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PROTEROZOIC UNCONFORMITY AND STRATABOUND URANIUM DEPOSITS

**REPORT OF THE WORKING GROUP ON URANIUM GEOLOGY
ORGANIZED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
EDITED BY
JOHN FERGUSON**



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IAEA, VIENNA, 1984
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FOREWORD

The great surge of interest and activity in exploration for uranium deposits over the last decade has added significantly to our knowledge of uranium geology and the nature of uranium deposits. Much of the information that has been developed by government and industry programmes has not been widely available and in many cases has not had the benefit of systematic gathering, organisation and publication. With the current cut-back in uranium exploration and research efforts there is a real danger that much of the knowledge gained will be lost and, with the anticipated resurgence of activities, will again have to be developed, with a consequent loss of time, money and effort. In an effort to gather together the most important information on the types of uranium deposits, a series of reports is being prepared, each covering a specific type of deposit. These reports are a product of the Agency's Working Group on Uranium Geology. This group, which has been active since 1970, has gathered and exchanged information on key questions of uranium geology and coordinated investigations on important geological questions. The Working Group has been carrying on several projects to prepare comprehensive reports on major types of uranium deposits. These reports are planned for completion and release in 1984. Findings of the work will be presented at the International Geologic Congress in Moscow in August 1984.

The topics of the Working Group on Uranium Geology projects and the names of the project leaders are:

Sedimentary Basins and Sandstone Type Deposits -

Warren Finch

Uranium Deposits in Proterozoic Quartz-Pebble Conglomerates -

Desmond Pretorius

Vein Type Uranium Deposits -

Helmut Fuchs

Proterozoic Unconformity and Stratabound Uranium Deposits -

John Ferguson

Surficial Deposits -

Dennis Toens.

The success of the projects is due to the dedication and efforts of the project leaders and their organisations, and the active participation and contribution of world experts on the types of deposits involved. The Agency wishes to extend its thanks to all involved in the projects for their efforts. The reports constitute an important addition to the literature on uranium geology and as such are expected to have a warm reception by the member states of the Agency and the uranium community, world-wide.

I.A.E.A., Vienna, May 1984

EDITORIAL NOTE

The authors who have contributed to this project are all actively engaged in research work in areas relating to their respective contributions. This advantage has allowed for updated syntheses which frequently includes work that has a restricted distribution and additionally incorporates new data. It is hoped that this report will help serve as an aid for exploration for Proterozoic unconformity and stratabound uranium deposits.

I am indebted to Dell Stafford for typing most of this manuscript and to the BMR Drafting Office for the production of numerous line drawings and maps, in particular, I would like to thank Ivon Chertok, Ingo Hartig, Natasha Kozin and Diana Pillinger.

John Ferguson

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**PROTEROZOIC STRATA-BOUND
URANIUM DEPOSITS
OF ZAMBIA AND ZAIRE**

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Abstract

The Katanga System, host to uranium and copper mineralization, is several thousands of metres thick and rests unconformably on an older complex of crystalline rocks and meta-sediments and is locally covered by Karoo sandstones or Kalahari sands. The deposition of the Katanga System took place during the Late Proterozoic in a wide complex basin extending from Shaba province in Zaire through a large part of Zambia and into eastern Angola. The sediments were affected by different grades of metamorphism, tectonic events, and by thermal events associated with post-tectonic metamorphism.

At the base of Katanga system there are 84 known copper deposits and 42 uranium occurrences. It is suggested that all the known uranium and copper occurrences are of an essentially syngenetic sedimentary origin. The mineralisation is found in the Lower Roan Formation near the base of the Katanga System occurring in rocks produced in similar environmental conditions and thus being stratigraphic controlled, however, their areal distribution is localised producing a regional metal zonation. Many of the uranium occurrences have a typical vein aspect. These transgressive relationships are not inconsistent with a syngenetic origin as evidenced by the vein morphology.

Exploration activities and genetic studies are ongoing throughout this metallogenic province.

INTRODUCTION

The Copperbelt areas of Zaire (Shaba Province) and Zambia which host the uranium deposits are located on the southern flank of the Congo Craton which is one of the major structural blocks of the African continent south of Sahara.

TABLE 1. Correlation of the Katanga System of the Domes, Zambian, and Shaban Copperbelt Areas

Domes area		Zambian Copperbelt area		Shaban Copperbelt area	
McGregor, 1964; Edwards, 1974; Arthur, 1974; Klinck, in press; and Appleton, in press		Mendelsohn, 1961; Binda and Mulgrew, 1974		Francois, 1974; Cahen, 1974; Cailteux, 1977	
Stratigraphic units	Rock type	Stratigraphic units	Rock type	Stratigraphic type	Rock type
West Lunga formation	Limestone and dolomite (Tillite)	Kundelungu group	Shale	Kundelungu supergroup	Sandstone and shale
			Tillite		Tillite
Luigishi formation	Carbonaceous shale	Mwashya group	Carbonaceous shale	Grand Conglomerate and Mwashya supergroup	Sandstone and shale
	Schists		Argillite		Dolomite
Wamikumbi formation	Dolomite and magnesite	Roan group	Dolomite	Roan supergroup	(Roan unit 4.2)
	Dolomitic schists		(Roan unit 1)		Dolomite
Wushingwi formation	Talc-specularitic quartzite	Roan group	Argillite, shale dolomitic schists (Roan units 2,3, and 4)	Roan supergroup	Dolomitic sandstone
	Quartzite (marker)		Quartzite (Roan unit 5)		Dolomite
Wushingwi formation	Mica schists	Roan group	Argillite, micaceous quartzite, impure dolomite (Roan unit 6)	Roan supergroup	Siliceous dolomite (Roan units 2.1 and 2.2)
	Biotite schists		(Quartzite, conglomerate) (Roan unit 7)		Dolomitic sandstone (Roan unit 1)
	Local conglomerate				?
Basement complex: granites, schists, gneisses, etc.					?

Uranium mineralisation was first discovered in the Shaba Province of Zaire in 1915 and sometime later in the Zambian Copperbelt, the discoveries in the North-Western Zambian Domes Area are fairly recent.

For sometime these three districts (Fig. 1) have been regarded as independent of one another forming three separate depositional basins, as suggested by the fact that there are marked differences between the three areas. A more careful examination of the geological environments demonstrates however that in each of these areas the lithologies merge into each other indicating that they form a single depositional domain.

The three areas are considered to be a part of a single geological unit. The mineralised areas are thought to have a common origin and to be linked to the same important metallogenic epoch; later tectonic overprinting has masked their petrogenetic links. This modelling served as the basis for the recent discovery of several uranium showings and deposits in the Domes Area of Zambia by Agip S.p.A.

While a considerable amount of data and information is currently available on the Copperbelt area of Zambia and Zaire, the studies on the Domes Area and on the basin's general palaeogeography and evolution are still scanty and fragmentary. More specific information on the Domes Area geology is included in this paper; as far as the other areas are concerned the interested reader is referred to the available literature and particularly to Benham et al. (1976); Binda and Mulgrew (1974); Cahen (1974); Derricks and Oosterbosh (1958); Derricks and Vaes (1956); Demesmaeker et al. (1962); Francois (1974); Garlick (1972); Oosterbosh (1962); Thoreau et du Trieu de Terdonck (1933).

REGIONAL GEOLOGICAL SETTING

The Katanga System, at the base of which all the copper, cobalt, uranium and nickel mineralisations are found (Table 2), unconformably rests on an older complex (gneisses, mica schists, quartzites, phyllites and granite) and is locally covered by Karoo sandstones or Kalahari sands.

The reconstruction of the history of the Katanga System basin is quite difficult not only because of its large size and its

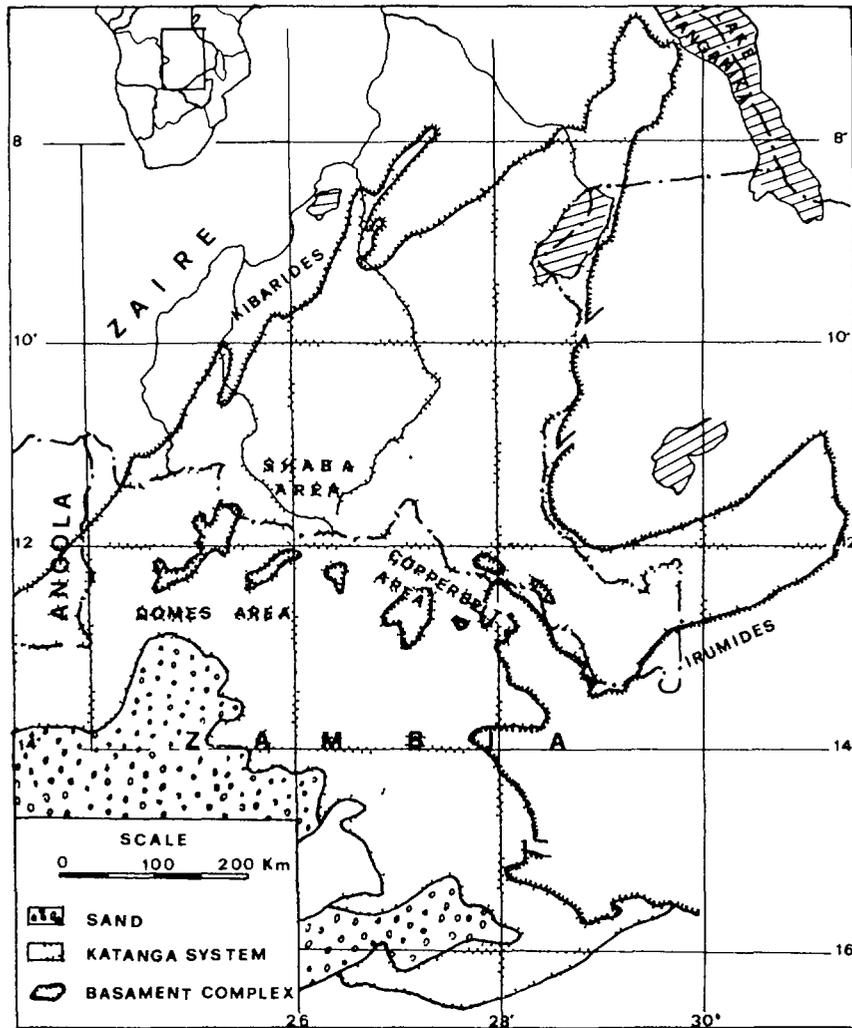


Fig 1. Distribution of the Katanga System
(after Francois, 1962)

original complexity but also because its domains underwent different tectono-metamorphic evolutions. The lack of adequate regional mapping makes for further difficulties. It follows that virtually unknown areas separate other areas for which a rich harvest of data is available.

The deposition of the mainly marine Katanga System took place in the period 840 m.y. and 1,300 m.y. (Cahen, 1970) in a wide complex basin extending from the Shaba province in Zaire through a large part of Zambia and eastern Angola. The south-western deposits are covered by more recent formations (Fig. 1). The full sequence is several thousands of metres thick: at the base are found the copper deposits of the Copperbelt areas of Zambia and Shaba.

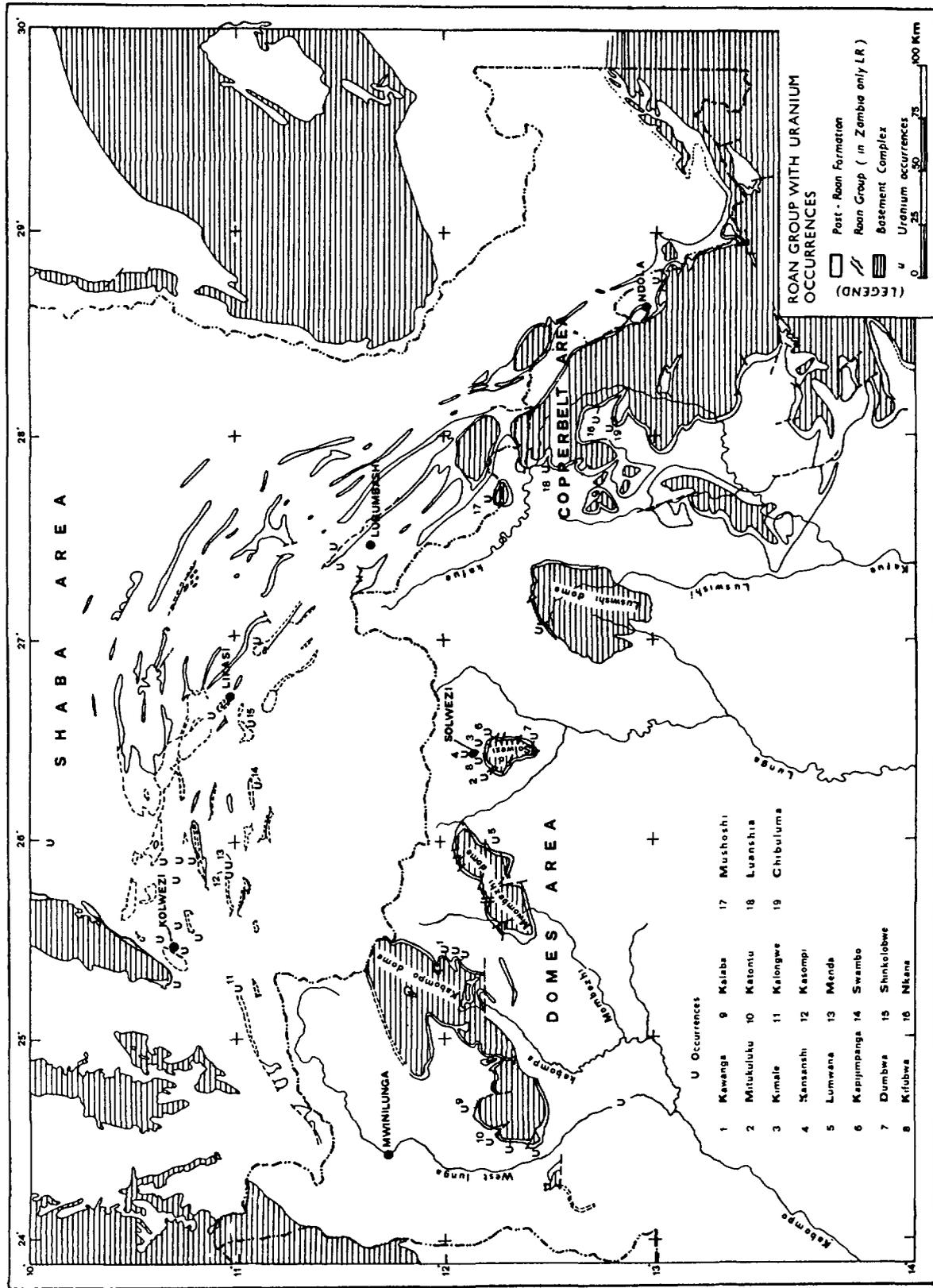


Fig. 2 Occurrences of Uranium in the Roan Group

In the Zambian Copperbelt area the sequence is subdivided, from bottom to top, into the Roan, Mwashya and Kundelungu Groups (Tables 1 and 2). The Roan Group is subdivided into a predominantly clastic, Lower Roan sub-Group, up to 1,000 m thick, and a predominantly dolomitic Upper Roan sub-Group, 500 to 800 m thick (Binda and Mulgrew, 1974). In Shaba the sequence is subdivided into the Roan, Mwashya and Kundelungu Supergroups, the Roan Supergroup being subdivided into four groups (Cahen, 1974). In the Domes Area the sequence is subdivided from bottom to top into Wushingwi, Wamikumbi, Luigishi, and West Lunga Formations.

There appears to be a general increase in metamorphic grade in the Katanga System from east to west and from north to south. In Shaba there is little evidence of metamorphism, and in the Zambian Copperbelt the metamorphic grade normally does not exceed greenschist facies (Mendelsohn, 1961). In the Solwezi area mineral assemblages indicate metamorphism of the greenschist facies, with local development of amphibolite facies (Arthurs, 1974). Lower Roan schists contain quartz, muscovite, and traces of phlogopite and iron oxides, with or without chlorite, biotite, or epidote. Kyanite occurs as individual crystals and needles, or in coarse aggregates at the unconformity between the basement and rocks of the Lower Roan Group. In the Kabompo Dome area, the metamorphic grade reached amphibolite facies in the basement and in the Wushingwi and the Wamikumbi Formations (Appleton, in prep.; Edwards, 1974). Assemblages characteristic of the Wushingwi Formation (Lower Roan) are kyanite + quartz, quartz + talc + phlogopite + chlorite, and kyanite + quartz + talc + phlogopite + chlorite. Chlorite is indicative of post-tectonic retrogressive metamorphism.

Shaban Copperbelt area

The arcuate Shaban Copperbelt covers an area of approximately 300 km. Uranium, copper, cobalt and nickel are found together, mainly along the southern margin of the arc, particularly at Kalongwe, Menda, Kasompi, Swambo and Shinkolobwe (Fig. 2). Copper-cobalt mineralisation, sometimes accompanied by uranium, is found in the central part of the arc at Musonoi, Kamoto, Mashumba, Kalumbwe, Mwinga, Mashitu, Kambove, Luishya and many

Table 2. Distribution of Copper Deposits and Uranium Occurrences in the Katanga System

Shaban Copperbelt			Zambian Copperbelt			Domes area			Total	
Stratigraphic units ^{1,3}	Number of Cu deposits	Number of U occurrences	Stratigraphic units ^{2,3}	Number of Cu deposits	Number of U occurrences	Stratigraphic units	Number of Cu deposits	Number of U occurrences	Number of Cu deposits	Number of U occurrences
K.s.3										
K.s.2.2										
K.s.2.1										
K.s.1.3.2										
K.s.1.3.1										
K.s.1.2.2										
K.s.1.2.1										
K.s.1.1			K.u. tillite							
K.i.1.4			K.l. shale			K.l. shale				
K.i.1.3										
K.i.1.2.2	2 ⁴		K.l			K.l				
K.i.1.2.1			limestone			limestone				
K.i.1.1			K.l. tillite			K.l. tillite				
R.4.2			Mwashya			Mwashya				
R.4.1	2		Upper Roan (R.u. 1)			Upper Roan				
								1?	2	1?
R.3?,R.2.3			R.u.2							
			R.1.4, R.1.3							
R.2.1,R.2.2	64	22	R.1.6,R.1.5	17	5	Lower Roan	3	15	84	42
R.1?	4 ⁵		R.1.7							
?			Basement			Basement				
								1?		1?
Total	66	22		17	5		3	15	86	42

¹ After Francois (1974) and Cahen (1974)

² Lower Roan subdivision from Binda et al. (1974)

³ Correlation between Roan of Shaban and Zambian Copperbelt established by Cailteux (1977)

⁴ One deposit of hydrothermal origin and one of supergene enrichment (Francois, 1974)

⁵ The four deposits are of supergene enrichment (Francois, 1974)

Abbreviations: K = Kundelungu; R = Roan; s = superior; i = inferior; u = upper; l = lower

other localities. In the northern part of the arc only traces of copper and cobalt, not accompanied by uranium, have been found.

The mineralised dolomitic rocks of the Lower Roan Group, in Shaba are found as separate masses enclosed in breccia. In central Shaba, the rocks are only slightly deformed, but farther south they are complexly folded and faulted. Because the contact between the Katanga System and the basement is not exposed, it is difficult to reconstruct the paleoenvironment. Francois (1974) suggested that transgression and terrigenous sedimentation initially took place on a continental platform in an oxidizing environment with the formation of a Roan 1 unit. The Roan 2, 3 and 4 units were then deposited under euxinic conditions, accompanied by local volcanic activity, especially at the Roan 4 level, and with the concomitant development of copper and uranium mineralisation at the Roan 2 level. Finally, the basin was filled with Kundelungu sediments in a variety of environmental conditions.

Mineralisation occurs in the basal 30 to 40 m of the Roan 2 unit of the Lower Roan Group (Table 2). The host rock is generally a siliceous dolomite, the main minerals being dolomite, quartz, magnesite, sericite, and chlorite, with apatite, tourmaline, and monazite as accessory phases. Original clayey sediments were weakly metamorphosed, with the formation of authigenic sericite and chlorite (Francois, 1974). The usual ore mineral assemblages are chalcocite-bornite-carrollite or chalcopyrite-carrollite. The common uranium minerals are thorium-free uraninite and secondary uranium minerals. The highest uranium concentrations are found in fracture zones or near the water table. All the disseminated black uranium minerals are localized at the base of the zone of copper-cobalt mineralisation (Cahen et al, 1971).

Recent isotopic age determination indicate that Roan sedimentation began more than 1,000 m.y. ago (Cahen, 1974). Three subsequent orogenic phases were dated at 840 ± 40 to 710 m.y., 670 ± 20 m.y., and 620 ± 20 m.y. (Cahen, 1970). Age determinations (Cahen et al., 1971) on the uranium minerals from different localities give the following results: >706 m.y., 670 ± 20 m.y., 620 ± 10 m.y., 582 ± 15 m.y., 555 ± 10 m.y. and 520 ± 20 m.y. (Fig. 3). Modification of the protore has been

brought about, with local conversion into rich ore, by tectonic, volcanic and thermal events, and alteration phenomena.

The uranium-copper-cobalt-nickel association is found in a different isopic zone from that of the main copper-cobalt association (Oosterbosch, 1962), the mineralisation has a typical vein aspect with epigenetic characteristics. The origin of the mineralisation, particularly its structural control, is a controversial one. A metallogenetic epoch different from the copper-cobalt association has been postulated (Oosterbosch, 1962). A magmatic origin has been proposed and the deposits at Shinkolobwe have been classified as hydrothermal (Thoreau et al., 1933; Derricks and Vaes, 1956; Derricks & Oosterbosch, 1958; Dahlkamp, 1978. Ngongo-Kashisha (1975) suggests for the two associations a unique metallogenetic process and Francois (1974) suggests a similar origin. Cahen et al. (1971) consider that the uranium deposits are due to the remobilisation of pre-tectonic mineralisation.

Zambian Copperbelt area

In the Zambian Copperbelt, which covers an area 112 km long and 56 km wide, uranium mineralisation is found at Nkana, Mushoshi, Luanshya, and Chibuluma in the basal part of the Katanga system. Mineralisation occurs as disseminations or fracture fillings stratigraphically below the copper ores, as at Chibuluma, or in rocks of shallow water origin adjacent to the cupriferous zones, as at Nkana (Mendelsohn, 1961). The host rocks are generally argillite, fine-grained carbonaceous quartzite, micaceous quartzite, and shale; they represent the earliest sediments deposited under reducing conditions, as in the Shaban area. The common accessory minerals are rutile, apatite, zircon, monazite and pyrite. The ore-bearing formation was affected by up to three phases of deformation during the Lufilian Orogeny and by the same thermal and volcanic events and alteration processes as the sediments of the Shaban area.

The uranium minerals are uraninite and its alteration products. Age determinations show that there are several generations of uranium mineralisation: $520 \pm$ m.y., 468 ± 15 m.y., 365 ± 40 m.y., and 235 ± 30 m.y. (Cahen et al., 1971). The first generation included copper, cobalt, iron and uranium, but sub-

sequently the proportions of the other metals decreased until only uranium remained. No uranium mineralisation older than 520 m.y. has been found. The dissemination and the vein-type uranium mineralisation have clear epigenetic characteristics (Cahen et al., 1961). The uranium mineralisation contrasts with the copper mineralisation, for which a syndepositional origin can be regarded as established.

Domes Area

The Domes Area (Fig. 2) in the northwestern province of Zambia extends for about 300 km from west to east and includes the Kabompo, Mwombezi, Solwezi and Luswichi Domes. Rocks of pre-Karoo age in the area belong to the basement complex and the Katanga System.

Gneisses, schists and granites of the basement complex occur in the cores of the Kabompo, Mwombezi and Solwezi Domes. In the Kabompo Dome, the basement rocks are divided into (a) gneisses, including leucogneiss, scapolite gneiss, and biotite-hornblende gneiss and (b) psammitic and pelitic rocks affected by two phases of migmatisation (Klinck, in press). Appleton (in press) similarly describes an older, partly migmatised gneiss complex and a younger formation of schists, both feldspathised and unfeldspathised. A gneiss group found in the Solwezi and Mwombezi Domes comprises biotite gneiss, schistose gneiss, amphibolite, and hornblendite. A later granite group, separated from the gneiss group by a migmatite zone, is composed of marginally foliated granite (Arthurs, 1974). The high radioactive background over large areas suggests that the basement complex could have been the original source of the uranium found in the basal Katangan rocks.

The lower units of the Katanga System crop out peripherally around the domes, whereas the higher stratigraphic units are found farther out in the surrounding country.

In the Kabompo Dome and adjacent areas, the Wushingwi Formation unconformably overlies the basement complex. The formation is composed of a sequence of talc-muscovite-kyanite quartzites and schists, with intraformational breccias and conglomerates (Appleton, in prep.). A basal conglomerate occurs locally. At

some localities, notably in the Solwezi Dome area, the base of the formation is not clearly defined, the assumed contact being a zone of kyanite schist (Arthurs, 1974). The Wushingwi Formation gives rise to prominent quartzitic ridges.

The overlying Wamikumbi Schist Formation comprises mainly biotite schists, variously with garnet, kyanite, actinolite, carbonate minerals, and scapolite. Quartzites, marbles, graphitic phyllites, banded ferruginous quartzites and schistose tillites are also included. In the Kansanshi borehole NK6 in the Solwezi area, the formation is represented by dolomite and muscovite-chlorite-talc schist, passing into micaceous and dolomitic quartzite (Arthurs, 1974). Unfoliated basic meta-volcanic rocks occur in the Wamikumbi Formation to the south and to the north of the Kabompo Dome (Appleton in press: Klinck, in press) as lenticular masses up to 3 km in length.

In western part of the Domes Area, the Luigishi Formation appears to overlie conformably the Wamikumbi Formation (Edwards, 1974), but in other areas, especially to the north of the Kabompo dome, it represents a more arenaceous facies of the Wamikumbi formation (Appleton, in prep.). It includes calcareous psammitic schists and psammities, variously containing biotite, scapolite, actinolite and garnet. The West Lunga Formation which follows is a thick sequence of folded pelitic metasediments with units of marble and tillites (Edwards, 1974). The tillites are considered to be predominantly glacial in origin, although in part they were probably modified by mass flow processes. The youngest Katangan unit, the Kanyidima Formation, crops out in the northwest. It is composed of calcitic marbles (Appleton, in prep.).

In the Wushingwi Formation the development of cross-bedding and intraformational breccias in a sedimentary sequence including carbonate (some probable bioherms) and coarse clastics, together with apatite and graphite, may indicate a shallow water, near-shore, reducing marine environment of deposition. Near-shore, possibly lagoonal, conditions are considered to have prevailed at the beginning of the deposition of the Wamikumbi Formation, followed by a transition to marine sedimentation. The intercalation of carbonate rocks may imply deposition in shallow water. Edwards (1974), considered the rocks of the Luigishi

Formation to have been originally sandy marls but was unable to find identifiable sedimentary structures. Shallow water deposition, possibly in a shelf environment, is suggested by Klinck (in press) for the West Lunga Formation.

Resulting from the absence of age determinations, the correlation of the Katanga sediments of the Domes Area can only be based on litho-stratigraphic features and on tectonic and morphological considerations. The Wushingwi, Wamikumbi Schist, Luigishi, and West Lunga Formations are included in the Katanga System because they lie unconformably on the basement complex and are lithologically similar to the Katanga rocks of the Copperbelt. Although the rocks of the Wushingwi Formation are relatively highly deformed and metamorphosed, they can be correlated with similar arenaceous units around the Mwombezhi and Solwezi Domes, and with arenaceous Lower Roan rocks of the Copperbelt. If the tillites are indeed of glacial origin, the West Lunga Formation may be correlated with Kindelungu of the Copperbelt (Edwards, 1974).

The Katanga metasediments contain unfoliated gabbro, meta-gabbro, metadolerite, and granitic rocks. Gabbroic rocks, including olivine gabbro, commonly form sills and plugs in the Luigishi and Wamikumbi Formations, and there are minor occurrences in the West Lunga Formation. Rocks of granitic composition include adamellite, quartz monzonite, tonalite, and diorite. Hornblende-epidote adamellites in Katangan metasediments younger than the Wushingwi Formation in the northwest of the Domes Area may represent the post-Lufilian Hook granite (Appleton, in press).

The Domes Area lies within the southern portion of the Lufilian arc and is composed of Katangan rocks subjected to three phases of deformation and metamorphism during the Lufilian Orogeny (840-620 m.y.). The mode of formation of the domes is uncertain, but it is generally believed that they were formed late in the Lufilian Orogeny, possibly by the interference of folds of the second and third phases (Klinck, in press).

Three major low-grade stratiform copper deposits are known in the Lower Roan of the Mwombezhi Dome. The ore-bearing horizon is a slightly carbonaceous shale. Deposition of the host rock and distribution of the sulfides are closely related to the palaeotopography. Mineralisation seems to be of syn-

sedimentary origin related to reducing conditions (Benham et al., 1976).

Uranium mineralisation occurs in the Lower Roan Group, which crops out for 600 km around the domes. Uranium mineralisation is confined to two horizons, one above and one below a quartzite marker horizon. At Kalaba and Katontu around the Kabompo Dome, uranium arsenates and vanadates, carnotite, gold, copper sulfides, traces of nickel, cobalt, lead, chromium and molybdenum occur in a brecciated talc schist just above the quartzite horizon. To the east of the West Lunga River, 15 km from the western edge of the Kabompo Dome, uranium and copper mineralisation occurs in a carbonaceous shale of the Katangan System, and metatorbernite has been identified in siltstone. Two boreholes, located on a radioactive anomaly, intersected leached uranium mineralisation at a 40 m depth (Edwards, 1974). Uraninite, brannerite, metatorbernite, monazite, molybdenite, and gold occur in quartz-carbonate veins at the Kansanshi copper mine (C. Legg, in Arthurs, 1974).

Below the quartzite marker horizon, uranium mineralisation occurs as uraninite, disseminated or in small veins, and as yellow secondary minerals. Five of the 15 known occurrences have been investigated by drilling and encouraging results have been obtained.

In the Kawanga area (Kabompo Dome), uranium occurs mainly as traces of autunite coating mica schist cropping out in the area of two small radiometric anomalies. Drilling intersected uranium mineralisation in mica schist below the quartzite marker horizon. Discontinuous mineralisation occurs at one or more levels the thickness of which can be several metres and has a U_3O_8 content up to 1 percent. One hole intersected mineralisation of such a grade over a thickness of about 25 m at a depth of more than 200 m. The mineralisation consists of thorium-free uraninite disseminated in schist or filling fractures several centimetres wide, and of secondary uranium minerals coating fracture surfaces. Kyanite schist from the mineralised zone carries quartz, epidote, kyanite, and muscovite and has granoblastic and poikiloblastic textures. Quartz shows a mosaic texture and epidote is present as irregularly shaped grains or as prismatic crystals. Kyanite occurs as individual crystals or in

aggregates. Accessory minerals include iron oxides, apatite, monazite, and rutile. The uranium mineral is autunite. A dark biotite schist, in which the schistosity is marked by flakes of biotite and muscovite and equidimensional grains of quartz, occurs below the mineralised zone. Tourmaline, apatite, zircon and opaque minerals are also present. The rock overlying the mineralised zone is a talc schist, containing unorientated plates of talc and crystals of rhombic pyroxene and kyanite. Accessory minerals include monazite and scapolite.

During the course of exploration for copper in the Mwombezi Dome area, Mwinilunga Mines Limited found occurrences of uranium on the surface and subsurface in the Lumwana area (McGregor, 1964; Benham et al., 1976). The uranium mineralisation is found in mica schist, as in the Kawanga area. In the Solwezi Dome area, numerous small occurrences of uranium mineralisation have been found, and drilling has been carried out at Dumbwa, Kapijimpanga, Kimale, and Mitukuluku. The mineralisation is similar to that already described. Secondary uranium minerals are found coating flakes of mica, talc, or chlorite along fractures and in veinlets containing quartz, talc, muscovite, apatite, and kyanite. The uranium minerals include autunite, meta-autunite, sabugalite, phosphoranite, vandendriesscheite, and gummite. At depth, the mineralisation consists of uraninite, disseminated or forming scattered veinlets, and secondary uranium minerals, as at Kawanga. The best mineralisation intersected in drill holes occurs at the Mitukuluku showing, where 1.4 percent U_3O_8 was found over a thickness of 9 m (C. Legg, in Arthurs, 1974). The host rock is quartz-mica-kyanite-talc-epidote-apatite-chlorite schist, underlying the marker quartzite.

The absolute ages of six samples from the Kawanga, Kimale, and Dumbwa areas, were determined at the Institute of Geological Sciences, Geochemical Division, London. The mean value for the 207/206 (U) ages is 536 ± 12 m.y.

The uranium mineralisation of the Domes Area is of the same age or is younger than that of the Shaban Copperbelt and is of the same age or older than that of the Zambian Copperbelt (Fig. 3). In the Domes Area and in the Zambian Copperbelt the mineralisation lies close to the basement where reactivation of granite gave rise to thermal events after such influences had

ceased elsewhere. In the Domes Area and in the Zambian Copperbelt, any uranium mineralisation ages older than 520 m.y. could have been suppressed by these later thermal events, during which uranium and other minerals were remobilized. In the Shaban Copperbelt, older uranium mineralisation was isolated in up-faulted blocks of the Lower Roan and only a very few minerals particularly sensitive to temperature were thermally affected.

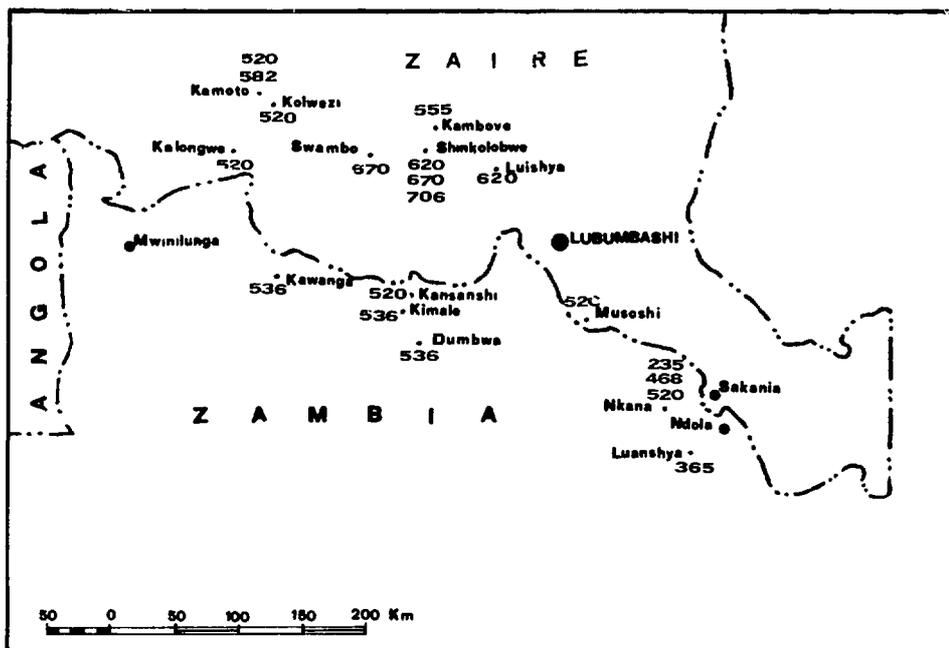


Fig 3 Isotopic ages of Uranium occurrences in the Katanga system (Modified after Cahen et al, 1971)

THE DEPOSITS' GEOLOGICAL SETTING

Shaban Copperbelt area

In the Shaban Copperbelt area Francois (1974) classifies 22 uranium occurrences as 7 proven deposits, 2 indicated deposits, 3 inferred deposits, and 10 showings. The most notable of these deposits is Shinkolobwe Mine (Derricks and Vaes, 1956; Derricks and Oosterbosh, 1958), the only one exploited. Although no official data have been published, the amount of uranium exploited could have been over 30,000 tonnes (U_3O_8) at an average grade between 0.4 and 0.5%. The mine was opened in 1921 and closed in 1960 as a result of a fire.

The uranium was found as uraninite or as secondary minerals (over 20 species) in the lower part of the R2 units at the base of the copper mineralisation. Uranium preferentially concentrated in the mylonite zones but originally could have had a

lensoid or stratigraphic dissemination similar to but more irregular and patchy than that of the copper mineralisation. Furthermore since the two elements have different geochemical behaviour characteristics they tend to fractionate. Protore could have undergone a long series of later remobilizations, the most important of which could be linked to the faulting of the mines alloctonous tectonic unit enclosed into an impermeable talc-schist breccia. Within this unit the uranium could have been free to move and concentrate in small fractures. Such remobilisation would have been responsible for the production of economic uranium grades. The host rock is a slab of Roan Group involved in a thrust zone and enclosed into a tectonic breccia; it rests over younger Kundelungu Strata. The mineralisation is found along open fractures within the dolomite. Mineralisation stops at the boundary with the enclosing breccia; the larger faults are always barren. After development of mineralisation in the slab only minor displacements followed. Uranium minerals are found both in veins (from a few decimetres up to a metre thick) and disseminated in the host rock. Uranium was accompanied by Cu, Co, Ni and traces of Mo, W and rare earth elements. Some native gold occurred as encrustations on uraninite. Gold grades from 10 to 60 grams per tonne. Some platinum and palladium is also present.

The following parageneses have been recognised - first phase: magnesite; 2nd phase: uraninite; 3rd phase: pyrite, selenium, molybdenum, monazite, chlorite; 4th phase: Co-Ni sulphides (and tectonization); 5th phase: chalcopyrite. Absolute age determinations on uranium minerals at Shinkolobwe yielded age ≥ 706 m.y., 670 ± 20 m.y. and 620 ± 10 m.y. Fluid inclusions found in the Cu-Co and U-Ni-Co-Cu mineralisation within unit R2 show identical characteristics suggesting that they were formed during the same metallogenetic event.

Zambian Copperbelt area

In the Zambian Copperbelt at least five uranium occurrences are known. The Nkana mineralisation is the only one that has been so far exploited with a total production of 110 tonnes U_3O_8 . Uranium ore occurred in the transition zone between a copper

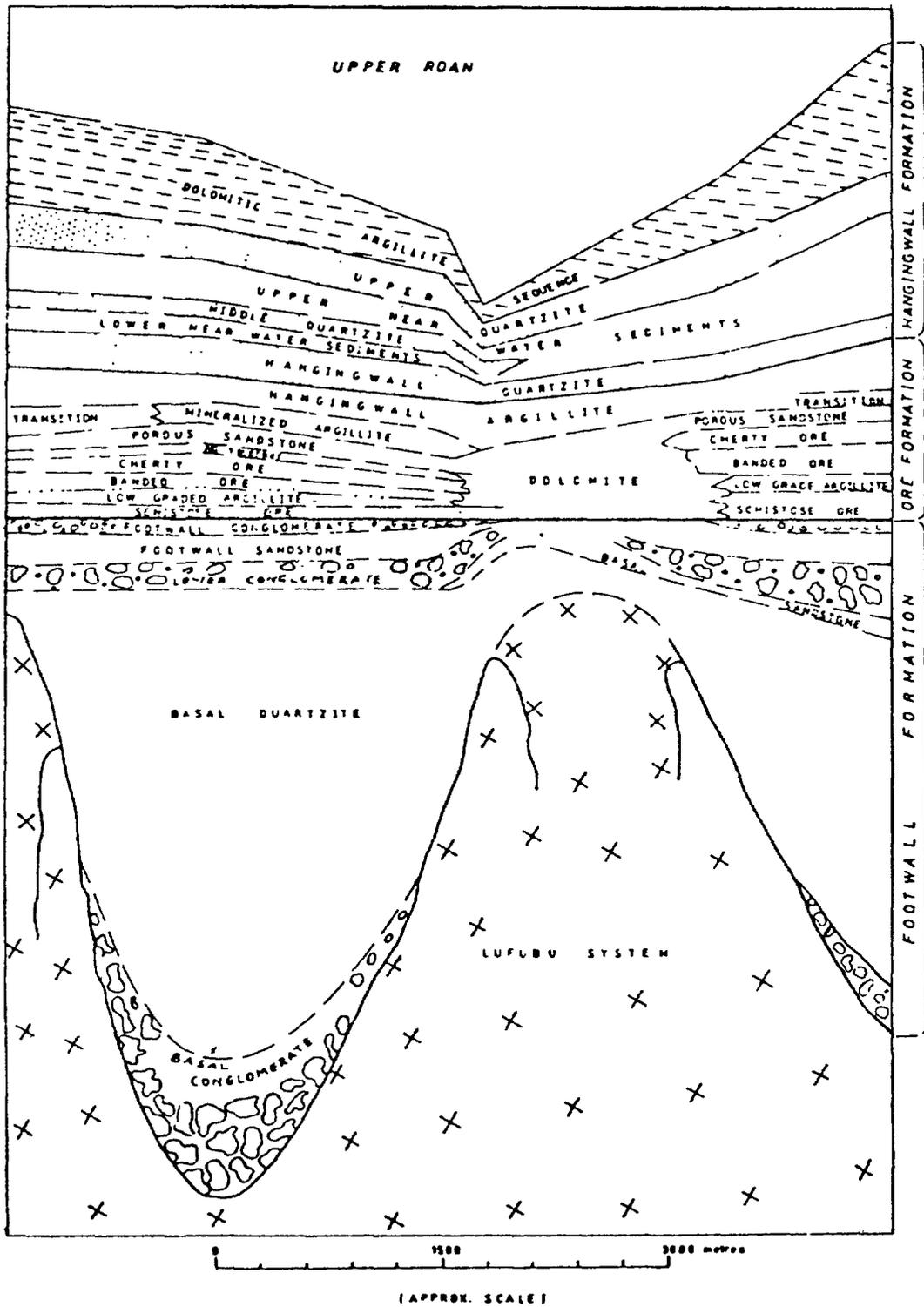


Fig. 4.- Diagram illustrating the topographic control of Lower Roan ore deposition from the Nkana area.

orebody and barren dolomites, this barren gap reflecting a buried 'basement' hill (Fig. 4).

Uranium mineralisation was present in complex argillitic sediments (the Cherty Ore) and in alternating sandy and argillaceous dolomites (the Banded Ore). The dominant primary uranium mineral is uraninite, occurring as fine disseminations and blebs, with a little brannerite and coffinite. Near surface oxidation produced uranophane, beta-uranotile and gummite. Numerous calcite, quartz, feldspar and anhydrite veins cut the deposit and were mineralised with brannerite and uraninite and traces of bornite and chalcopyrite.

Mineralisation has been found both as veins and disseminations. When the veins intersect a disseminated mineralised horizon the strata-bound ore grade decreases suggesting that the veins uranium came from the disseminations themselves. Quartz-feldspar veins that do not intersect the mineralised beds are always barren. Field evidence demonstrates that the entire mineralisation postdated the Lufilian Orogeny. Absolute age determinations at Nkana yielded ages of 520 ± 20 m.y., 468 ± 15 m.y. and 235 ± 30 m.y. The first generation (520 m.y.) showed the following mineral association: uraninite, melanite, bornite, chalcopyrite, digenite, calcite, chalcocite, quartz, biotite, albite, chlorite. The 468 m.y. old one showed uraninite, carbonate, pyrite, finally the third one (235 m.y.) showed botryoidal uraninite only..

Domes Area

Over 15 uranium occurrences are known around the basement domes of North-Western Zambia. So far none of them has been exploited and exploration is still going on. The best known of them, namely Kawanga has proved reserves of a few thousand tonnes U_3O_8 at an average grade of about 0.4%.

URANIUM ORE GENESIS AND CONTROLS

The protore and its relation to copper mineralisation

Stratigraphic correlations have been established between the Zambian and Shaban Copperbelts (Cailteux, 1976), but correlation of these areas with the Domes Area is uncertain. The

basins of deposition were for the most part of limited extent, especially for the lower parts of the Katanga System, so that there are many local facies changes. The basal sediments in the Zambian Copperbelt and Domes Areas are predominantly arenaceous, whereas those in the Shaban area are carbonates, but all are associated with copper, cobalt, and uranium mineralisation. The sediments deposited later were more uniform in composition and of greater lateral extent and are, therefore more readily correlatable. The sediments of the Katanga System were deposited in the period 1,300 to 620 m.y., those of the Roan Group probably before 1,000 m.y. (Cahen, 1970).

There is evidence of stratigraphic control, since the uranium occurrences and main radioactive anomalies of the Shaban and Zambian Copperbelts and the Domes Area appear to be restricted to a particular stratigraphic interval at the base of or adjacent to the copper-bearing horizons or to occur in different isopic zones. The known copper, cobalt, and uranium deposits all occur in an interval of sediments 100 to 150 m thick (30-40 m in the Shaban area) at the base of an 8,000 m thick sequence of sediments. In the Shaban area, all the black uranium oxides and more than 70 percent of the uranium occurrences are localised at the base of the zone of copper mineralisation. Secondary uranium minerals are found along fault zones and other fractures in decreasing amounts away from the mineralised horizon (Cahen et al. 1971).

Environmental controls are similar in the three areas for both the copper and the uranium mineralisation, as indicated by the presence of bioherms in the vicinity of the mineralised zones. It seems likely that the bioherms provided the required conditions to cause initial syngenetic precipitation of copper, cobalt and uranium in shallow marginal marine waters. Subsequent enrichment could have taken place during diagenesis. The zone of mineralisation therefore corresponds to reducing conditions in the depositional environment as attested by the presence of carbonaceous matter in most host rocks. Where oxidized minerals, such as hematite, rutile and ilmenite, are prominent, uranium mineralisation is weak or absent; there seems to be an irreconcilability between uranium mineralisation and the presence of some oxides. The host lithologies, therefore, can be said

to vary quite considerably but not the chemistry of the depositional environment which was the vital factor.

A mineral zoning is evident in the Zambian Copperbelt (Garlick 1972), at Lumwana in the Domes Area (McGregor, 1964), and in the Shaban area (Oosterbosch, 1962); from the footwall upward or from the shoreline seaward the sulfide minerals occur in zones represented by chalcocite, bornite, chalcopyrite, and pyrite. In the Shaban area particularly, uranium occurs below the copper mineralisation (Cahen, et al. 1971). In the Zambian Copperbelt and Domes Area, lithologic consideration suggest several cycles of transgression and regression, with the result that the uranium mineralisation occurs at various horizons within the zone of copper mineralisation and not exclusively at the base. An explanation of this distribution could be that initially precipitated uranium was again taken into solution as conditions changed from reducing during transgression to oxidising during regression.

Regional mineral zoning in the Shaban area has been studied by Ngongo-Kashisha (1975) who shows that in the southern part of the 300 km arc, uranium, copper, cobalt, nickel, monazite, and magnetite are predominant. In the central part of the arc, there is an increase in the amount of copper and cobalt and a decrease in the amount of uranium, nickel and magnetite, with monazite present only in traces. Only traces of copper and cobalt are found in the northern part of the area. On a regional scale in the Domes Area, the higher grades of copper occurrence, such as Kimale, are almost free from uranium and copper is absent from richest of the uranium occurrences including Kawanga and Mitukutulu; however both of these elements are found in deposits of intermediate grade, such as the Kapijimpanga occurrence. A similar relationship is apparent in the Zambian Copperbelt, where uranium of good grade occurs in a weak copper zone at Nkana, and in the Shaban Copperbelt area (Oosterbosch, 1962). According to syngenetic concepts, the mineral zoning appears to be related to the changing chemical and physical conditions within the zone of sedimentation as the depth of water increased or decreased with the advance or retreat of the shoreline (Garlick, 1972).

Convincing evidence is available for the syngenetic sedimentary origin of copper mineralisation; it seems that the evident stratigraphic, palaeotopographic and environmental controls require a similar interpretation for the uranium mineralisation. These conclusions are corroborated by the identical fluid-inclusion characteristics of the copper-cobalt mineralisation and uranium-copper-cobalt-nickel mineralisation (Ngongo-Kashisha, 1975), the fluid inclusions would be expected to be different if the uranium association belonged to an independent magmatic epoch as previously stated by Derricks et al. (1956, 1958), as postulated by Oosterbosch (1962) and as generally accepted in the geological literature, at least as far as the Shinkolobwe, Swambo and Kalongwe deposits are concerned.

Protore-changing processes

Many of the uranium occurrences have a typical vein aspect and all the isotopic ages of the minerals are post-sedimentary. These facts are not inconsistent with the previous conclusions if the processes which affected the protore are examined. These processes include diagenesis, metamorphism, tectonic events, supergene enrichment and thermal events associated with post-tectonic metamorphism; they modified the protore and converted it into ore with vein morphology.

In the Shaban area, the effects of metamorphism were slight. In the Domes and Zambian Copperbelt areas, the rocks were recrystallised and to a certain extent the economic minerals were segregated into veins which are bounded by barren zones. Generally it seems that, metamorphism only resulted in minor uranium migration over short distances.

