methods, and particularly indirect geophysical methods, depends on careful geological interpretation and supervision, and to a lesser extent on genetic interpretations.

EXPLORATION POTENTIAL IN SOUTHERN AFRICA

Empirical relationships and preferred near-surface genetic concepts suggest that favourable unconformities for localising unconformity-type uranium deposits in southern Africa should be overlain by fluvial red-beds younger than 2200 million years. There is evidence in the South African geological record to suggest that reducing environments prevailed prior to 2200 my. ago,and therefore that uranium was not readily soluble. Most often quoted are the occurrence of detrital uraninite and pyrite in the Witwatersrand conglomerates, although Feather and Koen (1975) have shown that at least some of the uranium could have been in solution. Other evidence includes divalent iron and manganese in carbonates of the 2200 - 2300 my. Transvaal Supergroup (Button, 1973), and the absence of hematite in pre-2200 my. palaeoweathering profiles (Button and Tyler, 1979). Most unconformities in southern Africa are of Precambrian age. Those younger than 2200 my. are listed in Table VII and the distribution of their overlying sedimentary basins illustrated in Figure 32.

Supergroup	Group or Formation	Approximate Age (m.y.)	Rests Unconformably/Disconformably on:
	Fish River		Schwarzrand Formation
Nama	Terminal Clastic Member of Schwarzrand	600	Spitzkopf and Huns limestone members of Schwarzrand Formation
	Kuibis		Older granitic and metamorphic rocks
Katanga		600-700	Older (? Archaean) granitic rocks and metamorphics
Damara	Mulden Carbonates	600-700	Damara carbonates Older granitic basement, Dordabis and equivalents
Dordabis and equivalents		800-1000	Older (? Archaean) granitic rocks
Umkondo and equivalents		1100-1800	Archaean granites, Limpopo Belt metamorphics, greenstone belts
Waterberg and equivalents		1800-2000	Archaean granites, Limpopo Belt metamorphics, Transvaal, Bushveld Complex

TABLE VII : Summary of major post-2200 my. Precambrian unconformities in southern Africa (From : Button and Tyler, 1978).

The only major post-Precambrian unconformity is that underlying the Karoo basin.

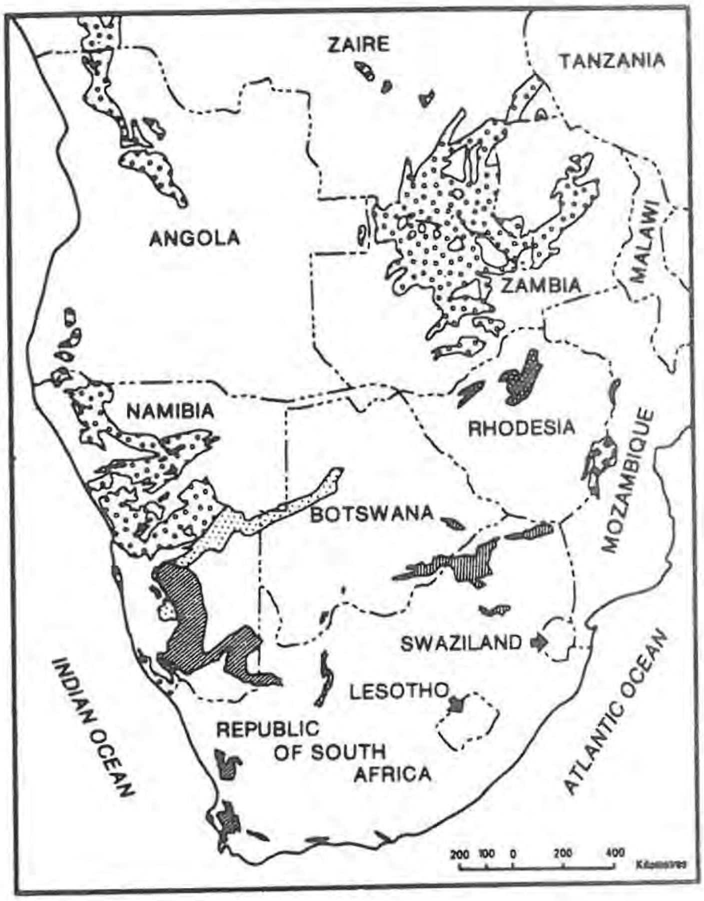
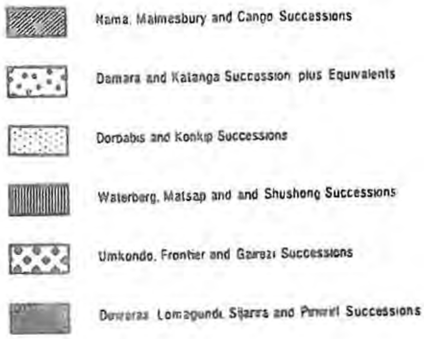