A major role in the protore-changing processes was played by tectonic events. The following generations of uranium mineralisation are known: ≥ 706 m.y. (Shinkolobwe); 670 ± 20 m.y. (Shinkolobwe and Swambo); 620 ± 10 m.y. (Shinkolobwe, Kalongwe, and Luishya); 555 ± 10 m.y. (Kambove West); 536 ± 12 (Kimale, Kawanga and Dumbwa); 520 ± 20 m.y. (Nkana, Kansanshi, Mushoshi and Kamoto); 468 ± 15 m.y. (Nkana); 356 ± 40 m.y. (Luanshya); and 235 ± 30 m.y. (Nkana). In the Shaban area, the range of mineralisation is from 706 to 520 m.y., whereas in the other areas the range is from 520 to 235 m.y. The earlier dates apply

Table 3 - Paragenetic of Minerals Association
(modified after Cahen et al., 1971)

Age of minerals	Paragenesis	Main syngenetic metal				
		Ni	Co	Cu	Fe	U
670 m.y. (Swambo)	(a) Uraninite; pyrite, monazite, chlorite; vaesite, siegenite; chalcopyrite					
670 and 620 m.y. (Shinkolobwe)	(a) Magnesite; uraninite; pyrite, molybdenite, monazite; vaesite, cattierite, siegenite; chalcopyrite.					
620 m.y. (Kalongwe)	(a) Uraninite; pyrite, chlorite; carrolite; bornite, chalcopyrite					
582 m.y. (Kamoto P)	(a) Uraninite; chlorite; carrolite; bornite, chalcopyrite					
555 m.y. (Kambove)	(a) Uraninite; chlorite; carrolite; bornite, chalcopyrite					
536 m.y. (Dumbwa, Kimale, Kawanga)	(b) Uraninite, muscovite, apatite, molybdenite, chlorite					
520 m.y. (Nkana)	(b) Uraninite, melonite, bornite, chalcopyrite, digenite, calcite, chalcocite, quartz, biotite, albite, chlorite; molybdenite					
520 m.y. (Kansanshi)	(b) Brannerite, chalcopyrite, calcite, pyrite, rutile bornite, molybdenite					
520 m.y. (Musoshi)	(b) Albite, uraninite, pyrite, carbonate, quartz, molybdenite					
520 m.y. (Kamoto P)	(b) Uraninite, carbonate, pyrite					
468 m.y. (Nkana)	(b) Uraninite, carbonate, pyrite					
365 m.y. (Luanshya)	(b) Pitchblende, calcite, dolomite					
235 m.y. (Nkana)	(b) Pitchblende					

(a) Paragenetic order; (b) paragenetic association; P = Principal

to the Shaban area where older generations were isolated in up-faulted blocks and preserved from the successive thermal effects following the tectonism. In the Zambian Copperbelt and Domes Areas, where the original mineralised zones remained close to the basement, the uranium minerals were exposed to the succeeding thermal effects and repeated mobilisation and redeposition took place; consequently, more uranium generations exist. According to Cahen et al. (1971) the uranium generations of 706, 670 ± 20 , and 620 ± 10 m.y. are connected with the first, second and third phases, respectively, of the Lufilian Orogeny. All three generations of uranium mineralisation are found at Shinlolobwe. The 670 m.y. generation represents an epigenetic reworking of the 706 m.y. mineralisation, and the 620 m.y. generation is a reworking of the 670 m.y. mineralisation. The 520 ± 20 m.y. generation has been related to a large thermal event associated with post-tectonic metamorphism (Belliere, 1961) which affected the three areas but had its greatest effect in the southeast. This major thermal event has been confirmed by potassium-argon age determinations and other geological considerations. Other lesser thermal influences up to 235 m.y. ago caused further redistribution of uranium mineralisation. Isotopic ages and their references to geologic events can be questionable, but metamorphic events, three main tectonic phases, one major thermal event, and supergene alteration are well known and documented facts in the Katanga System geology.

The paragenetic association of ore minerals confirms the hypothesis that the number of elements decreases after each remobilisation. All of the main ore metals, nickel, cobalt, copper, iron and uranium are present at the 670 m.y. stage. At 620 m.y. nickel has disappeared and cobalt, copper and iron disappear successively at the 520 m.y., 468 m.y., and 365 m.y. stages leaving only the highly mobile uranium at the final 235 m.y. stage (Table 3). In the paragenetic order uranium is normally the first metal to appear. The gradual impoverishment of the paragenetic associations after each remobilisation, without introduction of new metals, supports the hypothesis of one original mineralisation.

Supergene alteration affected the mineralisation to a greater or lesser extent. In the Shaban area the uranium minerals

occurring in up-faulted blocks were leached out and reconcentrated near the water table. Francois (1974) states that intense weathering often cancels form, original composition, and origin of the mineralised bodies. The Shinkolobwe deposit is one such example. In the Zambian Copperbelt and Domes Areas, uranium enrichment occurs in structures near the water table or in fracture fillings.

The newly described uranium occurrences of the Domes Area support the view of Cahen et al., (1971) that the present uranium concentrations are the results of remobilisation of the original mineralisation, reflecting well-documented geological events with no endogenetic processes being involved.

As far as the uranium origin is concerned, no specific investigation has been carried out. Nevertheless it can be assumed, as it has been done for the copper, that it came from the weathering of the basement although a possible contribution from submarine volcanism cannot be completely ruled out. It is however believed that whatever the source of uranium could have been, the protore formation has been syngenetic for both metals, uranium and copper.

Analogy with other mineralisation

The uranium occurrences of the Katanga System show certain similarities with occurrences elsewhere in the world. Reference is here made to the protore and not to the subsequent remobilisation events. A rough comparison can be attempted with deposits of the Northern Territory (Australia) and Saskatchewan (Canada). In the three regions the uranium bearing sediments were deposited at the base of a marginal marine sequence in a basin bordered by granites, gneisses, migmatites, and other metamorphic rocks. The presence of bioherms in Australian deposits (Needham & Stuart-Smith, 1976) and in the Zambian-Zairean occurrences indicates a euphotic zone, i.e. a shallow water or lagoonal environment. The presence of carbonaceous matter, adjacent to or intercalated with the mineralisation, suggests a reducing marine environment. The Olympic Dam deposit on the Roxby Downs Pastoral Station, South Australia, appears to have similarities to the deposits associated with the Katanga System (see Roberts & Hudson, this volume). The original mineralisation

subsequently underwent different geological histories, not only in the different regions but also in different places of the same region, leading to the present type of the mineralisation.

CONCLUSIONS

Uranium and copper mineralisation is present at the base of Katanga System. The mineralisation is considered to be closely related to a marine transgression over an ancient crystalline basement. An originally stratiform mineralisation was changed by later tectonic, metamorphic and thermal events, giving rise to the relatively high-grade vein-type occurrences now seen which represent epigenetic enrichment of the syngenetic protore.

In the Shaban Copperbelt area, the stratiform nature of the uranium mineralisation, closely associated with the southern facies of the Lower Roan Group, provides a target for exploration along 300 km of the mineralised arc. The probability of finding sub-outcropping mineralisation is minimal, but new technology - such as alpha-detection could be tested in the search for hidden concentrations of ore. Although large deposits of high-grade uranium mineralisation are unlikely to be found, low-grade occurrences could provide valuable by-product uranium for the copper industry. In the Zambian Copperbelt and Domes Areas, where the uranium isopic zones of the Lower Roan Group are not well localised, it may be necessary to elucidate the palaeogeography and palaeoenvironment of the known uranium occurrences.

Although the geology of the copper deposits has been thoroughly investigated, less attention has been given to the peculiar conditions of uranium mineralisation. It has been shown at Shinkolobwe, Nkana, Kawanga and Mitukutulu that rich concentrations of copper and uranium are mutually exclusive, so that exploration techniques for copper detection are different from those required for the location of uranium.

It is difficult to evaluate the possible uranium reserves of the Katanga System; at the moment exploration is still going on in all the three areas involving international companies. Tentatively the total amount of U_3O_8 concentration present at the base of the Katanga System could be estimated between 50,000 and 100,000 tonnes.

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URANIUM IN EARLY PROTEROZOIC AILLIK GROUP, LABRADOR

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Abstract

Uranium occurrences are widely distributed in tuffaceous-argillaceous beds and rhyolitic volcanic rocks of the Aillik Group of Early Proterozoic age. They include partially developed Kitts and Michelin deposits, containing 1560 and 7366 t U respectively. Uranium occurs mainly as disseminated fine pitchblende grains in lenticular concordant zones, and rarely as coarse pitchblende aggregates and thin veinlets.

The occurrences in the argillaceous-tuffaceous beds, including the Kitts deposit, are within a steeply dipping stratigraphic zone less than 50 m thick and over 20 km long. They are interpreted as 'syngenetic', with a source of uranium in an active felsic volcanic field in adjacent terrain. The occurrences in the rhyolitic rocks, including the Michelin deposit, are in elongate structural-stratigraphic belts or zones, and are characterized by a pronounced enrichment of soda and depletion of potash associated with mineralization. They are interpreted as 'epigenetic', related closely in time to the felsic volcanism that formed the host rocks 1767 ± 4 Ma ago according to a Rb/Sr isochron date.

The mineralized zones were affected to a varying degree by Hudsonian deformation and metamorphism. Some of the pitchblendes yielded nearly concordant dates close to 1750 Ma. Others from the south near the 'Grenville Front' indicate disturbance of isotopic equilibrium at the time of Grenville orogeny approximately 1100 Ma ago. This is corroborated by the isotopic composition of lead (Pb: 206/204: 532.45; 207/204: 97.163; 208/204: 36.726) in galena from the Michelin deposit. The overwhelmingly dominant uranogenic component of this lead has a Pb^{207}/Pb^{206} ratio of 0.1585 consistent with its extraction at 1180 Ma from 1767 Ma old pitchblende.

INTRODUCTION

The uranium district of central Labrador coast has been explored intermittently since the first discovery of a pitchblende vein there in 1954. Exploration to date has located a number of occurrences of uranium and molybdenum, including a few promising deposits and prospects although none have been productive as yet.

The first comprehensive study of the geological setting and genetic aspects of the uranium occurrences in the district was published by the writer in 1978. Since then additional exploration work has been carried out, and several geological studies have been done, notably by Clark (1979), Evans (1980), Kontak (1980), White and Martin (1980), Bailey (1979), Gower et al. (1982) and Ryan and Kay (1982). These have added valuable data and new perspectives. Many problems however remain unresolved in this geologically complex and economically promising area. Divergent opinions have been expressed on several important aspects of geology of the area as summarized by Gower et al. (ibid). An attempt is made here to emphasize those aspects that are relevant to the genesis of the uranium deposits.

REGIONAL GEOLOGY

Early Proterozoic Aillik Group was deposited on an Archean banded gneiss complex (Figs. 1 and 2), and was deformed into east-northeast to north trending folds, metamorphosed in the range of upper greenschist to lower amphibolite facies, and intruded by granites, during Hudsonian cycle approximately 1750 to 1550 Ma ago (Gandhi et al., 1969, Gandhi, 1978). To the south, these rocks are bounded by the 'Grenville Front', which is the northern limit of an extensive area affected strongly by deformation, metamorphism and intrusions approximately 1000 to 1200 Ma ago (Stevenson, 1970). Position and nature of the 'Grenville Front' are not well known in this region because of scarcity of outcrops due to extensive glacial drift cover.

Aillik Group

The Aillik Group is dominantly a bimodal sequence of basaltic and rhyolitic volcanic rocks interbedded with clastic sediments (Fig. 3). Rhyolitic volcanic rocks predominate in the upper part of the sequence. Facies variations over short distances are common, and stratigraphic relations are obscured by varying degree of deformation and intrusions. Thickness of the group is estimated as in the order

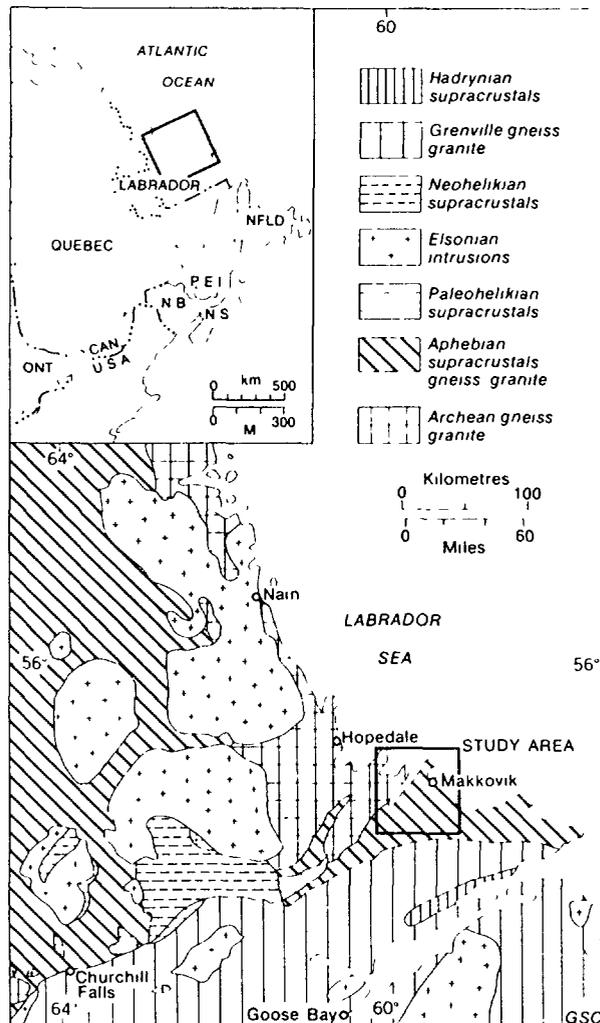


Figure 1. Location map of the study area and general geological features of the surrounding region of the eastern Canadian Shield (from Gandhi, 1978).

of 7600 m (Gandhi et al., 1969) or 8500 m (Clark, 1973). It is informally divided into the lower and upper Aillik groups.

The lower Aillik group is exposed only in the northwestern part of the study area along the Kitts-Post Hill belt near Kaipokok Bay (Figs. 2 and 3). On the southeast side of the bay, it is approximately 2700 m thick, generally dips steeply to the east-southeast, and is overlain by the upper Aillik group which is up to 900 m thick in this belt (Marten, 1977). Contacts of the sequence with the Archean basement to the northwest are faulted and sheared. On the southeastern side, the basement is thrust over the sequence. The thrust zone is obscured in part by intrusion of granodiorite gneiss and in part by extensive drift cover.

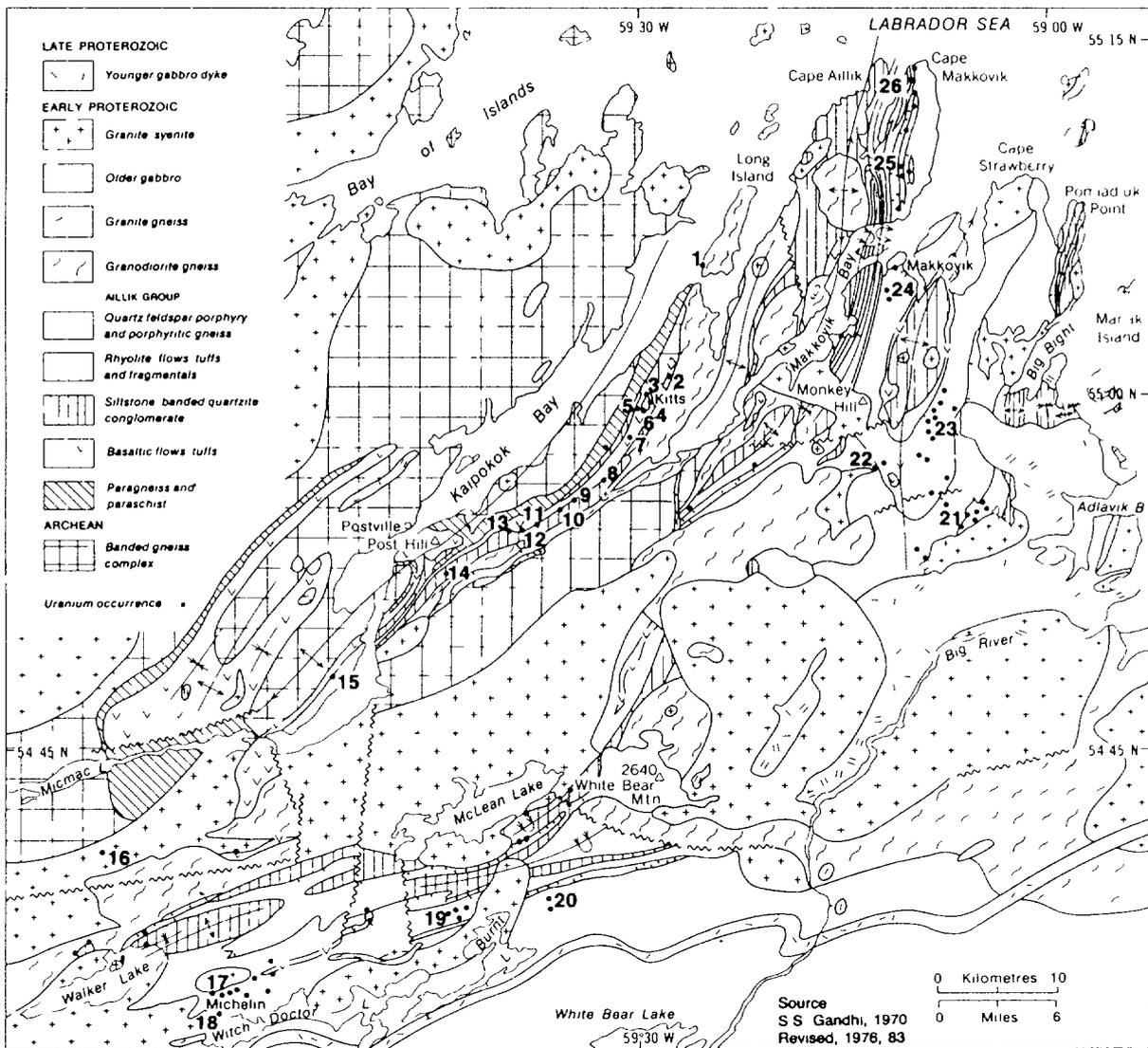


Figure 2. General geological map showing the Aillik Group and uranium occurrences in the group, Kaipokok Bay-Big River area, Labrador (from Gandhi, 1978, with minor modifications). Uranium occurrences:

- | | | |
|-----------------------------|----------------------|----------------------------|
| 1: Long Island, | 10: Knife, | 19: Burnt Lake, |
| 2: Anderson Ridge, | 11: Nash East, | 20: Emben, |
| 3: Kitts 'A' zone, | 12: Nash Main, | 21: Winter Lake, |
| 4: Kitts 'B' and 'C' zones, | 13: Nash West, | 22: Pitch Lake, |
| 5: Kiwi, | 14: Witch, | 23: Round Pond-Falls Lake, |
| 6: South, | 15: 'J' & 'B', | 24: John Michelin, |
| 7: Punch Lake, | 16: Anna Lake North, | 25: Sunil, |
| 8: Gear, | 17: Michelin, | 26: Cape Makkovik |
| 9: Inda, | 18: Rainbow, | molybdenite deposit |

The basal unit of the lower Aillik group is metasedimentary, and is comprised predominantly of micaceous schists and gneisses derived from siltstones and sandstones, with pyritic and graphitic horizons. It is approximately 800 m thick. A basaltic unit capping Post Hill, and extending to the southwest across the Kaipokok Bay, is underlain and overlain by some of the metasedimentary rocks, and is up to 1000 m thick (Fig. 3). The metasedimentary rocks from Kitts to Post

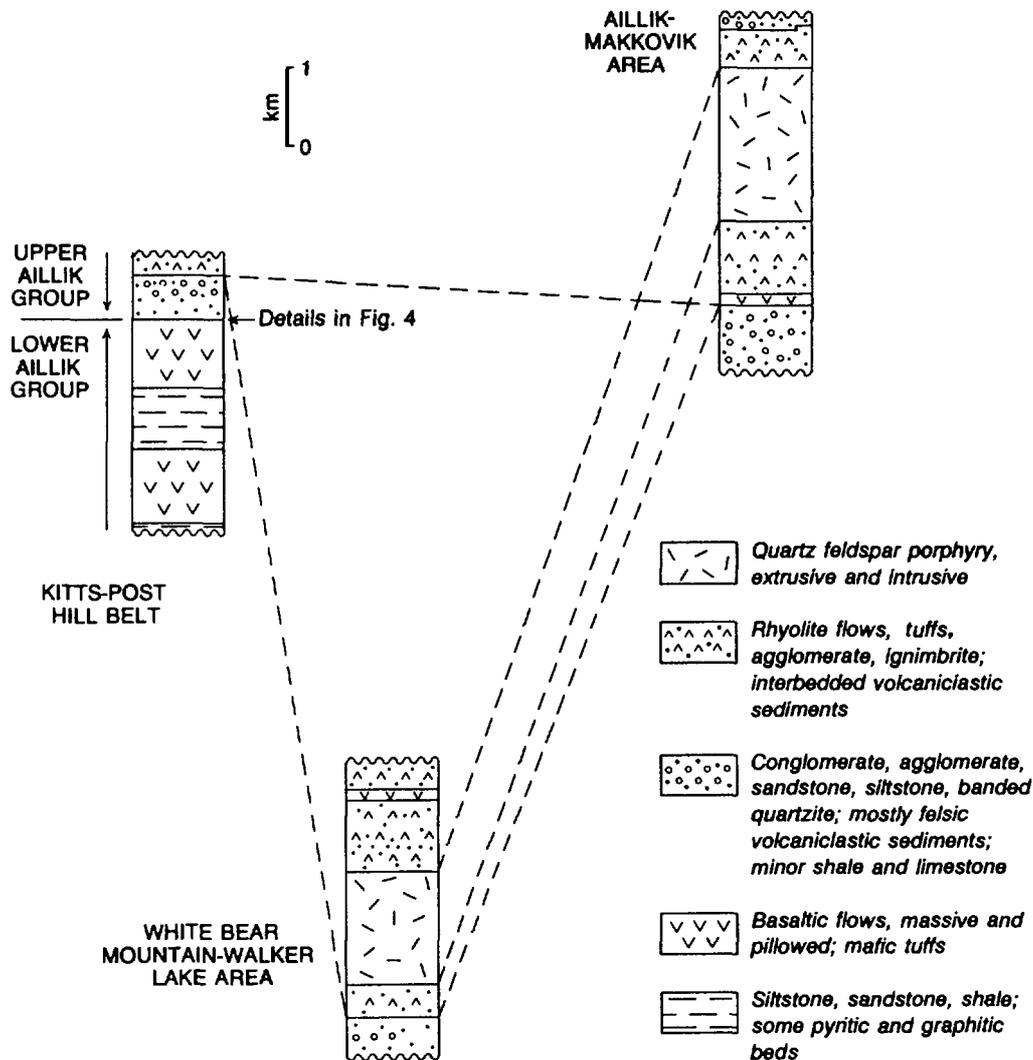


Figure 3. Generalized lithostratigraphy of the Aillik Group in three parts of the study area and tentative correlations.

Hill are overlain by well-exposed massive and pillowed basalt flows and mafic tuffs, approximately 900 m in thickness. The basalts range from marginally subalkaline (tholeiitic) to mildly alkaline, with soda predominant over potash (Evans, 1980; White and Martin, 1980).

The thick basaltic unit is overlain by a relatively thin stratigraphic zone or unit, less than 50 m thick, and referred to here as 'argillaceous-tuffaceous unit', which is an important host of uranium occurrences. It includes chert and argillite to the northeast, and laminated tuffs and tuffaceous siltstones to the southwest, as shown in Figure 4. It is described further under 'Host Rocks' of uranium occurrences. It grades into overlying felsic tuffaceous siltstones and banded quartzite, in the southwestern part of the belt, and into interbedded mafic tuffs, siliceous and calcareous beds in the middle part of the belt, and is overlain by

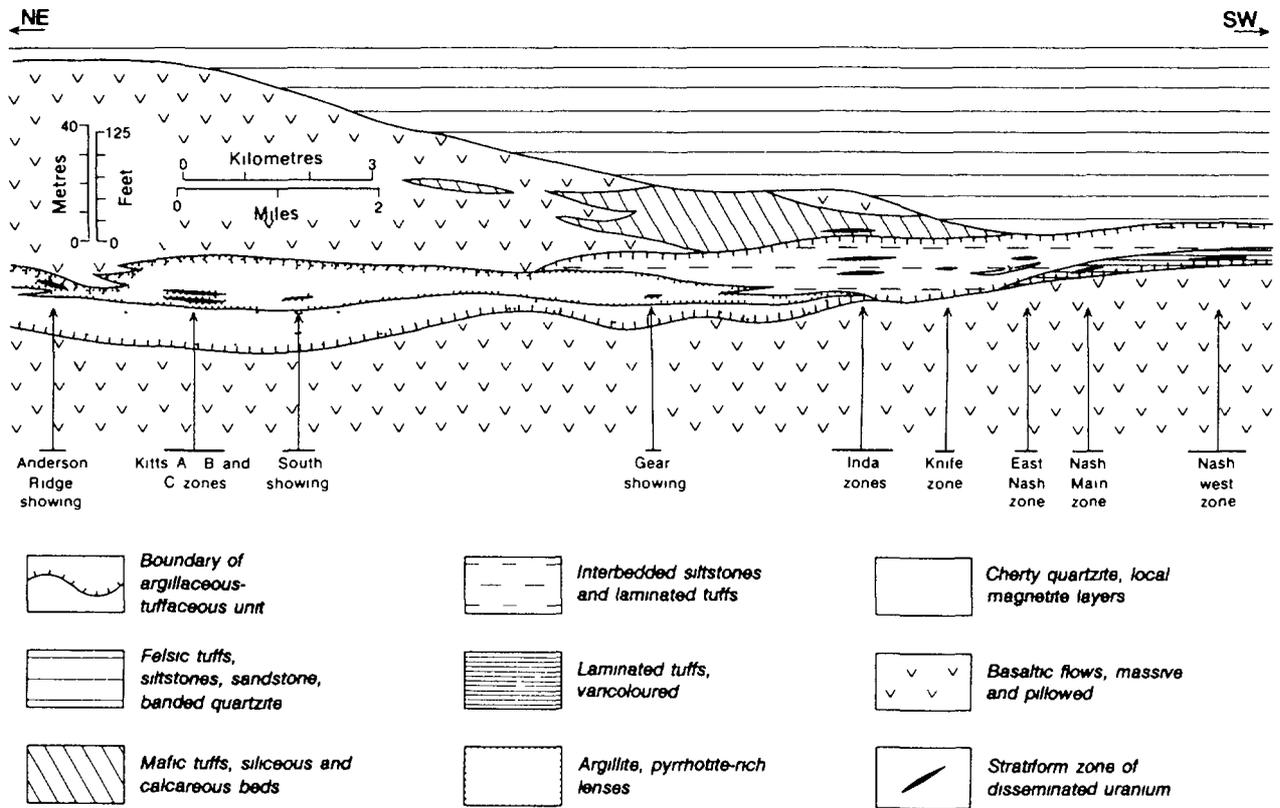


Figure 4. Relationship of stratigraphy and uranium occurrences in the Kitts-Post Hill belt, Labrador (modified after Gandhi, 1978).

pillowed basalt to the north. The laminated tuffs and tuffaceous siltstones contain abundant felsic layers that are interpreted as derived from rhyolitic tuffs. Influx of this felsic material marks the beginning of felsic volcanism of the upper Aillik group, hence the argillaceous-tuffaceous unit is interpreted here as the basal unit of the upper Aillik group. Stratigraphically equivalent rocks are not exposed in the remainder of the area of the Aillik Group to the east and south of the belt.

The argillaceous-tuffaceous unit is overlain by an assemblage of interbedded sandstone, siltstone, waterlain felsic tuffs, fine grained banded quartzite and calcareous beds, with an aggregate thickness of approximately 300 m. They dip steeply to the east-southeast. To the southeast, a quartz feldspar porphyry dyke striking parallel to the beds and upto 300 m wide, separates the beds from a conglomerate-agglomerate unit which is approximately 260 m thick. East of this unit are a mafic volcanic lens, and rhyolitic flows and tuffs that are southern continuation of the thick and extensive rhyolitic unit near Makkovik Bay (Gandhi et al., 1969; Gandhi, 1978). They may in part be interbedded with the sedimentary assemblage and the conglomerate-agglomerate unit. The quartz feldspar porphyry is related to the felsic volcanic activity of the upper Aillik group.

Appearance of the sedimentary assemblage deposited in shallow water, with contributions from the felsic volcanic activity, in the sequence of Kitts-Post Hill belt indicates a significant change in the depositional environments and provenance of the basin characterized by extensive pillow basalts and deeper water sediments of the lower Aillik group in the earlier stages (Gandhi, 1978, p. 1497).

Rocks of the upper Aillik group are extensive in the Aillik-Makkovik area and the White Bear Mountain-Walker Lake area, to the northeast and south of the Kitts-Post Hill belt respectively. Generalized lithostratigraphic sequence in the two areas is shown in Figure 3, but there are no marker beds to make definitive correlations from one area to the other, and between these areas and the Kitts-Post Hill belt. A few tentative correlations however are suggested as shown in the figure.

The oldest rocks in the two areas, exposed in the cores of major anticlines (Fig. 2), are interbedded sandstones, silstones, banded quartzites with some magnetite-rich beds and intraformational conglomerates, totalling over 1000 m in thickness. At a few localities shales, calcareous beds, and a chert-magnetite-amphibole iron formation, are present (Gandhi, 1978). Some of the beds in the unit show small scale cross-bedding and graded bedding. The conglomerates contain abundant rhyolitic clasts along with other lithologies, and at places grade into, or are interbedded with, rhyolitic agglomerate.

Basaltic volcanic rocks occur at the upper boundary of the sedimentary unit, and also in rhyolitic sequence above it. They are more abundant in the Aillik-Makkovik area than in the White Bear Mountain-Walker Lake area. They are relatively thin, with a maximum thickness of 150 m, compared to the basaltic units in the lower Aillik group, and are stratigraphically higher than them.

Rhyolitic volcanic and volcanoclastic rocks, and genetically related thick sill-like bodies of quartz feldspar porphyry, in part extrusive and in part intrusive, extends over most of the Aillik-Makkovik and White Bear Mountain-Walker Lake areas, and attain an aggregate thickness of over 3500 m in both the areas (Figs. 2 and 3). The rhyolitic rocks are varied in character, and include feldspar porphyritic, subporphyritic and nonporphyritic flows and tuffs, fine grained massive and flow-banded rhyolites, fine to coarse pyroclastics, air-fall tuffs and ash-flow tuffs or ignimbrites, and laharcic flows. Hence the volcanic activity was partly if not largely, subaerial. Some of the tuffs are reworked by surface

waters. Some lenses and beds of calcareous and siliciclastic sediments are also interbedded with the rhyolitic rocks.

The quartz feldspar porphyry contains coarse subhedral to euhedral crystals of feldspar and blue quartz set in a fine grained quartzo-feldspathic matrix, and is deformed to a varying degree. In the White Bear Mountain-Walker Lake area, the porphyritic unit is approximately 1500 m thick, and is generally massive to weakly foliated, but strong foliation and lineation are developed at many places, and obscure contacts with the rhyolitic rocks. In some outcrops, the porphyritic rock apparently grades into the rhyolitic rocks that include ignimbrites (Stevenson, 1970; Watson-White, 1976; Gandhi, 1978; Bailey, 1979). In addition to the major unit, there are dykes and irregular small bodies of relatively little deformed quartz feldspar porphyry in the area, and these may represent younger intrusions. In the Aillik-Makkovik area, a quartz feldspar porphyritic gneiss unit is extensive and has an estimated thickness of 3050 m (Gandhi et al., 1969). This may however be an overestimate because the Aillik Group as a whole in this area is tightly folded, but the folding is not apparent in this essentially uniform unit. Its gneissic texture is interpreted to be due to recrystallization of quartz feldspar porphyry, with development of quartz and hornblende streaks and growth and deformation of porphyroblasts of feldspar (Clark, 1971, 1973; Gandhi, 1978; White and Martin, 1980). It has sharp and generally concordant boundaries with other rhyolitic rocks of the area. It may be a sill or an extrusive unit.

An assemblage of conglomerate, siltstones, banded quartzites and rhyolitic rocks exposed at Big Bight on the east side of the Aillik-Makkovik area may be the youngest part of the Aillik Group in the study area.

The rhyolitic rocks of the upper Aillik group are marginally subalkaline, and show effects of alkali metasomatism as discussed later (Watson-White, 1976; Gandhi, 1978; Evans, 1980; White and Martin, 1980; Gower et al., 1982). Rb/Sr isotopic age determinations on the rhyolitic rocks reported by Watson-White (1976), Gandhi (1978) and Kontak (1980) are 1676 ± 16 Ma (4 point isochron, recalculated), 1659 Ma (errorchron, unreliable) and 1767 ± 4 Ma (5 point isochron) respectively. These are regarded as minimum ages.

Intrusions

Rocks intrusive into the Aillik Group include pre-kinematic amphibolitic dykes, small gabbro bodies, and quartz feldspar porphyry dykes and irregular bodies; large synkinematic intrusions of gneissic granodiorite to monzonite, referred to as Long Island gneiss, and lenses of granite gneiss; late kinematic to post-kinematic granite plutons, the gabbro-diorite differentiated intrusion of Adlavik Bay; and younger diorite-syenite, diabase and lamprophyre dykes. The quartz feldspar porphyry intrusions and some of the granitic plutons are believed to be epizonal intrusions related to the rhyolitic volcanics of the upper Aillik group.

The gneissic granodiorite of Long Island yielded a K-Ar date of 1832 ± 58 Ma (Gandhi et al., 1969) which is anomalous with respect to the Rb/Sr isotopic dates on the rhyolites intruded by it. This may be due to excess argon inherited from basement rocks and/or from the numerous mafic inclusions of unknown origin. Other K-Ar, Ar-Ar, and Rb-Sr dates on rocks of the Aillik Group, metamorphosed dykes, Adlavik gabbro and granitic intrusions range from 1750 to 1500 Ma (Gandhi et al., 1969, Gower et al., 1982). They suggest a long period of Hudsonian intrusive activity during the late Aphebian to early Paleohelikian time.

A large gabbro sheet-like body trending east-northeast near the southern boundary of the study area (Fig. 2) is one of the Helikian Michael gabbro intrusions which are extensive in the Grenville province (Stevenson, 1970; Gower et al., 1982). Other younger dykes in the study area range in age from 1000 to 400 Ma (Gandhi et al., 1969; Gandhi, 1978; Gower et al., 1982).

Structure

In the Kitts-Post Hill belt, the unconformity between the Archean basement and the Aillik Group was obliterated by intense tectonic sliding. Furthermore, along the east side of this belt, the basement is thrust over the group. Marten (1977) interpreted six stages of Hudsonian deformation: two early stages of thrust-slicing and tectonic interleaving in the belt, followed by three folding events in the Aillik Group, one major and two minor ones, and a late stage of faulting. On the west side of Kaipokok Bay, rocks of the lower Aillik group display similar polyphase deformation, according to Ryan and Kay (1982) who, in addition, suggested the possibility of post-Archean migmatization in the basement prior to the tectonic sliding.

In the Aillik-Makkovik area, Gandhi et al. (1969) recognized two broad, open anticlinal structures with synkinematic granite gneiss domes at the core, and adjacent tightly folded zones with local shearing and mylonitization. More detailed structural studies by Clark (1971, 1973, 1979) have shown four stages of deformation, of which the second was the most important one. It resulted in the northerly trending upright folds, a subvertical schistosity and subhorizontal mineral lineation in the plane of schistosity.

In the White Bear Mountain-Walker Lake area, sedimentary units along the north side are tightly folded with axial planes nearly vertical or overturned to the northwest (Fig. 2), but in the rhyolitic rocks to the south the folding is obscure because of lack of marker units. Folding on a small scale, however, is observed at many places. The degree of development of foliation in the rhyolites varies considerably across the regional east-northeast trend (Gandhi, 1978). Foliation commonly dips 50 to 60 degrees to the south-southeast, subparallel to recognizable lithologic boundaries in the rhyolites. En echelon shear zones and mylonitized zones are present. Bailey (1979) has interpreted a number of faults subparallel to the regional trend but relative movements along them are not known.

Tectonics

The Aillik Group is affected by the Hudsonian structural, metamorphic and intrusive events that resemble an orogenic cycle, but its lithological characters, in particular the abundant rhyolitic volcanics, are interpreted by Watson-White (1976), Gandhi (1978), and White and Martin (1980) to indicate a nonorogenic, continental rift environment of deposition rather than a classical geosynclinal accumulation. The rhyolitic rocks are marginally subalkaline and at least some of them are subaerial. They predominate over the basalts in a bimodal sequence of volcanics which lacks andesitic rocks. The absence of andesites is an important consideration in interpretation of the tectonic setting.

Basalts of the lower Aillik group are considered a part of the bimodal volcanic sequence of the Aillik Group as a whole by White and Martin (1980), whereas Clark (1979) and Wardle and Bailey (1981) proposed a fundamentally different tectonic setting for the lower Aillik group from that of the upper Aillik group, and proposed a major angular unconformity separating the two groups. The lower Aillik group, according to these authors, was deposited in a shelf environment transitional southwards into deeper water environment,

similar to that of Labrador Trough. Clark (ibid) suggested that deposition of the lower Aillik group was followed by collision of two cratons, erosion of the group in the Aillik-Makkovik area, development of transcurrent faults, major felsic volcanism and plutonism and continued deformation. Wardle and Bailey (ibid) on the other hand favoured a rift environment for the upper Aillik group, but regarded the apparent synorogenic timing of its felsic volcanism as problematic.

The possibility of a major unconformity between the lower and upper Aillik groups was earlier considered by Gandhi (1976) but field evidence for it was not found. Wardle and Bailey (ibid) inferred an angular unconformity from what they considered as relatively more intense polyphase deformation and higher grade of metamorphism in the lower Aillik group in comparison to simple structural style and lower grade of metamorphism in the upper Aillik group. The differences, however, are not as pronounced as they suggest, and can be attributed to the original lithological differences and to inhomogeneous deformation and metamorphism during a single 'orogenic' type of cycle as proposed by Gandhi et al. (1969) and Marten (1977). Wardle and Bailey (ibid) also referred to a polymict conglomerate unit in the Kitts-Post Hill belt, described by Marten (ibid) as the base of the upper Aillik group. According to Gandhi (1970, 1978) and Evans (1980) however, the conglomerate is structurally and stratigraphically above the east dipping siltstone-banded quartzite unit, which contains abundant waterlain felsic tuffs and conformably overlies the uranium-bearing argillaceous-tuffaceous unit. The conglomerate is thus an intraformational unit in the upper Aillik group rather than a basal conglomerate marking a major unconformity. Southern part of this 260 m thick and over 9 km long unit is described as metamorphosed rhyolitic agglomerate by Burbidge (1977). Evans (ibid) interpreted the unit as a submarine lahar. In any case, similar agglomeratic and conglomeratic intraformational units also occur elsewhere in the upper Aillik group.

Some structural readjustment of Hudsonian faults and shears in the proximity of the 'Grenville Front' is likely to have occurred during the Grenvillian events (Gandhi, 1978). For example, an Ar/Ar date of 1004 ± 5 Ma on biotite in a sample from a shear zone obtained by Archibald and Farrar as reported in Gower et al. (1982, p. 46), indicates Grenvillian effects. Gower et al. (ibid) inferred one major east-west fault extending from the head of Kaipokok Bay along the Adlavik Brook to the mouth of the Big River, and a dextral displacement of 18 km along it, and regarded it as Grenvillian in

age. Bailey (1979) has interpreted the broad mylonitized zones and nearly vertical L fabrics in the White Bear Mountain-Walker Lake area as Grenvillian developments along Hudsonian normal faults. Sheared and mylonitized zones however occur as far north as Cape Makkovik where Grenvillian effects are likely to be negligible, and are therefore regarded here as Hudsonian structures. Presence of muscovite in some of the rocks south of the Adlavik Brook and alteration of the post-Hudsonian east-west trending gabbro sheet are attributed to the Grenvillian metamorphism by Gower et al. (1982).

URANIUM OCCURENCES

Over 70 uranium occurrences* or groups of occurrences, containing pitchblende with negligible thorium, are known in rocks of the Aillik Group in the study area (Fig. 2), and some of these are economically promising prospects. Several pegmatitic uranium and thorium occurrences are found in the Archean basement complex and in granites intrusive into the Aillik Group. In addition, there are a number of molybdenite, pyrite and fluorite occurrences in the Aillik Group, but only a few of them are closely associated with the uranium occurrences in the group. These minerals however are common in the pegmatites associated with the intrusive granites.

Distribution

Most of the uranium occurrences in the Aillik Group are located in four elongate stratigraphic-structural belts or zones, namely the Kitts-Post Hill belt, Cape Makkovik-Monkey Hill belt, Falls Lake-Shoal Lake-Bernard Lake belt, and the White Bear Mountain-Walker Lake belt (Fig. 2) as described by Gandhi (1978). Those in the Kitts-Post Hill belt are hosted by a stratigraphic zone of argillaceous and tuffaceous beds, less than 50 m thick and traceable for over 20 km along the strike. In the other three belts, the host rocks are rhyolitic flows and tuffs.

Shape and Size

Most of the uranium occurrences are lenses or groups of echelon lenses of disseminated uranium minerals, subparallel to the moderately to steeply dipping host beds or lithologic units, and to

* Uranium concentration of approximately 0.01 per cent over 10 m strike length, or greater, detected radiometrically and/or by analyses of representative samples.

Table 1: Approximate tonnage and average grade of important uranium and molybdenum deposits in the Kaipokok Bay-Big River area, Labrador

Deposit or prospect (no.)	Tonnes	Average grade (per cent U)	Total U (tonnes)
Kitts (3,4)	347,000	0.449	1560
Inda (9)	496,000	0.119	590
Nash Main (12)	216,000	0.187	404
Gear (8)	33,000	0.102	34
Michelin (17)	7,366,000	0.100	7366
Rainbow (18)	90,000	0.127	144
Burnt Lake (19)	146,000	0.067	98
Sunil (25)	344,000	0.024 + 0.102% MoS ₂	82
Cape Makkovik (26)	2,000,000	0.250% MoS ₂ +locally up to 0.004% U	---

Data from Gower et al., 1982, p. 61, and A.A. Burgoyne, Brinco Mining Limited, Vancouver, British Columbia, personal communications, 1984.

Numbers in bracket: Location number in Fig. 2.

Uranium resources in the Kitts, Nash and Michelin deposits are regarded as 'Estimated Additional Resources' in high price category in terms of NEA/IAEA classification. Estimates for the Cape Makkovik molybdenum deposit include 30 per cent dilution by barren dykes.

the regional structural trend. The lenses are a few tens to a few hundreds of metres long in both the strike and dip directions, and up to a few metres thick. Elsewhere uranium minerals are disseminated irregularly and/or are confined to veins of variable orientation. High-grade veins and aggregates do occur, but they are rare.

Exploration to-date has outlined a small high-grade deposit, namely the Kitts deposit, and a larger, lower grade deposit, namely the Michelin deposit, and in addition a few prospects, as listed in Table 1. There are a number of other occurrences but they are insufficiently explored to arrive at their grade and tonnage, and most of them appear to be smaller or of lower grade than the ones listed in the table.

Host Rocks

A distinctive argillaceous-tuffaceous unit along the Kitts-Post Hill belt and the rhyolitic rocks east of this belt are the hosts of uranium occurrences in the Aillik Group (Figs. 2 and 4). Recognition

of the regional stratigraphic control of uranium mineralization in the Kitts-Post Hill belt was the most important guide in the discovery and exploration of prospects along the belt (Gandhi, 1970, 1977), and should have an impact on further exploration. Stratigraphic control in the rhyolitic sequence is less evident, due mainly to the lack of marker units, but three major stratigraphic-structural zones or belts have been recognized as favourable ones, namely the White Bear Mountain-Walker Lake belt, the Cape Makkovik-Monkey Hill belt, and the Falls Lake-Shoal Lake-Bernard Lake belt (Gandhi, 1970, 1978). Exploration efforts in the past were concentrated along these belts.

Argillaceous-tuffaceous unit (Kitts-Post Hill Belt): This unit is less than 50 m thick and is continuous along the strike for 20 km from the Kitts deposit to the Nash West showing (Figs. 2 and 4). Lithological variations are common along and across the strike (Fig. 4). To the north, argillite beds host the Kitts A, B, and C zones, and other occurrences including the Kiwi, Anderson Ridge, South and Gear showings (Fig. 2). The beds are grey to dark grey and a few millimetres to several centimetres thick. They are tightly folded, contorted, intruded by gabbro, sheared and metamorphosed at the Kitts deposit (Gandhi, 1978). They include some thin beds and lenses rich in graphite (1 to 2.5 per cent) and pyrrhotite (up to 10 per cent, with minor pyrite and chalcopyrite) that are the main hosts of pitchblende. Magnetite is present in varying amounts, and is locally abundant and forms distinct layers as at the Gear showing. Calcite occurs mainly as veinlets, and amounts up to 7 per cent at Kitts deposits. Pink variety of calcite is common at uranium occurrences. Pelitic beds commonly have porphyroblasts of garnet, and andalusite or chiastolite in a matrix of hornblende, sodic plagioclase, quartz, and some pyroxene and chlorite. Sillimanite tufts are developed in a buff white bed in contact with a gabbro intrusion near the Kitts deposit and are interpreted to have formed by contact metamorphism (Gandhi, 1977, 1978). Siltstones, metamorphosed to biotite-albite-quartz assemblages, and mafic tuffaceous beds and lenses are interbedded with the argillaceous beds. The siltstones (referred to as 'greywacke' by Evans, 1980) contain little or no graphite, but contain cummingtonite-anthophyllite ± actinolite and minor magensium chlorite. Available chemical analyses of the argillites (11 reported by Gandhi, 1977, and 9 by Evans, 1980) and of the greywackes (14 reported by Evans, *ibid*) show close affinities to basaltic rocks.

The argillite beds overlie and are locally interbedded with chert which at places contains magnetite layers. Relatively more competent chert has been brecciated and disrupted into isolated lenses in incompetent argillite during deformation. It is regarded as inorganic, volcanogenic in origin (Gandhi, 1978).

The chert and argillite apparently pinch out to the south of the Inda showing (Fig. 4). Facies changes are most marked at this showing, and mafic tuffs, interbedded mafic and felsic tuffs, argillaceous and calcareous beds are present. Pitchblende occurs in a main stratiform lens and three associated lenses at slightly higher stratigraphic levels. The main host rocks are fine grained, well-laminated tuffaceous beds, with green mafic and grey and pink felsic laminae. They are overlain by calcareous mafic tuffaceous beds, which also host some pitchblende. Pitchblende is closely associated with aegirine-augite in the laminated tuffs and with phlogopite in calcareous mafic tuffs (Evans, 1980). The latter also contain garnets which are vanadiferous. In the northern part of the Inda showing, some low-grade zones have disseminated pitchblende in sodic plagioclase-magnetite-sphene rich layers containing quartz, hornblende ± garnet, according to Evans (ibid).

Spotty and lean mineralized zones at the Knife and Nash East showings are in the rocks similar to that of the lower mineralized zone at the Inda showing. The Nash Main and Nash West deposits are in a distinctive laminated subunit that overlies pillow basalt and mafic tuff. The subunit is fine grained, tuffaceous with green, dark grey, buff and pink laminae. The minerals present are pyroxene (salite), garnet (grossular-andradite, vanadiferous), epidote, ferroan pargasite, albite, microcline, magnetite, calcite and minor sphene (Evans, 1980). Red colouration due to hematite is developed in the rocks where uranium content is relatively high. The laminae are contorted with folds plunging commonly to the south. Uranium concentration is commonly greater at fold hinges than along the limbs.

Host rocks at the Punch Lake showings (Fig. 2, No. 7), 3 km south of the Kitts deposit, where uranium occurrences are vein-type and disseminated-type, include mafic and laminated tuffs similar to the Nash West zone, according to Harder (1981).

The Witch showing, located approximately 5 km southwest of the Nash West showing (Fig. 2, No. 14) is in grey to pink coloured, felsic tuffaceous beds. These beds may be stratigraphically close to the laminated tuffaceous subunit of the Nash West and Nash Main deposits.

The J & B prospect is located approximately 12 km southwest of the Witch showing (Fig. 2, No. 15), on the west shore of Kaipokok Bay, and is in sheared rhyolitic tuffs and associated mafic flows or sills, of the upper part of the Aillik Group (Ryan and Kay, 1982). The rocks may be stratigraphically close to those at the Witch showing. Uranium-bearing zones, according to Lever and Davidson (1978), are stratiform.

In addition to the stratiform occurrences mentioned above, several uranium-bearing veins and fracture-fillings occur along the Kitts-Post Hill belt e.g. at the southwest corner of Long Island and one kilometre to the west of Punch Lake. These are hosted by quartzite-siltstone-argillite, basalts and paraschists.