FIGURE 32 : Map showing the distribution of Middle and Upper Precambrian basins in southern Africa (From : Button & Tyler, 1978)



The Waterberg Supergroup in the Transvaal, and its equivalents the Matsap and Shushong Successions in the northern Cape and Botswana respectively (Fig. 32) are the oldest units containing significant quantities of red conglomerates, sandstones, and shales. In the Transvaal the Waterberg overlies Archaean granites, metamorphic successions of the Limpopo Group, the Transvaal Supergroup, and the Bushveld Igneous Complex. Since the Archaean granites were probably the source of uranium in the older Dominion Reef Group, and the Witwatersrand, Ventersdorp and Transvaal Supergroups, they should constitute favourable targets where overlain by the Waterberg sediments. However, it is suggested that uranium, because of its incompatible nature, would be expected in the upper levels of the granite, and that these levels may have been removed by erosion during deposition of the earlier basins, thereby eliminating potential source rocks. In the Transvaal Supergroup some of the quartzites, black shales and volcanics may provide sources of uranium, but is is suggested that the relatively undeformed nature of the rocks is unsuitable because it provides limited exposure of favourable source and host rocks, and fewer structural traps. The tin-bearing Bushveld granites and the Rooiberg felsites probably constitute more favourable source rocks, since they were emplaced shortly before the development of the pre-Waterberg unconformity. Much of the tin mineralization, particularly in the Rooiberg tin field, is located in fractures and shear zones which have been related by Hunter (1976) to reactivation of the east-northeast trending Murchison lineament. It is suggested that similar structures may have provided traps for uranium mineralization where these are overlain by Waterberg sediments. In the northern Transvaal the Waterberg rocks overly the Limpopo mobile belt, which is composed of remobilized Archaean basement metamorphosed to the granulite facies, and supracrustal rocks of the Limpopo Group metamorphosed to the amphibolite facies. Whereas the metamorphic grades may have been somewhat high for these rocks to constitute favourable source rocks, it is suggested that the structural environment would be most suitable for the accumulation of uranium from other sources. Deposition of the Waterberg in the Limpopo belt took place on an irregular floor in fault-bounded basins and was accompanied by volcanic activity, the latter being indicative of the high heat flow in the mobile belt.

The overall tectonic setting of the Waterberg Supergroup is quite different from the Athabasca and Kombolgie Formations and it is suggested that in general the sub-Waterberg unconformity has less potential than its counterparts in Canada and Australia. It is noteworthy that if metamorphic-hydrothermal concepts are advocated, the potential would be confined entirely to the Limpopo mobile belt.