Metapelitic host rocks at the Anna Lake North occurrence, 8 km north of Walker Lake (Fig. 2, No. 16), are in granite gneiss-granite terrain (Willy, 1981). They appear to be similar to the argillaceous-tuffaceous unit, but they are too remote and isolated from the unit to make a reliable correlation.

Rhyolitic rocks of the upper Aillik group: Rhyolitic flows, tuffs, and fragmental rocks are hosts to numerous uranium occurrences east and south of the Kitts-Post Hill belt. The rocks vary considerably in texture, but chemically they fall within a rather small compositional range. Some units are magnetic due to an abundance of accessory magnetite.

Textural varieties distinguished in the field are massive and flow banded rhyolites, coarse feldspar porphyritic and subporphyritic rhyolite flows or tuffs, laminated and thinly bedded tuffs, fragmental rocks with rhyolitic lapilli, bombs and blocks, and tuffaceous sedimentary rocks. At the Michelin deposit, several mineralized lenses are subparallel to a sequence of interbedded coarse feldspar porphyritic and subporphyritic rhyolitic tuffaceous beds and fine grained, thin felsic beds and lenses, although in detail the mineralized lenses transect the lithological boundaries at low angles (Gandhi, 1978). Extensive quartz feldspar porphyry and porphyritic gneiss, which may in part be intrusive and in part ignimbritic, are hosts to several occurrences, most of which are close to the contacts with other rhyolitic rocks. The contacts are sharp, and distinctive as the rhyolites are generally fine grained and lack the coarse quartz crystals that are abundant in the porphyry and prophyritic gneiss. Most of the occurrences along the Cape Makkovik-Monkey Hill belt are along such contacts either between the major units or of lenses of rhyolites in the porphyritic gneiss.

The rhyolitic rocks are deformed to a varying degree, from relatively little deformed to schistose and highly streaked quartzofeldspathic gneisses, and mylonitized or granulated varieties. They are buff white, pale pink and light grey in colour, and have a distinctive red colouration, due to finely disseminated hematite, at and around high-grade uranium concentrations.

Some of the host tuffs are more mafic than rhyolitic tuffs e.g. at the Rainbow prospect, 2 km south of the Michelin deposit (Fig. 2, No. 18), the host bed is chloritic and calcareous. It overlies a mafic tuffaceous bed, and is overlain by aphanitic rhyolite. The host rock resembles some of the host rocks at the Inda and Gear showings in the Kitts-Post Hill belt. Furthermore, layers, lenses and aggregates rich in mafic silicates are preferentially mineralized in some of the occurrences e.g. at the Burnt Lake showings (Fig. 2, No. 19), stratiform mineralized zones occur in relatively more mafic layers containing aegirine-augite and magnesio-ribeckite (Bailey, 1979; Kontak, 1980).

A number of chemical analyses of unmineralized and mineralized rhyolitic rocks have been reported by Barua (1969), Watson-White (1976), Minatidis (1976), Gandhi (1978), Bailey (1979), Evans (1980), Kontak (1980), White and Martin (1980) and Gower et al. (1982). Gower et al. (ibid) listed 125 analyses of 10 groups of unmineralized rocks, and all of them except for a group of 4 dacitic rocks, are within a range of 70 to 78 per cent silica, 3 to 5 per cent soda and 4 to 6 per cent potash. No significant chemical differences are apparent among the groups of porphyritic rhyolite, nonporphyritic rhyolite, rhyolite tuff and quartz feldspar porphyry.

The mineralized rocks are texturally identical to the unmineralized equivalent rocks, except for the finely disseminated pitchblende and hematite amounting to a fraction of a per cent in the mineralized rock. There is however a significant increase in soda and corresponding depletion in potash and to a lesser extent of silica, reflected in albitization of feldspar (Gandhi, 1978; White and Martin, 1980; Evans, 1980). At other localities, potash enrichment and corresponding soda depletion are observed in the unmineralized rocks (Watson-White, 1976; White and Martin, 1980). Alkali metasomatism is widespread in the upper Aillik group. Hence some of the rhyolitic rocks have alkaline or mildly peralkaline affinities, although in general the rocks are high K, calc-alkaline in character.

Mineralogy

Pitchblende with negligible thorium, is virtually the only uranium-bearing phase in most of the occurrences. Coffinite and soddyite are associated with pitchblende in a few occurrences but these minerals are quantitatively insignificant compared to pitchblende. Yellow secondary uranium minerals are developed in the surface exposures, particularly at high-grade spots.

In the Kitts-Post Hill belt, pitchblende occurs mostly as disseminated grains less than 10 microns in diameter along thin laminae and beds and as small string-like aggregates along bedding planes in the argillaceous-tuffaceous host rocks (Hughson, 1958 a, b, c; Gandhi, 1977, 1978; Evans, 1980). It also occurs in high-grade concentrations in fold hinges, veins and shears, as in the Kitts deposit. These are apparently due to local remobilization and concentration, during deformation, of the originally disseminated mineral grains. In addition, there are late stage calcite veins which at places carry pitchblende.

The most important silicate mineral associated with pitchblende is hornblende. It contains abundant inclusions of opaque minerals including pitchblende. It is normally green in thin sections, but has brownish red colouration in highly radioactive spots. Textures observed at the Kitts, Gear, Inda and Nash deposits show that the hornblende is a post-mineralization metamorphic mineral (Marten, 1977; Gandhi, 1978; Evans, 1980). Other mafic silicates that are also associated with pitchblende and at places carry inclusions of it, are pyroxene, biotite, and chlorite. The latter is common along shear zones. Electron microprobe analyses done by Evans (1980) show iron-rich character of these minerals. He also found clinozoisite, pumpellyite and prehnite which apparently represent retrograde metamorphism. Quartz, albite and sphene are other silicates commonly present.

Sulphides, graphite and magnetite are present in varying amounts in the occurrences along the Kitts-Post Hill belt, but there is no apparent systematic spatial relationship between these minerals and pitchblende. Pyrrhotite, pyrite, chalcopyrite, and traces of molybdenite and arsenopyrite, are common in the argillite. The sulphides occur as disseminated grains, layers, lenses and also as veinlets. Hematite is not seen in argillite, but is common in tuffaceous beds rich in felsic components.

Analyses of mineralized samples and bulk ore samples show only traces of precious metals, thorium, yttrium and other rare earths,

and generally low concentrations of base metals, molybdenum and vanadium (Hughson, 1958, a, b, c; Gandhi, 1978; Evans, 1980). Fluorite is rare or absent in the uranium occurrences of the Kitts-Post Hill belt, in contrast to some of the occurrences in rhyolitic rocks elsewhere in the Aillik Group.

In the rhyolitic host rocks, uranium occurs as disseminated pitchblende or uraninite grains less than 10 microns in diameter, commonly as inclusions in mafic silicates and also at grain boundaries and in streaky aggregates with hematite and mafic minerals. Uraniferous grains and aggregates are concentrated along foliation and shear planes.

At the Michelin deposit, the main host and closely associated minerals are metamict sphene and aegirine augite, which form aggregates with alkali amphibole, ilmeno-magnetite partially oxidized to hematite, zircon, calcite, and apatite, and scarce phlogopite, andradite fluorite and pyrite, in quartz-albite rock. Variation in abundance of the mafic minerals imparts distinctive banding to some of the coarse feldspar porphyritic units. The bands are parallel to the lithologic boundaries, and range in widths up to several centimetres. In the nonporphyritic host rocks, the bands are light grey, reddish brown and dark grey (Gandhi, 1976).

Compositions of pitchblende or uraninite, sphene, aegirine, alkali amphibole and albite were determined by energy dispersive spectra and x-ray diffraction (Gandhi, 1978; Evans, 1980, White and Martin, 1980). Feldspar in both phenocrystic and groundmass phases of strongly mineralized rocks is nearly pure albite, with less than 1 per cent anorthite and orthoclase molecules (Gandhi, *ibid*, and Evans, *ibid*), which is indicative of soda metasomatism. The phenomenon is also evident from the chemical data. Analyses of 57 mineralized rocks reported by Gandhi (*ibid*), Evans (*ibid*) and White and Martin (*ibid*) show Na₂O content of 7 to 12 per cent and K₂O less than 0.5 per cent, whereas the unmineralized rhyolitic rocks in comparison contain 3 to 5 per cent Na₂O and 4 to 6 per cent K₂O. There is also a small decrease in silica content in the mineralized rocks compared to the unmineralized rocks. White and Martin (*ibid*) suggest that relatively mildly metasomatized rocks evolved by Na-for-K exchange, and more intensely metasomatized rocks evolved by (Na ± Al)-metasomatism, involving silica depletion, rather than by simple ion exchange. Evans (*ibid*) recognized increasing intensity of metasomatism towards the core of ore zones in the drill sections he studied, and outlined inner, outer and transitional metasomatic zones that envelope the ore zones. Some K₂O-enrichment is observed at the margins of the metasomatized zones.

Available data show little difference in contents of Th, rare earth elements, Mo and F between the mineralized and unmineralized rocks. Zr, Pb, CO₂ and Cl show an increase, and Th, Cu and S show a decrease with desilication of rocks according to White and Martin (1980). Data presented by them, and by Gandhi (1978) and Evans (1980), show that the strongly mineralized rocks commonly contain 1000 to 1500 ppm Zr in contrast to 300 to 700 ppm Zr in the unmineralized rocks. A slightly higher CO₂ content in mineralized rocks (0.9 to 1.3 per cent) compared to unmineralized rocks (0.60 to 0.63 per cent) is noted in a suite of 146 samples from 46 drill holes, analysed by Brinex Limited in search for guides to mineralization.

Mineralogy of most of the occurrences in rhyolites is similar to that at the Michelin deposit, with some variations in relative proportions of minerals and intensity of albitization. Thus the showings at Burnt Lake (Fig. 2, No. 19) are in coarse feldspar quartz porphyritic rhyolite, chemically similar to those at the Michelin deposit, and are associated with nonporphyritic rhyolite, tuffs, and lenses of lapilli tuffs and agglomerate (Gandhi, 1978). Mineralogical studies by Kontak (1980), including electron microprobe analyses, show that uraninite or pitchblende is preferentially associated with aegirine-augite, acmite and magnesio-riebeckite, that occur as disseminated grains, aggregates and layers or bands up to 0.5 cm thick. The pyroxenes predominate over amphibole. Other minerals present are biotite, zircon, apatite, hematite, magnetite, sphalerite, chalcopyrite, covellite, bornite, chalcocite, fluorite and galena. The feldspar is nearly pure albite. Kontak (ibid) regarded the mineralization as stratiform. This is also seen in the Emben South showing, 5 km east of Burnt Lake (Fig. 2, No. 20), where mineralization is restricted to a 0.5 to 1.5 m thick unit containing up to 10 per cent aegirine and 80 per cent albite, and notable amounts of riebeckite, magnetite, sphene, apatite, pyrite and some quartz, calcite and fluorite. The unit is tightly folded within an area 150 x 150 m with two antiforms and synforms plunging moderately to the southwest (Minatidis, 1976; Gandhi, 1976; Willy, 1982). A few small occurrences of pyrite, molybdenite and fluorite are found in rhyolitic rocks close to the east shore of Walker Lake.

In the Cape Makkovik-Monkey Hill belt, disseminated molybdenite, pyrite and fluorite occur with disseminated pitchblende (uraninite) at the Sunil showing (Fig. 2, No. 25) and in the Cape Makkovik molybdenum deposit (Fig. 2, No. 26) which contains only traces of

pitchblende in some places. The deposits are stratiform; the Sunil showing is 350 m long and up to 5 m thick, and the Cape Makkovik deposit is 2300 m long and up to 25 m thick. They dip 60 to 70 degrees to the east and are drilled to a depth of 100 to 150 m. They contain approximately 5 per cent pyrite and subordinate amounts of molybdenite (Table 1). The sulphides in the deposits occur commonly as discrete streaks several millimetres long, parallel to the foliation or schistosity of host rocks, and locally as veins (King, 1963; Gandhi et al., 1969; Barua, 1969; Gandhi, 1978). Pyrite also occurs as euhedral crystals scattered through the host rock. Pitchblende occurs as streaks at the Sunil showing (Barua, 1969). It is commonly not associated intimately with molybdenite-pyrite streaks. The host rhyolitic rock at both deposits is strongly enriched in soda and depleted in potash as at the Michelin deposit, and the feldspar in it is albite (Morse, 1961; Gill, 1966; Gandhi, 1967; Barua, *ibid*). Fluorite occurs as purple and colourless crystals closely associated with the sulphides. Other minerals present are quartz, hornblende, magnetite, zircon, apatite, actinolite, sphene, garnet, acmite or aegirine, epidote and calcite. Traces of chalcopyrite, sphalerite, galena, pyrrhotite and of silver are present in the Sunil showing.

In the vicinity of Makkovik, weak radioactivity occurs in skarn-like aggregates of pyroxene, garnet, magnetite and hematite, sphene (titanite), epidote, pyrite and scheelite in lenses of limestone that occur in the predominantly rhyolitic sequence (Beavan, 1958).

Occurrences in the Shoal Lake-Falls Lake-Round Pond zone also contain disseminations of fine grained pitchblende in rhyolitic flows, tuffs and relatively more mafic tuffaceous units. Host rocks are enriched in soda and depleted in potash (Gandhi, 1978). Traces of silver and selenium are noted in a few occurrences (Gandhi, *ibid*). The main occurrence at Winter Lake (Fig. 2, No. 21), approximately 12 km southeast of Monkey Hill peak, is at the folded contact of rhyolitic tuffaceous rock and what appears to be a mafic dyke. Pitchblende disseminations and veins occur at the crests of minor folds, along the contact for 100 m strike length. An associated narrow sulphide-calcite vein at one end of the showing contains sphalerite, covellite and stromeyerite (Beavan, 1958). A number of veins carrying chalcopyrite, pyrite, pyrrhotite, molybdenite and fluorite occur near Round Pond (Fig. 2, No. 23) in conglomerate underlying rhyolitic volcanic rocks containing lean disseminated pitchblende mineralization (Gandhi, 1969). Veins of pitchblende are more common in the Round Pond - Falls Lake area (Fig. 2, No. 23) than

elsewhere in the Aillik Group. The vein at Pitch Lake (Fig. 2, No. 22), 5 km to the south-southeast of Monkey Hill peak, which was the first uranium occurrence discovered in the area in 1954, contains massive and botryoidal pitchblende, gummite, hematite and fergusonite (Beavan, 1958). It occurs in a large amphibolite (mafic lava) lens intruded by granite.

Pitchblende and Galena Age Determinations

U-Pb isotopic ratios of pitchblende samples are plotted on the concordia diagram (Fig. 5).

Nine samples from the Kitts deposit yielded nearly concordant results. One of these, as reported by Gandhi (1978), gave an essentially concordant date of 1730 Ma from the Pb^{207}/Pb^{206} ratio. Eight other samples analyzed by Kontak (1980) yielded results indicating a very small range close to a concordant date of 1770 Ma. Two of the samples represented disseminated-type mineralization whereas others represented vein-type mineralization. The data indicate a single crystallization event approximately 1750 Ma ago, with little loss of radiogenic daughters since.

Samples from the Inda and Gear showings, on the other hand, yielded discordant results representing uranium loss or lead gain. The precise mechanism that can cause this is not known.

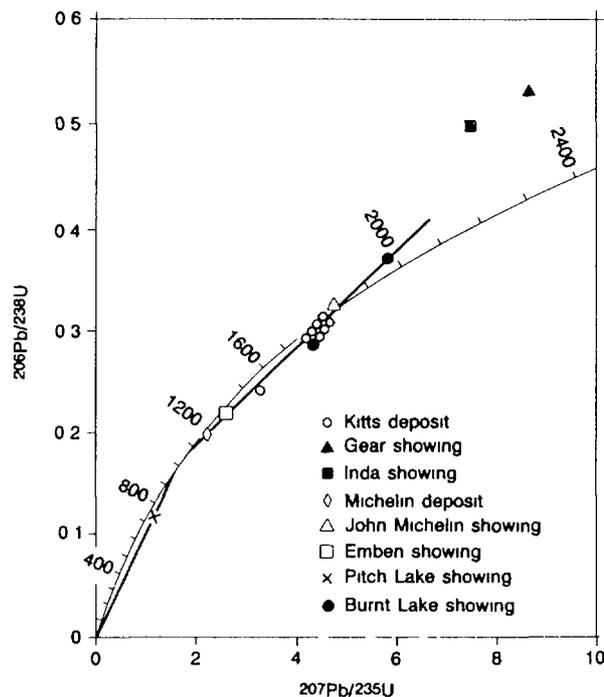


Figure 5. Concordia plot of pitchblendes from uranium occurrences in the Aillik Group, Kaipokok Bay - Big River area, Labrador (after Gandhi, 1978, with additional data points from Kontak, 1980).

Evans (1980) estimated ages of pitchblendes in the Kitts, Inda and Nash West deposits from elemental U/Pb ratios obtained by microprobe analyses of pitchblende grains. His calculated ages are: 1785 ± 115 Ma for Kitts (24 grains), 1844 ± 209 Ma for Inda (16 grains), and 1795 ± 159 Ma for Nash West (four sites in one large grain).

Among the uranium occurrences in rhyolitic rocks of the upper Aillik group, the John Michelin showing with disseminated pitchblende, located 2 km southwest of Makkovik (Fig. 2, No. 24), yielded a nearly concordant date of 1745 Ma from Pb^{207}/Pb^{206} ratio (Gandhi, 1978). This is very close to the dates obtained for the Kitts deposit. Uranium mineralization predates at least the last stages of Hudsonian deformation and metamorphism (Gandhi, 1978), hence these dates represent the time of these events. Together with a Rb/Sr isochron date of 1767 ± 4 Ma for the rhyolitic rocks 4 km northwest of the Michelin deposit (Kontak, 1980), these dates imply a rather short time interval for formation of the host rocks, uranium mineralization and Hudsonian deformation and metamorphism.

Samples from the Michelin deposit and the Emben showing gave relatively much younger Pb^{207}/Pb^{206} dates, of 1244 and 1364 Ma respectively. Both the samples however are from high-grade 'vein-type' concentrations exposed in trenches, and probably represent remobilization of uranium from originally disseminated-type, lower grade, more extensive mineralization (Gandhi, 1978). Two samples from the Burnt Lake showings gave discordant results; their Pb^{207}/Pb^{206} dates are 1770 and 1680 Ma (Kontak, 1980). The older date is from a drill core sample and the other one is from a trench sample. On the concordia diagram these two samples, and the ones from the Michelin deposit, and from the Emben and John Michelin showings, plot close to a line which intercepts the concordia at approximately 1800 Ma and 1100 Ma. This indicates that the disseminated-type uranium mineralization as represented by the John Michelin sample is close to 1800 Ma in age, and in case of the Burnt Lake, Michelin and Emben samples, it was affected by an episode that disturbed its isotopic equilibrium approximately 1100 Ma ago. This is supported by a date of 1017 Ma obtained by Evans (1980) for pitchblende grains in a foliated mafic dyke in the Michelin deposit, using the electron microprobe technique. It is in good agreement with an Ar^{40}/Ar^{39} date of 1004 ± 5 Ma mentioned earlier on biotite in a sample from a regional shear zone in the area (Gower et al., 1982, p. 46). A K-Ar date on another foliated, mafic dyke, approximately 25 cm thick, in the Michelin deposit, reported by Gandhi (1978), is somewhat younger at 919 ± 26 Ma.

The episode of disturbance of isotopic equilibrium and/or local redistribution of uranium leading to high-grade concentrations, approximately 1100 Ma ago coincides with the time of Grenville orogenic cycle. It is therefore attributed to the effects of Grenvillian structural and metamorphic events on the rocks in the southern part of the study area near the 'Grenville Front'. Mafic dykes are present near the Michelin and Emben sample localities, and Gandhi (1978, p. 1515-1516) suggested that local redistribution of uranium there may be due to the intrusion of the dykes. The dykes however are more than 10 m from the localities and their contact metamorphic effects, as in case of other dykes in the study area, are restricted to within a few centimetres from the contacts, beyond which there is no visible effect on the country rocks including the mineralized rhyolitic rocks. Furthermore, ages of these dykes are not known. Their effects on the samples thus remain speculative. In case they were emplaced prior to or during Grenville time, their influence on isotopic equilibrium of the samples, if any, would be difficult to isolate from the effects of Grenvillian structural and metamorphic events.

The pitchblende vein at Pitch Lake yielded a Pb^{207}/Pb^{206} date of 934 Ma (Beavan, 1958; Gandhi, 1978). The vein dips gently to the south and is exposed on a north-facing cliff along a fault trending east-northeast. It is possible that the relatively young date is a result of loss of radiogenic lead due to movements along the fault or due to weathering.

A recent isotopic study of galena from the Michelin deposit strongly supports the interpretation from the pitchblende data, of disturbance of isotopic equilibrium and local redistribution of uranium in occurrences in the southern part of the study area, during Grenville time. The sample is from a rare, lenticular aggregate of coarse grained calcite, amphibole and galena, approximately 10 cm in diameter and upto 1.5 cm thick, subparallel to regional foliation, in mineralized coarse feldspar porphyritic rhyolite. It is located 1.5 m south of a coarse feldspar porphyritic dioritic dyke which is approximately 20 cm thick and trends east-southeast. It is part of the mineralized rhyolite sample SSG-157-'75 described by Gandhi (1978, p. 1508-1509; from south wall of drift, 241 m east of crosscut). The isotopic analysis was performed by Geospec Consultants Limited (Edmonton, Alberta, Canada), and yielded ratios as follows: Pb^{206}/Pb^{204} :532.45, Pb^{207}/Pb^{204} :97.163 and Pb^{208}/Pb^{204} :36.726. Because of the overwhelming dominance of uranium component in this lead, choice of any reasonable

Proterozoic common lead will yield essentially the same Pb^{207}/Pb^{206} ratio (0.1585) for the radiogenic component.

The ratio puts constraints on the maximum and minimum time of formation of galena and of the source pitchblende. The calculated maximum age of the source pitchblende, assuming a continuous accumulation of the radiogenic lead in galena until the present time, is 2440 Ma. The calculated maximum age of galena, and hence minimum age of the source pitchblende, assuming that all the radiogenic component was generated and accumulated within a very short time interval, is 1490 Ma. Further constraints are imposed by the known geology, the pitchblende data and the Rb/Sr isochron date of 1767 ± 4 Ma for the rhyolitic host rocks (Kontak, 1980). Calculations using 1767 Ma as the age of the host rocks as well as of the initial uranium mineralization, which is supported by their geological relations and the pitchblende data, yield 1180 Ma as the time of galena formation. Other calculated pairs of dates for formation of the source pitchblende and of the galena respectively are: 1750 Ma and 1201 Ma, and 1800 Ma and 1138 Ma. The younger dates in these pairs are in approximate time range of 1200 to 1000 Ma generally accepted for Grenvillian orogeny. They are thus in general agreement with the time of episodic loss of radiogenic lead from pitchblende indicated by the concordia plot.

Genesis

The main features of uranium mineralization in the Aillik Group are:

- (i) Most of the pitchblende is finely disseminated.
- (ii) High-grade veinlets and fracture fillings that occur at and close to the zones of disseminated pitchblende appear to be younger than, and most probably resulted from local remobilization and concentration of originally disseminated pitchblende.
- (iii) The disseminated mineralization predated at least the last phase of Hudsonian deformation and metamorphism (Gandhi, 1978).
- (iv) The age of pitchblende in the disseminated zones is approximately 1750 Ma, and corresponds closely with the oldest Rb/Sr isochron date of 1767 ± 4 Ma obtained for the upper Aillik group rhyolites (Kontak, 1980).
- (v) Disseminated pitchblende is in stratiform layers and lenses that occur within relatively thin stratigraphic

zones; in an argillaceous-tuffaceous unit in the Kitts-Post Hill belt, and in dominantly felsic tuffaceous units in the rhyolitic sequence in the upper Aillik group.

- (vi) The favourable stratigraphic zones are characterized by rapid lithofacies variations.
- (vii) Rhyolitic host rocks are strongly enriched in soda and depleted in potash.
- (viii) Uranium is preferentially associated with layers and lenses rich in graphite, pyrite, magnetite and hornblende in the argillite, and with sodic pyroxene, sodic amphibole and sphene in the rhyolitic rocks.
- (ix) Disseminated molybdenite, pyrite and fluorite occur in some of the disseminated pitchblende zones in the north but are scarce or absent elsewhere.
- (x) Thorium and rare earths do not increase with uranium in the mineralized zones.
- (xi) Finely disseminated hematite is common in the mineralized zones, except for those in the argillite.
- (xii) Isotopic equilibrium in occurrences to the south near the 'Grenville Front' was affected by Grenvillian events approximately 1150 Ma ago, which caused local redistribution of uranium and formation of rare galena rich in uranogenic component.

These features, in particular the close spatial and temporal relationships of the rhyolitic rocks and uranium mineralization, invite linking genetically the mineralization to the felsic volcanic activity that was extensive at the time of the upper Aillik group.

A genetic model proposed by Gandhi (1978) and modified slightly here, invokes (a) syngenetic deposition of uranium derived from felsic volcanics by meteoric waters, in euxinic basins like the one where host beds of the Kitts-Post Hill belt were deposited, and (b) epigenetic mineralization in the rhyolitic rocks elsewhere by fluids generated at depth in the magma that gave rise to the rhyolites. The thick rhyolitic sequence is believed to be subareal in part at least, from the presence of units interpreted as air-fall tuffs and agglomerates, ignimbrites and lahars.

(a) Influx of felsic tuffaceous material at the time of deposition of the argillaceous-tuffaceous host unit in the Kitts-Post Hill belt (Figs. 3 and 4), marks the beginning of the felsic volcanism that produced a source of uranium-enriched sediments as well as of uranium in solution in meteoric waters. Strongly reducing

environment prevailed in part of the basin where argillite was deposited as indicated by sulphides and graphite in it, and favoured precipitation of uranium from the meteoric waters that entered the basin during sedimentation and diagenesis. Reducing conditions adequate to precipitate uranium in the same fashion, extended most probably where interbedded mafic and felsic tuffaceous, and calcareous sediments of the host unit were deposited. Such conditions may also have prevailed in some lakes during the subaerial volcanism, and may have led to concentration of uranium in lacustrine sediments (Sherborne et al., 1979; Curtis, 1981). Mafic tuffaceous-calcareous host beds of restricted extent at the Rainbow zone may represent such an environment.

(b) Uranium mineralization in the rhyolitic rocks on the other hand was brought about by reaction of mineralizing magmatic fluids with the host rocks (Gandhi, 1978). The fluids were enriched in sodium, uranium, and volatiles in particular CO₂, F and Cl. Such fluids were probably generated throughout the felsic volcanic cycle, but may have culminated during the waning stages of volcanism. They migrated through permeable avenues in the sequence, viz. non-welded tuffs and pyroclastic rocks, devitrified lavas, zones of frequent interlensing of various lithological units and of shears and faults due to incipient structural disturbances prior to major deformation. They reacted with the wall rocks, and brought about soda metasomatism and uranium mineralization in favourable zones. Uranium was precipitated by reactive titanium- and iron-bearing minerals, namely sphene, pyroxene and hornblende. The precipitation was most probably aided by boiling off of volatiles. Original distribution of the reactive minerals in the host rocks as disseminations and along certain layers and lenses, is largely responsible for the observed distribution of pitchblende. Molybdenite-pyrite-fluorite mineralization may be synchronous with the uranium mineralization or may represent a separate stage of evolving magmatic fluids. Its increasing abundance to the north suggests a regional metallogenic zoning.

Studies on Tertiary rhyolitic ash and lava flows in the western United States and experimental work show that heated, mildly alkaline oxygenated meteoric waters play an important role in leaching of uranium from devitrifying rhyolitic source rocks and precipitating it at favourable sites to form deposits (Rosholt et al., 1971; Zielinski, 1978, 1979, 1981; Zielinski et al., 1977). In case of the upper Aillik group, differing views have been expressed regarding relative importance of meteoric waters and juvenile fluids from the

volcano-plutonic complex, in bringing about the observed uranium mineralization. Gandhi (1978) regarded it unlikely that mineralization in the rhyolitic rocks was brought about entirely by the meteoric waters without any magmatic input, in view of the intense soda metasomatism which resembles fenitization, and the mineralogy, texture and geological setting of the mineralized zones. Low temperature hydrous minerals are notably absent, and it seems unlikely that evidence of their presence was completely obliterated by later metamorphism. Kontak (1980) favoured a combined role of meteoric waters that leached uranium from glass shards and felsic tuffs, and the volatile-rich fluids emanating from vents. White and Martin (1980) visualized convection cells of mildly alkaline aqueous fluids of meteoric origin near intrusive plugs and around inferred subjacent plutons related to volcanism. Gower et al. (1982) also postulated similar convection cells, but regarded the upper Aillik group as resting unconformably over deformed lower Aillik group at the time of mineralization. Evans (1980) on the other hand invoked only the low temperature, neutral to weakly alkaline, oxidizing groundwaters of meteoric and/or of connate marine origin, for leaching of uranium as well as zirconium from the felsic volcanic source rocks under diagenetic to zeolite facies pressure-temperature conditions. The metals, according to him, were transported and also precipitated at low temperature (zeolite facies), and redox changes and adsorption on Fe-Mn-Ti hydroxides played an important role in the precipitation. In contrast, White and Martin (ibid) emphasized a high temperature of precipitation of uranium, above the upper limits of the greenschist facies, implied by desilication of the Na-metasomatized host rocks (now albitites).

Post-mineralization deformation and metamorphism make it difficult to evaluate the influence of structure, in particular shearing, in the transport and deposition of uranium. Marten (1977) and Evans (1980) postulated a premineralization deformation in the Kitts-Post Hill belt, that produced permeable shear zones in the host unit, and derivation of uranium from the overlying felsic tuffaceous beds by solutions that eventually deposited it in the shear zones. It seems improbable, however, that the postulated favourable shear zones were restricted to the incompetent argillaceous and tuffaceous host beds and were parallel to the bedding, and that such shear zones were not developed in the underlying and overlying units of the Aillik Group. Marten (ibid) furthermore visualized the mineralizing solutions to be of metamorphic origin, rather than of magmatic or meteoric origin or a mixture of the two. Textures of the mineralized

zones however show that the growth of metamorphic minerals like hornblende effectively protected the pre-existing uranium in the host rock. This feature is inconsistent with the hypothesis of metamorphic remobilization of uranium from the source rocks.

CONCLUSIONS

Uranium in the Aillik Group is genetically related to the felsic volcanic rocks that are thick and extensive, and predominant over basalts in the upper part of the group. The bimodal volcanic sequence, with interbedded clastic sedimentary rocks, was deposited in a continental rift environment. Circulation of mineralizing fluids of either magmatic or meteoric or mixed origin, through the rhyolitic rocks, some of which are subaerial, either introduced or redistributed uranium in permeable zones at the time of volcanism or soon after it, but prior to major Hudsonian deformation and metamorphism. Some uranium was transported by meteoric waters to an euxinic basin at the beginning of the felsic volcanism where it was deposited syngenetically or during diagenesis in argillaceous beds and in interbedded mafic and felsic tuffaceous and calcareous sediments.

Isotopic data support the genetic hypothesis, and indicate the time of initial uranium mineralization in 1800 to 1750 Ma range. They also reveal a disturbance of isotopic equilibrium in the occurrences to the south near the 'Grenville Front' approximately 1150 Ma ago.

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**THE OLYMPIC DAM
COPPER-URANIUM-GOLD DEPOSIT,
ROXBY DOWNS, SOUTH AUSTRALIA**

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Abstract

The Olympic Dam copper-uranium-gold deposit in South Australia was discovered in 1975. It has an areal extent exceeding 20km^2 with vertical thicknesses of mineralization up to 350 metres. The deposit is estimated to contain in excess of 2,000 million tonnes of mineralized material with an average grade of 1.6 percent copper, 0.06 percent uranium oxides, and 0.6gm per tonne gold.

The unmetamorphosed coarse clastic Proterozoic sediments hosting the mineralization are probably no older than 1580 Ma and appear to fill a graben in granitic rocks beneath 350m of unmineralized, flat lying Adelaidean to Cambrian sediments.

Disseminated strata-bound bornite-chalcopyrite-pyrite is the dominant type of sulfide mineralization with lesser amounts of younger transgressive chalcocite-bornite. Uraninite, with lesser coffinite and brannerite occurs with the sulphide mineralization in a variety of textural forms and rare earths minerals bastnaesite and florencite occur in, and adjacent to sulphide mineralized zones. Gold and silver are a minor but significant component of the mineralization.

INTRODUCTION

The Olympic Dam copper-uranium-gold deposit constitutes a major resource of copper and uranium with an areal extent exceeding 20km^2 and vertical thickness of mineralization measured in tens to hundreds of metres (Roberts and Hudson, 1983). The deposit contains at least 2,000 million tonnes of mineralized material with an average grade of 1.6 percent copper, 0.06 percent uranium oxide (U_3O_8), and 0.6 g/tonne gold. Higher grade mineralization has been estimated at 450 million tonnes of 2.5% Cu, 0.08% U_3O_8 and 0.6gm/tonne Au. In addition significant concentrations of rare earths and silver occur. The deposit is located on Roxby Downs pastoral station, 650 kilometres north-northwest of Adelaide and 25 kilometres west of the opal mining town of Andamooka (Fig. 1).

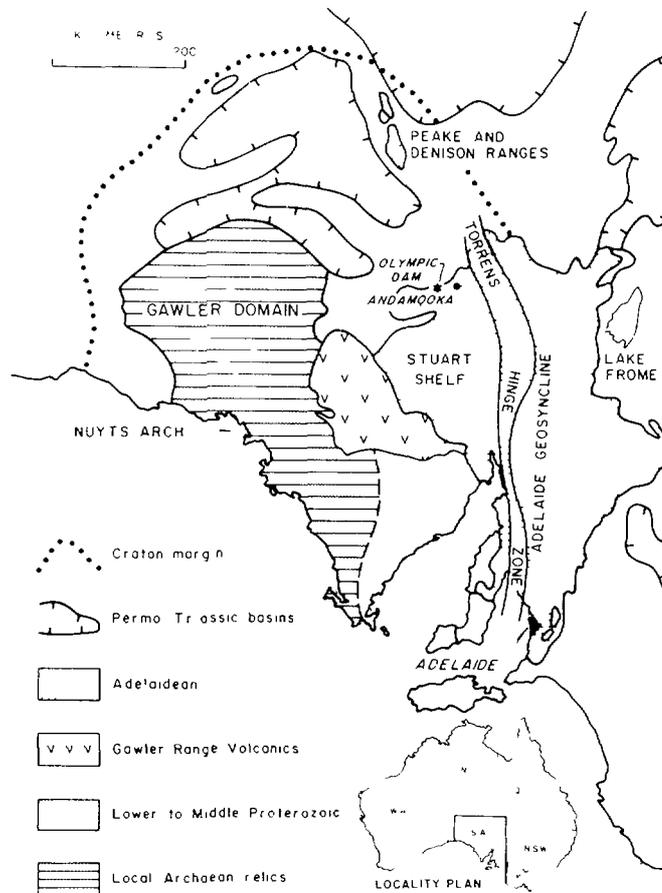


Fig. 1. Geologic map of the southern part of South Australia showing the main lithologic & tectonic features and the location of the Olympic Dam deposit.

Exploration for copper by Western Mining Corporation Limited which resulted in the discovery of the deposit was focused on South Australia in 1972 following research during the period 1969 to 1971 which related the formation of strata-bound copper deposits to solutions that had acquired copper during oxidative alteration of basalts (Haynes, 1972). In the Stuart Shelf region, regional gravity and magnetic data resulting from surveys by the Commonwealth Bureau of Mineral Resources and the South Australian Department of Mines and Energy suggested the possibility of basalts at depth and the interpretation of gravity and magnetic anomalies, and lineament mapping resulted in the selection of specific target areas, including the Olympic Dam area (Fig. 2). In 1974 a commitment was made to drill stratigraphic holes on two of the selected targets to test for the presence of favourable host rocks in the Upper Proterozoic cover sequence, and source rocks in the basement.

The first hole, RD1 in the Olympic Dam area, was completed in July 1975 after intersecting 38 metres of 1.05 percent copper in the basement at a depth of 353 metres. This encouraging, although uneconomic, mineralization led to the drilling

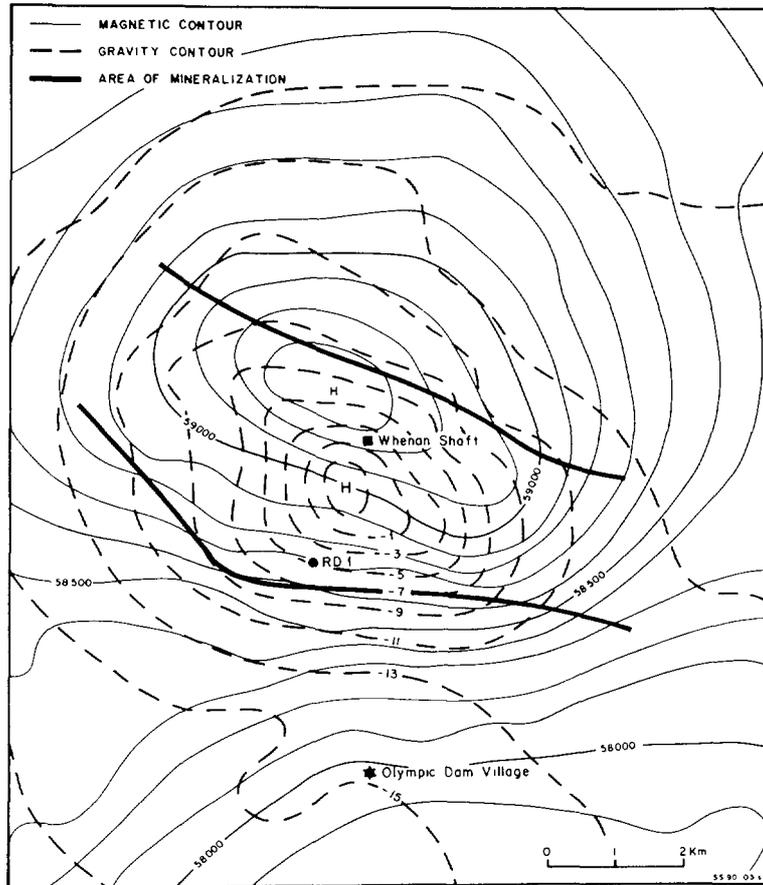


Fig. 2. Positive gravity and magnetic anomalies associated with the Olympic Dam deposit. Magnetic contours in nanoteslas; gravity in milliGals; H = centre of anomaly; RD1 = discovery hole.

of a pattern of holes in the area. The first two, RD3 and RD4 were barren, RD5 and RD8 intersected additional mineralization containing 1 percent copper, RD6 and RD7 were barren, and RD9 low grade. RD10 intersected 170 metres of 2.1 percent copper and over 0.05 percent uranium oxide and provided the first indication of significant uranium mineralization and the great potential of the area that has been confirmed by subsequent drilling.

The gravity anomaly which was attributed to a shallow basement of basaltic rock is now known to result from the dense hematite-rich breccias associated with the mineralization. The magnetic anomaly is still largely unexplained and modelling indicates it results from a large magnetic body beyond the current depth of drilling. Host rocks for the type of strata-bound copper deposit predicted in the original concept do not occur in the area and mineralization is confined to rocks beneath the Upper Proterozoic sedimentary sequences.

Detailed assessment of the prospect commenced in 1979 as a joint venture between Roxby Mining Corporation, a wholly owned subsidiary of Western Mining Corporation Limited, BP Australia Limited and BP Petroleum Development

TABLE 1

TYPICAL Cu-U MINERALIZED DRILL HOLE INTERSECTIONS

Drill Hole	Interval (m)	Thickness (m)	Cu (%)	U ₃ O ₈ (kg/tonne)	Au (gm/tonne)
RD1	353 - 391	38	1.05	0.10	-
RD10	348 - 518	170	2.12	0.59	-
RD19	422 - 436	14	2.00	tr	15.4
	684 - 758	74	3.04	0.45	-
RD20	369 - 580	211	2.10	0.80	-
RD24	343 - 649	306	1.00	0.20	-
	811 - 1003	192	0.60	0.16	-
	1003 - 1128	125	1.10	0.33	-
RD39	368 - 414	146	3.25	0.68	-

Location of drill holes indicated in Figure 3.

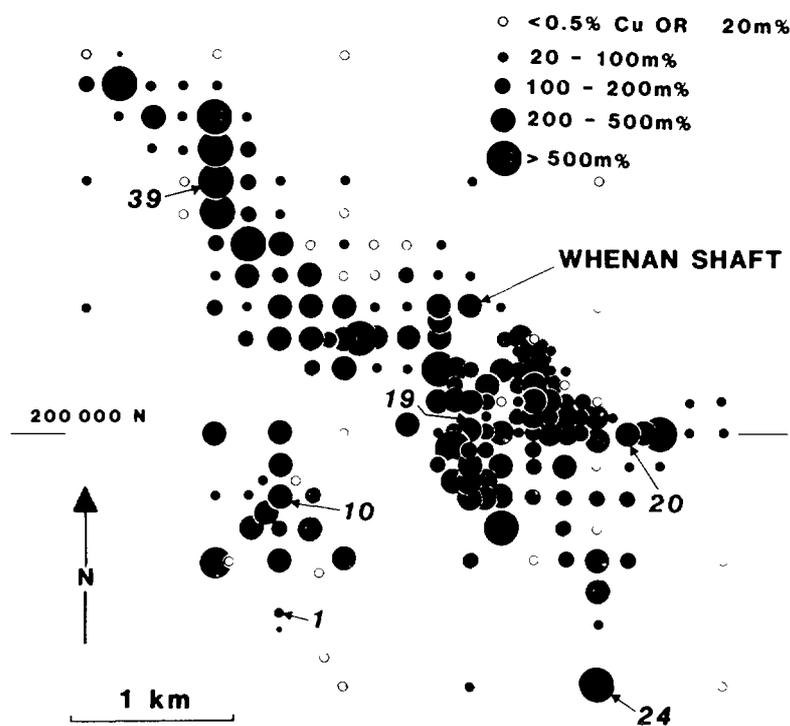


Fig. 3. Location of diamond drill holes showing greater than 0.5 percent copper intersections. See Table 1 for intersection in numbered drill holes.

Limited. Intensive vertical diamond drilling over an area in excess of 25 square kilometres has resulted in a success rate of over 80 percent mineralized drill holes (Fig. 3, Table 1). The Whenan Exploration Shaft has been completed to 500m and underground exploration and bulk sampling is in progress. All observations, interpretations and speculations presented in this paper are on data from diamond drilling.

REGIONAL GEOLOGICAL SETTING

The Olympic Dam deposit occurs within the Stuart Shelf Region (Fig. 1), an area of flat-lying Adelaidean and Cambrian sediments separated from the Adelaide Geosyncline to the east by a major zone of north-south faulting termed the Torrens Hinge Zone by Thomson (1969), (Preiss *et al.*, 1980). To the west and southwest, the sediment cover of the Stuart Shelf laps onto exposed rocks of the Gawler Craton (Rutland *et al.*, 1980). The basement to the Stuart Shelf is considered to consist of Gawler domain rocks and it is within this basement that the Olympic Dam deposit occurs. No correlation between the Olympic Dam succession and specific units of the tectonically composite Gawler domain can be made at this stage although regional stratigraphic data suggest that the Olympic Dam sequence is undeformed Middle Proterozoic sequence. The deposit straddles a west-northwest trending photolineament corridor at the intersection of a major north-northwest trending gravity lineament (O'Driscoll and Keenihan, 1980; O'Driscoll, 1982).

Early Proterozoic metasediments and reworked Archaean gneisses of the Gawler Craton (Fig. 1) were strongly deformed and intruded by granite as a result of the Kimban Orogeny (1820 to about 1580 Ma; Webb *et al.*, 1982). Voluminous subaerial felsic volcanics (The Gawler Range Volcanics) are relatively flat lying and form a large basin-like feature in the approximate centre of the Gawler domain, surrounded by post tectonic granites (Fig. 1). The volcanics and associated granites lack penetrative deformation and have ages between about 1525 and 1450 Ma (Webb *et al.*, 1982).

The Adelaide Geosyncline to the east contains a 10km thick sequence of Upper Proterozoic and Cambrian sediments and minor basic volcanics. The Beda Volcanics which occur in the south eastern part of the Stuart Shelf and in the Geosyncline have been dated at 1076 Ma (Webb and Coates, 1980). The rocks of the Geosyncline display a marked 500 Ma deformation and granite intrusion event, the Delamerian Orogeny but those of the Stuart Shelf are unaffected by the 500 Ma event.

In the Olympic Dam area about 350 metres of cover sediments are separated from the underlying basement rocks by a major unconformity. A number of prospects containing sub-economic copper or copper-uranium mineralization have been identified outside the Olympic Dam area by drilling of geophysical anomalies. The style of mineralization in some of these is very broadly similar to that under discussion.

GEOLOGY OF THE OLYMPIC DAM DEPOSIT

Stratigraphy

The host sequence for the Olympic Dam mineralization is unmetamorphosed medium to coarse-grained, potassium feldspar-rich, alkali feldspar granite surrounding sedimentary breccias or rudites (Roberts and Hudson, 1983). Dolerite intrudes the granite and breccias, but not the cover sediments.

Breccias have been classified into two broad groups on the basis of clast type and matrix content: (1) Monomict: one clast type present. Matrix content usually less than 10 percent; and (2) Polymict: two or more clast types in various proportions and matrix content 10 to 80 percent, usually greater than 30 percent. The polymict group is further divided into three sub-groups: (1) one clast type predominant (greater than 80 percent of clasts), (2) two clast types predominant (about 40 percent each), and (3) three or more clast types with none predominant. The two clast and three or more clast groups contain most of the significant mineralization.

A large number of different clast types occur in the polymict breccias including altered basement granite; felsic, intermediate and mafic volcanics; various types of hematite-rich rocks including banded iron formation and hematitic siltstone; arenite; carbonate; fluorite; barite and sulfides (Fig. 7). Reworked clasts of breccias are common, particularly towards the top of the sequence. Clast sizes range up to 12m but most are in the range 1 to 3 cm.

Eight different types of matrix are defined on the basis of composition and colour. Crystalline black and grey hematite, granular brown hematite and earthy red hematite are the main matrix types but sericite, chlorite and siderite-rich types are also observed. Arkosic matrices are also common in some parts of the deposit. The grain size of the matrix material is 0.05mm to 2mm and it is generally a fine-grained equivalent of the clasts present in the breccia. Silty and clayey matrices are uncommon.

The sediments have been divided into two main lithostratigraphic units, the Olympic Dam Formation and the Greenfield Formation. Both formations have

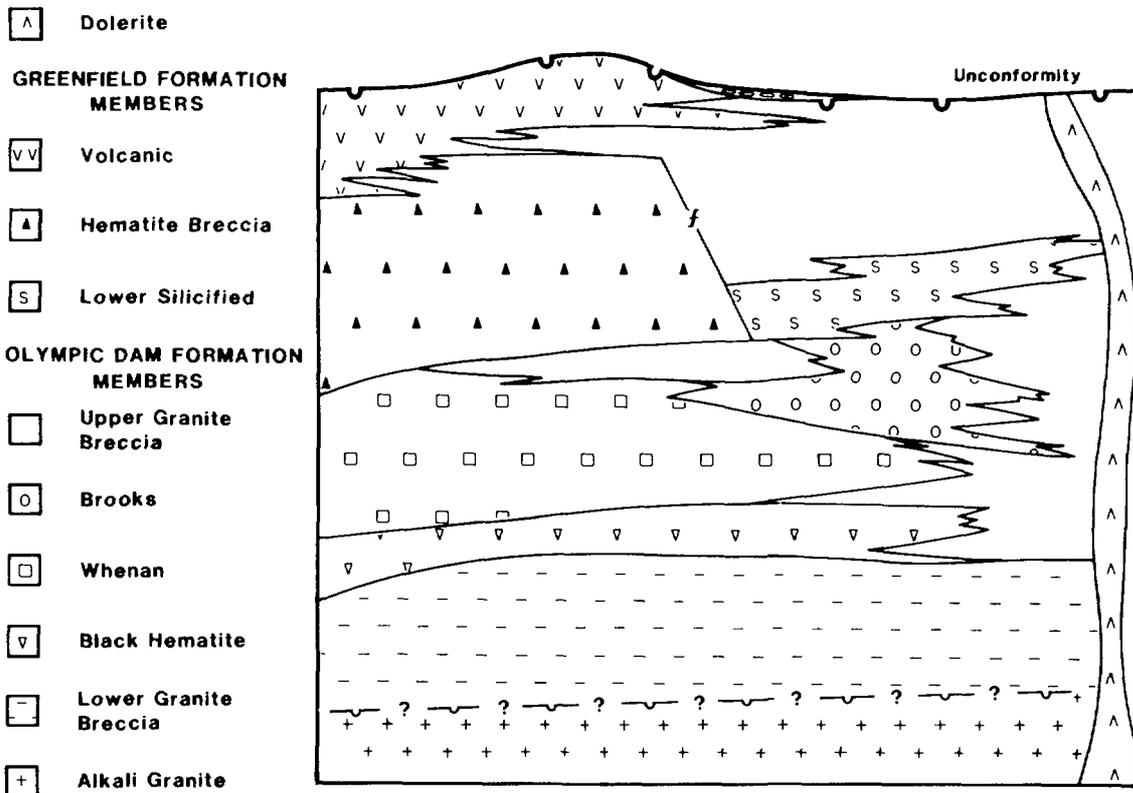


Fig. 4. Diagrammatic composite stratigraphic section of pre-Adelaidean units. Lithologies are summarized in Table 2. Approximate vertical extent is 1,500 to 2,000m.

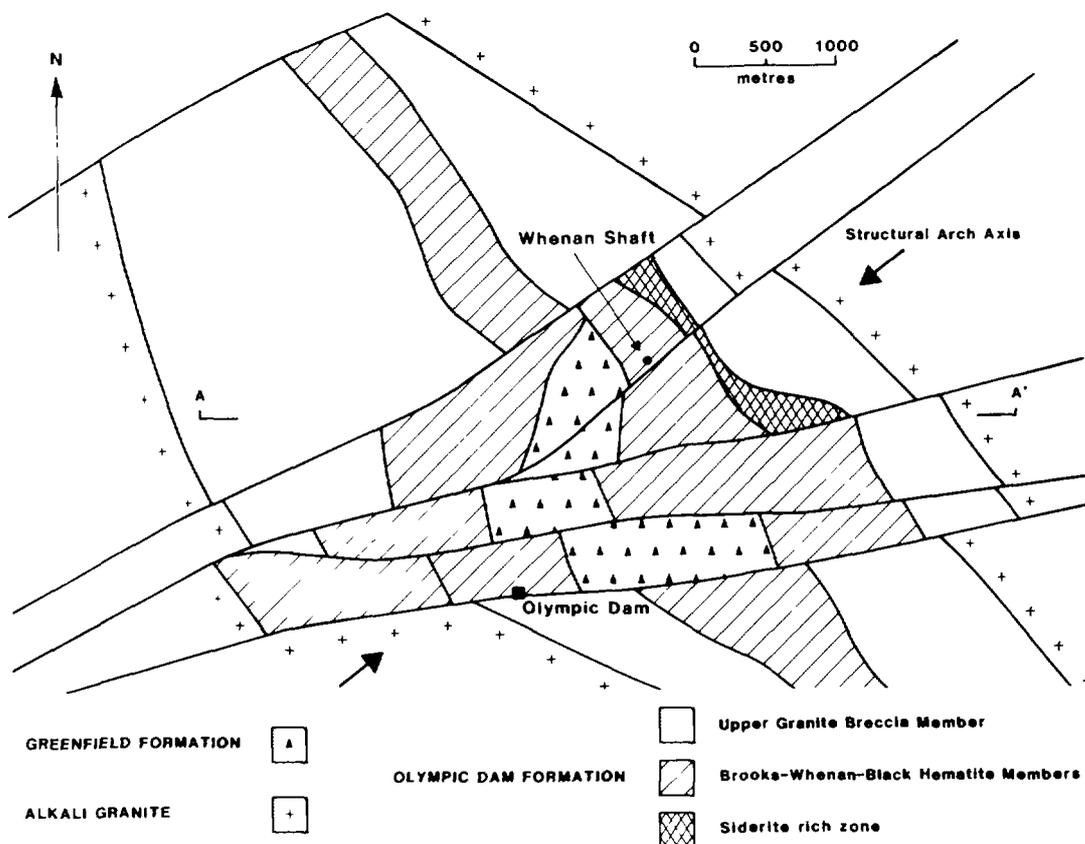


Fig. 5. Generalized geologic plan of the Olympic Dam deposit at the -450m level.

TABLE 2

OLYMPIC DAM STRATIGRAPHY

Unit	Thickness (max.)	Lithology
Andamooka Limestone	60m	Massive, locally bedded limestone.
Wilpena Group		
Arcoona Quartzite	200m	White & red massive & cross bedded sandstone.
Corraberra Sandstone	20m	Red, massive & cross bedded sandstone.
Tregolana Shale	200m	Thinly laminated red & green shales.
----- UNCONFORMITY -----		
Greenfield Formation		
Volcanic Member	250m	Interbedded altered felsic volcanics, volcanic breccias, conglomerates & banded iron formation.
Hematite Breccia Member	500m	Hematite rich breccias with thin interbeds of polymict breccias & hematite siltstones. Veined by silica and barite.
Lower Silicified Member	275m	Strongly hematized & silicified polymict breccias dominated by quartz, hematite & altered volcanics.
Olympic Dam Formation		
Upper Granite Breccia Member	1000m	Granite breccia & weakly polymict granite breccias, matrix-poor. Sericite & hematite altered. Chalcocite-bornite mineralized zones.
Brooks Member	300m	Polymict breccias with a variety of clast types - sericitized felsic volcanic clasts diagnostic. Discrete felsic volcanic lenses. Variable matrix of brown and black hematite. Reworked clasts of underlying members. Variably mineralized with bornite (chalcocite), & chalcopyrite. Siderite clasts locally abundant.
Whenan Member	350m	Polymict breccias, red & black hematite clasts & matrices. Cyclic zones of matrix-rich & matrix-poor breccias. Bedded & graded units common. Strongly mineralized with bornite-chalcopyrite (pyrite).
Black Hematite Member	150m	Black hematite dominated breccias both as clast & matrix. Specular hematite, chlorite & siderite in matrix. Porous, often vuggy. Pyrite (chalcopyrite) mineralized.
Lower Granite Breccia Member	800m+	Granite breccia with thin polymict breccia lenses often containing distinctive chlorite altered volcanic clasts. Chlorite altered contact with above member & granophyre clasts.

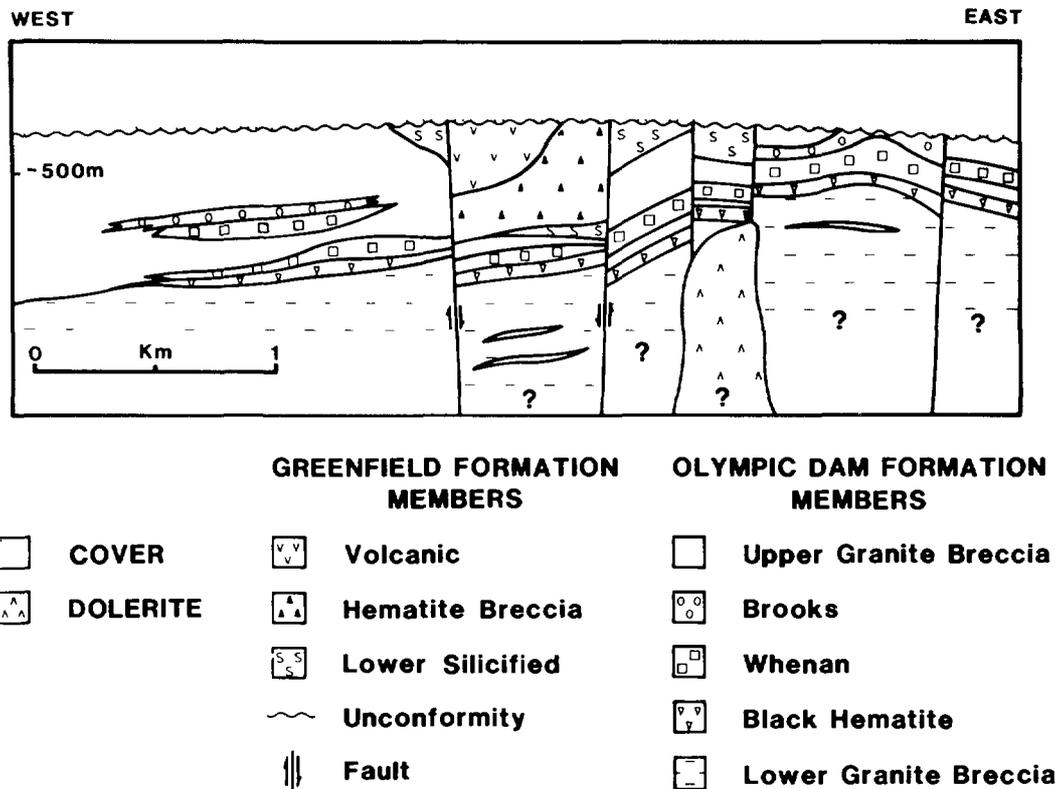


Fig. 6. East-west cross section of the Olympic Dam deposit at 200,000N (A-A' in Fig. 5).

several members. Contacts between the formations and members within formations are often disconformable. Drilling has not penetrated the base of the Olympic Dam Formation.

A composite stratigraphic section of the basement units is illustrated in Figure 4, their broad distribution in plan at the -450m level, and in section at 200,000N is shown in Figs. 5 and 6. Table 2 summarises their lithology.

Olympic Dam Formation

The Olympic Dam Formation is in excess of 1000m thick and comprises five members as indicated in Table 2 (Roberts and Hudson, 1983).

Lower Granite Breccia Member: This member consists of predominantly matrix-poor breccias containing basement granite clasts with rare, thin lenses of pyrite and hematite-rich polymict breccias. The breccias show varying degrees of alteration to sericite, hematite and chlorite. Chlorite alteration occurs at both the upper and lower contacts of the polymict breccia lenses and is particularly well developed below the Black Hematite Member. In some areas microgranite dykes intrude this member but do not extend into the overlying members.

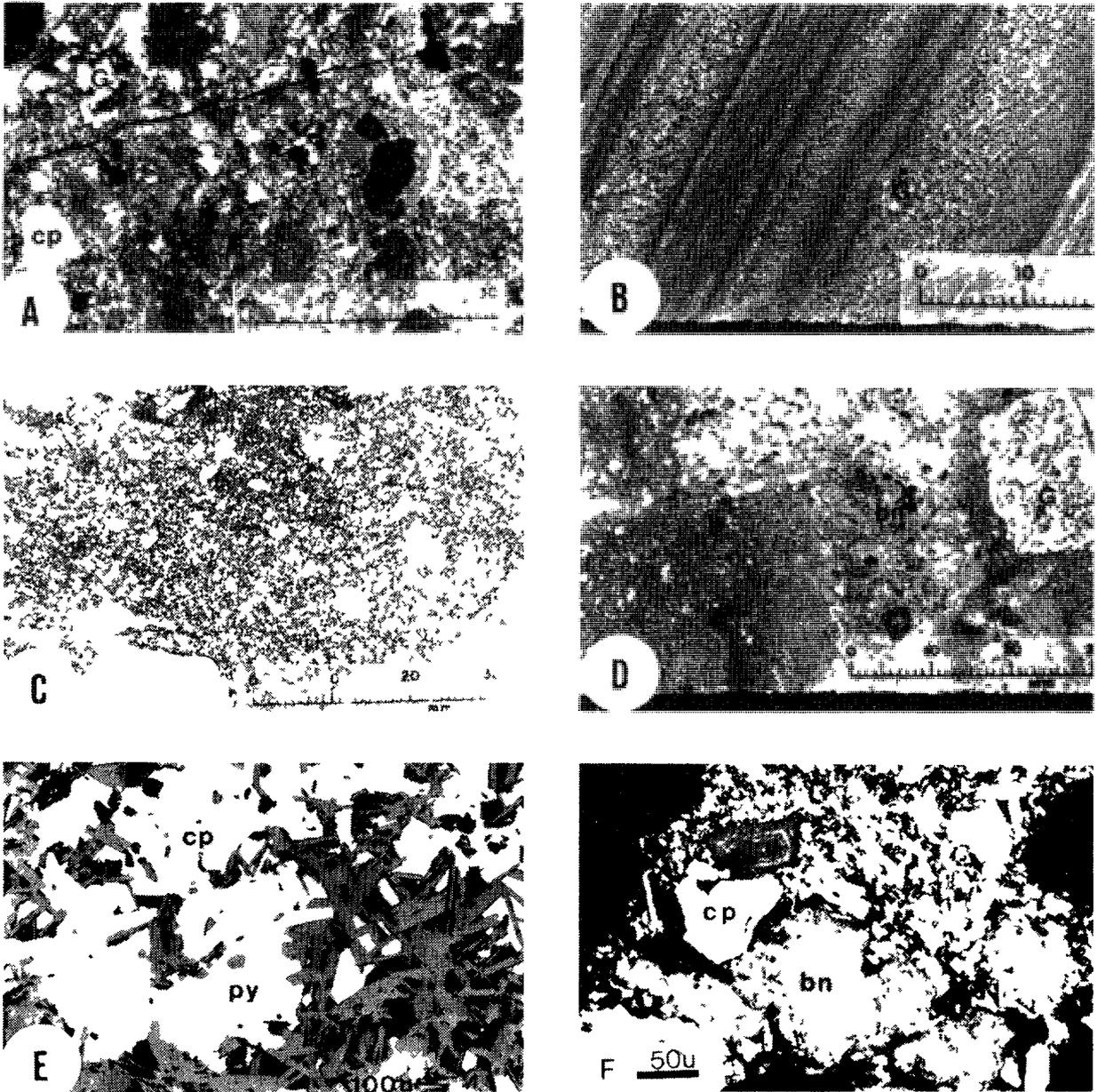


Fig.7. Photographs (A-D) of cut sections of drill core and photomicrographs (E and F) of stratabound mineralization. A. Polymict breccia of granite (G), hematite (H), fluorite (black), and chalcopyrite (cp) with disseminated chalcopyrite and fluorite in the matrix. Cross-cutting fluorite vein. Note gross bedding; top = right. B. Thin graded-bedded units in Whenan Member. Note grading of chalcopyrite (white), micro-faulting and load cast around granite clast (G), top = right. C. Clastic and disseminated chalcopyrite (white) in matrix-rich breccia. D. Disseminated and clastic bornite (bn) in red-brown hematite matrix-rich breccia with altered granite clast (G). E. Chalcopyrite (cp) with pyrite (py), intergrown with hematite laths. F. Bornite (bn) with fine-grained annular zones of hematite, and chalcopyrite (cp) in hematite with quartz clasts and a zoned intergrowth of uraninite-bornite (u).

Black Hematite Member: This is the basal member of the main mineralized zone. It contains beds of massive unbrecciated hematite as well as breccias with black crystalline hematite dominant both as clasts and in matrices. Specularite, fluorite, siderite and chlorite are present in the matrix and the breccias contain thin vuggy and porous zones. Pyrite-rich mineralization is characteristic of the breccias in this member.

Whenan Member: This member consists of a series of thin (up to 15m thick) beds of polymict matrix-rich breccias and matrix-poor granite-rich breccias aggregating to a total thickness in excess of 200m in many areas. The breccias are intercalated with thin bedded silty lenses and arenitic sediment bands. The hematite in the lower beds is dominantly black and that in the beds towards the top of the member is reddish brown. Sedimentary features such as graded bedding (Fig. 7B) and upwards-fining beds up to 3 metres thick occur, and series of upwards-fining beds are not uncommon. Load casts, scours and, less commonly, cross-bedding are present. This member hosts most of the chalcopyrite-bornite mineralization in the deposit. Most of the sulfides occur in the matrix-rich beds.

Brooks Member: This member is not always developed and granite clasts are more abundant than in the underlying Whenan Member. The matrix content is variable and is predominantly brown hematite. Characteristic clasts in this member are sericitized felsic volcanics and reworked Whenan Member and Black Hematite Member clasts. Siderite-rich clasts are also common in some areas. Mineralization is commonly restricted to the matrix-rich zones and is irregularly developed. Bornite and chalcopyrite are the dominant sulfides with minor chalcocite in some areas. Discrete lenses of pale green sericitized volcanics are common.

Upper Granite Breccia Member: Although lithologically similar to the Lower Granite Breccia Member, this member is not chloritic, but is usually sericite, hematite and silica altered. Mineralization is restricted to thin (less than 10m thick) lenses, and veins composed of hematite, fluorite, chalcocite and bornite. Thin lenses and dikes of strongly sericitized felsic volcanics are common.

Distribution of Members: The five members of the Olympic Dam Formation are not always intersected in drill holes and they display complex facies relationships in many areas. In the northwestern part of the deposit the three middle members are extensively interbedded with the Upper Granite Breccia Member although features of the Black Hematite Member, Whenan Member and Brooks Member are observed. On the northeast flank of the

main mineralized zone (Fig. 5) siderite is a major matrix and clast component in the three members and their definition is less clear, particularly the Black Hematite Member. Elsewhere, the Black Hematite Member and Whenan Member may be separated by barren granite-breccia lenses.

Greenfield Formation

The Greenfield Formation is up to 700m thick and comprises the very hematite-rich upper units of the stratigraphic sequence preserved in downfaulted blocks, it has both conformable and disconformable contacts with the Olympic Dam Formation (Fig. 5). The unit has been subdivided into the Silicified Member, the Hematite Breccia Member and the Volcanic Member. The Silicified Member consists of polymict breccias containing clasts of hematite, quartz and volcanics in hematite-rich matrices. The breccias are strongly silicified and veined by silica and barite. The members of the Greenfield Formation are poorly mineralized.

Distribution of Members: The Greenfield Formation is restricted in its distribution and within it, the Silicified Member and the Volcanic Member are also restricted. The Silicified Member is developed along the eastern part, and the Volcanic Member appears to be restricted to the northern and eastern parts of the Greenfield Formation block (Fig. 5).

Structure

Locally the sequence hosting the Olympic Dam mineralization is confined by a fault-bounded trough informally called the Olympic Dam Graben. The graben has a probable northwest trend with a length in excess of 7km and a maximum width of 5km. The base of the sedimentary sequence in the graben has not been intersected in drilling and the sequence therefore has a minimum thickness of 1km. The main structural elements of the graben are shown in Fig. 8.

The graben is arched about a northeast-trending axis. Limited evidence also suggests local arching within the graben about north-west axes with the development of small localised domes and basins in some areas (N. Oreskes and W. Brown, pers. comm., 1982). Dip-slip and strike-slip faults occur parallel to both the graben and main arch axis and fault displacement is concentrated on the northeast margin of the graben. Faults roughly parallel to the graben axis are displaced by those at a high angle to the axis. None of the faults dislocate the cover sediments. The arching, faulting and erosion prior to the deposition of the cover sediments exposed lower members of the Olympic Dam Formation on the

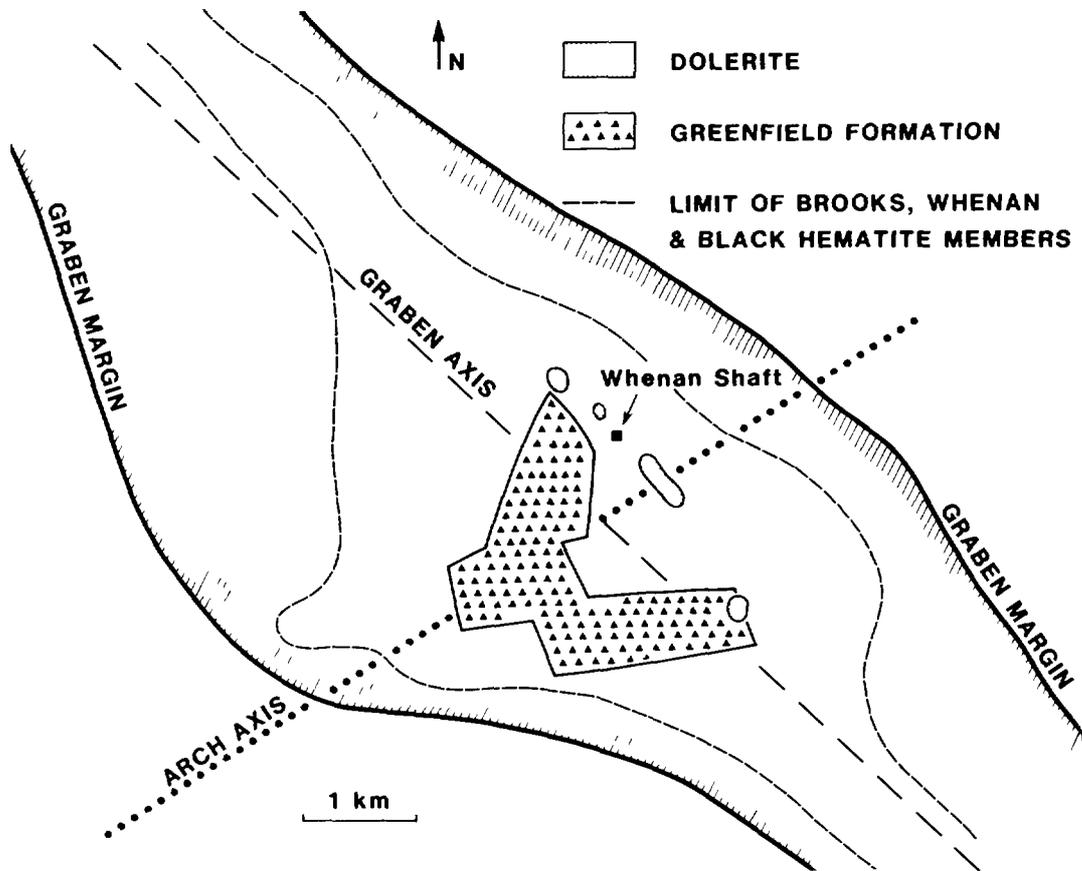


Fig. 8. Plan showing main structural elements of the Olympic Dam graben.

unconformity in the vicinity of the crest of the arch (east of Whenan Shaft). Upper members of the Olympic Dam Formation are thicker to the southeast and northwest. Remnants of the previously more extensive Greenfield Formation have been preserved in downfaulted blocks in the crest of the arch.

The Olympic Dam Formation dips to the southwest at 15° to 20° in the southeastern half of the graben. Limited data suggest a flatter north or northeast dip in the northwest half. Local steepening and reversal of dips are observed near faults, synsedimentary slump breccias and local domes. Widespread slump structures are present in thinly bedded units.

Intense shearing has not been observed but intervals of closely jointed and fractured drillcore, and zones of very intense alteration, could be indicative of faults. There are marked variations over short lateral distances in the depth to distinctive units within the stratigraphic sequence. Thick lithological units disappear and upper stratigraphic units can be adjacent to lower stratigraphic units indicating vertical displacement. Extensive lateral (strike-slip) displacement also occurs in the graben-fill sequence with maximum displacement parallel to the graben long-axis. In many areas contemporaneous (growth) faults dislocate the lower members of the Olympic Dam Formation but do not affect the Brooks

Member and Upper Granite Breccia Member. Evidence of widespread penetrative deformation and intense folding has not been observed.

Alteration

All rocks in the Olympic Dam Graben are altered to varying degrees. The dominant alteration minerals are hematite, sericite, chlorite, silica and carbonate. There are two types of alteration - a weak pervasive type affecting all rocks and a distinct, more intensive type related to mineralization.

1. Pervasive alteration. Hematite, sericite and chlorite alteration affects all rock types with dolerite least affected. Localized areas of silica and carbonate alteration occur. This style of alteration is most apparent in breccias with a high granite component where feldspars and ferromagnesian minerals are replaced.
2. Intense alteration. Intense hematite and chlorite alteration are associated with mineralization in the lower parts of the Olympic Dam Formation. Sericite and silica alteration are predominant in the upper members of this formation.

The broad vertical zonation of intense alteration can be used as a general guide to position in the stratigraphic sequence when distinctive units are lacking.

MINERALIZATION

Copper, uranium, rare earths, gold and silver mineralization occur in the Olympic Dam deposit. The bulk of the potential ore grade mineralization occurs in the Olympic Dam Formation. There is normally a direct relationship between the amount of mineralization and the amount of matrix in the host breccias.

Copper Mineralization

Two distinct types of copper mineralization are defined on the basis of sulphide assemblage, rock association and stratigraphic position (Roberts and Hudson, 1983). The older mineralization is strata-bound and the younger is largely transgressive. Significant uranium, rare earths and gold mineralization is associated with both types. The two types are normally mutually exclusive but some areas of overlap occur.

Bornite (chalcocite)-chalcopyrite-pyrite strata-bound mineralization: The strata-bound type occurs in the three hematite matrix-rich members of the

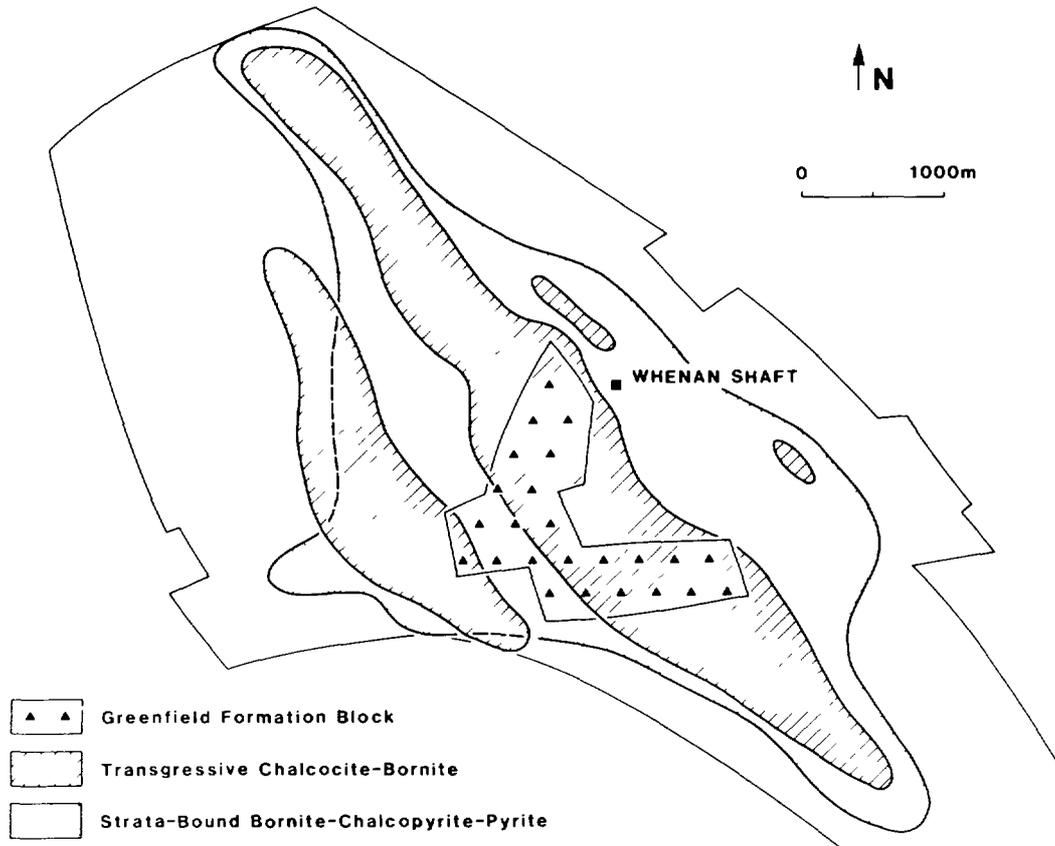


Fig. 9. Plan of the distribution of sulfide mineralization types.

Olympic Dam Formation throughout the graben (Fig. 9), but reaches its maximum thickness (up to 350m thick) in the north east crest zone of the main structural arch. Most of the sulfides occur in the matrix as uniform disseminations (0.1-2mm) that make up 5 to 20 percent of the rock but some are present as coarse clastic fragments up to 5cm in size (Fig. 7). Replacement and micro-cavity fill textures are common and in some finely bedded thin layers stratiform sulfides are present. Rock clasts containing disseminated sulfides, and sulfide rims on clasts are abundant in some areas.

The dominant gangue minerals in the strata-bound type are hematite, quartz, sericite and fluorite in high grade copper zones.

Vertical zoning of sulfides is broadly consistent, grading from a relatively sulfur-rich copper-poor assemblage (pyrite(chalcopyrite)) at the base of the Black Hematite Member, to a relatively copper-rich sulfur-poor assemblage (bornite-chalcopyrite) at the top of the Whenan Member, and in the Brooks Member. Supergene processes are not considered to be a major factor in sulphide zonation (Roberts and Hudson, 1983).

Minor ore minerals in the strata-bound mineralization are carrollite, cobaltite, native silver, silver telluride and gold.

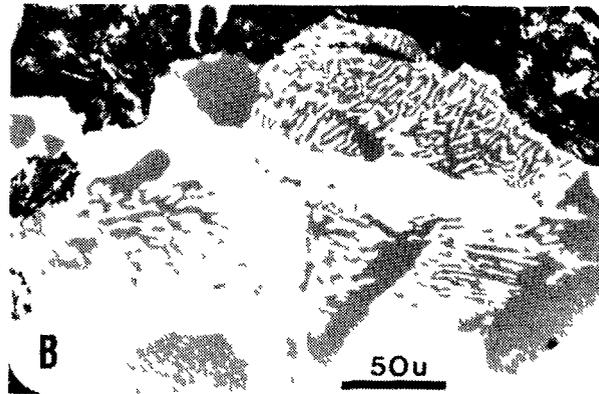
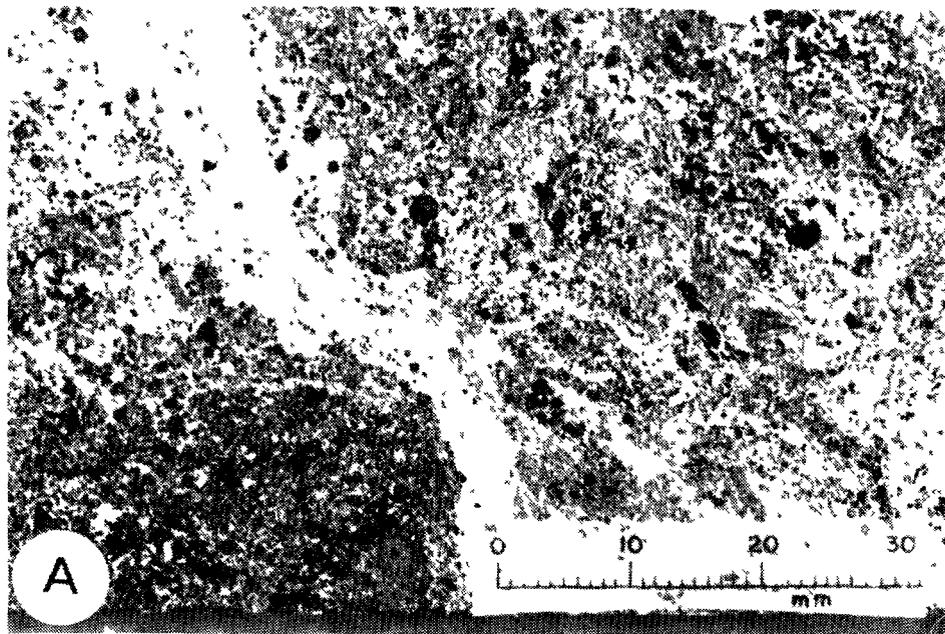


Fig. 10. Photograph (A) and photomicrograph (B) of transgressive mineralization. A. Disseminated and lensoid chalcocite-bornite (white) with fluorite (black) in hematite matrix. B. Complex vermiform intergrowth of chalcocite (white) and bornite (gray).

Transgressive chalcocite-bornite mineralization: Cross cutting veins and irregular conformable lenses of uranium-bearing chalcocite-bornite mineralization are found in the Brooks Member and Upper Granite Breccia Member of the Olympic Dam Formation (Fig. 10). This younger mineralization is confined to linear zones parallel to the long axis of the graben with the main zone being at least 6km long and up to 0.7km wide (Fig. 9). Smaller zones are developed to the northeast and southwest of the main trend. The thickest intersections of mineralization of this type are in excess of 300m. The thickness of mineralized zones is not necessarily dependent on the host unit thickness or lithology and there is no consistent

relationship between the concentration of sulfides and matrix content as in the strata-bound mineralization.

The grain size of the sulfides varies from sub-micron inclusions in hematite to massive clasts up to 10 centimetres across, but most are less than 0.5mm. In all textural types the chalcocite and bornite are complexly intergrown (Fig. 10).

The dominant gangue constituents are hematite, fluorite and quartz with lesser sericite and chlorite.

Minor ore mineral constituents are native gold and silver, digenite, covellite, cobaltite, a copper-nickel-cobalt arsenate and native copper.

Uranium Mineralization

Three uranium mineral species have been identified. The pitchblende variety of uraninite (UO_2) is the most abundant. Coffinite ($\text{U}(\text{SiO}_4)_{1-x}(\text{OH})_{4x}$) is subordinate to uraninite while brannerite ($(\text{U,Ca,Ce})(\text{Ti,Fe})_2\text{O}_6$) accounts for only a minor proportion of the uranium mineralization. The grain size of the uranium minerals varies from sub-micron to several millimetres but most of the grains are less than 50 microns.

Uraninite and coffinite are intimately associated and occur throughout the mineralized zones with sulfides, sericite, hematite, fluorite and to a lesser extent, chlorite. Their form varies markedly and includes globular aggregates, micro-veinlets penetrating grain boundaries, fracture coatings, grain and crystal rims and oriented intergrowths with sulfides (T.R. Peachey pers. comm., 1981, Grey, 1978), (Fig. 11). A close association with bornite occurs in areas of uranium mineral veining.

Brannerite is restricted in its distribution and usually occurs in veins in the Brooks Member of the Olympic Dam Formation. It is closely associated with rutile (anatase), sericite and hematite and usually occurs as patchy aggregates of irregular grains within sericite or as grain composites with hematite. The brannerite grains are always surrounded by small (1 to 10 microns) grains of titanium oxide (rutile, anatase). Zircon crystals and grains are also present in the halo of oxide grains.

Other Mineralization

Rare earths minerals bastnaesite $(\text{Ce,Lu})\text{CO}_3(\text{F,OH})$ and florencite $(\text{CeAl}_3(\text{PO}_4)_2(\text{OH})_6)$ and free gold are associated with both types of copper-uranium mineralization.

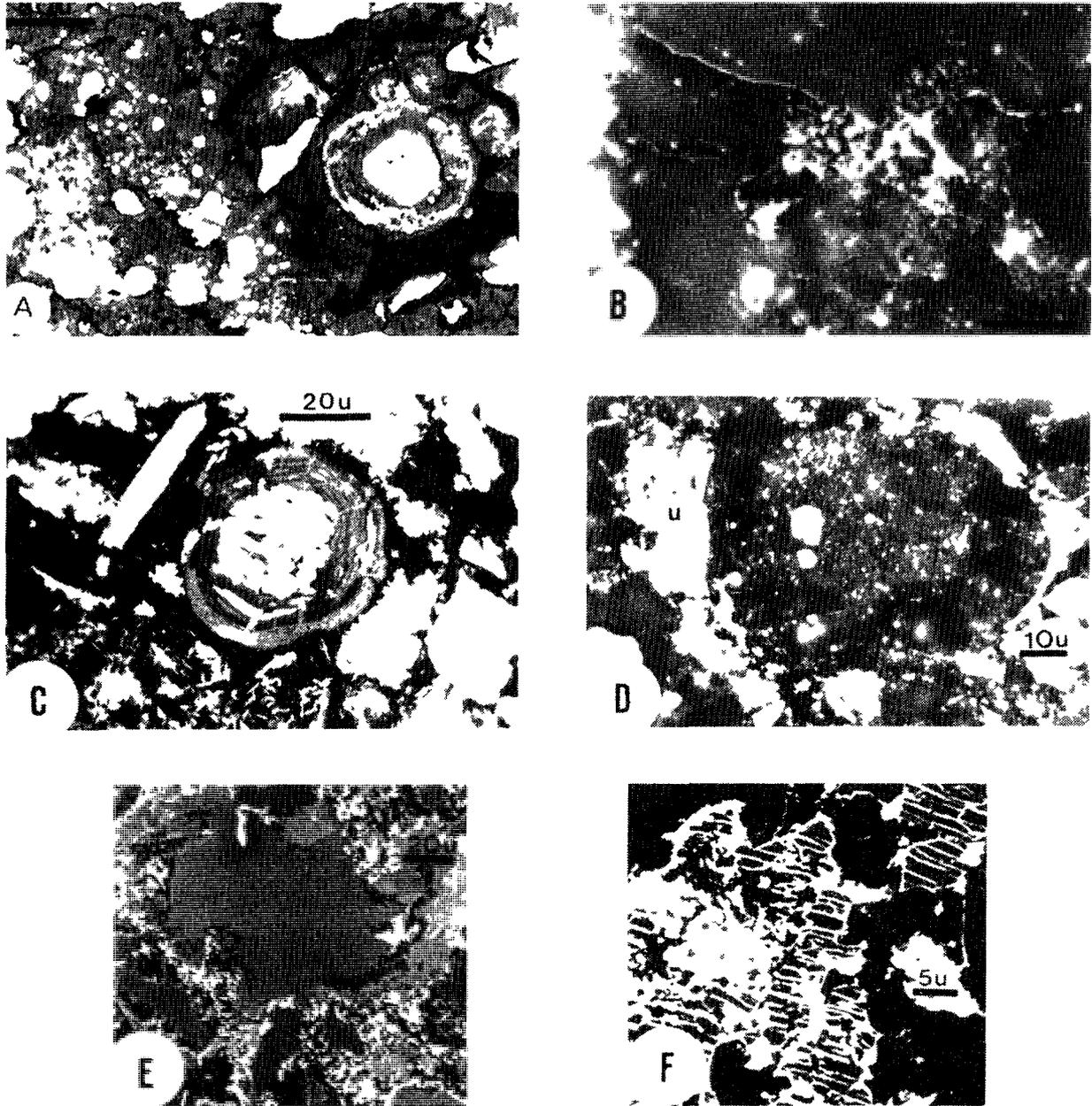


Fig. 11. Uranium mineralization, photomicrographs (A-D) and scanning electron micrographs (E, F) of typical mineral textures. A. Coarse-grained uraninite (dark gray) with coffinite (light gray) replacing and surrounding bornite (white). B. Uraninite veinlets (gray) with bornite (white) in quartz. C. Concentrically zoned intergrowth of chalcopyrite (white), bornite (gray) and uraninite (dark gray) in quartz with hematite and chalcopyrite. D. Uraninite-coffinite (u) surrounding a silicate clast with hematite (white). E. Very fine-grained uraninite (white) rimming bornite. F. Uraninite (white) in bornite; note crystallographic control of veinlets (E & F after Grey, 1978).

TABLE 4**COMPOSITION OF MINERALIZATION TYPES**

	Strata-bound bn-cp-py		Transgressive cc-bn	
	1	2	3	4
Cu %	1.15	1.72	2.55	2.80
U ₃ O ₈	440	640	335	440
Au	0.4	0.5	2.4	0.15
Ag	1.0	2.0	7.0	4.0
La	1300	1700	1800	200
Ce	2000	2700	2650	2200
Pb	90	85	30	60
Zn	130	80	60	85
Ni	300	290	280	4
Co	135	120	10	70
Mo	50	48	110	36
As	85	65	130	60
Sb	8	6	4	4
Bi	4	8	4	4
Te	4	10	10	10
Hg	0.08	0.05	0.05	0.05
Sn	42	30	45	20
Cd	1	1	1	1
Pt	0.05	0.05	0.05	0.05
Pd	0.01	0.05	0.05	0.05
Y	110	135	35	90
F %	1.37	1.50	0.90	0.90
BaO	7250	3450	9300	3520
Fe %	37.70	30.40	17.40	21.50
SiO ₂ %	29.60	34.50	49.10	44.50
CO ₂ %	0.97	1.90	0.20	0.08
P ₂ O ₅ %	0.20	0.50	0.80	0.15
MnO %	0.10	0.10	0.01	0.01
S %	2.03	2.00	0.66	1.13

Concentrations in ppm unless stated.

bn-bornite, cc-chalcocite, cp-chalcopyrite, py-pyrite

1. and 2. - Composite bulk samples from 10 (5 in each) drill hole intersections near the Whenan Shaft.

3. - Composite bulk sample from 6 drill hole intersections south of the Whenan Shaft.

4. - Composite bulk sample from 7 drill hole intersections in the northwest part of the deposit.

All analyses by Comlabs Pty. Ltd., Adelaide, South Australia.

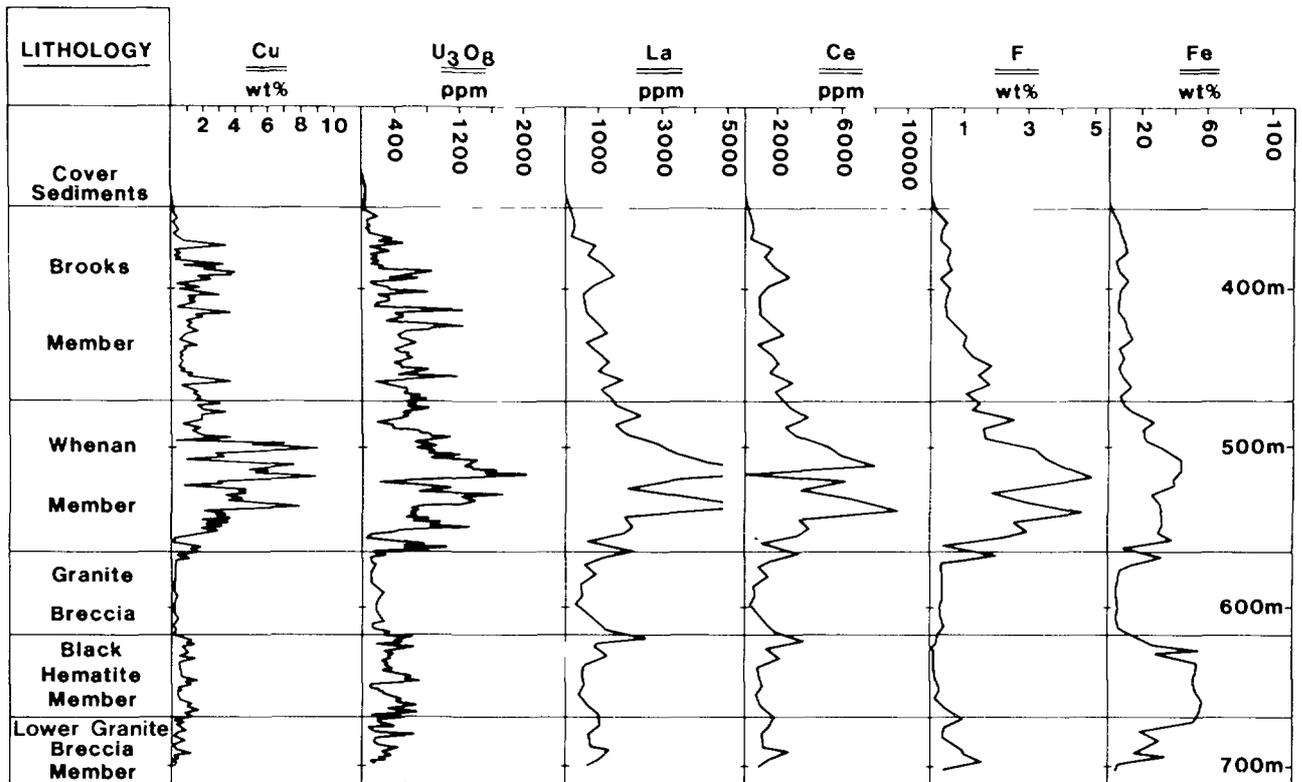


Fig. 12. Down-hole plot from drill hole RD55 of Cu, U₃O₈, La, Ce, F and Fe in strata-bound mineralization showing relationship of these elements to lithology.

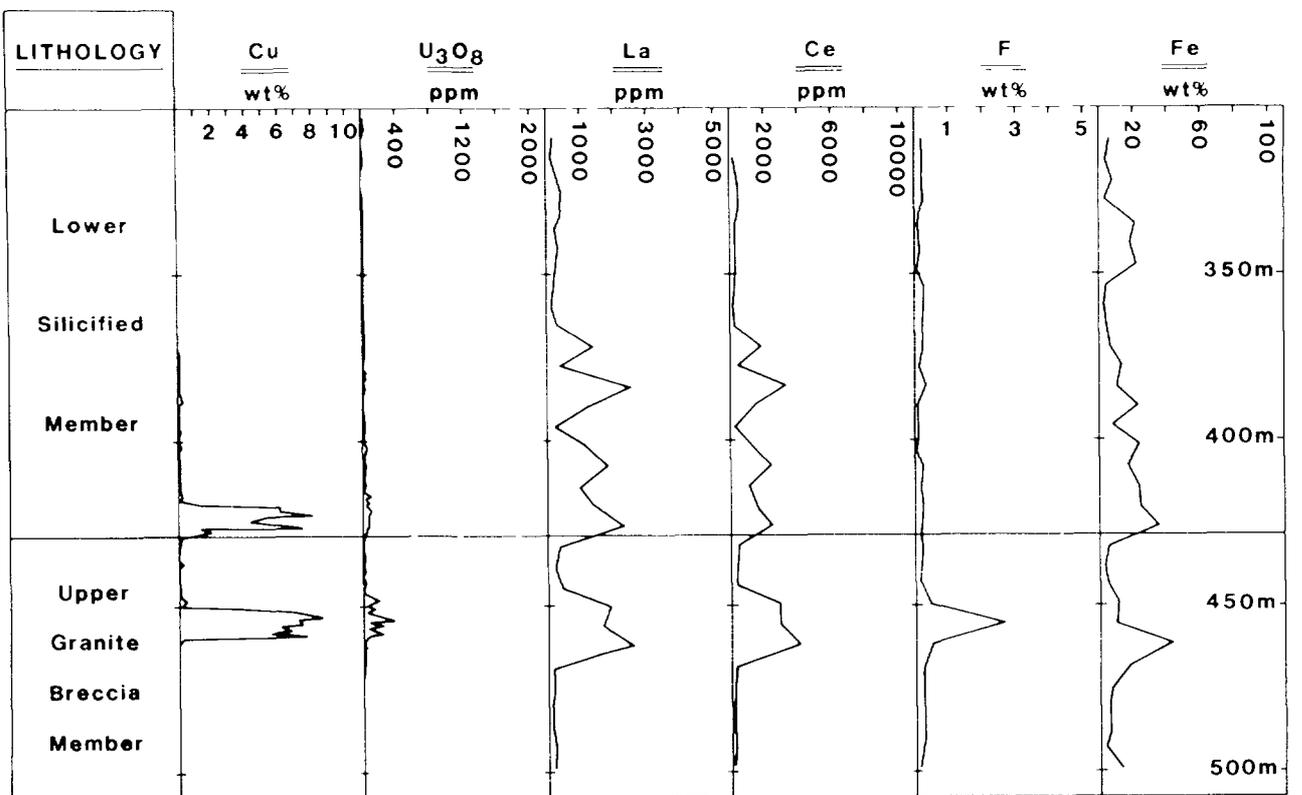


Fig. 13. Down-hole plot from drill hole RD47 of Cu, U₃O₈, La, Ce, F and Fe in transgressive mineralization.

Geochemistry

The general composition of the two main mineralization types are indicated in Table 3 and the concentrations of the main ore elements copper, uranium, lanthanum, cerium, fluorine and iron and their relationships to lithology in the strata-bound mineralization are illustrated in Fig. 12. A general positive correlation is evident for these elements in matrix-rich breccia units. The correlation is not as well defined on a detailed scale but positive correlations exist between uranium and the light rare earths lanthanum and cerium. A less defined positive correlation exists between these elements and fluorine.

Ore element relations in the transgressive mineralization are shown in Fig. 13.

A number of general trends are apparent from simple element plots. These are:

- . Copper, uranium, iron, lanthanum, cerium and fluorine are concentrated in matrix-rich polymict breccia units.
- . Iron increases towards the base of strata-bound mineralized zones.
- . Copper distribution is more uniform towards the base of mineralized zones.
- . Uranium and lanthanum plus cerium can occur in relatively high concentrations without associated high copper concentrations but the reverse is rarely observed.
- . Cobalt concentration is elevated in the lower, more pyrite-rich, parts of strata-bound mineralized zones.
- . Barium content tends to be antipathetic to copper, uranium, lanthanum, cerium.
- . Copper and uranium contents are low in siderite-rich zones which are usually lower in the sequence except in the northeast part of the main mineralized area.
- . Lead and zinc contents are very low throughout the copper mineralized area.
- . Silver content tends to be higher in bornite rich mineralized zones but its distribution is erratic within these zones.

DISCUSSION

The Olympic Dam deposit is an example of a very unusual type of sediment-hosted mineralization and no analagous deposits appear to have been documented. As the delineation of the deposit is at an early stage and data are incomplete, the following discussion is a preliminary attempt at synthesizing some of the features of the lithology and mineralization.

Formation of the Deposit

The initial activity leading to the formation of the Olympic Dam deposit appears to have been the development of a thick pile of sedimentary breccias (the Olympic Dam Formation) in a northwest trending trough in response to major faulting. The essential features of the pile are a series of matrix-rich polymict breccia units (Black Hematite Member, Whenan Member and Brooks Member) which contain strata-bound copper, uranium, rare earths and gold mineralization and are underlain and overlain by barren granite breccias.