All of the other Precambrian unconformities overlie granitic and/or metamorphic rocks (Table VII) which could provide both sources for uranium, and structural and lithological traps. Red-bed sequences occur at the base of the Katanga Succession, suggesting some potential below and adjacent to these rocks. Both the Damara and Nama Supergroups contain marginal marine basal arenaceous members that are not typical red-bed sequences, suggesting limited potential for their underlying unconformities. The Umkondo Basin in Rhodesia (Fig. 32) contains red continental sediments higher up in the sequence. These may indicate some potential in basement rocks adjacent to the Umkondo basin but probably limited potential along the unconformity.

The unconformity at the base of the Karroo is mainly overlain by Dwyka tillite, and is considered to be unsuitable for the formation of unconformity-type deposits. However the climatic change to continental weathering conditions during Beaufort times is similar to that described by Barbier (1974, 1978) in connection with the French pitchblende vein deposits, and it is therefore suggested that limited potential could exist in some of the basement rocks exposed during Beaufort times provided they have not subsequently been removed by erosion. The sandstone-type deposits in sandstones of the Beaufort Group are sufficient evidence that uranium was available during those times.

Although abundant favourable source-rocks, host rocks, and structural environments are provided by vast areas of granitic and metamorphic basement in southern Africa, it is suggested that the tectonic setting and depositional environments of most of the sedimentary basins are generally unfavourable for the formation of unconformity-type uranium deposits on the scale shown by deposits in Australia and Canada.

CONCLUSION

Unconformity-type uranium deposits are a relatively new class of high-grade, economically important, vein-type, ore deposit. They are typified by their mode of occurrence in Australia and Canada, where they are spatially related to Lower-Middle Proterozoic unconformities, overlain by fluvial red sandstone sequences, and underlain by metasedimentary assemblages. The deposits are structurally controlled and commonly hosted by pyritic, graphitic, chloritic and calcareous schists, and quartzo-feldspathic schists, accompanied by chloritic, and to a lesser extent, sericitic and hematitic alteration. Some similar characteristics displayed by vein-type deposits in the Beaverlodge district of Canada, and others in France, Portugal, and the Schwartzwalder mine in the U.S.A., suggest that they too are unconformity-type deposits.

Near-surface supergene genetic concepts are favoured because they best explain the limited depth extent of the deposits below the unconformity, and their association with red beds. Fluid-inclusion temperature data and age relationships are explained by diagenetic activity related to depth of burial and possibly to mafic intrusions.

There is world-wide potential for further discoveries of unconformity-type deposits. From an empirical point of view Lower-Middle Proterozoic unconformities present the best exploration targets. The pronounced association of high-grade deposits with Lower Proterozoic rocks may reflect the postulated 2200 my. change to oxygenated atmospheric conditions, or may be related to the development of granitic crust (and therefore potential source rocks) in the late Archaean. Uranium would tend to become more dispersed with time because of its high mobility in surficial environments. However genetic considerations, and evidence from European deposits and the Schwartzwalder mine, suggest that younger unconformities are also important exploration targets.

Of the several Precambrian unconformities developed in southern Africa only those below the Waterberg and Katanga Supergroups fulfill the requirements of the preferred near-surface genetic models for the unconformity-type deposits, since they are overlain by red-bed sequences. On the other hand the overall tectonic setting of the

Waterberg Supergroup is considered to be generally unfavourable for large-scale development of unconformity-type deposits. Although the other Precambrian unconformities truncate favourable granitic and metamorphic rocks, the general absence of well-developed red-bed sequences suggest that their potential may be even more limited. The presence of red-beds higher up in the Umkondo basin and the post-Precambrian Karroo basin, suggest that basement rocks adjacent to these basins may have potential in areas which were not eroded subsequent to deposition of the red beds.

ACKNOWLEDGEMENTS

I would like to extend my sincere thanks to Professor Bob Mason for his guidance and encouragement throughout the year, and for his helpful suggestions regarding this dissertation.

Discussions with, and assistance from Dr. Roger Jacob and other staff members are gratefully acknowledged, as is the help of Larry Neuhoff who proof-read a part of this dissertation.