The breccias were probably deposited in an arid subaerial environment by debris flows, mudflows, lahars and rock avalanches along active fault scarps. Depositional environments and coarse-grained sediments with similar lithological characteristics to those in the Olympic Dam deposit have been described in the literature (see Roberts and Hudson, 1983) but none of these examples is mineralized.

The first mineralizing event occurred during sedimentation, with deposition of strata-bound hematite, sulfides, uranium and rare earths minerals, gold and silver, fluorite, siderite and barite. This event could have been related to geothermal activity resulting from volcanism but has some similarities with stratiform copper deposits (Roberts and Hudson, 1983). The later epigenetic chalcocite-bornite and gold mineralization with associated uranium and rare earths was introduced in favourable structural and lithological zones during the waning stages of the earlier mineralizing event (Fig. 14). Fluorite, barite, siderite and hematite veins were also formed at this time.

The mineralized part of the sequence is overlain by distinctive hematite-rich breccias, banded iron formation, volcanic breccias and conglomerates, felsic lavas and tuffs which indicate that volcanism occurred during deposition of at least part of the breccia sequence. The thinly bedded iron formations were probably deposited in a playa lake environment with iron possibly being introduced from a fumarolic source.

Rapid facies changes in the basin of deposition, contemporaneous faulting and later faulting produced a complicated geometry in the mineralized zones. Dolerite dykes intruded the sequence which was then eroded and later covered by stable shelf sediments. The absence of penetrative deformation and metamorphism in the deposit indicates an age younger than the 1580 Ma and older deformation events of the Gawler domain to the south and older than the dolerite dikes which do not intrude the Adelaidean cover sequence.

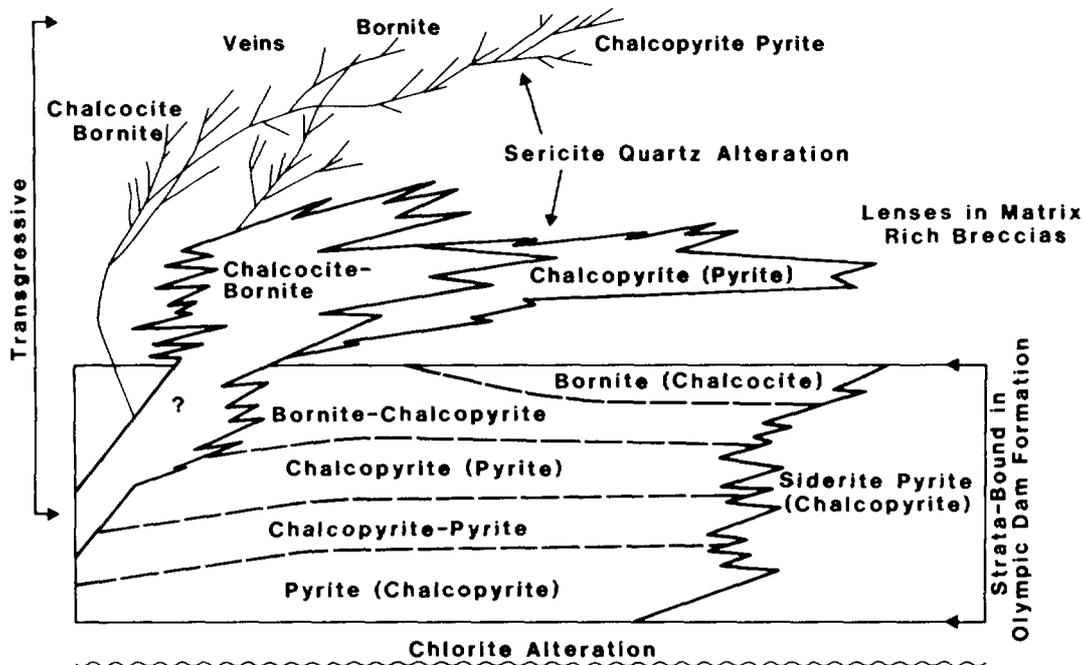


Fig. 14. Diagrammatic representation of the two types of mineralization in the Olympic Dam deposit.

The unusual association of copper, iron, uranium, rare earths and gold, the overall oxidized host environment, the sulfide zoning and alteration related to mineralization, pose a number of interesting conceptual problems. The high potassium, rare earths, barium and fluorine contents are suggestive of alkaline-igneous activity in the region but the alkaline igneous rocks have not been found at Olympic Dam. The copper, iron and gold probably originated from a mafic source. Some of the hematite may also have resulted from the in-situ oxidation of siderite, magnetite and chlorite.

The Hematite Association

The strata-bound mineralization occurs within hematite-rich rocks. Much of the hematite appears to have been deposited from solution, and textures indicate simultaneous, rhythmic and sequential deposition of sulfides and hematite. The association of hematite with sulfides, the sulfide-hematite textures, the occurrence of barite adjacent to mineralized zones, the antipathetic relation between barite and sulfides, and the relative absence of sulfides in siderite-bearing rocks indicate that the sulfide precipitation could have been caused by the simultaneous oxidation of ferrous iron and reduction of sulfate. The ferrous iron could have been introduced by hot springs along the active faults into the sulfate-rich waters of playa lakes in the Olympic Dam graben (D.W. Haynes, pers. comm., 1981).

An analogous process of sulfate reduction and ferrous iron oxidation has been described by Mottl et al. (1979) and Seyfried and Dibble (1980). The well-developed chlorite alteration zone below the mineralization may be the result of initial percolation of ferrous iron-rich electrolyte into the underlying porous breccia.

The higher level, transgressive, chalcocite-bornite-gold mineralization appears to be epigenetic and later than the strata-bound mineralization. The common association of sulfides and directly precipitated quartz and the well-developed alteration halo around sulfide veins suggests that the temperature of deposition was probably higher than in the strata-bound type.

Uranium and Rare Earths

The uranium and rare earth mineral textures indicate that they were deposited both during and after the main sulfide mineralizing event. The composition and close association of uranium and rare earth minerals with sulfides, fluorite and hematite indicate that fluorine, iron, carbonate, phosphate and sulfur were closely related to the transport and deposition of uranium and rare earths. The association of uranium-fluorine is a common one in many volcanic-related uranium deposits in continental environments (Curtis, 1981) and supports the mineralization-volcanism hypothesis. The very close association of uranium and directly precipitated hematite in what appears to be a low-temperature strata-bound deposit is very unusual (Nash et al., 1981). However, the intimate association of the tetravalent uranium species and hematite could indicate that the ferrous iron oxidation and reduction of hexavalent uranium (present as a sulfate in the playa lakes) was a possible precipitating process for some of the uranium (D.W. Haynes, pers. comm., 1982).

Conclusions

The most unusual features of the Olympic Dam deposit are:

- (1) the association of high concentrations of iron, copper and gold with high concentrations of uranium, fluorine and rare earths;
- (2) the evidence of simultaneous rhythmic and sequential deposition of sulphides and hematite;
- (3) the deposition during sedimentation in a very high energy environment; and
- (4) the size of the deposit.

The present uncertainty of interpretations will diminish with further drilling, underground development and research, and until this is accomplished, attempts to explain the genesis of the deposit will continue to be speculative.

Acknowledgement

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Mrs. J. Hall typed the manuscript, Mr. J. Collins and Mr. C. Furstner prepared the figures.

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**STRATA-BOUND URANIUM DEPOSITS
IN THE DRIPPING SPRING QUARTZITE,
GILA COUNTY, ARIZONA, USA**

A model for their formation

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Abstract

Uranium deposits in the Proterozoic Dripping Spring Quartzite are stratabound in diagenetically altered, potassium-rich and carbonaceous volcanogenic siltstones. The deposits are localized near Proterozoic diabase intrusions and along monoclines that deform the essentially flat-lying sequence. Uraninite and coffinite are both in vertical veins and in sub-horizontal to horizontal veins along stylolites and bedding planes, and are disseminated in fine-grained, potassium-feldspar-rich layers.

The uranium deposits in the Dripping Spring Quartzite are thought to be diagenetic/sedimentary concentrations that were later remobilized during diabase emplacement. Uranium, which may have been released from the volcanogenic sediments during diagenesis, could have been transported and concentrated in carbonaceous siltstones at the time of diagenesis and stylolite formation. Circulating fluids associated with diabase emplacement remobilized and concentrated uranium in carbonaceous siltstones close to diabase.

INTRODUCTION

Uranium deposits in the Proterozoic Dripping Spring Quartzite have been known since the 1950's, when more than 100 occurrences were identified in Gila County, Arizona, mostly in the Sierra Ancha region (Fig. 1). Renewed interest in these deposits during the 1970's resulted in additional exploration and drilling. The deposits and prospects are of particular interest because they are the only known examples in the United States of Proterozoic strata-bound uranium deposits in essentially flat-lying, only locally metamorphosed, sedimentary rocks. Granger and Raup

(1969a,b), who studied the deposits in detail during the period of mining in the 1950's, proposed that the uranium was derived from diabase intrusions, but Williams (1957) and Nutt (1981) suggested

that the deposits were remobilized sedimentary concentrations. This paper, an extension of the ideas of Nutt (1981), is in part based on the study of core drilled by Wyoming Mineral Corporation in the Workman Creek area and on data supplied by Uranerz, U.S.A., Inc.

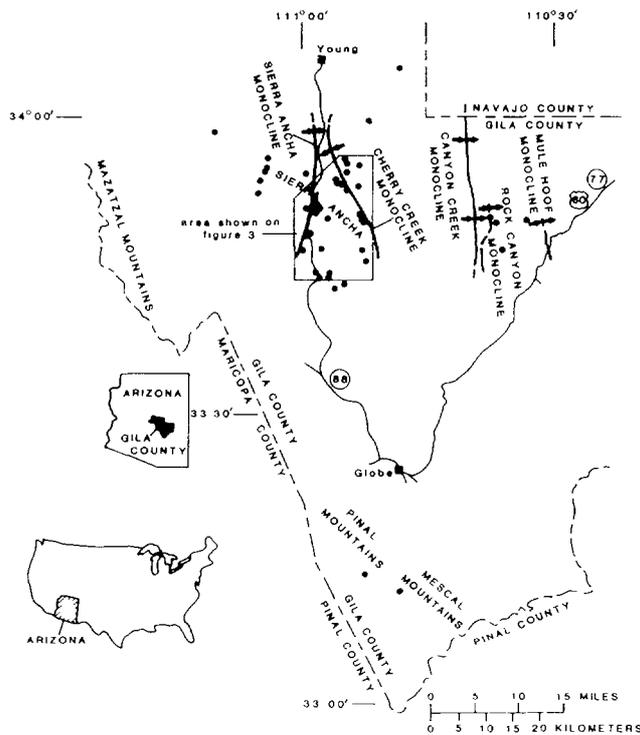


Figure 1. Location map of the study area in Gila County, Arizona, U.S.A., showing uranium deposits (●) and monoclines. Modified from Granger and Raup (1969a,b).

REGIONAL GEOLOGY

The Dripping Spring Quartzite is part of the Proterozoic Apache Group in east-central and southeastern Arizona (Fig. 2). The Apache, a nearly horizontal sequence of clastic sedimentary, carbonate, and volcanogenic rocks, unconformably overlies a

basement of folded and locally metamorphosed volcanic and sedimentary rocks, the Alder Group and Mazatzal Quartzite, that were intruded by granitic rocks (Fig. 2). The zircon U-Pb ages of the basement rocks range from about 1705 m.y. for the Alder Group (Ludwig, 1974; oral comm., 1983) to 1430 ± 30 m.y. for granitic intrusions (Silver, 1968; Ludwig and Silver, 1977). The Proterozoic Troy Quartzite lies unconformably above the Apache Group. Granger and Raup (1964, 1969a), Shride (1967), and Bergquist and others (1981) have mapped and described the rocks in the Sierra Ancha region. Smith (1969, 1970), Smith and Silver (1975), and Nehru and Prinz (1970) studied diabase sills in the Sierra Ancha. Wilson (1939) and Anderson and Wirth (1981) examined regional relations of the basement rocks, and Anderson and Wirth (1981) have suggested regional tectonic settings for the Proterozoic rocks.

The uranium deposits in the Dripping Spring Quartzite, as well as outcrops of the Apache Group, are predominantly in Gila County (Fig. 1), and particularly in the Sierra Ancha region, although the Dripping Spring Quartzite is present elsewhere in southeastern

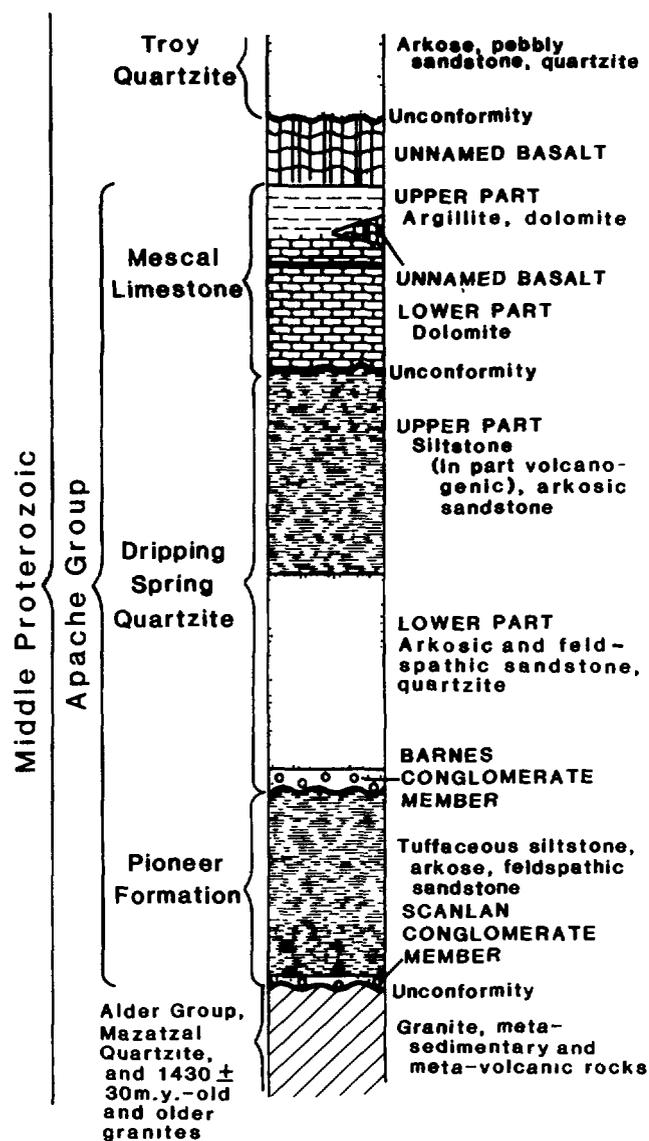


Figure 2. Stratigraphic section of the Apache Group. Modified from Granger and Raup (1964).

grade of 0.05 percent U_3O_8 and an average grade of 0.11 percent.

Apache Group

The Apache Group, consisting of the Pioneer Formation, Dripping Spring Quartzite, and Mescal Limestone (Fig. 2), overlies 1430 ± 30 m.y.-old granitic plutons (Silver, 1968; Ludwig and Silver, 1977) and is intruded by 1100-1150 m.y.-old diabase (Silver, 1960; Smith and Silver, 1975). In the Sierra Ancha, the

Arizona. The Sierra Ancha region is in the southern part of the Colorado Plateau Province, in a zone transitional to the Basin and Range Province to the south. As typical throughout the Colorado Plateau, the strata are nearly horizontal except where folded by monoclines (Fig. 1). Faults and joints cut the Apache Group.

During the 1950's 21,360 t of ore with an average grade of 0.24 percent U_3O_8 were produced from 14 mines in the Dripping Spring Quartzite, 80 percent of the production coming from the Workman Creek and Red Bluff properties (Otton and others, 1981). An additional 1,170 t averaged 0.07 percent. Recent drilling at Workman Creek has outlined an orebody with an estimated 4,410 t U_3O_8 indicated in place resources at a cut-off

1440 m.y.-old Ruin Granite (Ludwig and Silver, 1977) underlies the Apache Group. The Pioneer, the oldest unit in the Apache Group, consists of a basal conglomerate, the Scanlan Conglomerate Member, overlain by tuffaceous siltstone containing devitrified glass shards (Gastil, 1954), arkose, and feldspathic sandstone. Geologists from Uranerz, U.S.A., Inc., report that in the Sierra Ancha a well-developed regolith separates the underlying Ruin Granite from the Scanlan Conglomerate Member. The basal conglomerate, the Barnes Conglomerate Member, of the Dripping Spring Quartzite unconformably overlies the Pioneer Formation and is overlain by fine-grained sandstone and siltstone of the Dripping Spring Quartzite. The Mescal Limestone unconformably overlies the Dripping Spring Quartzite and consists of a lower member of cherty dolomite with halite molds and an upper member of cherty, stromatolitic dolomite, argillite, and, locally, basalt. Basalt flows cap the Mescal. A stratigraphically continuous, 4.5- to 12.0-m-thick carbonate breccia underlying the carbonate sequence has been interpreted by Shride (1967) to be the result of dissolution of evaporites and subsequent collapse of higher portions of the section.

The Troy Quartzite, although not part of the Apache Group, is Proterozoic in age and was probably deposited in the same basin as the Apache Group. Fine- to medium-grained arkose, pebbly sandstone, and quartzite make up the unit, which lies unconformably above the Mescal.

Diabase intrudes nearly all sections of the Apache Group and the Troy Quartzite. The diabase occurs predominantly as sill-like sheets 10-350 m thick, but contacts are locally discordant. The large Sierra Ancha sill, formed by multiple intrusions of a high-alumina magma, has a central layer of feldspathic olivine-rich diabase and upper and lower layers of olivine diabase (Smith, 1970). The diabase is extensively deuterically altered along the contacts.

Granophyre, coarsely recrystallized rocks, and hornfels occur along the contact separating diabase and the Dripping Spring Quartzite. The granophyres formed by melting and remobilization of sedimentary rocks (Smith, 1969; Smith and Silver, 1975). Micro-litic cavities are common in the granophyres.

Dripping Spring Quartzite

The Dripping Spring Quartzite - actually misnamed as it is largely composed of potassium-feldspar-rich rocks - is divided into lower and upper parts (Fig. 2) by Bergquist and others (1981). Granger and Raup (1964) defined additional units during their study of the Dripping Spring Quartzite and the uranium deposits, but the regional mapping units are sufficient for this discussion.

The lower part, 85-110 m thick, consists of fine- to medium-grained arkosic and feldspathic sandstone, underlain by the basal Barnes Conglomerate Member. Chemical analyses from Smith (1969) show that two arkosic sandstones collected in the Dragoon Mountains (southeast of the Sierra Ancha) have K_2O contents of 6.2 and 8.3 percent, which are higher than the normal values for arkosic and feldspathic sandstones. Minor quantities of fine-grained potassium feldspar in the matrix are seen in thin sections from some samples of the lower part.

The upper part, the ore-bearing sequence, is 75-110 m thick and consists of siltstone and arkosic sandstone. Rare impure carbonate rocks are preserved as pyroxene-rich layers in contact metamorphosed siltstone. Carbonaceous siltstones, locally interlayered with arkosic sandstone, occur in the lower section of the upper part and host the uranium deposits. Arkosic sandstone and siltstone (not carbonaceous) compose the upper section of the upper part.

Stylolites are common in the upper part, where as many as 30 stylolites occur in a one centimeter-thick layer. Stylolites commonly separate coarse- and fine-grained strata and are concentrated within fine-grained layers. Residuum, which accumulates as the more soluble material is lost to intrastratal fluids, is along the stylolite surfaces and consists predominantly of sphene, TiO_2 , carbonaceous matter, and pyrite.

Mineralogy and chemistry of siltstones in the upper part

The siltstones in the upper part are composed predominantly of fine-grained potassium feldspar that is generally $<5\mu m$ in diameter (Granger and Raup, 1964). Granger and Raup (1964) identified the feldspar as monoclinic, except in hornfelsic rocks where the feldspar was microcline (triclinic). G. A. Desborough (oral comm., 1983) confirmed by X-ray diffraction the presence of both monoclinic feldspar and microcline, but also identified microcline in

rocks that do not appear hornfelsic in hand specimen. Potassium feldspar composes from approximately 50 to more than 90 percent of the siltstone in the ore-bearing sequence of the upper part (visual estimate from thin sections). The chemical composition of these rocks reflects this high feldspar content with correspondingly high K_2O values of 8 to 13.8 percent (Table 1). Medium-grained quartz and feldspar grains, commonly with irregular boundaries, are scattered through the potassium-feldspar-rich layers.

Siltstones stratigraphically higher in the upper part have potassium feldspar content visually estimated from thin sections to be commonly 50 to 60 percent, but X-ray diffraction work has also identified samples containing as much as a 95 percent potassium feldspar (G.A. Desborough, oral comm., 1983). Smith (1969) noted that these carbon-poor rocks in the upper section of the upper part were also K_2O -rich.

The significance of the presence of fine-grained potassium feldspar and high K_2O values.

High K_2O content and large amounts of fine-grained potassium feldspar in siltstones suggest that the rocks are authigenically altered volcanogenic rocks (Kastner and Siever, 1979). The presence of authigenic feldspar in altered tuffs has been well documented by Sheppard and Gude (1968, 1969, 1973). The feldspar that forms during diagenesis of marine strata is monoclinic (G. A. Desborough, oral comm., 1983). Although diagenesis has destroyed primary textures, the high K_2O content and the abundance of fine-grained potassium feldspar in the upper part of the Dripping Spring Quartzite indicate that this unit has a large volcanic component. The rocks composed of about 95 percent feldspar may be diagenetically altered tuffs, and those with lesser amounts of feldspar are probably reworked volcanoclastic rocks interlayered with detrital quartz and feldspar.

The high K_2O and low Na_2O contents of these rocks cannot be easily explained by isochemical alteration of volcanic rocks. Saline pore water trapped or evolved during diagenesis of the Dripping Spring Quartzite or fluids from the overlying evaporite-bearing Mescal Limestone are possible sources of potassium. Sodium may have been lost to solutions during formation of potassium feldspar from zeolites, which form as an intermediate product

Table 1--Chemical analyses of samples from the Dripping Spring Quartzite
[Asterisk, *, not measured; LOI, loss on ignition.]

	1-172 ¹	2-119 ²	4-38 ³	5-95 ⁴	5-126 ⁵	7-71 ⁶	7-88 ⁷	DS78-5 ⁸	DS78-20A2 ⁹
SiO ₂	62.2	56.8	63.2	43.6	57.8	61.3	59.0	62.9	62.0
Al ₂ O ₃	15.2	14.1	14.8	10.8	14.8	16.2	14.7	16.4	15.2
Fe ₂ O ₃	2.2	2.8	3.6	11.1	4.2	2.1	4.0	0.28	1.7
FeO	1.3	1.7	*	2.8	1.6	1.2	1.7	0.08	4.9
MgO	0.46	2.7	0.42	5.2	1.8	0.62	1.3	0.12	2.3
CaO	1.4	3.1	0.41	0.97	0.82	0.68	0.20	0.18	0.18
Na ₂ O	0.21	0.2	0.68	0.07	0.11	0.10	0.11	0.16	0.23
K ₂ O	12.5	11.9	11.5	8.0	12.1	13.8	12.3	13.3	8.8
H ₂ O ⁺	0.47	1.2	0.89	2.6	1.3	0.62	1.1	0.82	2.7
H ₂ O ⁻	0.10	0.79	0.41	2.5	0.86	0.24	0.82	0.40	0.25
TiO ₂	1.2	1.2	1.3	0.95	0.94	0.77	0.72	0.92	0.66
P ₂ O ₅	0.17	0.09	0.09	0.15	0.16	0.17	0.08	0.18	0.13
MnO	0.04	0.08	<0.01	0.10	0.03	0.01	0.04	0.02	0.10
CO ₂	0.01	0.32	0.01	0.11	0.07	0.12	0.02	0.02	0.02
Total %	97.5	97.0	97.3	89.0	96.6	97.9	96.0	95.8	99.2
LOI	*	*	*	2.7	0.6	0.31	0.68	3.1	*
Organic C %	0.05	0.14	0.63	1.15	0.27	0.13	0.25	2.92	0.03
U (ppm)	299	4210	6.73	11,200	2690	611	8420	16.4	5.18
Pb (ppm)	40	500	<20	1020	200	90	830	48	544
Cu (ppm)	1000	930	90	41,000	640	30	2400	7	145
Mo (ppm)	50	56	<10	<10	36	91	43	9	<2
V (ppm)	*	95	97	82	80	46	51	49	70
Zn (ppm)	13	54	14	76	6	6	9	22	152

Rapid rock analyses of major oxides measured at U.S. Geological Survey laboratories by N.

Skinner, D. Kobilis, and Z. Hamlin. Method described under "single solution" in U.S. Geological Bulletin 1401.

U determined by delayed neutron activation at U.S. Geological Survey laboratories by H.

Millard, Jr., M. Coughlin, B. Vaughn, M. Schneider, W. Stang, S. Lasater, B. Keaten, C. Bliss, and C. McFee.

Cu, Pb, Mo, V, and Zn determined by optical spectroscopy at U.S. Geological laboratories by P.

Briggs, G. Riddle, V. Shaw, and B. Hatfield

C determined by combustion, LECO

1. Upper part, hornfelsic volcanogenic siltstone. No microscopically visible uranium minerals, but radioluxograph shows radioactivity concentrated in finely layered strata. Sample from Workman Creek core.
2. Upper part, finely laminated hornfelsic volcanogenic siltstone with visible uraninite and coffinite. Sample from Workman Creek core.
3. Upper part, hornfelsic carbonaceous volcanogenic siltstone. Sample from Workman Creek core.
4. Upper part, hornfelsic carbonaceous volcanogenic siltstone with coffinite both disseminated and in veins. Sample from Workman Creek core.
5. Upper part, hornfelsic volcanogenic siltstone with uraniferous chlorite veins and coffinite. Sample from Workman Creek core.
6. Upper part, hornfelsic volcanogenic siltstone. Uranium minerals are not visible microscopically, but radioluxographs show disseminated radioactivity. Sample from Workman Creek core.
7. Upper part, hornfelsic volcanogenic siltstone with coffinite in veins and disseminated. Sample from Workman Creek ore.
8. Upper part, altered(?) carbonaceous volcanogenic siltstone. Collected by J. K. Otton, from SE 1/4 sec. 13, T5N, R14E, McFadden Peak Quadrangle, Arizona (1:62,500).
9. Upper part, altered(?) siltstone with volcanogenic component and fine-grained sandstone. Collected by J. K. Otton, from near Buckaroo Flats, T7N, R13E, Copper Mtn. Quadrangle, Arizona (1:24,000).

between volcanic glass and feldspar: $\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O} + \text{SiO}_2 + \text{K}^+ \rightarrow \text{KAlSi}_3\text{O}_8 + \text{H}_2\text{O} + \text{Na}^+$ (Surdam, 1977).

The carbonaceous siltstone in the lower section of the upper part has the highest K₂O values, the most authigenic potassium feldspar, and presumably the greatest volcanic component, but above

average K_2O values and the presence of fine-grained potassium feldspar elsewhere in the Dripping Spring Quartzite indicate that much of the sequence may have some volcanic component. Detailed stratigraphic sampling is needed to show the abundance and distribution of potassium-feldspar-rich rocks. Interestingly, the argillite in the Mescal Limestone also has high K_2O content, suggesting that this part of the Mescal also has a volcanic component.

The effect of diagenesis and metamorphism on the Dripping Spring Quartzite

Diagenesis has profoundly altered the Dripping Spring Quartzite. Volcanogenic siltstones now have unusually high K_2O contents and are composed of fine-grained potassium feldspar, and volcanic textures and volcanoclastic fragments have been largely destroyed. Detrital quartz and feldspar grains and overgrowths of the same are irregular in outline because of extensive dissolution, especially where the grains are in contact with authigenic potassium feldspar.

Widespread stylolite occurrence suggests extensive dissolution and fluid circulation. Because dissolution that results in stylolite formation may cause thinning of the stratigraphic section - as much as 50 percent volume loss (Glover, 1969) - the presence of numerous stylolites in the Dripping Spring Quartzite suggests that an appreciable amount of the section has been removed. Dissolved sediments may include evaporites, a possible source of K_2O , and carbonate rocks, which are now only locally observed as calc-silicate layers in hornfelsic rocks.

Diabase intrusions are found throughout the thinly bedded ore-bearing upper part. Although macroscopically visible effects of the diabase on the Dripping Spring Quartzite are restricted to granophyre and recrystallized rocks within about 30 m of the diabase (Granger and Raup, 1964) and metasomatism was confined to rocks near the diabase (Smith, 1969; Smith and Silver, 1975), the widespread presence of sphene and what Granger and Raup (1964) called spotted rocks (rocks with spherically shaped altered spots) suggests that diabase intrusions extensively altered the Dripping Spring Quartzite. The occurrence of microcline, instead of monoclinic feldspar, outside the immediate vicinity of the diabase suggests that a large volume of rock was affected by low-grade thermal metamorphism, probably caused by extensive fluid movement

and heating of the Dripping Spring Quartzite during diabase emplacement; the extent of metamorphism probably depended on the permeability of the rocks. Detailed sampling of stratigraphic sections and X-ray identification of the types of feldspar in the rocks are needed to determine the actual extent of metamorphism in the Dripping Spring Quartzite.

Smith and Silver (1975) suggested that the presence of miarolitic cavities in the granophyres and the extensive alteration of diabase near contacts indicate that water from the country rocks circulated through the diabase.

Depositional Environment of the Apache Group

The Apache Group was predominantly deposited in a shallow water environment in a stable cratonic setting (Anderson and Wirth, 1981). The occurrence of carbonaceous siltstones in the Dripping Spring Quartzite is indicative of deposition of these sediments in a restricted environment. Carbonate rocks, evaporite molds, and stromatolites in the overlying Mescal Limestone suggest a supra-tidal to intertidal setting. The presence of relict glass shards in the Pioneer Formation, high K_2O contents and authigenic potassium feldspar in the Dripping Spring Quartzite and Mescal Limestone, and basalt in the Mescal Limestone is evidence of volcanic activity at the time of deposition of the Apache Group. The products of this intermittent volcanic activity were most voluminous during deposition of the Pioneer, the upper part of the Dripping Spring, and the upper part of the Mescal and following deposition of the Mescal.

GEOLOGIC SETTING OF URANIUM DEPOSITS

The uranium deposits in the Sierra Ancha region are strata-bound in the Dripping Spring Quartzite (Fig. 3). The deposits are in the carbonaceous volcanogenic siltstone sequence in the upper part, are near diabase sills, and are predominantly restricted to strata above and below a quartzite stratigraphic marker bed. The most productive areas in the Sierra Ancha were near Workman Creek and Red Bluff (Fig. 3). Granger and Raup (1969a) noted uranium enrichment in a carbonaceous shale in the Mescal Limestone; this uranium occurrence is essentially the same as those in the Dripping Spring Quartzite where uranium is locally enriched in carbonaceous zones in siltstones. Uranium occurrences in the Sierra Ancha were

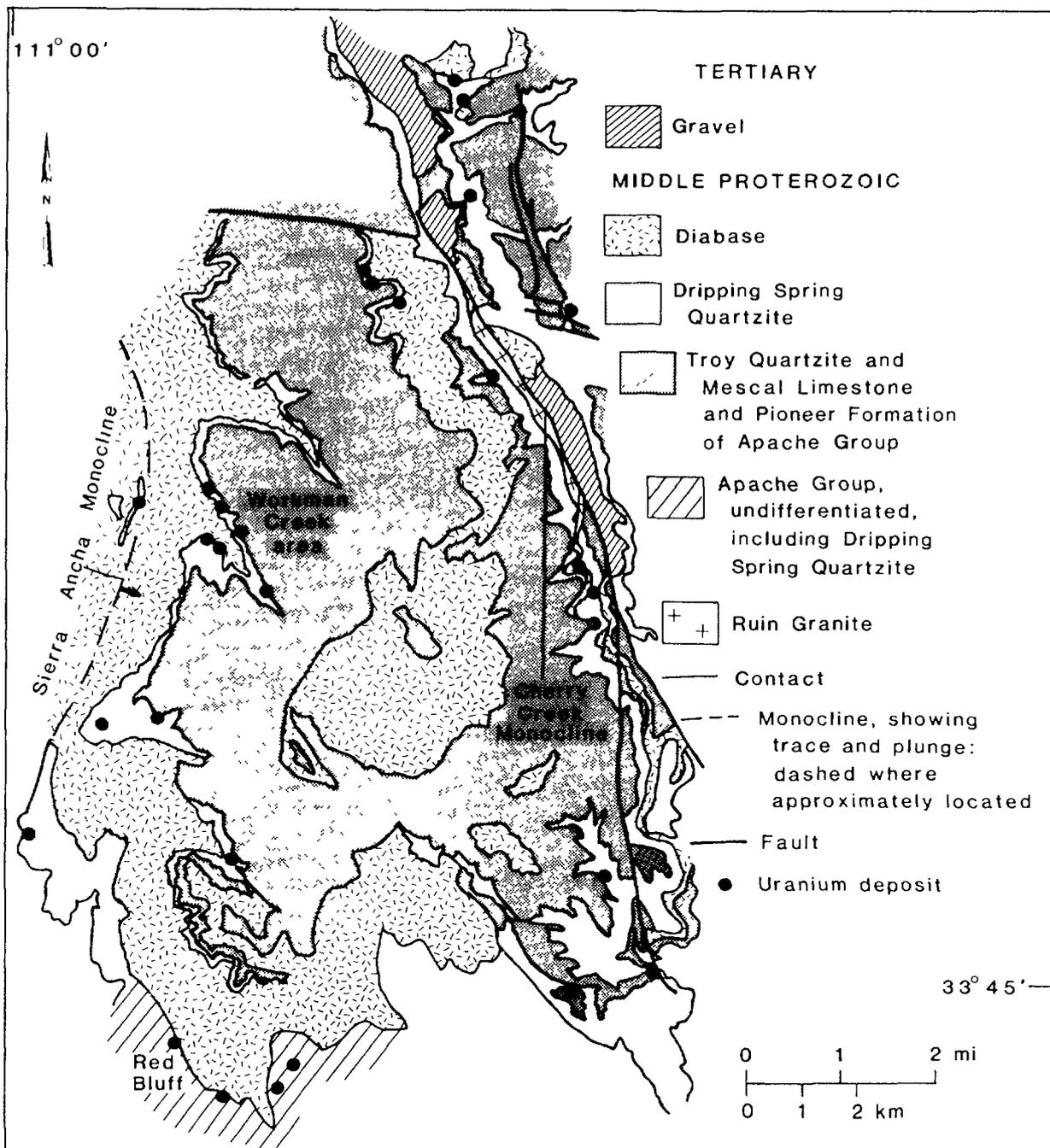


Figure 3. Uranium deposit localities and geologic map of the Dripping Spring Quartzite and diabase in the area of the Sierra Ancha and Cherry Creek monoclines (Cherry Creek monocline is coincident with faults). Geology is from Bergquist and others (1981), Granger and Raup (1964), and Wilson and others (1959). Deposit locations are from H. C. Granger (written comm., 1983).

also found by geologists of Uranerz, U.S.A., Inc. in uraniferous quartz-hematite-apatite matrix filling fractures and shear zones in the granitic regolith at and near the unconformity separating the Ruin Granite and the Apache Group.

Although the deposits are strata-bound, uranium concentration was apparently influenced by both structure and the presence of

diabase. Granger and Raup (1969a) were impressed by the proximity of diabase to uranium deposits, and an airborne magnetic survey conducted by Uranerz, U.S.A., Inc. confirms the association of diabase and uranium anomalies (oral comm., 1983). It should be noted, however, that in the Sierra Ancha diabase sills are so widespread in the Dripping Spring Quartzite that most outcrops of Dripping Spring Quartzite are near diabase or, possibly, near areas where the diabase has been eroded. Many of the deposits are localized along the trend of the monoclines (Fig. 1), most commonly on the downdip side. Uranerz geologists have correlated the numerous deposits of the Workman Creek area with the intersection of an anomalous magnetic zone and complex faults associated with the Sierra Ancha monocline. The Red Bluff deposit is situated near diabase intruded along a fault and deposits are also clustered near the Cherry Creek monocline and associated faults (Fig. 3). Williams (1957) states that the ore is localized along north-northeast and north-northwest fractures that formed prior to ore formation. The uraniferous quartz-hematite-apatite fracture and breccia matrix in the regolith at the unconformity is also concentrated along the trend of the monoclines, near the uranium deposits in the Dripping Spring Quartzite.

Uranium in the Dripping Spring Quartzite is both disseminated and in veins. The mines worked in the 1950's were developed primarily in high-grade vertical veins. Core from the Workman Creek area, however, shows that uranium is also strata-bound on both the outcrop and thin-section scale and is concentrated in horizontal and subhorizontal veins, commonly along bedding planes and stylolites (Fig. 4). Even in coarse-grained recrystallized rocks uranium is concentrated along remnant stylolites. Disseminated uranium is in fine-grained, potassium-feldspar-rich layers; uranium is conspicuously absent from coarse-grained clastic and pyroxene-rich layers (Fig. 4).

Uranium ore occurs as uraninite and uranium silicate mineral(s). Uranium silicate was identified by the presence of uranium and silicon in qualitative analyses on the electron microprobe energy dispersive X-ray analysis system, and powder camera X-ray work confirmed the presence of coffinite mixed with other unidentified fine-grained minerals. Secondary uranium minerals are also present. Radioluxographs of fine-grained samples that contain no visible uranium minerals show the presence of

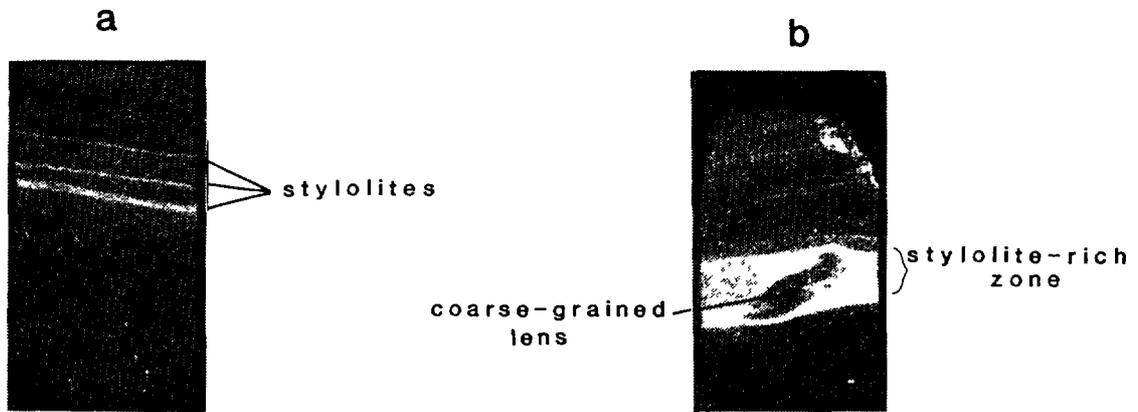


Figure 4. Radioluxographs of thin-section samples from the Dripping Spring Quartzite. Light areas have high radioactivity. a. Radioactivity is disseminated and concentrated along stylolites. Radioluxograph exposure time, 46.5 hours. b. Radioactivity is noticeably absent in coarse-grained lens within fine-grained, stylolite-rich section. Radioluxograph exposure time, 7.5 hours.

uranium, either in submicroscopic grains, on grain boundaries, or incorporated in minerals such as sphene. Sphene-filled stylolites are commonly very radioactive.

Uraninite (called uraninite 1 in Granger and Raup, 1969a) is in veins and disseminated in layers that contain as much as 40 percent uraninite. Grains are euhedral and subhedral and $<20\mu\text{m}$ in size. An unidentified uranium-silicate mineral commonly forms thin rims around uraninite, and coffinite is concentrated along the edges of some uraninite-rich layers. Uraninite is associated with sphene, chalcopyrite, pyrite, galena, molybdenite, pyrrhotite, graphite, and, in a few places, ilmenite. All these minerals, except graphite, may contain inclusions of uraninite; uraninite inclusions are also in recrystallized feldspar matrix and phlogopite.

Coffinite (called uraninite 2 in Granger and Raup, 1969a) distribution is similar to that of uraninite. Disseminated coffinite is yellow brown in transmitted light, $<25\mu\text{m}$ in size, and euhedral to subhedral. Coffinite in veins locally has a mottled gray-brown color in reflected light and differing ability to transmit light; this variability in color and reflectivity is probably due to the presence of fine-grained minerals mixed with the coffinite. Fine-grained galena cubes are invariably scattered through coffinite and aid in identification of the coffinite. Coffinite is associated with chlorite, chalcopyrite, pyrrhotite, pyrite, molybdenite, and galena.

Veins of coffinite contain inclusions of uraninite that make up major to minor parts of the veins. These uraninite inclusions,

the thin rims of uranium silicate on uraninite, and the coffinite concentrated along the edges of uraninite-rich layers suggest that coffinite formed after uraninite.

Alteration, which occurs only locally in the Dripping Spring Quartzite deposits, is primarily composed of chlorite, iron sulfides, iron oxides, and unidentified, fine-grained, clear to brown, highly birefringent minerals and is most common in coffinite-rich rocks. Coffinite, chlorite, pyrite, and chalcopyrite occur together in pods that are scattered throughout uraniumiferous rocks. Near ore minerals and veins, feldspar grains have a cloudy, brown appearance probably caused by partial alteration to clays. Radioactive jarosite veins fill cross-cutting fractures.

The major element chemistry of uranium-bearing and barren siltstone samples is quite similar (Table 1). Both have anomalously high K_2O values, indicating potassium was not introduced during ore-forming events. Magnesium and Fe_2O_3 values are highest in chloritically altered rocks, the latter in part due to the presence of fine iron sulfides and oxides mixed with the chlorite.

Other metals are also appreciably enriched in the uranium deposits. In 42 samples of high K_2O siltstone from the Workman Creek prospect, molybdenum values ranged from less than 10 to 297 ppm and averaged 59 ppm (values of less than 10 - the lower limit of detection - were assigned a value of 5 ppm); in these same samples copper values ranged from 27 to 41,000 ppm and averaged 1,998 ppm. Within the prospect, copper and uranium correlate positively; the correlation coefficient for the 42 samples is 0.7108. In contrast, within the deposit molybdenum has no correlation with either copper or uranium; the correlation coefficient for molybdenum and copper is -0.0857, and the molybdenum - uranium correlation coefficient is -0.0652.

Anomalous silver (0.7-70 ppm), cobalt, nickel, zirconium, tin, and lanthanum were reported in vertical veins and wall rocks (Uranerz, U.S.A., Inc., written comm., 1983), although it is not clear that these elements were carried by the same fluids that carried the uranium. Silver values are commonly greater in the wall rocks than in the veins. Vanadium is not enriched in the ore zones and zinc values are not high in the core from Workman Creek, although zinc is enriched in veins sampled by Uranerz. Lead values average 121 ppm in the Workman Creek core, with the range of values from less than 20 to 1,020 ppm.

The age of high-grade veinlets of uranium minerals were determined to be about 1050 m.y. (Granger and Raup, 1969a), approximately the same age as the diabase sills. A more extensive project of age determinations of uraninite- and coffinite-rich samples might clarify the relationship between diabase intrusions and uranium deposition.

SOURCE, TRANSPORT, AND DEPOSITION OF URANIUM

There are at least two possible sources for uranium in the Sierra Ancha region. The volcanogenic component within the Dripping Spring Quartzite could have been a nearby source of uranium, and the underlying Ruin Granite constitutes a possible distal source. The Ruin Granite typically has 2.5 to 8 ppm uranium (Anderson and Wirth, 1981) and the uraniferous quartz-hematite-apatite fracture and breccia matrix in the regolith has as much as 1350 ppm uranium. Uranium derived from the granite or regolith could have moved up structures into the Dripping Spring Quartzite and been reduced in carbonaceous zones. However, because of the extensive diagenesis, dissolution, and thermal metamorphism that have affected and apparently moved fluids through the Dripping Spring Quartzite, the simpler and favored model derives uranium from altered volcanogenic rocks.

The diabase, thought by Granger and Raup (1969a) and Neuerburg and Granger (1960) to be the source of uranium, was probably most important as a heat source in moving fluids and uranium within the sedimentary rocks. Only local metasomatism of the siltstone occurred along the edges of the diabase, and there is no evidence for development in the diabase of either an early or late stage volatile fluid carrying incompatible elements. On the contrary, the extensive deuteric alteration and the miarolitic cavities in the granophyres indicate that fluids moved from the country rock into the margins of the diabase. No large scale loss of uranium along the margins of the diabase has been documented.

The uranium in the quartz-hematite-apatite fracture and breccia matrix in the granitic regolith may have been derived from either the Dripping Spring Quartzite or the granitic basement. Because the uranium occurrences in the granite along the unconformity are in the vicinity of the Dripping Spring Quartzite deposits, these apatite-rich concentrations may be exploration

guides to undiscovered uranium deposits in the Dripping Spring Quartzite.

Uranium derived from the Dripping Spring Quartzite could have been liberated from volcanogenic siltstones during the diagenetic alteration that formed the potassium feldspar. Analyses of the uranium content of volcanic zircons from the Dripping Spring Quartzite could be used to determine if the volcanic rocks were enriched in uranium. Uranium, released to solutions during diagenesis and stylolite formation, could have been deposited where it encountered a reducing environment associated with carbonaceous matter. Granger and Raup (1969a) describe small, low-grade strata-bound concentrations of uranium in the Dripping Spring Quartzite that may be protore that developed during the extensive diagenesis. Inclusions of uraninite in metamorphic minerals suggest that sedimentary or diagenetic uranium concentrations were later metamorphosed.

Regardless of the validity of the postulated development of a sedimentary protore, the spatial association of diabase and uranium deposits and the presence of vertical uranium veins suggest that the diabase was involved in remobilization of uranium and formation of the deposits as they now occur. The presence of fine-grained microcline, indicative of thermal metamorphism, in the altered volcanogenic siltstones suggests extensive fluid circulation in permeable rocks in the upper part of the Dripping Spring Quartzite, perhaps during diabase intrusion. Fluid drawn toward the diabase may have traveled along bedding planes, stylolites, and through porous rock, carrying uranium originally liberated during diagenesis and depositing uranium in reducing environments associated with carbon-rich sedimentary rocks. Concentration of uranium along stylolites, bedding planes, vertical structures, and in fine-grained potassium-feldspar-rich layers was probably dependent on the permeability of these rocks and structures. Cemented clastic layers and rare carbonate strata, which contain little uranium now, were impermeable to the uranium-bearing fluids. The distribution of the deposits near a quartzite stratigraphic marker bed suggests that these strata were an impermeable barrier to either diagenetic or hydrothermal uranium-bearing fluids, or, alternatively, that uranium-bearing fluids preferentially traveled through this unit. Areas disrupted by monoclines and associated fracturing probably

were most susceptible to hot circulating fluids, and, therefore, were the areas most likely to have concentration of uranium.

Chloritic alteration remobilized uranium locally, but apparently had little effect on the geometry of ore bodies. The timing of the chloritic alteration event is unknown.

The association of uranium, copper, and molybdenum in the deposits may be indicative of deposition of copper and molybdenum from the same circulating fluid that carried uranium or may be a result of a separate period(s) of fluid movement along the same structures.

DISCUSSION

The elements proposed as critical to the formation of the deposits in the Dripping Spring Quartzite are: volcanogenic sediments, which may have been the source of uranium; extensive diagenetic alteration and dissolution during stylolite formation that could have liberated and transported uranium; carbonaceous matter and (or) sulfur that could have established a reducing environment for deposition of uranium; and diabase intrusions that remobilized and concentrated uranium. Alteration only locally affected the uranium distribution.

There are intriguing similarities between the deposits in the Sierra Ancha region and the large Australian and Canadian unconformity-type deposits: Proterozoic age; strata-bound character of the deposits; shallow water, carbonaceous host rocks; an unconformity separating the ore-bearing sequence from a granitic or gneissic basement; development of a regolith at an unconformity; uranium enrichment in the regolith near the unconformity; apatite-rich concentrations near deposits; and diabase intrusions. Striking, and perhaps critical, differences between the Dripping Spring Quartzite and unconformity-type deposits are the lack of metamorphism and intense alteration in the Dripping Spring Quartzite and the differences in ages: the Dripping Spring Quartzite and basement rocks are Middle Proterozoic; the larger unconformity-type deposits are in Lower and Middle Proterozoic rocks overlying Archean basement. Regardless of their relationship to unconformity-type deposits, the uranium deposits in the Dripping Spring Quartzite may be considered an intermediate stage between strata-bound sedimentary or diagenetic concentrations and the

remobilized, high-grade deposits in metamorphosed and highly altered rocks.

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**THE LIANSHANGUAN URANIUM DEPOSIT,
NORTHEAST CHINA**

*Some petrological and geochemical
constraints on genesis*

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Abstract

The Lianshanguan uranium deposits are located in the Lianoning Province of northeastern China. The deposits occur in a transitional zone lying between an Archaean craton and Lower Proterozoic miogeosynclinal sequences. Three types of uranium mineralisation are present in the area; syngenetic mineralisation occurs in the basal psammitic units of the Lower Proterozoic rocks which, during metamorphism in the period 1900 to 1800 Ma, was partly mobilised and concentrated in the meta-sediments. Late-orogenic granite emplacement in the Lower Proterozoic saw the development of uranium-bearing alkali solutions that initially produced metasomatic white migmatite in fracture zones marginal to the granites. Ore grades are relatively rich in these alkali hypo-meso metasomatic uranium deposits. With precipitation of potassium and sodium from the metasomatising solutions uranium became further enriched in the evolved fluids. Precipitation of uranium from these fluids produced meso-epithermal mineralisation of the fissure filling type. All three types of uranium mineralisation have been overprinted by tectonic movements associated with activation of the platform cover in the period 90 to 220 Ma.

INTRODUCTION

Lianshanguan uranium deposit is located 120 km south of Shenyang, eastern Liaoning province, at 40°59'N and 123°30'E (Fig.1).

The geological setting of the region is similar to other uranium-producing regions occurring in Precambrian platforms. Ground radiometry has revealed that some uranium occurrences occur near the unconformity surface separating Lower Proterozoic sequences and Archaean granite. In 1978, a uranium deposit was found having surface exposure and extensions verified by drilling.

The preliminary results of the earlier work was published by Qin Fei & Hu Shaokang (1980).

In this paper we present the results of work recently carried out which includes regional setting, petrology and geochemistry. This data has enabled further constraints to be placed on metallogenic modelling for the province.

REGIONAL GEOLOGICAL SETTING

The Lianshanguan uranium deposit is located in the transitional zone between an Archaean craton of the Northern China Platform and a Lower Proterozoic Miogeosyncline sequence (Liaohe Group) which occurs on the southern edge of the Lianshanguan Dome Anticline.

Three tectono-stratigraphic units are present in the area, namely the Archaean crystalline basement, a Lower Proterozoic meta-sedimentary sequence and an Upper Proterozoic-Phanerozoic sedimentary platform cover (Fig. 1).

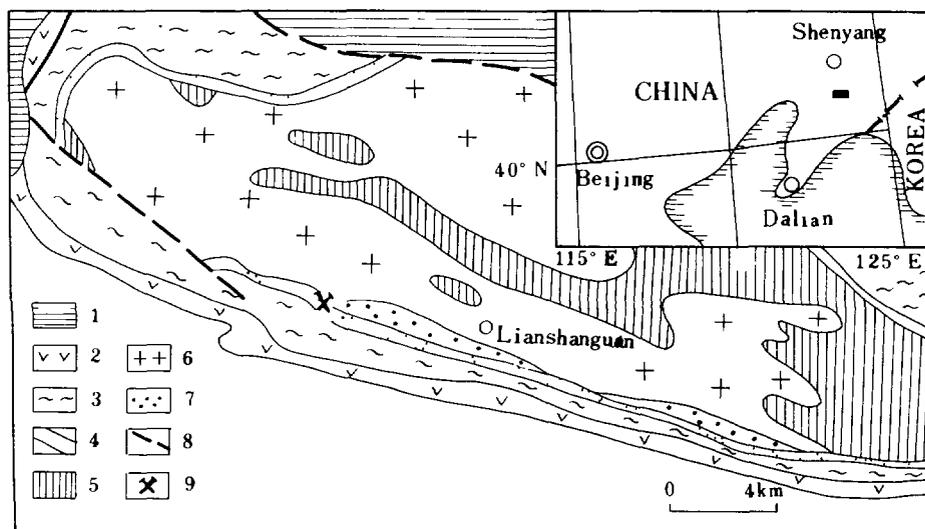


Fig. 1 Generalized geologic map of Lianshanguan region showing the location of the uranium deposit

1. Upper Proterozoic-Phanerozoic sedimentary cover

Lower Proterozoic Units

2. Metavolcanic rocks 3. Schist

4. Quartzite

Archaean

5. Metamorphic strata 6. K-granite

7. White migmatite (alkaline metasomatite)

8. Fault

9. Uranium deposit

Crystalline basement

Crystalline basement is composed of Archaean K-granite and xenoliths of Anshan Group which are distributed in the core of anticline. The dominant rock is monzogranite with lesser granodiorite. U-Pb concordia on the granitic zircon indicates an age of about 2530 Ma. The late Lower Proterozoic regional metamorphism locally produced gneissic textures in the granites and metasomatic effects were responsible for the introduction of K and Na. The older Anshan Group rocks now comprise amphibolite, chlorite-actinolite schist, granulite, banded magnetite quartzite and mica-quartzschist. Originally these rocks are thought to have been basic calc-alkaline volcanic rocks and argillo-arenaceous iron-rich sediments.

Resulting from the late Archaean intrusive event, the metamorphic units mostly occur as screens and xenoliths in the granitic rocks. The crystalline rocks and inclusions have anomalously high U-contents thus making them a potential provenance source for the uranium deposits.

Metasediment series

The Lower Proterozoic Liaohé Group, formed in miogeosyncline conditions, is widely developed in Lianshanguan area. It is distributed along the margin of the Archaean craton, and unconformably overlies it. In the Lianshanguan area, the Liaohé Group surrounds an arch anticline. The lower part of the Liaohé Group comprises metamorphosed sandstone, conglomerate, graphite-bearing biotite schist, and marble intercalated with acid volcanics. Thick-bedded carbonates intercalated with schist comprise the middle portion. The upper Liaohé Group schist and slate are intercalated with quartzite. The sediments produce a whole rock Pb-Pb isochron age of about 2185 Ma suggesting an age of deposition.

Platform type sedimentary cover

The sedimentary cover is mainly distributed in the northern part of Lianshanguan area (Fig. 1). Upper Proterozoic rocks comprise slightly metamorphic feldspathic-quartzite-sandstone, marl and shale; these are unconformably overlain by the Cambrian-Ordovician sediments with no angular discordance. The Palaeozoic rocks consist of sandstone, shale and limestone and are frequently in faulted contact with Archaean-Lower Proterozoic sequences.

EVOLUTION OF THE AREA

In the Lianshanguan area the Archaean greenstone-gneiss terrane underwent multiple metamorphism and complex deformation, with fold and fault structures well developed. Following on these tectonic events the Archaean craton underwent erosion and peneplanation. Then crust rifted in Lower Proterozoic times and a new geosyncline was developed. Initial sedimentation saw the accumulation of terrigenous coarse clastics, in which the main uranium-bearing unit occurs. The Lianshanguan area is situated in the marginal parts of the geosyncline. With increasing sedimentation marine incursion occurred in the deepening basin with pelitic and carbonate sediments being deposited.

Sedimentation terminated with a major tectonic event dated at 1900 to 1800 Ma. Metamorphism reached amphibolite facies and additional E-W trend linear folds were developed. Reactivation of the basement granites resulted in emplacement into the overlying formations. Owing to the difference in physico-mechanic properties between the crystalline rock and sedimentary strata frequent intense compressions took place along the interface of these two units. Mica-quartz schist with marked schistosity occupy the central parts of the compressed zones. The mobile elements, such as K and Na, were activated and carried in solutions to bring about metasomatism within these structural zones, thereby producing the white migmatite zone ranging in width from tens of metres to in excess of 100 m. This alkali metasomatism has controlled the location of economic uranium mineralisation in the area.

The Lianshanguan area is flanked by the Hercynian orogenic belt to the north and by the western Pacific plate in the east. Movements within these tectonic belts has resulted in the platform rocks of the Late Paleozoic-Mesozoic era, being faulted and intruded. The platform activation has resulted in movement of radiogenic lead producing galena in the environs of the Lianshanguan uranium deposit.

GEOLOGY OF THE URANIUM DEPOSITS

The Lianshanguan uranium deposit occurs in quartzite and schist at the base of Lower Proterozoic and additionally occurs in the white migmatite and altered fracture zones developed in the granite within the unconformable structural zone. The ore-bearing

horizons belong to Liaohé Group, Langzishan Formation, the total thickness of which is 300-630 m. One representative section is as follows:

Overlying beds : dolomitic marble, metamorphic volcanic rock.

Langzishan Formation :

Upper member : 9) Graphite mica schist

8) Tremolite marble intercalated with mica-schist, granulite (21 m thick)

Middle member: 7) Garnet mica schist intercalated mica-quartzite (40 m thick)

6) Feldspathic quartzite intercalated with garnet mica schist (22 m thick)

5) Graphite-staurolite-garnet mica-schist (99 m thick)

4) Garnet hornblende schist, garnet biotite schist (10 m thick)

Lower member : 3) Mica quartzose schist, staurolite-garnet-mica-schist intercalated with mica-quartzite (ore-bearing bed) (20 m thick)

2) Quartzite, feldspathic-quartzite, metamorphosed conglomerate intercalated with mica-quartzite (ore-bearing bed) (30 m thick)

1) Metamorphosed granitic sand-conglomerate (Ancient weathering mantle) (1-4 m thick).

Basement : Red granite

From the section it is apparent that the Langzishan Formation is composed of a suite of terrigenous detrital rocks, belonging to the littoral and neritic facies. The dark grey quartzite and mica-quartz schist in the second and third beds are the primary uranium-bearing units.

The main economic uranium mineralization is distributed along the metasomatite-structural zone between the Granite Complex and Lower Proterozoic metamorphic rocks (Fig. 2). The mineralized zone is concordant with the bedding, trending NW-SE and dipping to the S at angles varying from 30° to 60° . The uranium ore-bodies are located in the brecciated, jointed and deformed zone within the white migmatite, as well as in quartzite or mica-quartzite schist.

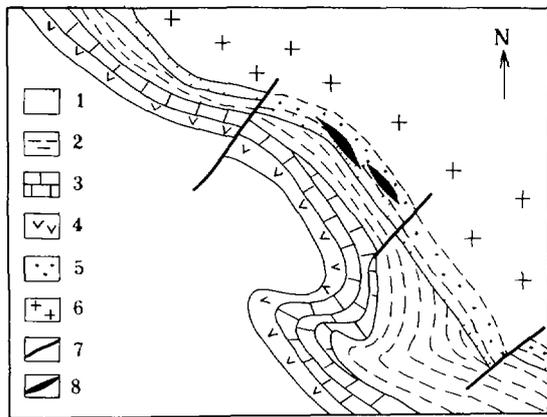


Fig. 2. Geologic map of the Lianshanguan uranium deposit

1. Quartzite
2. Schist
3. Marble
4. Metavolcanic rocks
5. White migmatite
6. K-granite
7. Fault
8. Uranium ore bodies

Table 1. Uranium mineralization characteristics

types of uranium metamorphosed mineralization	hypo-mesothermal meso-epithermal		
mineralization characters	sedimentary	metasomatic	filling
host rocks	dark grey quartzite mica quartzite biotite granulite	white migmatite	altered granite
form of ore bodies	layer, layer-like	lens, vein-like	veinlet
texture & structure	impregnated, cemented	cemented breccia, oolitic spherulitic, concentric	
economic uranium minerals	uraninite	meta-pitchblende	pitchblende
associated minerals	pyrite, galena, graphite, biotite, garnet	alkali feldspar, chlorite, muscovite, galena, pyrite	calcite, fluorite quartz galena, pyrite, hematite
wall rock alteration	unaltered	albitization, chloritization, sericitization	fluoritization, carbonatization, silicification, hematitization
temperature of mineralization	450 ^o -550 ^o C	280 ^o -250 ^o C	170 ^o -230 ^o C
U-Pb dating	2,100 m.y.	1,900 m.y.	1,830 m.y.

Types of uranium mineralization

Uranium mineralization occurs in three situations: sedimentary metamorphosed; hypo-meso hydrothermal metasomatic; and meso-epithermal filling. They differ from one another in terms of their host rocks, mineral association, texture and structure of

uranium ore, wall rock alteration, form of ore bodies and occurrence (Table 1). The major and trace elements of the host rocks in the U-deposits are shown in table 2.

(i) Metamorphosed sedimentary mineralization

The uranium mineralization of the metamorphosed sedimentary type is distributed within the structural-metasomatic zone

Table 2. Major & trace elements of host rocks in the Lianshanguan U-deposit

host rock	quartzite	urano-ferous quartzite	granite	altered granite	white migmatite	ore-bearing white migmatite
main element(%)						
SiO ₂	94.03	93.59	75.21	75.68	75.16	76.17
TiO ₂	0.06	0.06	0.11	0.08	0.13	0.14
Al ₂ O ₃	2.38	1.26	13.24	13.24	14.0	12.56
Fe ₂ O ₃	0.18	0.29	0.81	0.81	0.69	0.56
FeO	0.59	0.72	0.91	0.52	0.85	0.90
MnO	0.01	0.01	0.03	0.03	0.03	0.04
MgO	0	0	0.19	0.17	0.17	0.28
CaO	0.20	0.24	0.48	0.60	0.52	1.08
Na ₂ O	0.23	0.07	3.05	3.58	4.38	4.11
K ₂ O	0.15	0.31	5.44	4.69	3.30	2.36
P ₂ O ₅	0.02	0.04	0.20	0.13	0.17	0.09
S	0	0.66	-	-	-	-
C	0	0.02	-	-	-	-
Na ₂ O	1.53	0.23	0.56	0.76	1.33	1.74
K ₂ O						
trace elements (ppm)						
Cu	62	80	16		31	84
Zr	72	43	45		48	83
Ga	4	7	13		14	11
Cr	20	10	12		12	14
Ni	15	20	10		12	19
V	14	30	10		13	14
Pb	15	250	8.4		25	240
U	12	730	8.7		16	753
Th	7.4	34	45		37	38
Y	45	17	38		35	45

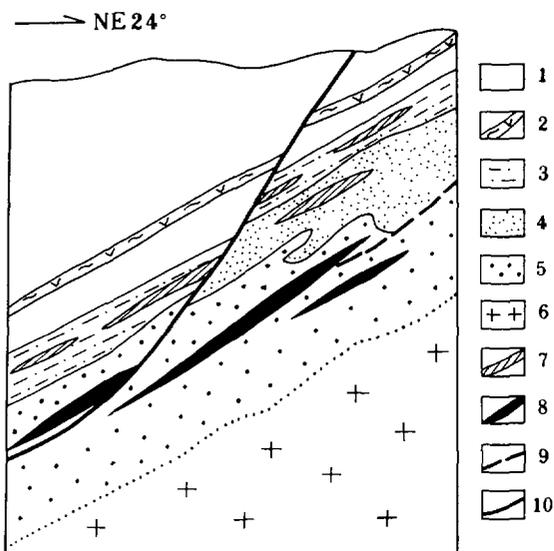


Fig. 3. Cross section of the Liashanguan uranium deposit

1. Mica schist
2. Amphibole schist
3. Interbedded zone of quartzite and schist
4. Quartzite
5. White migmatite
6. K-granite
7. Metamorphosed sedimentary uranium ore body
8. Metasomatic hydrothermal uranium ore body
9. Shear zone
10. Fault

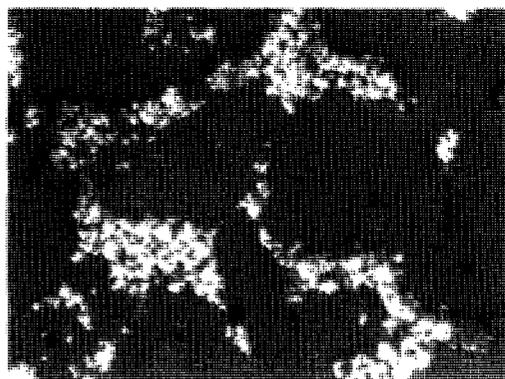


Fig. 4. Microuraninite (grey) with pyrite (white) distribute in the groundmass

(Fig. 3). The host rocks are dark-grey quartzite, mica-quartz schist and biotite granulite. Ore bodies are stratified or strataform with only moderate thickness. Generally, the ore grade is less than 0.1% U.

There is no clearly defined boundary between uranium mineralized zones and wall rock. The composition of ore is rather simple, the main economic uranium minerals are microuraninite, occurring in the voids of detrital mineral grains or in form of disseminations included in biotite, garnet, feldspar and other minerals (Fig. 4).

The chemical composition of ore-bearing and barren rocks indicates a slight enrichment of Al, K, Fe, C, S, in the mineralized rocks. A positive correlation exists between U and the total content of S and C. This correlation suggests that uranium owes its concentration to reducing and absorbent conditions. Additionally ferrous iron and pelitic material may have aided the concen-

tration process. Trace elements of both ore and wall rock zones are almost identical except for Pb which was probably produced by radioactive decay of U.

(ii) Alkali hypo-meso metasomatic mineralization

This type of uranium mineralization is strictly controlled by the structural-metasomatic zone. The ore bodies occur in the structural breccia and border fracture zone of the white migmatite, as lenses or lenticles. Ore grade is relatively rich, locally reaching 5% U. The main economic uranium mineral is meta-pitchblende occurring in colloidal form. Pentagonal and hexagonal crystal-grains are present and can be seen under high magnification (Fig. 5). The paragenetic mineral sequence is albite, K-feldspar, chlorite, muscovite, minor amount of pyrite, galena and pyrrhotite.

The original rocks comprising the white migmatite were mainly quartzite, feldspar-quartzite and granite. During the metasomatic process abundant Na and K was introduced to form sodic plagioclase and K-feldspar. Relative to the granite the white migmatite has an increased $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio (0.56 to 0.76) and with quartzite, the ratio has increased from 0.29 to 1.33 (Table 2). It shows that the alkalic metasomatising solution was enriched in sodium. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio is much higher in the ore-bearing metasomatic rock, averaging 1.74. This indicates that there is a close relationship between uranium mineralization and Na-metasomatism. Apart from the higher Pb content in the ore, the remaining trace elements show little variation within mineralized and non-mineralized zones.

(iii) Mesoepithermal filling type mineralization

This type of uranium mineralization occurs mainly within fractures of altered granite. The ore bodies form mono-veins and stockwork or reticulated-veins occur on a small scale.

The main economic uranium minerals of this type are pitchblende having spherulitic or oolitic texture. The paragenetic sequence of the opaque minerals are pyrite, galena, sphalerite and chalcopyrite; the gangue minerals are mainly composed of calcite, fluorite, quartz and sericite. The pitchblende is in close association with sulphides, dark-grey or light red calcite and dark-violet fluorite.



Fig. 5. Meta-uraninite with pentagonal and hexagonal form

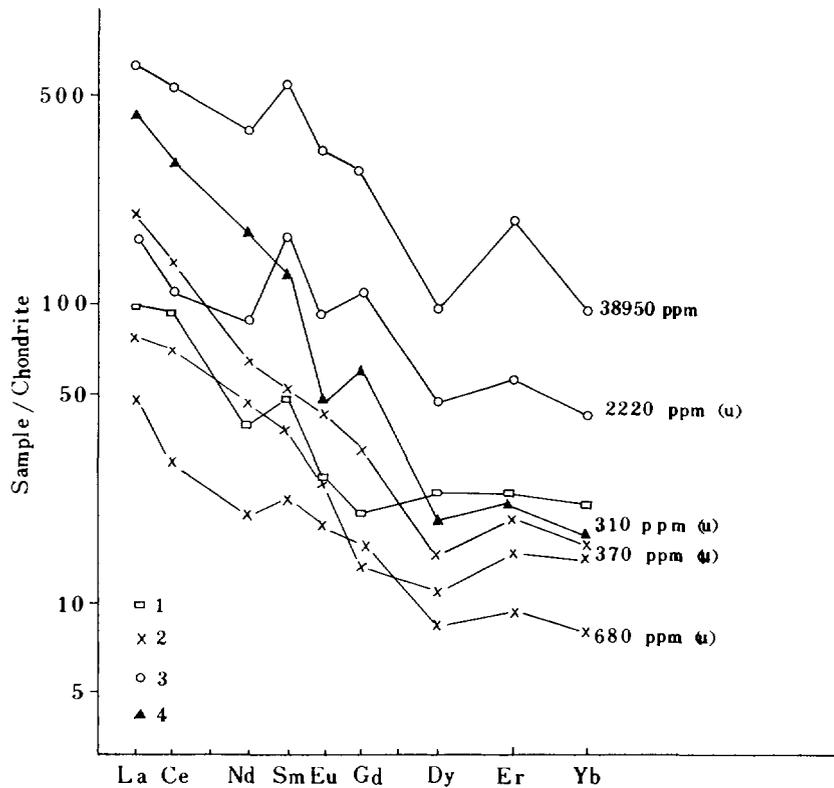


Fig. 6. Chondrite-normalized REE patterns of different genetic type uranium ore

1. Schist
2. Metamorphosed sedimentary uranium ore
3. Hydrothermal metasomatic uranium ore
4. Hydrothermal filling uranium ore

GEOCHEMISTRY

Rare-earth elements

Rare-earth elements of ore and host rocks are shown in table 3 and figure 6. The chondrite-normalized patterns of rare-earth elements of the ore-bearing quartzite, schist in Langzishan Formation and Basement Granite are quite similar. The La/Yb ratio

Table 3. Rare-earth elements of the three types of uranium mineralization (ppm)

mineralization types	metamorphosed sedimentary			hypo-mesothermal metasomatic		meso-epithermal filling
	sample no.	292	177	242	317	121
La	60.4	19.4	24.1	51.6	190.4	136.5
Ce	109.1	23.4	56	88.7	407	236.1
Pr	14.6	3.1	10.1	17.1	68.7	33.3
Nd	37.6	11.4	26.7	51.8	227.1	101.1
Sm	9.7	4.5	7.1	31.5	106	24
Eu	3.1	1.3	1.8	6.5	22.2	3.3
Gd	8.5	3.8	3.4	28.6	67.3	15
Dy	4.5	2.6	3.4	15.4	30.9	5.9
Er	4.1	1.9	3.1	11.4	41.1	4.2
Yb	3.2	1.6	3.0	8.7	19.8	3.4
Σ REE	254.8	68.5	138.7	311	1180.5	563
$\frac{\text{LREE}}{\text{HREE}}$	11.4	5.8	9.6	3.8	6.3	18.5
$\frac{\text{La}}{\text{Yb}}$	18.9	9.3	8	5.9	9.6	40.1
$\frac{\text{Eu}}{\text{Eu}^*}$	1.13	0.94	1	0.66	0.76	0.5
U	370	740	680	2220	38950	310

is between 8 and 15 indicating enrichment in the light rare-earth elements. The reason for the Eu-anomaly is unclear. There are some differences between the REE patterns of ore-bearing rocks and normal quartzite and schist. The ore zones have lower REE concentrations. Usually with uranium increase there is a reduction of REE content probably because uranium is concentrated in the fine grained detrital rocks with only minor amounts of heavy minerals.

The REE pattern within ores of the hydrothermal-metasomatic type are similar. The higher the uranium content, the more abundant are the REE. The fractionation of light rare-earth elements is poor, the La/Yb ratio is between 4 and 10, and drops as the uranium content rises.

Although there is a low uranium content in the ore of the hydrothermal filling type of mineralization the REE content is

relatively high with the La/Yb ratio reaching 40. It would appear that the low temperatures associated with this type of mineralization results in light REE enrichment.

Sulfur Isotopes

The sulfur isotopes of pyrite, both in the ore and sundry wall rocks, indicate that the uranium mineralization has characteristics of both sedimentary metamorphism and metamorphosed hydrothermal alteration (Fig. 7).

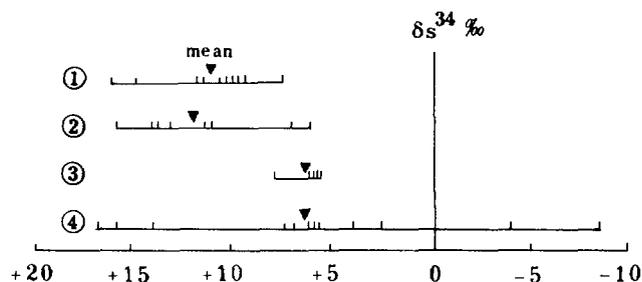


Fig. 7. Sulfur isotope composition of the pyrite in host rocks and uranium ore

1. Pitchblende vein
2. White migmatite
3. Uranium-bearing quartzite and schist
4. Quartzite and schist

$\delta^{34}\text{S}$ of pyrite, present in quartzite or schist, varies from -8.4% to +16.8%; the average value is +6.1%. The fact that the $\delta^{34}\text{S}$ range is similar to sulfate present in palaeo-marine waters suggests a similar origin. The pyrite associated with uranium minerals in the ore-bearing quartzite has an average $\delta^{34}\text{S}$ of +6.3%. This is about the same as the wall rock values found in the quartzite host suggesting a sedimentary origin for this type of uranium mineralization.

The $\delta^{34}\text{S}$ of pyrite in the white migmatite and vein filling type uranium mineralization all have positive values. This indicates that the sulfur does not come from a deep source, but is probably derived from the reconstituted country rocks; the associated uranium is also probably derived from the wall rocks having been mineralized after hydrothermal metasomatism.

U-Pb Radiometric isotopes

U-Pb isotope dating shows that the Lianshanguan uranium deposit is a product of multistage mineralization. Three diff-

erent metallo-genetic ages of uranium mineralization can be dated. The age of metamorphosed sedimentary uranium mineralization is 2114^{+129}_{-122} Ma. The alkalic metasomatic stage is dated at 1891^{+79}_{-71} Ma; and the hydrothermal filling stage at 1829^{+33}_{-30} Ma. The last two ages approach the model U-Pb age of the three stages of the white migmatite (1917 ± 77 Ma). Additionally the three types of uranium mineralization have all been overprinted by tectonic movements associated with activation of the platform during the period 90 to 220 Ma.

FLUID INCLUSIONS

The formation temperature of the vein pitchblende has been measured by the decrepitation method, and by the homogenization temperature of fluid inclusions in fluorite, calcite and quartz associated with the pitchblende. The decrepitation and homogenization temperatures of these minerals could be divided into two groups. The first is 280° - 350° C found in the hypo-mesohydrothermal minerogenesis, this represents the formation temperature of alkalic metasomatic U-mineralization. The mineral association of which is meta-pitchblende, alkali feldspar, quartz and small amounts of sulfides. The second is 160° - 230° C occurring in the meso-epithermal minerogenesis, this represents the formation temperature of hydrothermal filling uranium mineralization. The main mineral associations here are pitchblende, calcite fluorite and microcrystalline quartz.

METALLOGENETIC CONTROLS

As stated above, the formation of Lianshanguan uranium deposit underwent complex processes, it is controlled by sedimentation, regional metamorphism, structural movement and metasomatism. The major control factors are different for the various mineralization types; these controls can be generalized as follows:

Uranium source

The U abundance and U-extracting rate of the main hosts in this region are arranged in tables 4 and 5 and in figure 8. It shows that the U contents of these rocks are all higher than average crustal abundances. The U abundance of quartzite and that of the white migmatite are especially high, they also have high U-extracting rates. This suggests that there is a high degree of

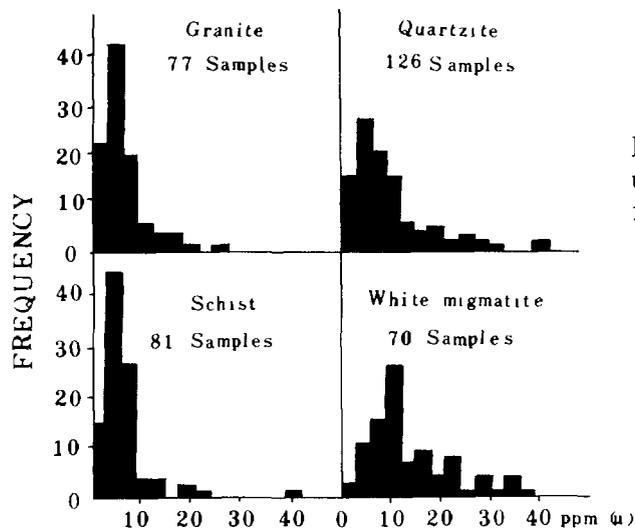


Fig. 8. Histogram of the uranium content of the main host rocks.

Table 4. Uranium content of the main host rocks

lithology	number of samples	average content of uranium(ppm)	mean square deviation(6X)
granite	77	6.25	4.50
schist	81	6.65	5.60
quartzite	126	10.20	8.72
white migmatite	70	14.36	8.84

Table 5. Uranium extracting rate of main host rocks

lithology	uranium(ppm)	extracting rate(%)	extracting condition
granite	9.2-14	6.0	in normal temperature and 1% Na ₂ CO ₃ solution, the ratio of sample to solution is 1:10
schist	16	14.1	
quartzite	21.0-88	23.1	
white migmatite	19-130	28.4	

mobilized uranium in these rocks. As the basement granite and ore-bearing hosts in this region also have high U contents it is apparent that the area was anomalously enriched in uranium. The basement granite, undergoing a long period of weathering and erosion, provided the uranium source for the formation of syngenetic U-bearing horizons in the basal members of the Lower Proterozoic. Economic uranium grades were produced during metamorphism and metasomatism.

Sedimentation

Most of the uranium occurrences in the region are localised in terrigenous detrital rocks of the Langzishan Formation which has stratabound characteristics. This uranium-bearing formation was deposited on the margins of the Archaean craton under miogeosyncline conditions during Lower Proterozoic times. The Langzishan Formation unconformably overlies the basement granite complex, belonging to the lower part of a transgressive cycle. This Formation, although widely distributed, only has uranium concentrated where the lithologic lithofacies and palaeogeographic conditions are favorable.

The spatial distribution of the original horizons, rich in uranium, is controlled by the base trough near shoreline conditions. In the late Archaean, the basement granitic complex was exposed to the surface and underwent peneplanation. On the peneplain surface local rivers scoured troughs which controlled the thickness and lithofacies of the U-bearing horizons. In general, the Lianshanguan deposit is located in a NS striking basal trough with better uranium values mainly distributed in the centre and eastern slope of the trough (Fig. 9).

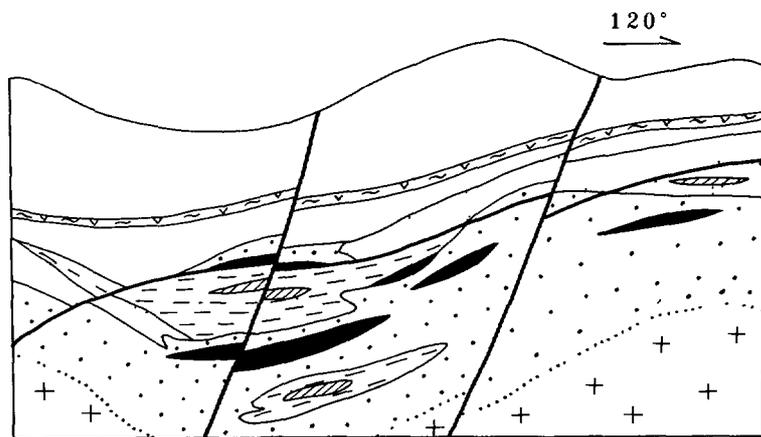


Fig. 9. Longitudinal section of the Lianshanguan uranium deposit (symbols as in figure 3)

The interbeds of sandstone and argillite in the base trough are the favourable lithofacies for formation of horizons rich in uranium. The meta-sedimentary uranium mineralization in the Lianshanguan deposit is present mainly in black-grey quartzite and mica-quartz schist developed in the basal part of Langzishan Formation. Where the ratio of quartzite thickness to the total thickness of the ore-bearing zone is less than 35%, uranium

grades improve. Where this ratio is higher than 50% mineralization is poor. All this suggests that the sedimentary lithofacies exerted a controlling role in the distribution of uranium mineralization. The change of sedimentary facies is strongly controlled by the paleogeographic environment. In the uplifted parts the thick-bedded macroclastic sediments occur in an oxidizing environment, which was unfavorable for uranium precipitation and concentration. In the distal facies of the basal trough argillic and sandy sedimentary beds were produced. This zone lies in a transitional redox environment, that was favorable for uranium precipitation and concentration. Also these interbedded sandstones and argillites produced permeable and impermeable layers, which was advantageous to the circulating of U-bearing ground water resulting in further uranium precipitation.

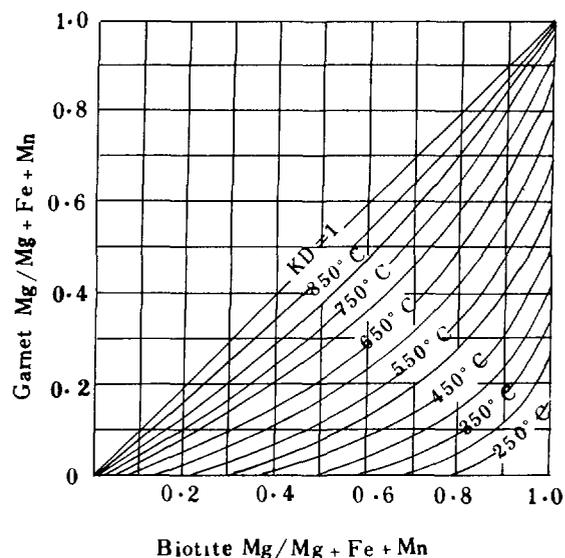
Those lithologies rich in reducing mediums resulted in local uranium concentration. The U-bearing hosts of the Lianshanguan deposit are rich in clays, carbonaceous matter and pyrite and possess a dark colour. These rocks have a sulfur content of 0.05-0.98%, 0.05-0.74% in organic carbon; a positive correlation is present between U and the total amount of S and C. This suggests that U-bearing horizons were formed under weak reducing conditions.

Regional metamorphism

The ore-bearing rocks in the region have undergone a low to medium grade of regional metamorphism. The metamorphic grade was favorable for uranium concentration, with the lower grade metamorphic rocks being a favorable place for the production of meta-sedimentary uranium mineralization.

The main metamorphic mineral associations of the ore-bearing strata are staurolite-almandine-biotite-muscovite-quartz and muscovite-biotite-plagioclase-quartz, which belong to the greenschist facies or almandine-staurolite subfacies of the amphibolite facies. The Mg/Mg+Fe+Mn distribution coefficient (Fig. 10) of the biotite-garnet mineral pair in the rocks suggests a temperature of formation of about 500^o-550^oC at a pressure of 5-10 kb. Hydrothermal solutions associated with this metamorphism reconcentrated the syngenetic uranium to form micro-grained uraninite, which is held in the metamorphic silicate minerals, or distributed along mineral grain boundaries and cracks. As a result of metamorphism the meta-sedimentary uranium deposits were formed from original syngenetic concentrations.

Fig. 10. Relationship between distribution coefficient of Mg/Mg+Fe+Mn for the garnet-biotite pair



Tectonic condition

Tectonism was an important controlling factor of the distribution of uranium in the Lianshanguan uranium deposits. Tectonic movements associated with late Lower Proterozoic times resulted in structural deformation characterized by plastic flow. In the course of plastic fold deformation, tectonic emplacement of the reactivated basement granite took place along the folding axis to form the Lianshanguan arch anticline. At a late-stage of granite emplacement compressive fractures were formed along the contact zone between the granite and meta-sedimentary rocks and also parallel to folding axes. These faults possess characteristics of multistage activation, which were welded or filled by white migmatite in the early stage and subjected to brittle faulting in the later stage that gave rise to fractures and crush zones. These fractures provide the passageway for uranium-enriched fluid migration. These zones are the favorable sites for the hydrothermal rich ore bodies. The major economic orebodies of the deposit are located in strike faults and interstratified fracture zones (Fig. 3). The main ore-zones are brecciated and developed in areas where the dip changes from gentle to steep; the crushed zones of the elongated belt of white migmatite formed along interstratified fracture zones. Other structure forms such as schistosity, gneissosity and micro-cracks are also favorable sites for uranium concentration.

Migma-metasomatism and alkalic hydrothermalism

The hydrothermal uranium mineralization in this region is spatially closely related to the alkalic metasomatism that produced the white migmatite. The main expressions are:

- a) Hydrothermal uranium mineralization occurring in the inner structural breccia zones or border fracture zones of the white migmatite. Pitchblende is especially in close association with the late fine-grained albite. The correlation between U and Na is positive.
- b) The paragenetic association of minerals and trace elements of ore-bearing and non ore-bearing white migmatites is essentially similar. The composition of uranium ore is rather simple, apart from the higher content of U, Th, Pb and REE no other metallogenic elements display enrichment.
- c) The uranium metallogenic age is similar to the age of the white migmatite. U-Pb dating of white migmatite is 1,917 Ma, and the age of alkalic hydrothermal metasomatic uranium mineralization is 1,891 Ma.
- d) The formational temperature of pitchblende is between 250^o-350^oC, belonging to the range of hypo-mesothermal hydrothermalism.

The above information suggests that the hydrothermal uranium mineralization has characteristics of succeeding to and evolving from the migma-metasomatic solution in respects of time, space, composition and temperature. The metallogenic hydrothermal solution was derived from the alkalic migmatite solution in its post-migmatitic metasomatic stage. The controlling role of migma-metasomatism alkalic hydrothermalism in uranium mineralization can be summarized as follows:

- a) The migmatization in this region was generated during the regional metamorphism in the late Lower Proterozoic era. In the late stages of regional metamorphism reactivation of the basement granitic complex resulted in mobilisation of elements such as K, Na and U. This metasomatism occurs on both sides of the contact zone and forms the primary alkalic U-bearing fluid facies (migmatitic solution).

The migration of this alkalic U-bearing fluid through the fracture zones resulted in wall rock metasomatism and extraction of uranium. The U-bearing primary alkalic solution became concentrated in local parts of the white

migmatite (e.g. uranium content and extracting rate of white migmatite in Lianshanguan deposit are all higher than those of other rocks). These solutions became further enriched in uranium to form the late alkalic solutions, thus acting as a rich uranium source for the hydrothermal uranium mineralization.

- b) The Na-bearing alkalic hydrothermal solution formed in the post-migma-metasomatic stage, uranium could be carried in the form of a carbonate uranyl complex. The higher the pH of the solution, the more stable this uranyl complex became. A favorable depositional site could have been produced by decreasing temperature and pressure, changing redox conditions, reducing of pH (caused by separating alkalic metal from solution in the process of alkalic metasomatism). The uranyl complex could be uncoupled under these circumstances with reduction taking place producing pitchblende.
- c) Migmatitic or hydrothermal alkalic metasomatism of the area is mainly represented by the replacement of potassium by sodium. Because the ion radius of sodium is smaller than that of potassium, the equal-ion replacement of K by Na resulted in an increase in void space within the minerals resulting in higher porosity of the rocks, and a permeable spongy texture. It is suggested that inhomogeneity resulting from metasomatism led to a reduction in the mechanical strength of the rocks allowing them to be easily fractured and thereby forming favorable structural traps for uranium mineralization.

THE SUGGESTED GENETIC MODEL

Petrogenetic modelling of the uranium mineralization at the Lianshanguan deposit can be summarised as follows:

After the late Archaean orogeny, the uranium enriched metamorphic rocks and granite complex underwent weathering and erosion. Labile uranium was leached out from these rocks and carried by runoff into the offshore basal trough. The uranium was fixed by absorption on clays and reduced by carbonaceous matter, pyrite and changing redox conditions to form low-grade

syngenetic uranium concentrations in the basal part of the Lower Proterozoic psammitic sequence. Subsequently the rocks were metamorphosed during the late Lower Proterozoic to greenschist amphibolite facies. Part of the syngenetic uranium was mobilised during metamorphism and concentrated to form the meta-sedimentary type of mineralization.

Late-orogenic granite emplacement took place during the regional and metamorphic event. This event produced a series of compressive faults and interstratified fracture zones paralleling the granite contact. During this tectonism uranium-bearing alkali migmatitic solutions were produced. These metasomatising solutions migrated along fracture zones and replacement of the wall rocks took place to form an elongated belt of white migmatite. In this process, alkali solution extracted uranium from the surrounding rocks; with precipitation of some K and Na the uranium became enriched. These solutions further evolved into the uranium-rich post-migmatitic alkalic hydrothermal solutions. In these hydrothermal solutions uranium was transported as the carbonated uranyl complex. Under suitable physiochemical conditions uranium was precipitated in fracture systems producing the alkalic hydrothermal metasomatic type of mineralisation.

After formation of the alkalic metasomatic uranium mineralization, the residual hydrothermal solution migrated to lower pressure regimes. With falling temperature, and separating out of the alkalic metals, the solutions evolved became weakly acid and formed meso-epithermal mineralization of the fissure filling type. These deposits are characterised by the mineral association sulfide-pitchblende or fluorite-pitchblende found in tension cracks far removed from the original thermal source.

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PINE CREEK GEOSYNCLINE, N.T.

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Abstract

The Pine Creek Geosyncline comprises about 14 km of chronostratigraphic mainly pelitic and psammitic Early Proterozoic sediments with interlayered tuff units, resting on granitic late Archaean complexes exposed as small domes. Sedimentation took place in one basin, and most stratigraphic units are represented throughout the basin. The sediments were regionally deformed and metamorphosed at 1800 Ma. Tightly folded greenschist facies strata in the centre grade into isoclinally deformed amphibolite facies metamorphics in the west and northeast, granulites are present in the extreme northeast. Pre and post-orogenic continental tholeiites, and post-orogenic granite diapirs intrude the Early Proterozoic metasediments, and the granites are surrounded by hornfels zones up to 10 km wide in the greenschist facies terrane. Cover rocks of Carpentarian (Middle Proterozoic) and younger ages rest on all these rocks unconformably and conceal the original basin margins.

The Early Proterozoic metasediments are mainly pelites which are commonly carbonaceous, lesser psammites and carbonates, and minor rudites. Volcanic rocks make up about 10 percent of the total sequence. The environment of deposition ranges from shallow-marine to supratidal and fluviatile for most of the sequence, and to flysch in the topmost part.

The Early Proterozoic strata are overlain with marked angularity by mostly subhorizontal fluviatile sandstone and basalt of Middle to Late Proterozoic age. A veneer of Mesozoic and Cainozoic sediments conceals much of the Early Proterozoic sequence, particularly in coastal areas.

The uranium deposits post-date the ~1800 Ma regional metamorphic event; isotopic dating of uraninite and galena in the ore bodies indicates ages of mineralisation at ~1600 Ma, ~900 Ma and ~500 Ma. The ore bodies have a number of features in common; they are stratabound, located within breccia zones, are of a shallow depth, contained in rocks that underwent low-temperature retrogressive metamorphism and metasomatism, and occur immediately below the Early/Middle Proterozoic unconformity. It is suggested that these ore bodies were produced by downward percolating meteoric waters transporting uranyl complexes which due to reducing conditions in the breccia zones precipitated uranium oxide.

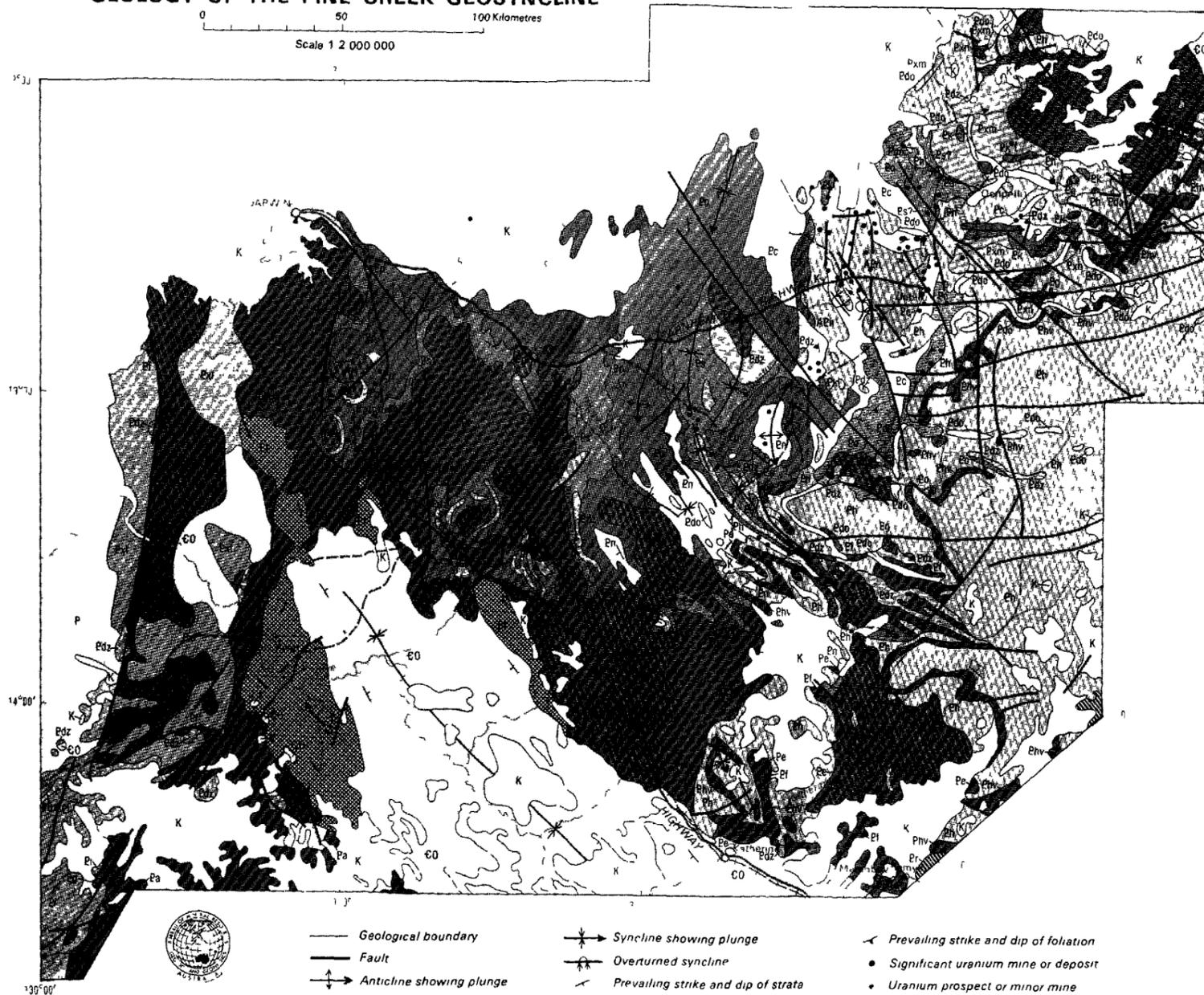
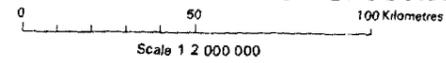
As continental crustal development in post-2,200 Ma times appears mainly to follow uniformitarian lines, the only variable which could explain the concentration of vein-type uranium in the 2,200-1,700 Ma period appears to be a steadily evolving atmosphere. It is suggested that during these times the hydrosphere was sufficiently oxidising for uranyl transport, but that rapidly reducing conditions were met short distances into the lithosphere. Reduction resulted in precipitation of uranium as UO_2 from meteoric water into suitable structural traps, which were largely developed during periods of prolonged erosion. The structural traps may also have been active during the early sedimentation of the Middle Proterozoic cover rocks. Rapid development of impermeable cover rocks preserved the uranium deposits.

INTRODUCTION

The Pine Creek Geosyncline is a roughly triangular area of about 66 000 km² south and east of Darwin, which contains Early Proterozoic metasediments, dolerite and granite interspersed with minor granitoid Archaean basement domes. It is surrounded by younger sedimentary basins from Middle Proterozoic to Mesozoic in age, and is mantled in many parts by Cainozoic deposits. The economic uranium occurrences define 3 fields, the Rum Jungle and Alligator Rivers fields each centred on inliers of Archaean basement, and the South Alligator Valley field in an area of extensive dip-slip faulting (Fig. 1).

Of the present known reserves of vein-type uranium in the western world, approximately 90% are confined to rocks of Proteroz-

GEOLOGY OF THE PINE CREEK GEOSYNCLINE



CRETACEOUS	K	Sandstone siltstone
PERMIAN	p	Siltstone sandstone minor limestone conglomerate
CAMBRIAN ORDOVICIAN	CO	Limestone sandstone siltstone basalt conglomerate
FITZMAURICE GROUP		Sandstone shale siltstone dolomite conglomerate
AUVERGNE GROUP		Siltstone shale sandstone minor dolomite
BULLITA GROUP		Siltstone minor dolomite
TOLMER GROUP		Sandstone dolomite siltstone
MOUNT RIGG GROUP		Sandstone conglomerate limestone
KATHERINE RIVER GROUP		Sandstone minor limestone siltstone and conglomerate Interbedded intermediate to basic volcanics
OENPELLI DOLERITE	Edo	Olivine dolerite and differentiates
EDITH RIVER VOLCANICS		Acid and minor basic volcanics pyroclastics sandstone
HERMIT CREEK METAMORPHICS		Granite adamellite granodiorite minor syenite
MYRA FALLS METAMORPHICS		Schist gneiss amphibolite migmatite
LITCHFIELD COMPLEX		Pelitic schist lit par lit gneiss
NIMBUWAH COMPLEX		Granite granodiorite pegmatite migmatite
NOURLANGIE SCHIST		Migmatite granite granodiorite
ZAMU DOLERITE		Quartz schist
FINNISS RIVER GROUP		Dolerite and differentiates amphibolite in east
SOUTH ALLIGATOR GROUP		Siltstone greywacke sandstone acid to basic lavas pyroclastics
MOUNT PARTRIDGE GROUP		Carbonaceous and ferruginous shale with chert bands carbonate tuff andesite bit
CAHILL FORMATION	Ec	Sandstone siltstone shale quartzite arkose conglomerate dolomite schist and gneiss in east
NAMOONA GROUP	En	Schist gneiss quartzite carbonaceous with carbonate and calc silicate gneiss in lower part
MANTON GROUP	Em	Calcareous and carbonaceous shale sandstone limestone dolomite arkose conglomerate schist and marble in east
KAKADU GROUP		Magnesite dolomite conglomerate arkose sandstone
NANAMBU COMPLEX		Leucogneiss quartzite schist
RUM JUNGLE COMPLEX		Leucogranite migmatite gneiss granite schist
WATERHOUSE COMPLEX		Gneiss granite schist metasediments Granite gneiss amphibolite migmatite dolomite metasediments



- Geological boundary
- Fault
- ↕ Anticline showing plunge
- ↘ Syncline showing plunge
- ↗ Overturned syncline
- ↖ Prevailing strike and dip of strata
- ↙ Prevailing strike and dip of foliation
- Significant uranium mine or deposit
- Uranium prospect or minor mine

oic age. If this skewness is real, a unique set of conditions is required to account for it.