I am most grateful to the Gold Division of Anglo American Corporation for giving me the opportunity to attend the M.Sc. course, and for financial assistance.

I would especially like to thank Mrs. Maureen Jackson for all her help during the year, and particularly for her patience in typying this dissertation and other projects.

Finally, I would like to thank my wife Anita, and children, James and Kate, for their love and understanding throughout a difficult year.

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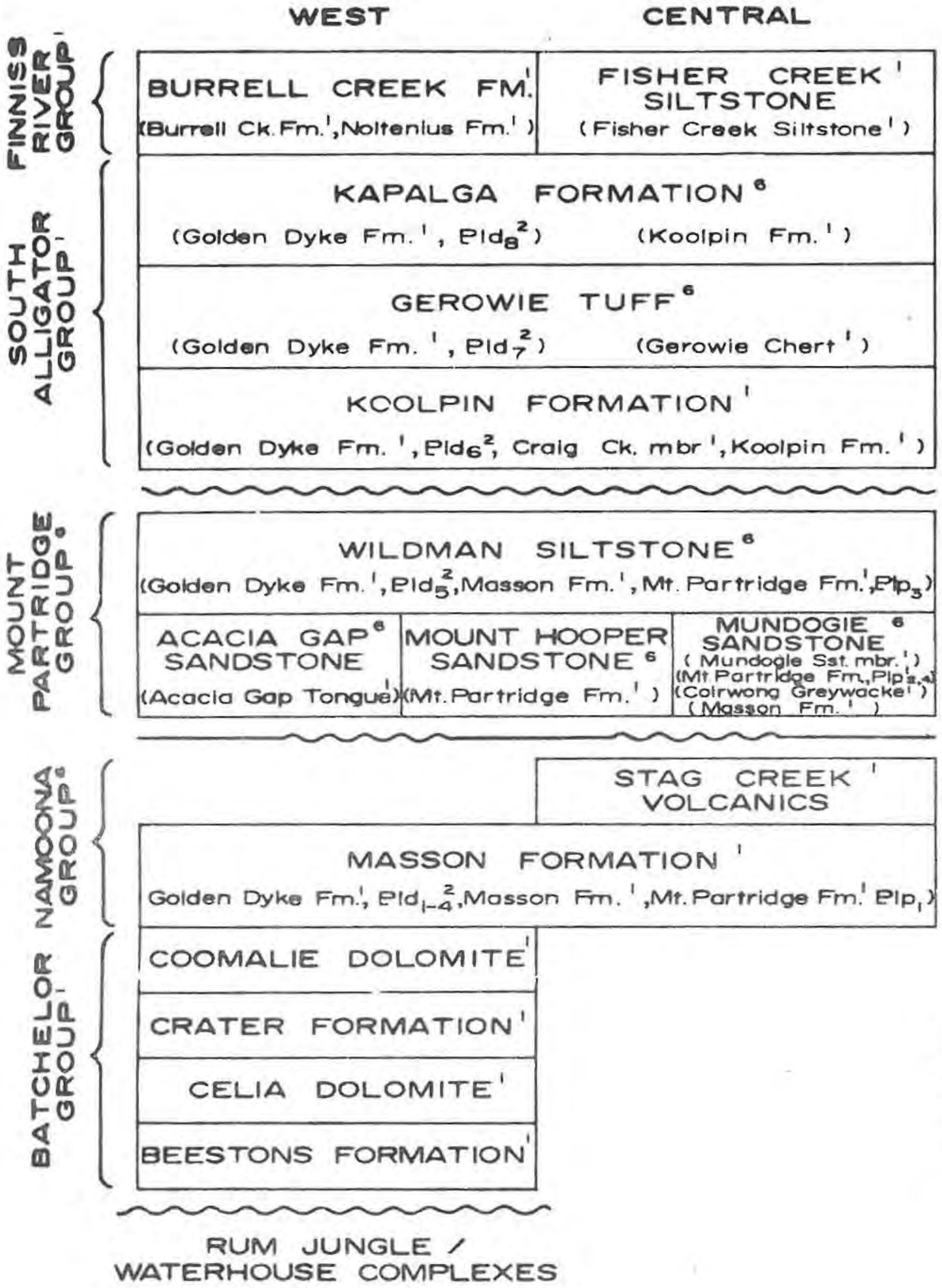
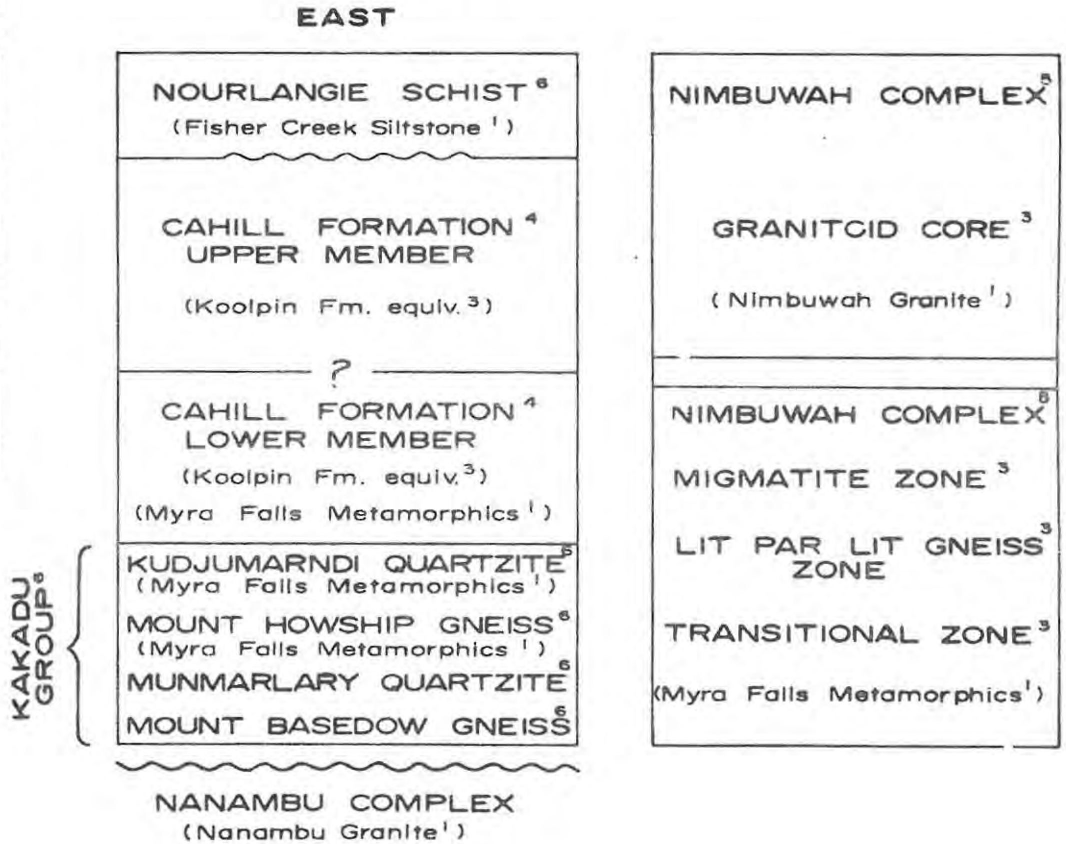
PINE CREEK GEOSYNCLINE 1978 REVISED STRATIGRAPHY

(WHERE CHANGED OLD NAMES APPEAR IN BRACKETS)

DEFINED BY :

1. B. Walpole et al , 1968
2. K. Johnson , 1978
3. S. Needham et al , 1974
4. S. Needham and Stuart-Smith , 1976
5. Rix , 1965
6. S. Needham , 1979





APPENDIX I