The development of uranium in quartz-pebble conglomerates, confined as they are to the period 2,800-2,200 Ma (Robertson, 1974), has been ascribed to changing plutonic activity in the period 3,000-2,700 Ma (Moreau, 1974) as well as to the prevailing atmospheric conditions (Simpson and Bowles, in press). Development of quartz-pebble conglomerate uranium deposits thus coincides with major tectonic changes corresponding to the first development of stabilised cratons and ensuing development of intracratonic sedimentary basins (Glikson, 1979; Sutton, 1979). This tectonism, coupled with the first development of algal colonies (Nagy et al., 1976) created a favourable set of conditions for the formation of quartz-pebble conglomerate uranium deposits (Pretorius, 1975).

If, however, we look at the post-2,200 Ma period, which also corresponds to the first extensive development of red beds (Cloud, 1976), there does not appear to be any unique geological and/or chemical conditions to account for the original concentration of vein-type uranium deposits within the 2,200-1,700 Ma time span.

Our studies of vein-type uranium deposits in the Proterozoic have been confined mostly to those within the Lower Proterozoic sequence of the Pine Creek Geosyncline. Using this area as our type-model, we have attempted to account for the extensive development of vein-type uranium deposits originally formed within the time span 2,200-1,700 Ma.

REGIONAL GEOLOGY

Up to 14 km of Early Proterozoic metasediments with interbedded volcanics and mafic sills are preserved in a layercake sequence which generally thins westwards (Fig. 1; Table 1). A regional metamorphic event between 1870 and 1800 m.y. metamorphosed the strata to mainly greenschist facies; however, amphibolite and minor granulite facies dominates in the northeast, in the Alligator Rivers region. Proven Archaean rocks are restricted to mainly granite-gneiss of the Rum Jungle, Waterhouse and Nanambu Complexes, which form mantled gneiss domes near the presently exposed western and eastern margins of the inlier.

TABLE 1. SUMMARY OF ARCHAEOAN TO MIDDLE PROTEROZOIC STRATIGRAPHY OF THE PINE CREEK GEOSYNCLINE

	Unit	Lithology	Thick- ness (m)	Age (Ma)
MIDDLE TO LATE PROTEROZOIC	MINOR DOLERITE	quartz dolerite dykes and small plug-like bodies		1200 ± 35
	MUDGINBERBI PHONOLITE MUNMARLARY PHONOLITE	phonolite dykes	1	1316 ± 50
	TOLMER GROUP	sandstone, dolomite, siltstone	1000	
	KATHERINE RIVER GROUP	sandstone, conglomerate, minor greywacke, siltstone. Interbedded basalt-andesite volcanics and pyroclastics	1200	1648 ± 29 (basalt)
late EARLY PROTEROZOIC TRANSITIONAL IGNEOUS ACTIVITY -1870-1650 Ma	OENPELLI DOLERITE	layered tholeiitic dolerite lopoliths	<250	1688 ± 13
	EDITH RIVER GROUP	ignimbrite, microgranite, rhyolite, minor basalt and cherty sediments; basal sandstone, arkose	1200	1808 ± 8 (ignimbrite)
	POST-OROGENIC GRANITE EMBLACEMENT	biotite granite, adamellite, syenite, granodiorite (numerous plutons)		1730 - 1800
	EL SHERANA GROUP	rhyolite, greywacke, siltstone, sandstone, basalt		
	MYRA FALLS METAMORPHICS & NOURLANGIE SCHIST	layered schist, gneiss (metamorphosed and partly migmatized Early Proterozoic sediments)		1800
	NIMBUWAH COMPLEX	granitoid migmatite, granite, gneiss, schist (anatexis of Early Proterozoic granite)		1803 - 1870
	ZAMU DOLERITE	layered tholeiitic dolerite sills and minor dykes	<2500	1914 ± 170
EARLY PROTEROZOIC SEDIMENTATION -1870-2400 Ma	FINNISS RIVER GROUP (flysch)	siltstone, slate, shale, greywacke, arkose quartzite, schist, minor interbedded volcanics	1500- 5000	
	SOUTH ALLIGATOR GROUP (shallow marine chemical, volcanic)	pyritic black shale and siltstone, chert-banded and nodulated hematitic siltstone and black shale, algal carbonate, banded iron formation, jaspillite, tuff, greywacke near top	<5000	1884 ± 3 (dacite)
	MOUNT PARTRIDGE GROUP (fluvial, near- shore chemical, supra- tidal)	sandstone, siltstone, arkose, shale, conglomerate, quartzite, carbonaceous siltstone & shale, dolomite, magnesite; minor interbedded volcanics	<5000	
	CAHILL FORMATION (supratidal, fluvial)	quartz schist, pelitic and partly carbonaceous near base with lenses magnesite	3000	
	NAMOONA GROUP (shallow marine, chemical, detrital, supratidal)	pyritic carbonaceous shale and siltstone calcareous in places, calcareous sandstone, tuff, agglomerate; arkose, sandstone and massive dolomite in west.	<3500	
	KAKADU GROUP (fluvial)	sandstone, arkose, siltstone, conglomerate, quartzite, schist, gneiss	-1000	
ARCHAEOAN BASEMENT	NANAMBU COMPLEX	granite, augen gneiss, leucogneiss, minor quartzite and schist (includes accreted Early Proterozoic metamorphics)		1800 (gneiss) -2500 (granite)
	RUM JUNGLE COMPLEX WATERHOUSE COMPLEX	coarse, medium, and porphyritic adamellite, biotite-muscovite granite, migmatite, gneiss, schist, pegmatite, meta-diorite, banded iron formation		2500

The higher grade metasediments grade northeastwards into the migmatitic Myra Falls Metamorphics, where in places sedimentary 'resisters' indicate the sedimentary parentage and allow correlation with the un-migmatized terrane. The intensity of folding also increases generally towards the northeast - tight to isoclinal folds with steep limbs in the central parts progress through overturned tight to isoclinal folds to polyphase isoclinal folds in the Alligator Rivers region. In the extreme northeast pre-

orogenic granite was partly migmatized along with the surrounding metasediments.

The metamorphics are unconformably overlain by valley-fill felsic volcanics and pyroclastics and these are intruded by post-orogenic granites and dolerite. All these rocks are overlain with marked regional unconformity by Middle and Late Proterozoic plateau sandstone and volcanics.

Basement Complexes

Archaean ages are established for the Rum Jungle and Waterhouse Complexes in the western part of the Geosyncline, and for parts of the Nanambu Complex in the east (Page, 1976; Page et al., 1980; Richards et al., 1977). Walpole et al., (1968) interpreted the Litchfield Complex and Hermit Creek Metamorphics, in the extreme west, as wholly or partly Archaean; little isotopic work has been done on these rocks, but Berkman (1980) reports muscovite-biotite schist in the Litchfield Complex as a probable correlative of the Burrell Creek Formation (topmost unit in the geosynclinal pile), and Needham et al., (1980) suggest that granites in the Complex have some features in common with the migmatitic granites. Page (1980) indicates that the Rb-Sr systematics of the Litchfield Complex are similar to those of the 1870-1800 Ma Nimbuwah Complex.

Rum Jungle and Waterhouse Complexes

The Rum Jungle and Waterhouse Complexes are roughly oval granite-gneiss domes up to 400 km² in the west of the Geosyncline. They are the dominant rock units in the Rum Jungle district, with anomalous concentrations of uranium (12 and 13 ppm respectively, Ferguson & Winer, 1980). Each Complex contains several granite and gneissic granite phases with veins and dykes of pegmatite and amphibolite and tourmaline veins. Metasediments, banded iron formation, volcanics and metabasics in the Complexes are thought to pre-date the granites. On field relationships the leucocratic granite of the Rum Jungle Complex is considered to be the youngest phase; this rock type gives an age of about 2400 Ma (Richards & Rhodes, 1967; Page et al., 1980). Rhodes (1965) compared the Rum Jungle Complex to a mantled gneiss dome; Stephansson and Johnson (1976) suggested that both Complexes were domed by solid-state diapiric intrusion of granite during the 1870-1800 Ma orogeny.

Nanambu Complex

Rocks of this Complex are poorly exposed over an area of about 45 km by 80 km between the South and East Alligator Rivers in the northeast of the Geosyncline. Needham & Stuart-Smith (1980) defined three groups of rocks in the Complex: Archaean two-mica granite; porphyroblastic foliated biotite granite and augen gneiss which is Archaean granite metamorphosed by the 1870-1800 Ma event; and pegmatoid leucocratic gneiss, migmatite and schist which is Early Proterozoic arkosic material accreted to the granitic Complex at 1870-1800 Ma. Field distinction of the 3 phases is not always clear. The age relationships of the phases were indicated by isotopic dating techniques (Page et al., 1980). On the southern and western margins of the Complex the leucocratic gneiss may contain resisters of Early Proterozoic quartzite, and the leucocratic gneiss grades out into meta-arkose of the Early Proterozoic metasedimentary sequence.

The Nanambu Complex is a likely source of uranium for the Alligator Rivers area uranium deposits, as the two-mica Archaean granite gneiss is known to contain accessory uraninite (McAndrew & Finlay, 1980). Mean uranium content is 9 ppm U (Ferguson & Winer, 1980).

Geosynclinal sedimentation

The stratigraphy of the Early Proterozoic sediments and interbedded volcanic rocks is summarised in table 1, and diagrammatic relationships are shown in figure 3.

At least 14 km of sediments and volcanics were deposited in parts of the basin. The margins of the basin are concealed by younger strata, so the size of the basin is unknown. The basin is probably continuous under cover with other Early Proterozoic sequences in northern Australia such as the Arnhem, Tennant Creek, Granites-Tanami and Arunta Blocks (Fig. 2). Sedimentation took place between 2400 Ma (the age of the youngest basement rocks) and 1870 Ma (the age of pre-metamorphic granodiorites) in the northeast (Page et al., 1980). Volcanics interbedded with the sediments (in the South Alligator Group) yield an age of about 1890 Ma (R.W. Page, pers. comm. May 1983). The sediments are mainly pelites, which are commonly carbonaceous and/or pyritic and/or calcareous at depth. Other lithologies present are sandstone, crystalline carbonate, calcarenite, tuff and conglomerate.

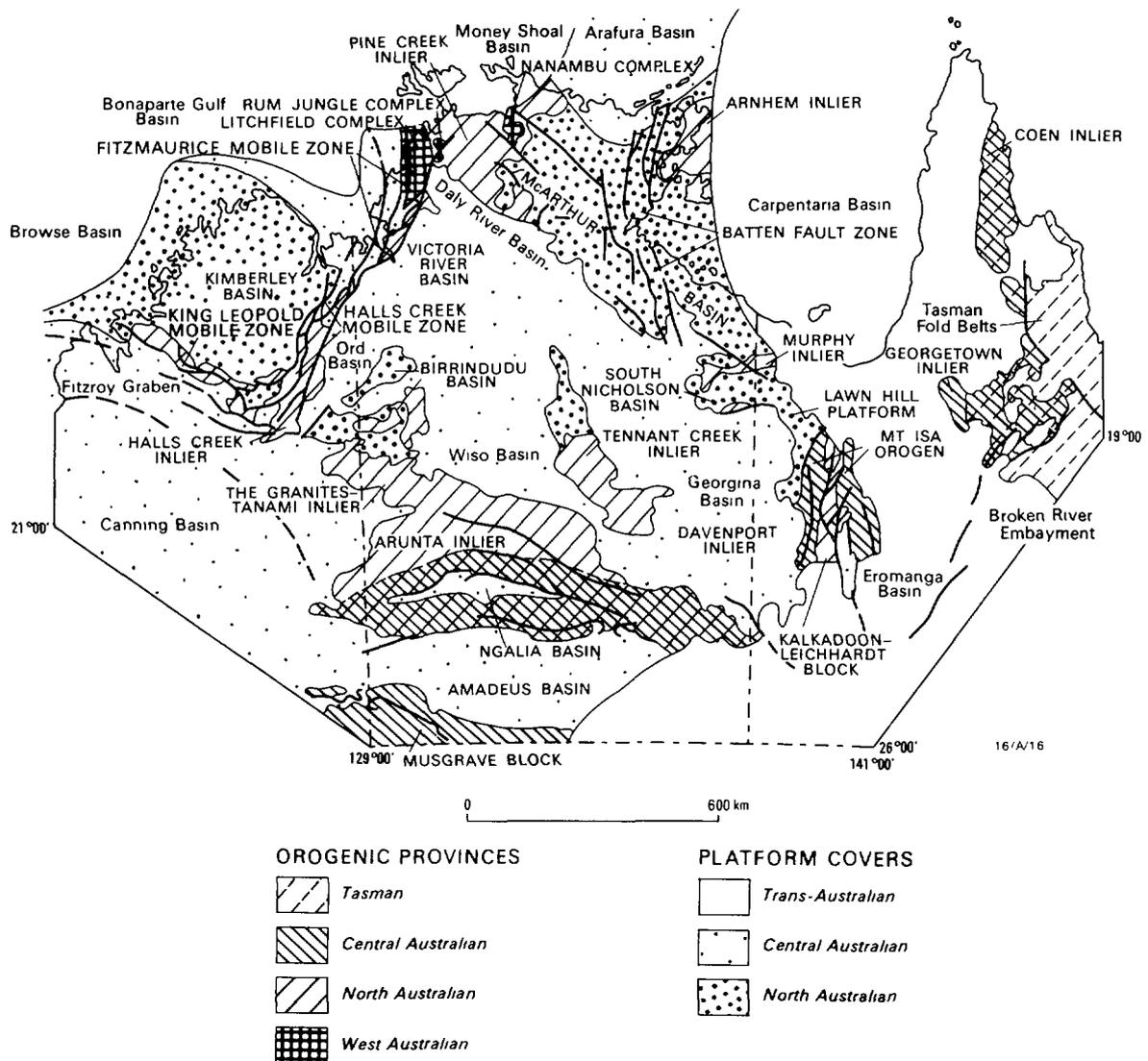


Fig. 2 Principal tectonic elements, northern Australia (Plumb et al., 1981).

The psammitic units are mainly fluviatile. The provenance of the Namooona and Kakadu Group psammities was probably the adjacent basement complexes, whilst grainsize distribution suggests a northern provenance for the Mount Partridge Group, and a western source for the Finnis River Group (Stuart-Smith et al., 1980). Widespread algal carbonate and evaporite pseudomorphs indicate mainly very shallow to supratidal environments for the carbonates (Crick & Muir, 1980). The pelites were probably deposited in neritic conditions, and the greywackes may represent tectonic deepening of the basin heralding the 1870-1800 Ma event.

Sedimentation took place in an intracratonic basin covering at least 100 000 km². The earliest known Early Proterozoic sediments, the psammities of the Namooona and Kadadu Groups, rest

unconformably on Archaean basement and exposure is generally confined to areas adjacent to exposed basement. These basal sediments may extend over much of the basin at depth. Those of the Namoon Group surround the Rum Jungle and Waterhouse Complexes, and contain arkosic rudite, psammite, conglomerate, and minor shale. The Kakadu Group, which is best developed adjacent to the Nanambu Complex, comprises mainly meta-arkose and paragneiss, which in places grade into leucogneiss of the Complex.

These psammites are overlain by carbonaceous and calcareous pelites and psammites of the Masson Formation, which extends from west of the Rum Jungle Complex almost to the South Alligator River; further east it is probably equivalent to the lower member of the Cahill Formation, a partly calcareous and carbonaceous sequence of micaceous quartzo-feldspathic schist, with lenses of massive carbonate near its base (Needham & Stuart-Smith, 1976). The Cahill Formation is host to uranium and other mineralisation in the Alligator Rivers area. Volcanic breccia and basalt of the Stag Creek Volcanics are conformable on the Masson Formation in the central part of the Geosyncline. Elsewhere, constituting the Mount Partridge Group, a wedge-shaped assemblage of sandstone, siltstone and conglomerate of the Mundogie Sandstone and Crater Formation, overlies the Masson Formation. It represents an extensive fluvial fan which grew from the north, although coarser clasts in the Rum Jungle area indicate rejuvenation of basement inliers in the west. Stromatolitic carbonate of the Celia and Coomalie Dolomites indicate that Archaean basement formed islands in the Rum Jungle area until at least mid-Mount Partridge Group time.

The alluvial fan deposits fine upwards into banded partly carbonaceous siltstone of the Wildman Siltstone. Its equivalent in the Rum Jungle area, the Whites Formation, hosts U-Cu-Pb-Zn deposits at or near the contact with the Coomalie Dolomite below. Minor mafic volcanic units lie near the top of the Wildman Siltstone up to 100 km east of Rum Jungle.

A distinctive assemblage of iron-rich sediments, carbonate, and tuff of the South Alligator Group rests, in places unconformably, over the older groups. The lowest member of this group, the Koolpin Formation, is mostly pyritic carbonaceous shale which commonly contains chert-bands and nodules, algal carbonate, and

banded iron formation. These rocks are generally altered near-surface to chert-banded hematite siltstone and massive siliceous rocks. Chert-banded hematitic siltstone also crops out as interbeds in the overlying massive tuff and argillite of the Gerowie Tuff. Rocks similar to the ferruginous siltstone of the Koolpin Formation also crop out in the Alligator Rivers Uranium Field, and are critical to correlation in the northeastern part of the Geosyncline.

Conformity of the ash-fall rocks of the Gerowie Tuff verifies the chronostratigraphic nature of the sedimentary pile. The Gerowie Tuff is overlain by Kapalga Formation rocks, which are a transitional suite between Koolpin-type rocks (less iron-rich and less chert than in the Koolpin Formation) and greywacke of the Finnis River Group, with interbeds of Gerowie Tuff-type tuff and argillite.

Uranium \pm gold deposits of the South Alligator Valley area are hosted by pyritic highly carbonaceous shale of the Koolpin Formation, and commonly lie on the faulted contact with pyroclastic sandstone of post-orogenic, late Early Proterozoic age.

The uppermost part of the Early Proterozoic succession is represented largely by a monotonous sequence of siltstone, slate, shale, greywacke, and minor arkose, quartzite, conglomerate, and schist, of the Burrell Creek Formation of the Finniss River Group. In the west, where greywacke is mostly volcanolithic, these rocks grade laterally and upwards to quartz sandstone and minor conglomerate of the Chilling Sandstone (Walpole et al., 1968). The Burrell Creek Formation commonly displays turbiditic sedimentary features, including graded beds, scour marks, flute casts and flame structures.

Transitional igneous activity

At or near the end of sedimentation, the Zamu Complex, a suite of continental tholeiites with a composite thickness of about 1.5 km, intruded the sediments mainly as sills. The sills were folded and metamorphosed with the host rocks by the 1870-1800 Ma regional event (Ferguson & Needham, 1978). In the medium to high grade metamorphic domain and in the contact aureoles of the post-orogenic granites the rocks are amphibolite, but elsewhere the original textures and mineralogy are partly to wholly preserved; in places hornfelsic zones in the adjacent sediments are apparent.

The rocks range from quartz dolerite with felsic differentiates, to dacite, and are commonest in the South Alligator Group.

The close of Early Proterozoic sedimentation is probably indicated by intrusion of granodiorite and tonalite of the Nimbuwah Complex, in the extreme northeast of the Geosyncline, at about 1870 Ma (Page et al., 1980). This event may also have triggered off a long period of deformation and metamorphism which culminated at about 1800 Ma, the age which is ubiquitously recorded by K-Ar isotopic systems in the metamorphics and many of the basement rocks of the region. The tonalites and granodiorites of the Nimbuwah Complex underwent partial migmatization in this period, as did the Early Proterozoic sediments in the same area. Resisters of quartzite, carbonaceous schist, calc-silicate gneiss and marble, indicate that some of these rocks were originally of the Kakadu Group or Cahill Formation; those metamorphic rocks to which no sedimentary parentage can be objectively determined are ascribed to the Nourlangie Schist, or the partly metamorphically differentiated Myra Falls Metamorphics (Needham, 1982).

The metamorphics were intruded by numerous post-orogenic granite plutons, which have an age range of about 1800-1740 Ma (Page et al., 1980). Several plutons coalesced to form the Cullen Granite batholith in the centre of the Geosyncline. This is the largest granitic body (3600 km²), and extends under cover rocks of the Daly River Basin (Tucker et al., 1980). Diapiric intrusion of 'solid state' granite below the Rum Jungle and Waterhouse Complexes has been described as a mechanism for rejuvenation of these Complexes by uplift (Stephansson & Johnson, 1976).

Felsic and minor mafic volcanics and volcanoclastics of the late Early Proterozoic El Sherana Group and Edith River Volcanics (~1760 Ma; Leggo in Walpole et al., 1968) are probably comagmatic with the diapiric granites. A significant period of erosion between the 1870-1800 Ma metamorphic and deformation event, and extrusion of volcanic rocks in these two groups, is indicated by their valley-fill nature.

The final igneous event prior to Middle Proterozoic platform sedimentation was intrusion at 1699 Ma (Page et al., 1980) of a series of continental tholeiitic lopoliths - the Oenpelli Dolerite - at about 1-2 km depth (Stuart-Smith & Ferguson, 1978). These intrusions consist of porphyritic olivine dolerite, quartz dolerite

and granophyre sheets, in places over 250 m thick, and minor dykes. The lopoliths form long, arcuate basement ridges to platform sedimentation, indicating another substantial period of erosion.

The pattern of sedimentation followed by orogenesis and a period of post-orogenic igneous activity seen in the Pine Creek Geosyncline is consistent with the model of evolution of Proterozoic mobile belts described by Glikson (1976), and applied to the PCG by Stuart-Smith et al., (1980).

Cover rocks

Middle Proterozoic plateau-forming sandstone and minor interbedded, mainly intermediate, volcanics of the Kombolgie Formation rest with marked unconformity on older rocks, covering the eastern extent of the Early Proterozoic metasediments and their gneissic equivalents which are exposed in a few inliers within the sandstone plateau. Minor dolerite intrusions of Late Proterozoic age cut the sandstone in places; some additional similar intrusions may be represented by long linear magnetic patterns coincident with major fractures in the sandstone. These intrusions, and Late Proterozoic phonolite dykes which intrude the Nanambu and Nimbuwah Complexes, represent the final known igneous events in the region (Page et al., 1980).

Late Proterozoic sediments are exposed at the margins of extensive Cretaceous tablelands in the southwest of the Pine Creek Geosyncline. The age of the sandstone-dominant Tolmer Group which crops out in the same area is obscure, as no relationships are exposed between it and rocks of proven Late Proterozoic age; it appears basal to the Late Proterozoic sequence. The northern and southern margins of the Geosyncline are concealed by Mesozoic and Palaeozoic strata.

A palaeo-weathering profile is common below the Kombolgie Formation, and a rare regolith is developed in some places. A regolith is common below the Cretaceous, and lateritisation took place during the Tertiary. Hays (1965) identified three Cainozoic land surfaces which are commonly superimposed, and extensive deep weathering profiles (up to 60 m) are developed.

The proximity of Kombolgie Formation sandstone to the uranium deposits of the Alligator Rivers area and South Alligator Valley, and of the Depot Creek Sandstone Member of the Tolmer Group to the uranium deposits of the Rum Jungle area, has focused attention on

the sandstone as a possible source of uranium or as a vital part of uranium ore genesis. The Kombolgie Formation is not however rich in uranium and airborne radiometric anomalies in the Formation are restricted to laterites developed downslope from interbedded intermediate to mafic volcanic members (Needham et al., 1973). Heavier elements may be concentrated in purple beds which are common in some areas near the base of the unit. The lithologies are mainly coarse, clean, moderately well-sorted subangular to sub-rounded buff to white quartz sandstone, with pebbly horizons and conglomerate beds more common near the base. Clasts are mainly moderately to well-rounded quartzite and vein quartz; clasts of Early Proterozoic rocks are rare. There are very rare siltstone beds up to 5 cm thick. The sandstone is commonly devoid of a matrix except nearer the base where a white clay matrix is often present. The rock ranges from loose and friable, to well indurated, to silicified on stable exposed surfaces and along joints.

The unconformity plane has a morphology similar to that of the undulating sand plains which cover much of the Geosyncline today. The unconformity undulates gently with an amplitude of about 20 m although there are scattered basement hills and ridges up to 250 m. The Oenpelli Dolerite forms large arcuate basement ridges up to 100 m high and the post-orogenic granites in places form plateaux about 100 m above the general level of the unconformity. The unconformity plane is displaced by numerous faults which mainly throw the sandstone only a few tens of metres. However, a throw of at least 200 m has been substantiated for the Koongarra reverse fault (Foy & Pedersen, 1975). Extensive faulting of blocks of Kombolgie Formation sandstone is recorded in or near the Ranger 1 and Jabiluka 1 ore bodies (Eupene et al., 1975); Hegge, 1977). There does not appear to be any broad relationship between the elevation of the unconformity and the distribution of mineralisation. The contact at the base of the Depot Creek Sandstone Member is regionally anomalously radioactive, but the unconformity of the base of the Kombolgie Formation has no radiometric expression. However, metamorphics and granites below the Kombolgie Formation are commonly altered, in places to more than 50 m below the unconformity. Granite and gneiss at the top of this palaeo-weathering-profile are commonly altered to a blotchy pale-green and purple quartz-clay rock. In places this profile

may be more radioactive than its unweathered parent, but no analyses are available of the amount and distribution of uranium within this profile.

DISTRIBUTION OF URANIUM OCCURRENCES

Sixty-seven uranium occurrences (Table 2) with visible uranium minerals, or significant uranium prospects, are scattered mainly in the east in a broadly NE-trending belt which terminates abruptly at a linear edge along the South Alligator Valley uranium field, and along a NW trend running from Rum Jungle to Katherine, (Fig. 4). The pattern partly reflects areas of most intense exploration for uranium, i.e. around the deposits of the three major fields, and along the Stuart Highway (the latter by hand-held geiger counters clutched by 'weekend prospectors' in the 1950's; Annabell, 1971), but some alignments are indicated which seem to control the broad distribution of the deposits. This apparent control is strongest in the South Alligator Valley area, where most of the deposits are close to a major NW strike-slip fault (Crick et al., 1980).

In an analysis on the distribution of metallic mines and prospects in the Pine Creek Geosyncline, Needham (in press) indicates a strong relationship between the distribution of uranium occurrences and the Cahill, Whites, and Koolpin Formations (Fig. 5a; 26, 13 and 22% of occurrences respectively).

The dominance of favoured stratigraphic units in determining uranium distribution is even clearer when uranium is expressed as tonnes U_3O_8 (Fig. 5b). There is also a strong positive relationship between distribution of uranium occurrences and proximity to Archaean masses (Fig. 6), although no occurrences of significance are known within them. A low-order relationship is evident with lineaments (as both lineament density and lineament intersections), and alignments represented by the distribution of uranium deposits could indicate a fundamental fracture control to the distribution. No relationship is evident with the distribution of the post-orogenic granites, even though most of the uranium prospects in the south are hosted by them. The relationship between uranium distribution and the present-day position of the cover-rock unconformity may be more apparent than real, and more properly related to the thinner Mesozoic and Cainozoic cover over

TABLE 2. URANIUM MINES AND PROSPECTS OF THE PINE CREEK GEOSYNCLINE (amended from Needham, 1981)

Name	Reference no. Fig 3. Metals	Production (reserves) tonnes U ₃₀₈ or tonnes other metals as shown	Grade, U as U ₃₀₈	Geometry	Ore character	Host lithologies	Host formation	Metamorphic grade	Controls	Classification
Black Rock	1 U	prospect		disseminated irregular, offset by faulting	disseminated uraninite	chlorite & mica quartz schist	Nimbuwah Complex	retrograded m.amphibolite	unconformity, ?fault, chlorite alteration	metamorphic hydrothermal + epigenetic, uncf. related?
Fadpole	2 U	prospect		irregular to planar, thin	uraninite in pegmatite	quartz mica schist + quartzite	"	m.amphibolite	pegmatite	hydrothermal
Nabarlek	3 U	12,000 (stockpiled, being treated)	1.98%	steep tabular to shallow cigar	massive and disseminated pitchblende, near-surface oxidised halo	chlorite mica quartz schist	Myra Falls Metamorphics	retrograded m.amphibolite	shear zone ?unconformity, ?chlorite alteration	metamorphic hydrothermal unc. related, ?stratabound (relict)
	4 U	prospect		tabular 60°	secondary near surface	quartz mica schist and graphite schist	Cahill Formation	"		
Gurrigarrri	5 U	prospect		tabular 60°	secondary near surface	quartz mica schist and graphite schist	"	m.amphibolite	stratabound, quartz stockwork breccia	stratabound, metamorphic hydrothermal, + epigenetic, uncf. related?
Gorrunghur	6 U	prospect			secondary near surface	quartz mica schist	"	"		
Caramal	7 U	prospect		arcuate band 70°	sooty pitchblende in breccia veins	hematitic chlorite quartz schist	Myra Falls Metamorphics	retrograded m.amphibolite	unconformity, ?stratabound (relict), chlorite alter- ation?	stratabound?, metamorphic hydrothermal + epigenetic, uncf. related?
Beatrice	8 U	prospect		irregular to planar steep	minute dissemination and vein-filling films of sooty pitchblende, secondaries in weathered zone	sericite hematite mica chlorite quartz schist	Nimbuwah Complex	"	shear zone breccias, unconformity	metamorphic hydrothermal + epigenetic, uncf. related?
Arrara	9 U	prospect		tabular shallow	secondary, at base of pre-Kombolgie weathering profile	chlorite quartz sericite schist	Koolpin Formation?	"	pre-Kombolgie weathering zone, ?stratabound, ?fault	stratabound, uncf. related, ?epigenetic
Jabiluka 1	10 U	(3,484)	0.256%	folded layers and lenses 0-70°, in 4 main strat- iform ore-bearing horizons	disseminated & vein filling pitchblende, & selvages to chlorite & alteration zones. Minor coffinite and brannerite	quartz sericite chlorite + graphite schist	Cahill Formation	retrograded m.amphibolite	stratiform, unconformity, chlorite alteration, brecciation	stratabound, metamorphic hydrothermal & epigenetic, uncf. related?
Jabiluka 2	11 U, Au	(203,800) (8.1 Au)	0.39% 15.3gm/T Au		"	"	"	"	"	"
Jabiluka 3	12 U	prospect			similar to Jabiluka 1 & 2	similar to Jabiluka 1 & 2	"	"		
Ranger 5	13 U	prospect					"	m.amphibolite	stratabound?	
Ranger 68	14 U	testing incomplete		irregular breccia pipe	sooty & colloform pitch- blende. Minor secondaries	chloritised breccia & pegmatoid, quartz seric- ite chlorite schist; nearby carbonate	"	retrograded m.amphibolite	chlorite alteration & brecciation at Nanambu Complex/Cahill Fm contact	stratabound & metamorphic hydrothermal + epigenetic, uncf. related?
Ranger 4	15 U	prospect		'medium to low grade' small body	irregular to tabular	chloritic pegmatoid breccia in dolomite	"	"	"	"
7J	16 U, Au	prospect		'viable ore body likely'	disseminated pitchblende, near-surface secondaries	chlorite + graphite schist, hematitic near surface	"	retrograded m.amphibolite	stratabound, chlorite alteration, unconformity	stratabound + metamorphic hydrothermal + epigenetic, uncf. related?
Hades Flat	17 U	{727}			pitchblende in fractures & breccia zones, minor thuc- colite, near-surface second- aries	chlorite schist, chloritic breccia	"	"	chlorite alteration and brecciation at Nanambu Complex/Cahill Fm contact, unconformity	"

Table 2 cont'd

Name	Reference no. Fig 3. Metals	Production (reserves) tonnes U ₃ O ₈ or tonnes other metals as shown	Grade, U as U ₃ O ₈	Geometry	Occ character	Host lithologies	Host formation	Metamorphic grade	Contacts	Classification
Austatom 1	18 U	(confidential)	best reported drill intersections 1.5 m @ 0.48%, 5 m @ 0.21%		disseminated pitchblende in schist below Cretaceous	Lower Cahill schists	Cahill Formation	retrograded m.amphibolite	chlorite alteration and brecciation at Nanambu Complex/Cahill Fm contact, unconformity	stratabound + metamorphic hydrothermal + epigenetic, uncf. related?
Ranger 1 No. 4 Anomaly	19 U	prospect	'thin, low grade mineralisation'				"	"		
No. 3 Orebody	20 U	(50,000)	0.3%	shallow-dipping tabular to lensoid body with conformable base, and blind, down-dip lenses			"	"		
No. 1 Orebody	21 U	(50,000)	0.3%	inverse cone with down-dip conformable lenses	massive, disseminated and filmy pitchblende mainly in chlorite rock and chlorite schist, and carbonaceous schist, particularly in brecciated zones	chlorite schist & micro- gneiss, silicified carbon- ate, massive chlorite, graphite schist	Cahill Fm & Nanambu Complex Cahill Formation	"	stratabound, brecciation, chlorite alteration, silicification, unconformity	stratabound + ?metamorphic hydrothermal + epigenetic - probably carbonate solution. Uncf. related?
No. 2 Anomaly	22 U	prospect	'significant primary & secondary mineralisation'				"	"		
No. 9 Anomaly	23 U	prospect	'medium grade secondary mineralisation' (no deeper drilling)				"	"		
No. 5 Anomaly	24 U	prospect					"	"		
Koongarra	25 U	(12,300)	0.346%	coalesced stratiform lenses form elongate wedge, dip 55°	disseminated pitchblende, secondary tail near surface	quartz chlorite & graph- ite schists, garnet quartz muscovite chlorite schist	"	"	stratabound to stratiform chlorite alteration, brecciation, ?faulting, ?unconformity	stratabound + metamorphic hydrothermal + epigenetic, uncf. related?
Five Sisters	26 U	prospect			no visible uranium minerals	carbonaceous phyllite	Nourlangie Schist	"	carbon, unconformity	
Graveside	27 U	prospect		tabular steep lodes	minor secondary minerals	breccia zones in phyl- lites, nearby meta- dolerite	"	m.greenschist	breccia, ?unconformity	?epigenetic
Anomaly 2J	28 U	prospect	0.98%		'yellow-green micaceous uranyl phosphate'	weathered tuffaceous shale & basalt	Stag Creek Volcanics	"	faulting, ?stratabound	syngenetic/supergene
Teague	29 U, Au			linear near-surface	patchy secondaries along faulted sst/sltst contact & in fractures	carbonaceous siltstone, sandstone	Koolpin Fm & Coronation Sst	l.greenschist	faulting, carbonaceous shale, nearby acid volcanics, unconformity	epigenetic
Rockhole	30 U, Au	152 Au included under El Sherana	1.1%	several irregular tabular steep bodies along reverse fault	patchy pitchblende, near- surface secondaries	"	"	"	"	"
O'Dwyers	31 U, Au			"	"	"	"	"	"	"
Sterrets	32 U, Au			"	"	"	"	"	"	"
Airstrip	33 U	prospect		near-surface x4 radioactivity	no visible mineralisation	"	Koolpin Formation	"	"	"
Sandstone	34 U	prospect	300 ppm U ₃ O ₈ , 4850 ppm Th, (14 ppm U ₃ O ₈ at depth)		"	andesite, sandstone lenses	Plum Tree Volcanics	unmetamorphosed	stratabound	supergene

El Sherana West	35	U, Au, Ag	185 .007 Ag	0.8%	irregular to carrot-shaped bodies aligned along strike	patches, veins & disseminations of pitchblende, mainly in fractures. Near surface secondaries. Minor Au, Pb	cherty ferruginous siltstone, carbonaceous siltstone, sandstone	Koolpin Fm & Coronation Sst	1.greenschist	carbonaceous shale, nearby acid volcanics, ?faulting, unconformity	epigenetic
El Sherana	36	U, Au	226 .33 Au	0.5%							
Koolpin	37	U	3	0.12%		sooty & massive pitchblende in fractures	carbonaceous shale	Koolpin Formation	1.greenschist	?faulting, unconformity	epigenetic
Scinto 6	38	U	3	0.15%		secondary mineralisation	sheared and jointed volcanics	Coronation Sandstone	unmetamorphosed	"	epigenetic supergene?
Palette	39	U, Au	124 Au incl. under El Sherana	2.5%	pipe inclined 45°, cuts across shale/sandstone contact	vein & massive nodular pitchblende, veins native gold, minor secondaries	carbonaceous shale, sandstone	Koolpin Fm & Coronation Sst	1.greenschist	"	epigenetic
Skull	40	U	3	0.5%	irregular	pitchblende nodules in shears	carbonaceous shale	Koolpin Formation	1.greenschist	?faulting, unconformity	epigenetic
Saddle Ridge	41	U	78	0.2%	steep tabular	secondaries, mainly meta-torbernite, minor sooty pitchblende below orebody	bleached carbonaceous shale, rhyolite & tuff	Koolpin Fm & Coronation Sst	"	carbonaceous shale, nearby acid volcanics, fault, unconformity	"
Scinto 5	42	U	22	0.4%	irregular	secondaries, minor pitchblende	bleached white & red ferruginous shale	Koolpin Formation	"	"	supergene?
Coronation Hill	43	U, Au	75	0.3%	several irregular ore shoots	sooty pitchblende, disseminated & patchy, native gold	volcanolithic and carbonaceous schist breccia	Coronation Sandstone	unmetamorphosed	carbonaceous shale, brecciation, unconformity	"
Sleisbeck	44	U	3	0.46%	irregular near-surface in breccia	pitchblende, secondaries, with phosphate and minor Cu, Ni, Co, As	chloritic carbonaceous schist, quartzite, mudstone	Kapalga Formation	1.greenschist	?breccia	?epigenetic
ABC	45	U	prospect	0.4%	shallow irregular	autunite, phosphuranylite	interbedded tuff and amygdaloidal basalt	Kombolgie Formation	unmetamorphosed	host volcanics, ?nearby deep fracturing	epigenetic/syngenetic?
Edith River	46	U	prospect		patchy bodies in N or NW shears	disseminated torbernite & meta-autunite ± apatite & hematite in quartz veins	silicified greisenised granite	Cullen Granite	"	hydrothermal alteration zones & quartz veining in granite	"
	47	U	prospect		"	"	"	"	"	"	"
Tennysons	48	U	prospect		"	"	"	"	"	"	"
	49	U	prospect	0.1-0.2%	"	"	"	"	"	"	"
	50	U	prospect	at surface	"	"	"	"	"	"	"
	51	U	prospect		"	"	"	"	"	"	"
Hors & O'Connors	52	U	prospect		"	"	"	"	"	"	"
Yenberrie	53	U	prospect		steep tabular reefs, parallel to aplite dykes. Also dissem. in joints & mica-rich seams	greisenised quartz aplite dykes containing Wolfram & minor molybdenite and torbernite in quartz veins. Fe, Cu, Bi sulphides at depth	aplite dykes in granite	"	"	altered aprites near roof of granite	"
	54	W, Mo, Bi, U	0.125 Mo 160 WO ₃								
Yenberrie	55	U	prospect		patchy bodies in N or NW shears	disseminated torbernite & meta-autunite ± apatite & hematite in quartz veins	silicified greisenised granite	"	"	hydrothermal alteration zones & quartz veining in granite	"
Fergusson River	56	U	prospect		patchy bodies in N or NW shears	disseminated torbernite & meta-autunite ± apatite & hematite in quartz veins	silicified greisenised granite	"	"	hydrothermal alteration zones & quartz veining in granite	"
Fleur de Lys	57	U, Cu	0.15		patches in conformable shear zones & joints & along bedding planes	uraninite+pyrite+chalcocopyrite in shears. U+Cu oxides near surface	siltstone, slate	Koolpin Formation	1.greenschist	altered shears and joints	hydrothermal; possible exhalative/epigenetic
George Creek	58	U	1	0.26%	pod & stringers in weak steep N shear	pitchblende, pyrite, chalcocopyrite in joints & minor shears, torbernite at surface	"	Burrell Creek Formation	"	"	"

Table 2 cont'd

Name	Reference no., Fig 3, Metals	Production (reserves) tonnes U ₃ O ₈ or tonnes other metals as shown	Grade, U as U ₃ O ₈	Geometry	Ore character	Host lithologies	Host formation	Metamorphic grade	Controls	Classification
Adelaide River	59 U	45	0.5%	steep N shear zone, irregular ore zone pitches S45°	pitchblende, pyrite, chalcopyrite in irregular quartz veins, & dissem. in host rocks	"	"	"	"	"
White's	60 U,Cu,Pb, Co,Ni	1069 1.8 Ag, 861 Co, 15 000 Cu, 4100 Pb	0.16% 25.7 g/T Ag 2.2% Cu 0.6% Pb	roughly conformable steep 17-27 m wide NE shear zone	uraninite, torbernite, chalcopyrite, bornite + galena as disseminations + veins	sheared graphitic sericitic, chloritic & pyritic shale	Whites Formation	1.greenschist	Whites Fm/Coomalie Dolomite contact, stratabound, shear zones on synclinal limb, nearby basement granite, unconformity	syngenetic + epigenetic + supergene
Dyson's	61 U	534	0.34%	conformable NE shear 8 m wide, steep	vein & dissem. uraninite, saleeite	sheared graphitic shale hematitic dolomite	Whites Fm & Coomalie Dolomite	"	"	"
Mount Fitch	62 U, Cu	(1500) (1885 Cu)	.042% 290,000 T @ 0.6% Cu	2 U bodies, E 110x30x20 m deep, N 160x110x100 m deep, 3 Cu lenses in 4 km conformable enriched zone	fine Ptucolite in clayey graphite schist bands, veinlets in magnesite. Near surface Cu-enrichment in clays	chlorite sericite graphitic schist, magnesite	Whites Fm & Coomalie Dolomite	"	"	"
Mount Burton	63 U, Cu	12,6 100 Cu	0.17% 1.3% Cu	small conformable lens	dissem. torbernite, pitchblende, malachite, chalcocite	pyritic black slate, minor quartzite	Whites Formation	"	"	"
Dolerite Ridge	64 U,Pb,Cu, Zn	prospect					"	"	"	"
Area 55	65 U,Pb,Zn, Cu	prospect		irregular pods in shears & plunging fold axes		pyritic black shale, dolomite	Whites Fm & Coomalie Dolomite	"	"	"
Rum Jungle Creek	66 U	prospect				chloritic & graphitic shale	Whites Formation	"	"	"
Rum Jungle Creek South	67 U	2612	0.4%	horizontal cigar 60 m x 245 m, 30 m depth	fine sooty pitchblende coatings, minor veins & stockworks	chloritic & graphitic pyritic shale	"	"	"	"

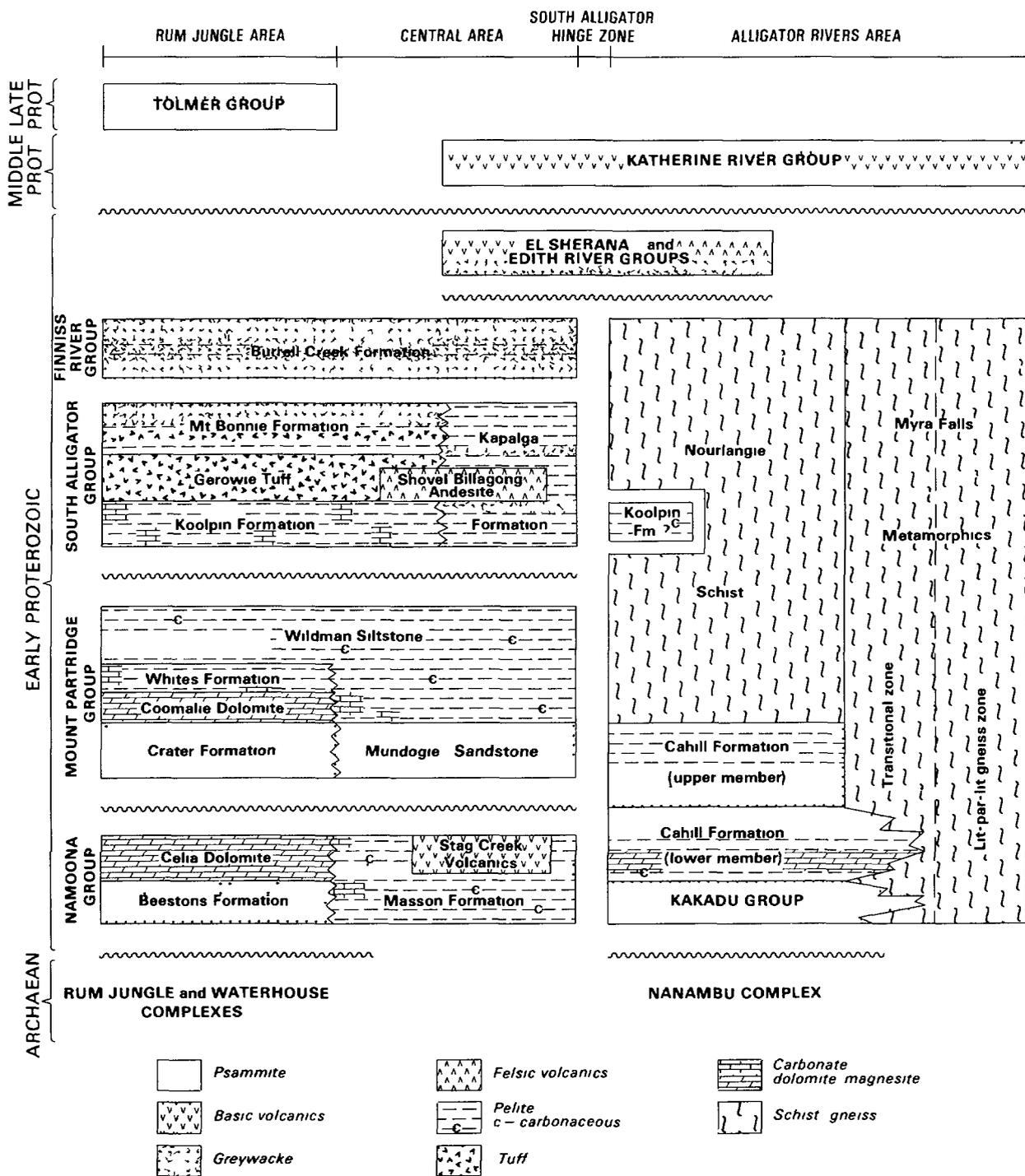
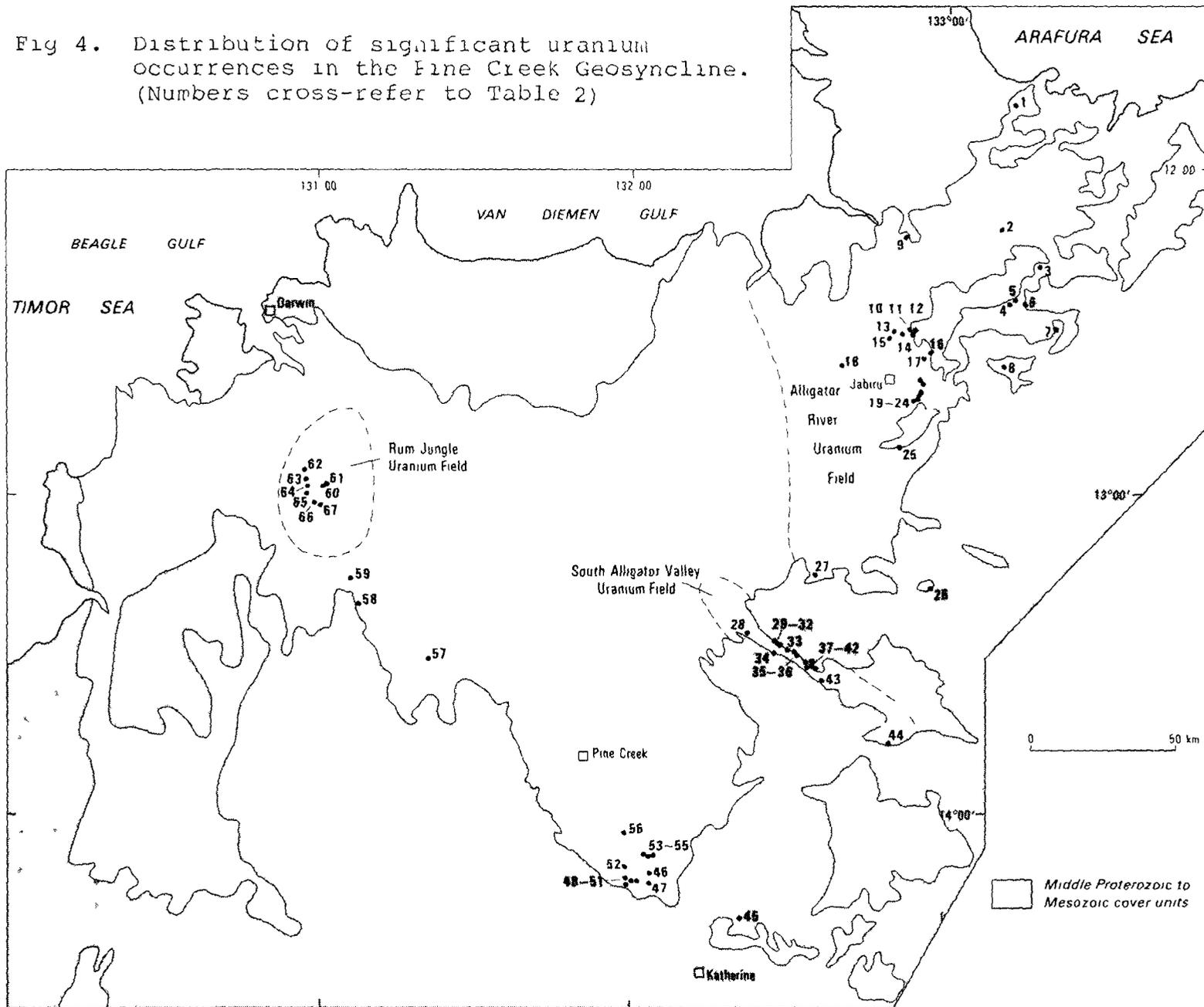


Fig 3. Diagrammatic stratigraphy of the Pine Creek Geosyncline

Early Proterozoic bedrock near the cliff-like edge of the Middle-Late Proterozoic plateau sandstones. The thinner cover has allowed more effective use of conventional uranium exploration technology in these areas in contrast to the poorly and ineffectually explored areas marked by thicker cover, particularly near the coast.

Fig 4. Distribution of significant uranium occurrences in the Pine Creek Geosyncline. (Numbers cross-refer to Table 2)



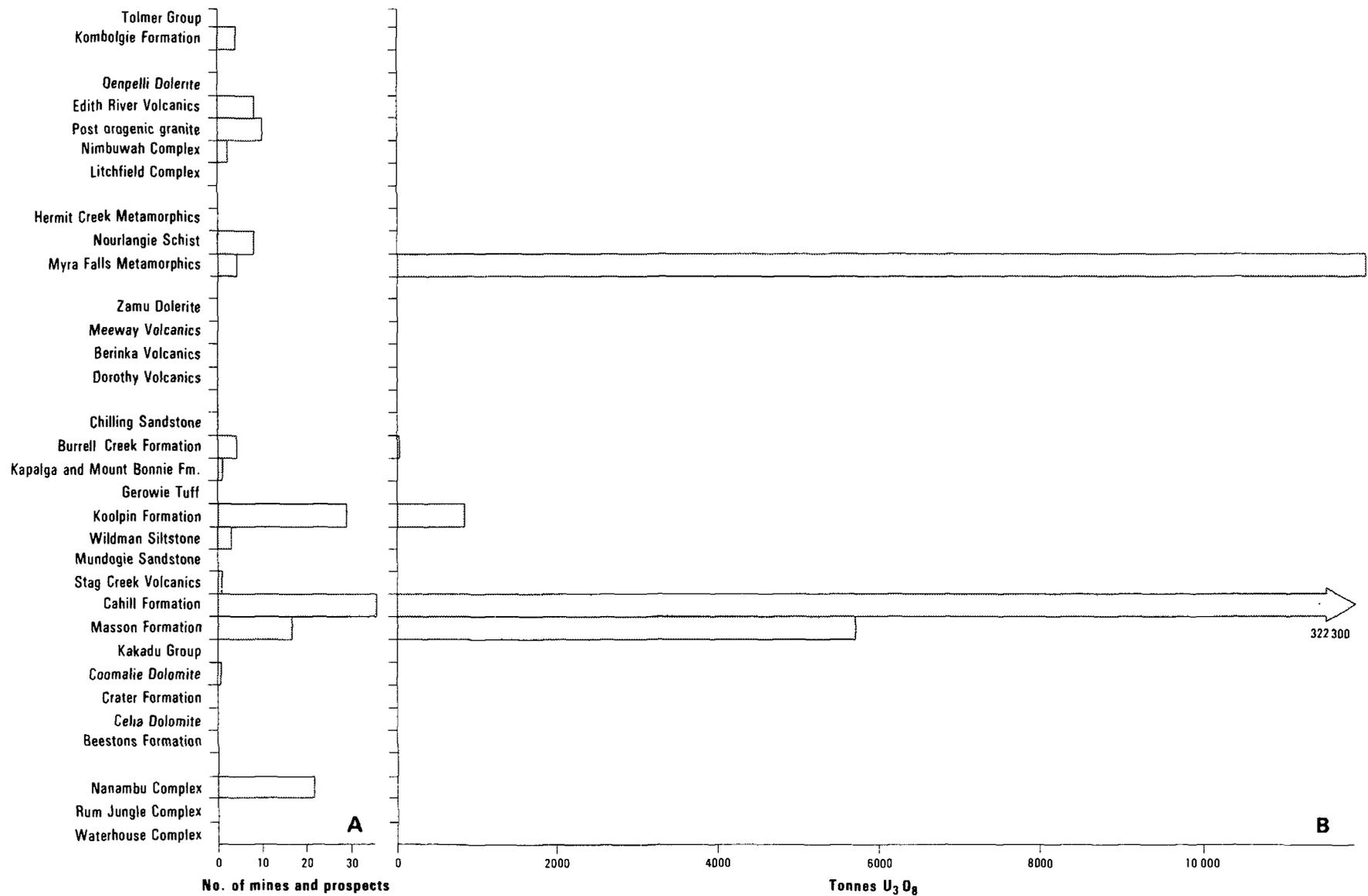


Fig 5. Distribution of uranium
 A) number of occurrences, and
 B) tonnes U₃O₈ production and reserves in Pine Creek rock units

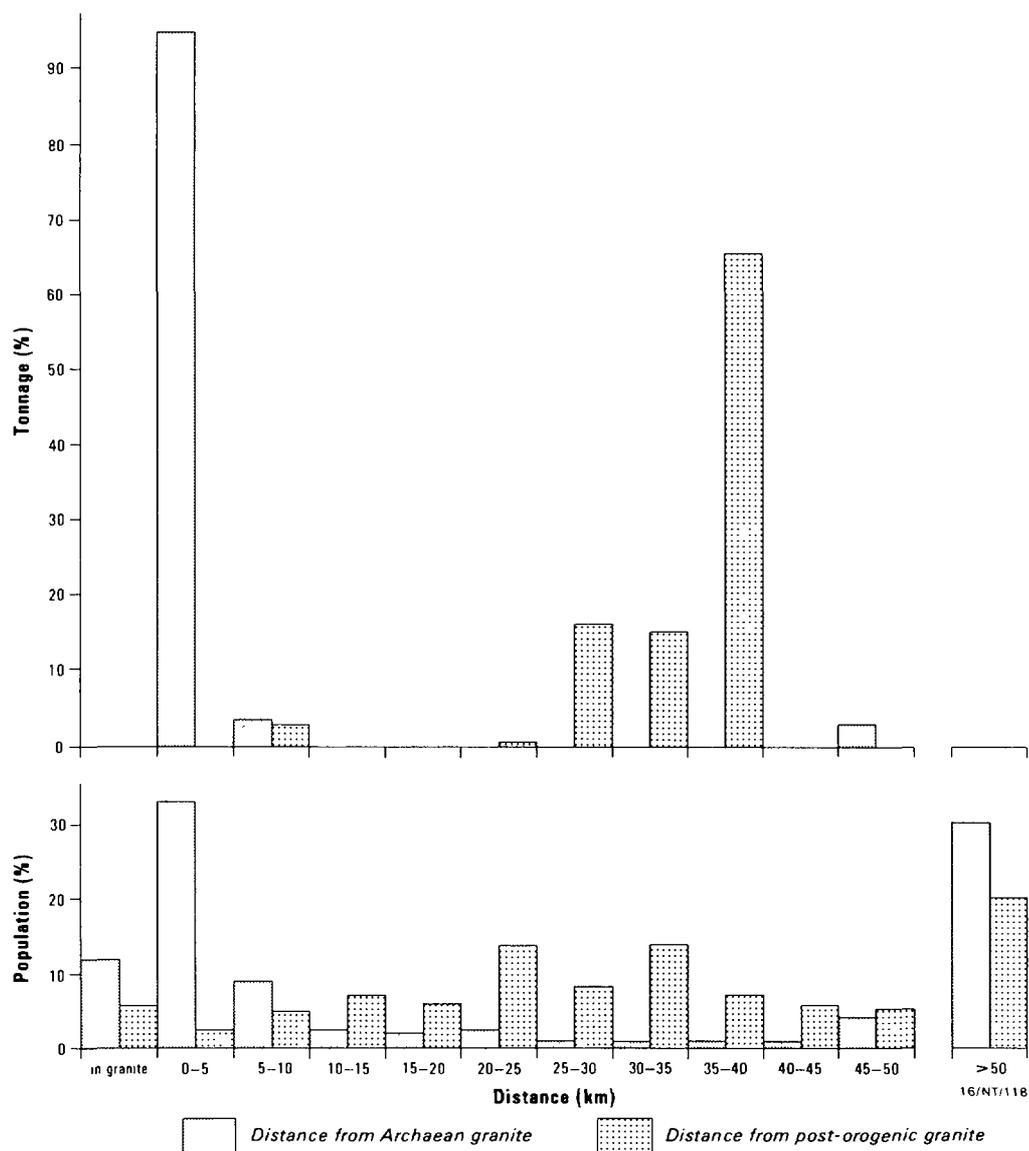


Fig 6. Proximity of Pine Creek uranium occurrences from Archaean and Proterozoic granite

GEOLOGICAL SETTING OF DEPOSITS

The clustering of uranium occurrences naturally defines 3 major uranium fields, and a scatter of prospects aligned NW between Darwin and Katherine (Fig. 4). Within each field the uranium deposits share many common features and lie in the same host formation, but the host formation is different in each field.

Descriptions of individual uranium deposits and some prospects in the Pine Creek Geosyncline have been given elsewhere in literature (e.g. Ferguson and Goleby, 1980). Table 2 summarises the main features of these occurrences in terms of their grade, tonnage, geometry, host formation and lithologies, and ore characteristics, and also outlines possible controls on mineralisation. In this section the three main uranium fields are

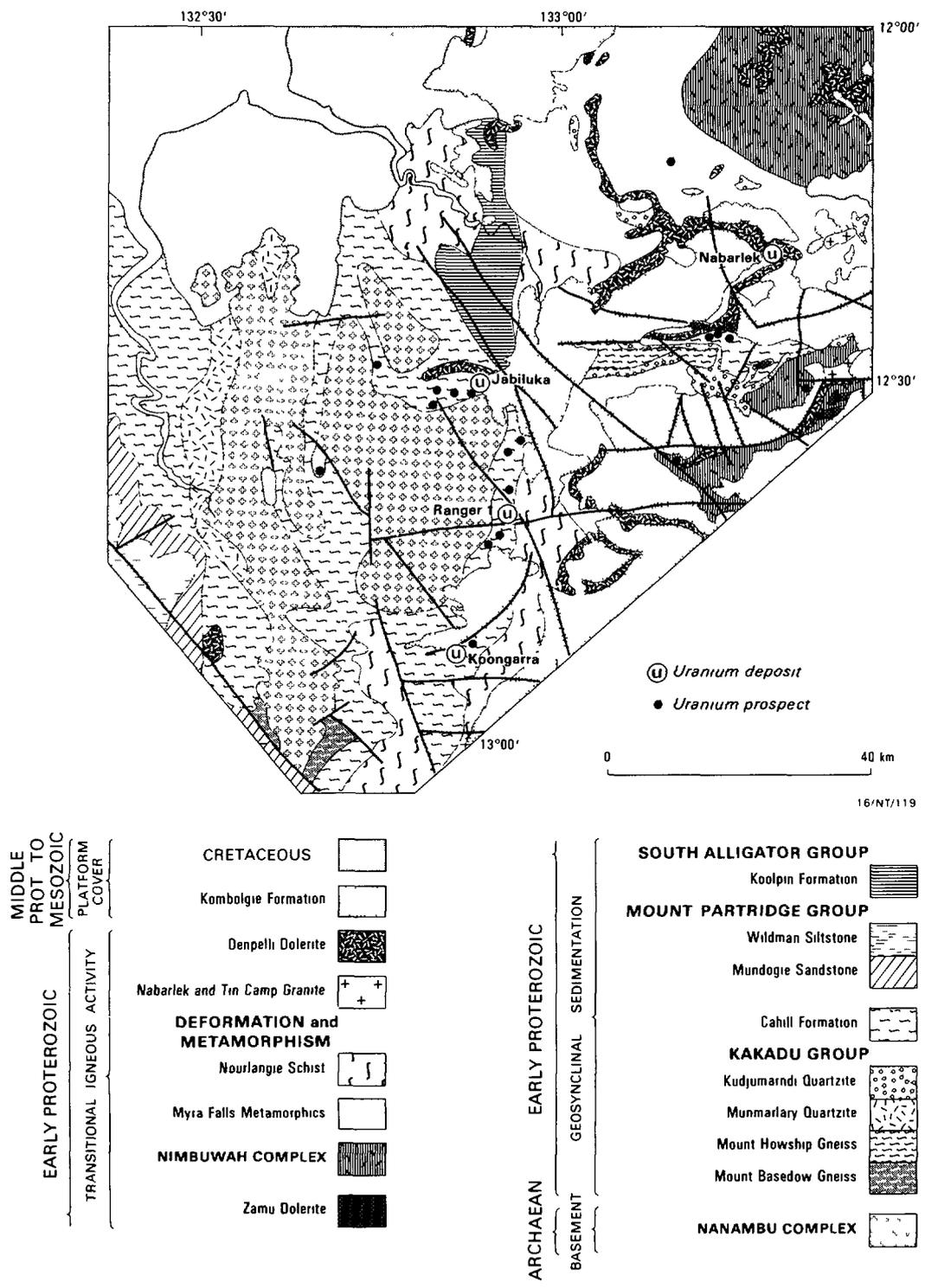


Fig 7. Geology of the Alligator Rivers Uranium Field

discussed, with the emphasis on similarities and differences between deposits rather than detailed deposit descriptions.

Deposits in the Alligator Rivers Uranium Field (ARUF) are the most recent (post-1970 A.D.) and spectacular U discoveries in the Pine Creek Geosyncline (PCG), and are either in the early stages of mining or yet to be mined. Some of these deposits have been the subject of a wide variety of detailed geochemical and petro-

logical studies and as development proceeds further studies can be expected to enhance our understanding of them. By contrast, the deposits in the Rum Jungle Uranium Field (RJUF) and South Alligator Valley Uranium Field (SAVUF) were discovered in the 1950's, and mine and milling operations ceased in the 1960's. They did not receive the same attention and consequently cannot be documented as thoroughly as the Alligator Rivers deposit.

ALLIGATOR RIVERS URANIUM FIELD (ARUF)

The Alligator Rivers Uranium Field covers about 22 500 km² in the northeast of the PCG and contains the Jabiluka, Ranger 1, Koongarra and Nabarlek deposits (Fig. 7). The area is distinct from other parts of the geosyncline in that metamorphic grade (medium to high-grade), and degree of deformation (four periods of deformation and isoclinal folding), are markedly greater (Ferguson, 1980; Needham & Stuart-Smith, 1980). The uranium discoveries were made in 1970 and 1971. Subsequent formation of a National Park in the area has precluded effective exploration of the region since the discovery years.

The area between the South and East Alligator Rivers is dominated by the Nanambu Complex, which contains granitoids that record Archaean (up to 2500 Ma) and ~1800 Ma orogenic events, and accreted Early Proterozoic feldspathic and quartzitic gneiss and schist. The gneiss is, in places (mainly south of the complex), gradational outwards into Mount Basedow Gneiss, the lowest recognisable part of the Early Proterozoic metasedimentary sequence. The Munmarlary Quartzite is a quartz-rich equivalent of the gneiss on the western flank of the complex. The overlying Cahill Formation onlaps in places to rest directly on Archaean granite of the Nanambu Complex. This formation contains all the uranium deposits and most of the uranium prospects of the area, and is the prime guide to uranium exploration. Needham and Stuart-Smith (1976) have divided the Cahill Formation into two members: a lower member, which is host to the uranium mineralisation and is characterised by the presence of carbonaceous units and carbonate rocks, and includes an interlayered sequence of mica schist, chloritised feldspathic quartzite, quartz schist, para-amphibolite and calc-silicate rock; an upper more psammitic member which contains quartz schist, feldspathic schist, feldspathic quartzite, and conglomerate. The Cahill Formation is overlain,

in places unconformably, by the Nourlangie Schist, a monotonous sequence of mainly quartz mica schist. Ferruginous siltstone with finely crystalline quartz bands exposed in the north may be metamorphosed equivalents of the Koolpin Formation.

East of the East Alligator River the Early Proterozoic metasediments grade into metamorphically differentiated schist and gneiss of the Myra Falls Metamorphics. Some distinctive lithologies can be mapped out as 'resisters' which can be correlated with the Kakadu Group and Cahill Formation. In the extreme east, pre-orogenic granite intruded at ~1870 Ma was metamorphosed and partly differentiated along with the metasediments to form the migmatitic Nimbuwah Complex; its composition ranges from granitic to granodioritic in the north, to tonalitic in places south of Nabarlek.

The orogenic event probably began at the time of intrusion of the pre-deformation granite, and culminated at about 1800 Ma. Pre-orogenic tholeiitic dolerite sills (Zamu Dolerite) are preserved throughout the area as strongly foliated amphibolite. Post-orogenic (1730-1780 Ma) granite - trondhjemite forms small stocks east and south of Nabarlek, and post-orogenic (~1690 Ma) tholeiitic dolerite intruded as extensive lopoliths throughout the region east of the Nanambu Complex.

The Middle Proterozoic Kombolgie Formation forms a sub-horizontal sheet of sandstone and interbedded mainly andesitic volcanics about 200-1000 m thick, generally marked by a sheer cliff rising abruptly above the lower undulating terrain formed by the older rocks. A major erosional period is represented by the unconformable contact, as at least 1-2 km of supracrustals were removed to expose the Oenpelli Dolerite lopoliths. Small pockets of tuffaceous sediments along the contact are probable distal equivalents of the mainly felsic late Early Proterozoic volcanism centred in the South Alligator Valley Uranium Field. Minor phonolite and dolerite dykes were emplaced between about 1370-1200 Ma ago, concentrated in the Nanambu and Nimbuwah Complexes. Mesozoic and Cainozoic marine to terrestrial deposits form a northward-thickening veneer (up to 80 m thick) in the northwest, and colluvial sand and laterite masks much of the Early Proterozoic rocks throughout the region.

Jabiluka, Ranger, Koongarra and most of the other prospects are stratabound within the Early Proterozoic Cahill Formation. Nabarlek is hosted by the Myra Falls Metamorphics, but this unit is thought to be a correlative of the Cahill Formation (Needham, 1982). The carbonate rocks near the Jabiluka, Ranger 1 and Koongarra deposits were derived from evaporites (Crick & Muir, 1980), indicating a supratidal depositional environment. Cahill Formation carbonate west of the Nanambu Complex, where no significant uranium occurrences are known, was deposited under open marine conditions (Needham, 1982); this and the stratabound nature of the deposits suggest that supratidal deposition was a possible prerequisite for uranium concentration in the lower Cahill Formation.

The major deposits (geological plans and cross sections are given in Figures 8-14) are in close proximity to a sharply defined unconformity with overlying Middle Proterozoic Kombolgie Formation sandstone; an unconformity which approximates closely with the present day land surface. The Kombolgie Formation generally forms a prominent escarpment in close proximity to the deposits; although the Jabiluka 2 deposit is concealed by up to 220 m of Kombolgie Formation sandstone. The deposits have a strong spatial association with granitoid/metasedimentary contacts. The Archaean Nanambu Complex is known to exist 1.5 km south of Jabiluka; it forms the footwall to the Ranger orebodies; and at Koongarra, it crops out 6.5 km NNW of the deposit. At Nabarlek, the late Early Proterozoic Nabarlek Granite crops out 16 km to the east of the deposit and has been intersected at a vertical depth of 470 m below the orebody.

Host rocks to the major deposits are predominantly quartz muscovite chlorite schists (Figs 8-14) which are commonly characterised by segregation banding (in places accompanied by crenulation) where any one of the three minerals may be dominant in individual bands. The sequence at Nabarlek differs in that quartz tends to be minor or absent, except toward the southern end of the orebody and in metasediments below the Oenpelli Dolerite. In all deposits, quartz tends to be tabular, have wavy extinction, and to show horse-tail fractures passing continuously across adjacent grains and containing minute inclusions. In strongly deformed schists, the quartz has developed brittle fracture and pressure

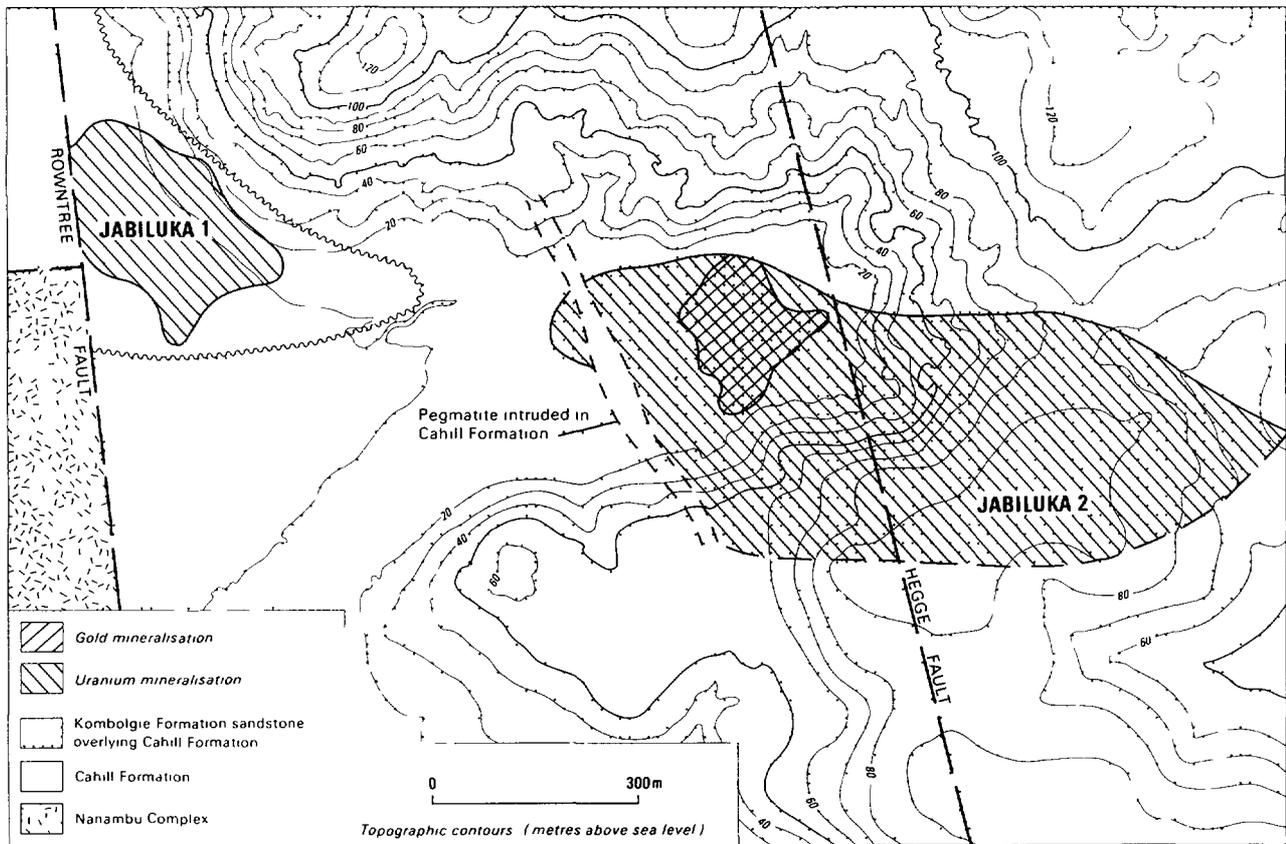


Fig 8. Solid geology of Jabiluka 1 and 2 uranium-gold deposits (adapted from revised unpublished data by courtesy of Pancontinental Mining Ltd)

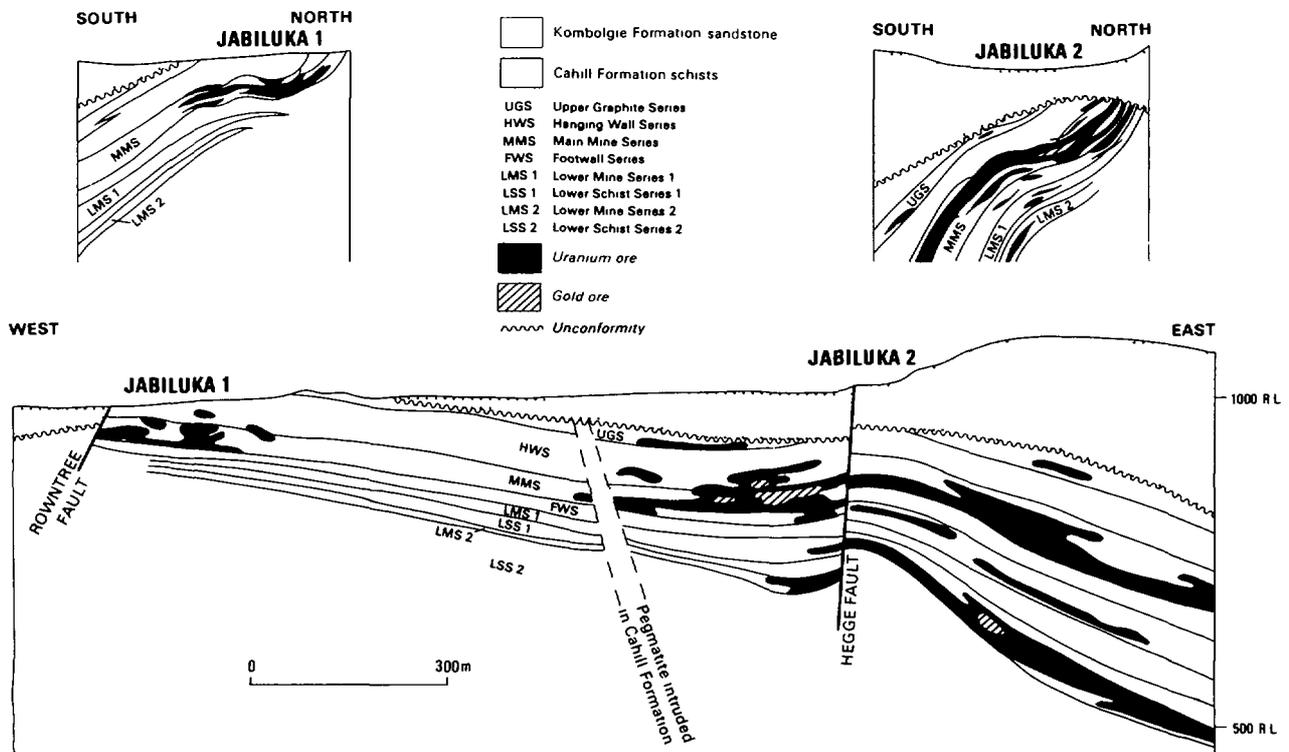


Fig 9. Generalised long-section and cross-sections of Jabiluka 1 and 2 uranium-gold deposits (adapted from revised, unpublished data by courtesy of Pancontinental Mining Ltd)

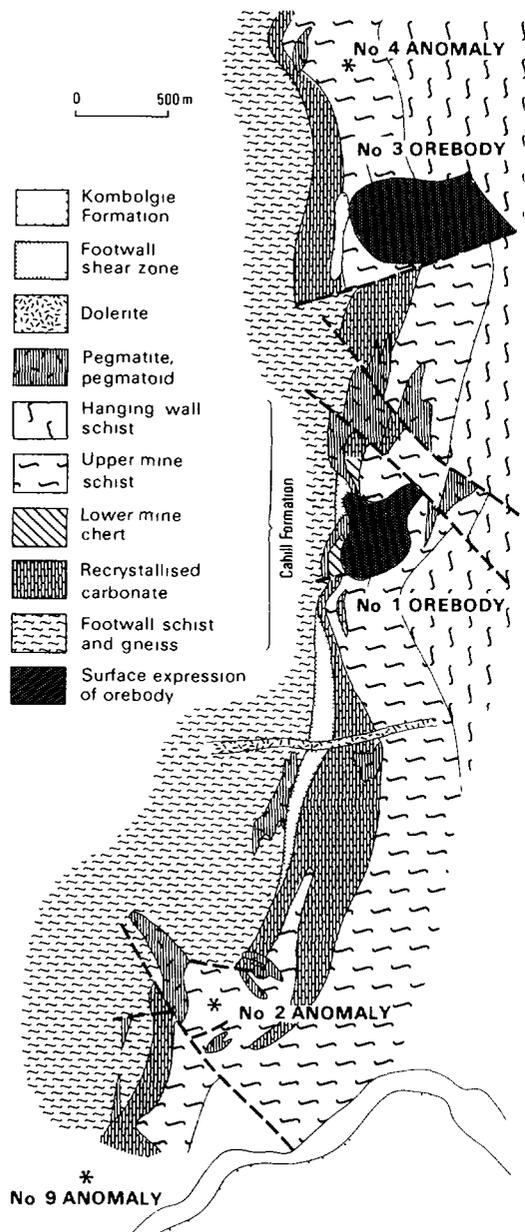


Fig 10.

Generalised geological plan of the Ranger 1 orebodies and prospects (after Eupene & others, 1975; Hegge & others 1980)

solution features, which has resulted in partial recrystallisation. Usually muscovite and less commonly biotite and chlorite show two periods of growth. Early distorted flakes define the schistosity, and later undeformed flakes are superposed on the foliation. Fine sericitic mica is generally present, and may occur as an alteration product of minor feldspar. At Nabarlek, sericite rich patches set in a chlorite matrix give rise to minor spotted schists, and elongated grains of leucoxene \pm sphene, which are parallel to the schistosity, give some rocks a flecked appearance. Porphyroblasts of almandine garnet are locally abundant in all deposits. Thin quartz veins, which are both discordant and concordant to the schistosity and appear to predate and postdate the regional meta-

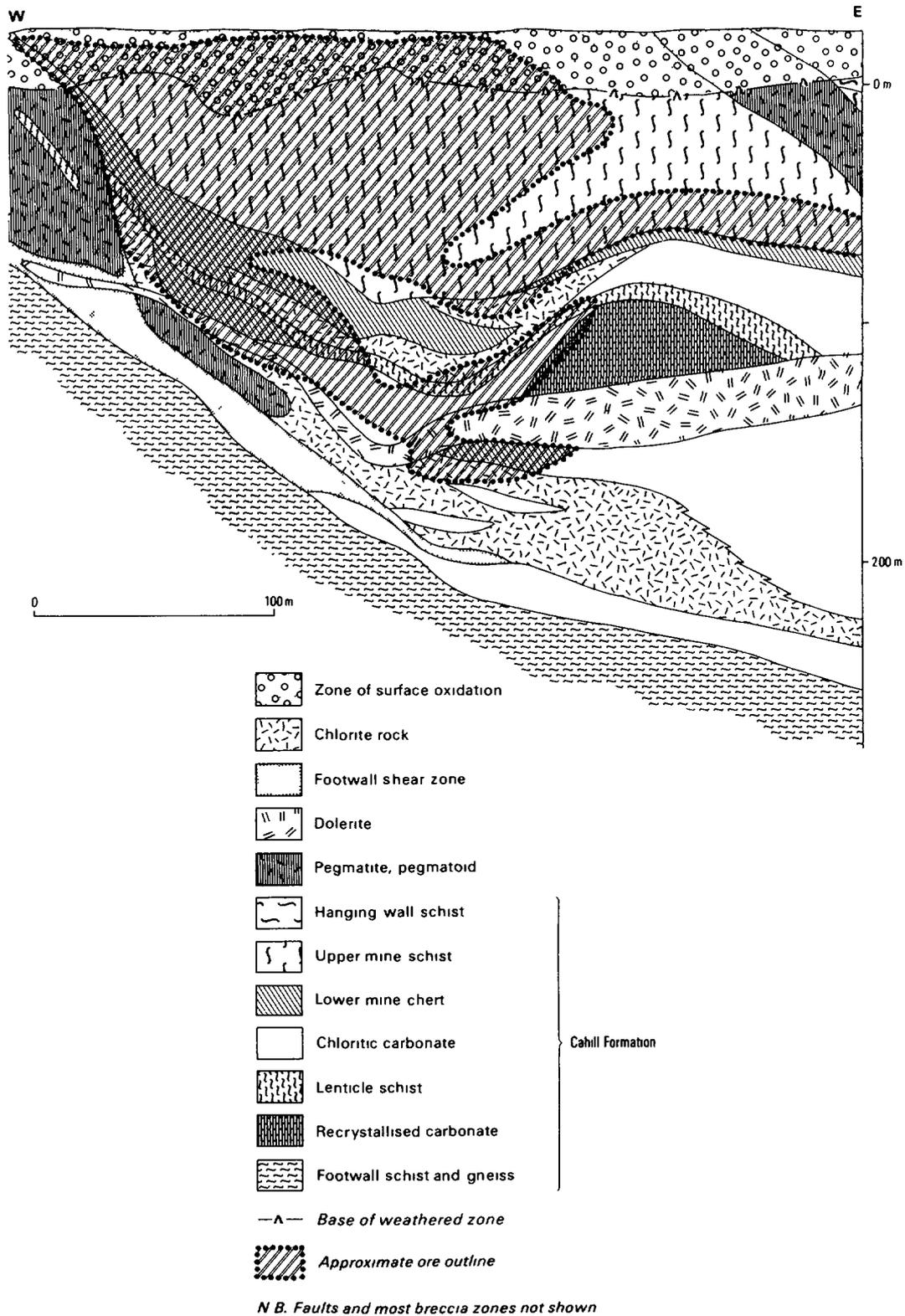


Fig 11. Cross-section of the Ranger 1 No. 1 orebody (after Eupene & others, 1975; Hegge & others, 1980)

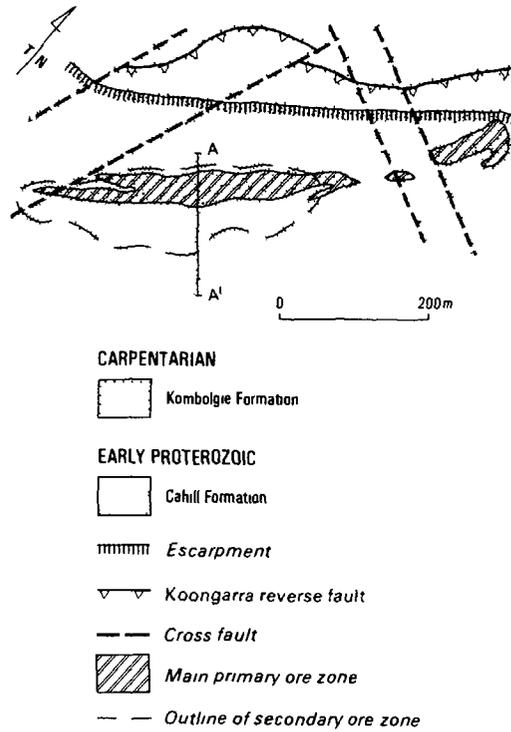


Fig 12. Plan of the Koongarra deposit (after Foy & Pedersen, 1975; Hegge & others, 1980)

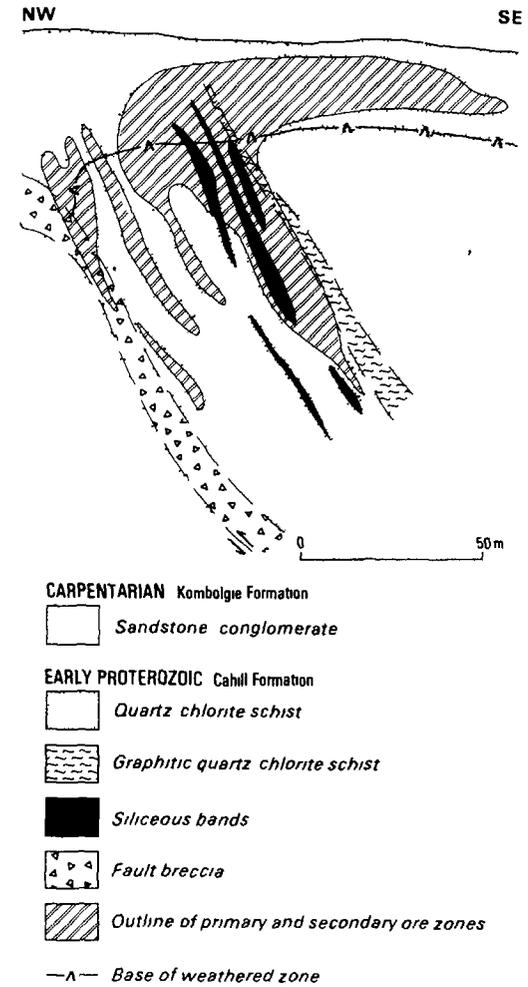


Fig 13. Cross-section of the Koongarra No. 1 orebody along line A-A in Figure 7 (after Foy & Pedersen, 1975; Hegge & others, 1980)

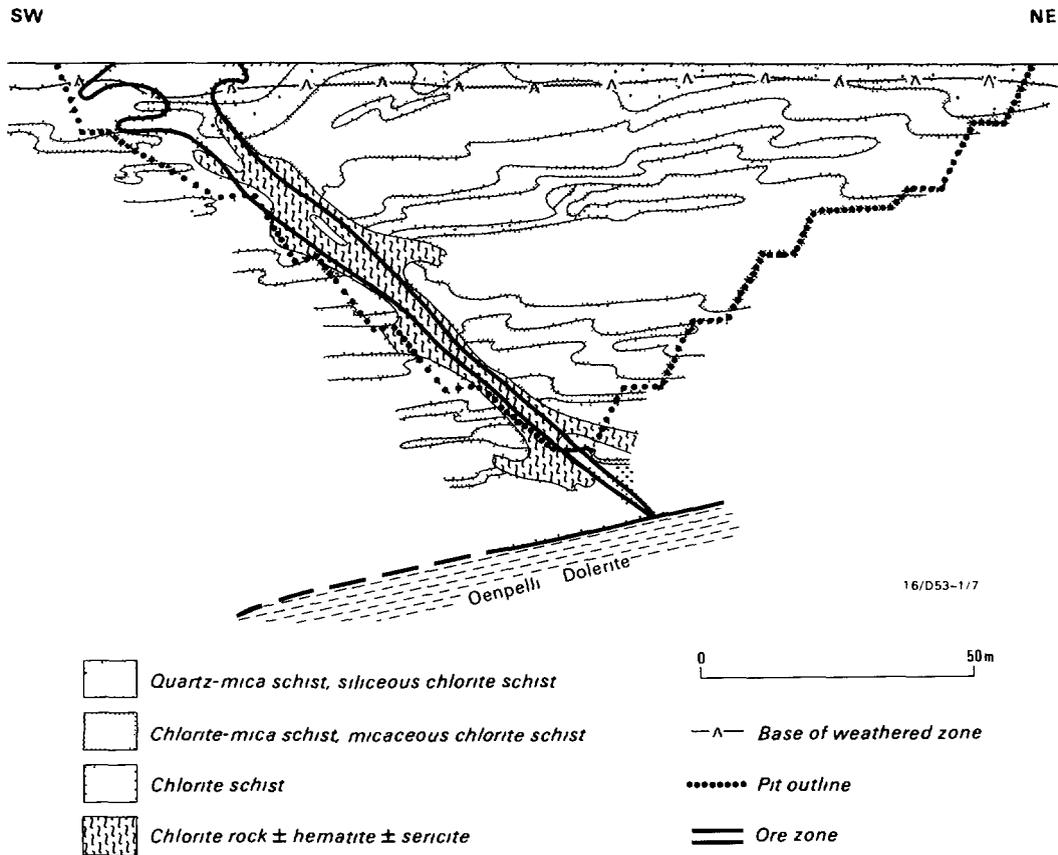


Fig 14. Cross-section at the southern end of the Nabarlek orebody. Modified from mine section 9553; published by courtesy of Queensland Mines Ltd

morphism, are common at Jabiluka, Ranger and Koongarra, and rarer at Nabarlek.

In the vicinity of all of the deposits, a pervasive chlorite dominated alteration halo surrounds the mineralisation. At Jabiluka, this halo extends into the overlying Kombolgie Formation sandstone cover sequence (Gustafson and Curtis, 1983) and is known to extend laterally more than 200 m from ore (Binns et al., 1980). The chlorite ranges from cryptocrystalline to flaky, and generally occurs as a partial or complete replacement of biotite and muscovite. At Jabiluka, it completely pseudomorphs garnet and amphibole, and in tourmaline-bearing granitoid pegmatite dykes, alkali feldspar has also been extensively chloritised. At Ranger 1, the chloritisation is more restricted and less intense; the Hangingwall Sequence contains fresh garnet and K-feldspar in pelitic schist, and unaltered hornblende and plagioclase occur in interbedded amphibolite. Minor K-feldspar, plagioclase, and hornblende persist in the Upper Mine Sequence. Chloritisation is

most intense in the Ranger ore zones, especially the Lower Mine Sequence, where feldspars in granitic pegmatites have altered to chlorite and dolerite has been completely chloritised. At Koongarra, garnet is either completely chloritised or surrounded by an outer layer of chlorite elongated parallel to the schistosity. The garnet may contain helical trails of opaque inclusions. Foy & Pedersen (1975) have reported feldspar in several drillholes and have also noted the presence of partially or completely chloritised hornblende. Chloritisation is pervasive at Nabarlek in meta-sediments above and below the Oenpelli Dolerite; it also affects the margins of the dolerite and the underlying Nabarlek Granite, which has been intersected below the orebody at a depth of 470 m. Chlorite forms pseudomorphs after biotite, actinolite, muscovite, and appears to have replaced garnet.

With the exception of Nabarlek, the uranium deposits are all associated with massive bedded dolomite and/or magnesite. This association is characterised by the disappearance, or marked thinning of carbonate sequences within the ore zones, and a corresponding increase in the degree of disruption and brecciation in the orebodies. Chert replacement of the carbonates is a common feature (Ewers and Ferguson, 1980), and Eupene (1979) has postulated that this disruption in the ore zones has been caused by the silicification of carbonate resulting in volume reduction and subsequent collapse. Ferguson et al. (1980) have suggested that solution of massive carbonate led to the formation of collapse dolines, and that these acted as structural traps and sites for ore-formation. At Nabarlek, the absence of massive carbonate in the vicinity of the orebody indicates that collapse dolines are not relevant to the structural setting of this deposit (Ewers et al., 1983).

Accessory minerals found in the wall rocks of some or all of the deposits include tourmaline, apatite, sphene, leucoxene, zircon, epidote-group minerals, rutile, gypsum and opaques. Euhedral prisms of pleochroic green tourmaline, sphene, apatite and epidote-group minerals are common and tend to be concentrated in muscovite-rich and chlorite-rich zones. Rutile and gypsum are generally rare, though sagenitic growths of rutile are common in flaky chlorite in wall rocks at Nabarlek. The opaques include graphite, hematite and minor sulphide (mainly pyrite). Graphite occurs

throughout the sequence at Jabiluka, whereas it is confined to the base of the Upper Mine Schists at Ranger, and is restricted to a schist overlying the primary mineralisation at Koongarra. Graphite was reported in handspecimen only from schist adjacent to the Nabarlek orebody (Lees and Tammekand, 1979); however, its presence has not been confirmed in a more recent study (Ewers et al., 1983). Hematite is a common accessory mineral, particularly in wall rocks at Nabarlek, where it occurs as fine disseminations or elongate grains which parallel the schistosity.

The two most striking features in all of the deposits are the tendency for mineralisation to occur within zones of brecciation, and for it to be intimately associated with chlorite. Reasons for this brecciation and the association of ore with chlorite have been considered in a variety of ore genesis models and will be dealt with later in this chapter. However, it is worth noting that, unlike the other deposits, the Nabarlek orebody occurs in what is interpreted as a shear zone (Anthony, 1975) and is grossly discordant with the enclosing metasediments. The breccia fragments are typically chlorite- and/or sericite-bearing meta-arenites, intensely chloritised material, and chert which is commonly a replacement of carbonate. At Jabiluka, Ranger and Koongarra, fragments may contain graphite or hematite. At Nabarlek, the original composition of the fragments (and also the matrix) is difficult to ascertain because of the intensity of chloritisation and a later sericitisation in the ore zone (Ewers et al., 1983); however, it is reasonable to assume that the fragments are from the enclosing host rocks. In all deposits, the fragments are usually angular and rotated. Textures and lithology generally indicate that the brecciation developed after the regional metamorphism (ca. 1800 Ma) and that there was a high percentage of voids between the fragments. The breccias are cemented by chlorite \pm quartz \pm hematite \pm uraninite, and at Jabiluka, Ranger and Koongarra, graphite and minor sulphides can occur in the matrix. Graphite has not been identified in the Nabarlek ore-zone rocks; however, recent isotopic work on minor carbonate associated with the mineralisation suggests that organic material was originally present (Ewers et al., 1983). At Ranger, vugs and fractures which remained open at the time the breccias were initially cemented, have subsequently been infilled with euhedral quartz and chlorite, and can also contain hematite, sulphides, and carbonates. There

is also evidence that later deformation in the Ranger deposit has caused some breccias to be rebrecciated before being cemented a second time with chlorite.

Massive chlorite \pm sericite \pm hematite rocks and intensely altered schists are common in the Nabarlek ore zone and highlight a significant difference between ore zone rocks at Nabarlek and those in the other deposits. At Nabarlek, hematite and sericite are major constituents and are spatially related to mineralisation even though their development is minor and seemingly unrelated to mineralisation in the other deposits. Recent petrographic work has indicated that the ore zone at Nabarlek has undergone progressive and pervasive sericitisation (probably about 920 Ma), resulting in the widespread replacement and breakdown of chlorite, the formation of hematite, and the solution and redeposition of uraninite (Ewers et al., 1983). To date, these events have not been recognised in the other deposits.

Multiple generations of chlorite have been observed in all deposits; the grain size, colour, pleochroism, and interference colours of these different generations are wide ranging, and their relationships to one another very complex. In the ore zones, there appears to be no correlation between mineralisation and the composition or texture of a particular variety of chlorite. Chlorite compositions in both the host rocks and ore zone overlap and are highly variable with respect to Al, Fe, Mg, and to a lesser extent Si; although, in general, Mg-rich and Al-rich varieties predominate.

The primary ore mineral assemblage in each deposit is dominated by uraninite, though minor coffinite and brannerite occur in the Jabiluka and Nabarlek deposits. Eupene et al. (1975) have also reported minor brannerite at Ranger. Thucolite is known from Jabiluka (Binns et al., 1980) and has been reported from the Ranger 1 No. 3 orebody (G.H. Taylor in Eupene, 1979). The close proximity of all deposits to the present land surface and the absence of a sufficient thickness of cover rocks in most instances has exposed the primary mineralisation to the effects of weathering. Uraninite has been oxidised and replaced by an array of secondary uranium minerals, to form a wide low grade envelope, which is particularly well developed over the Koongarra and Nabarlek deposits.

The uraninite is invariably associated with chlorite, particularly where it fills interstices between breccia fragments. In many instances, subsequent sericitisation in the Nabarlek ore zone has resulted in the wholesale replacement of chlorite and the preservation of residual massive uraninite; however, these residuals commonly contain uraninite-chlorite intergrowths.

The uraninite exists in a variety of forms - disseminated uraninite occurs as cubes 10-100 μm across, but these may coalesce to form clusters, strings, and massive uraninite. Colloform textures with associated concentric banding, and radial fractures are common in massive varieties, and can give way to reticulated and lacework patterns where silicate inclusions are abundant. Uraninite also forms thin veins coating foliation planes and these may become braided where the uraninite becomes interstitial to flaky micas. Fine stringers of uraninite sometimes fill fractures which are discordant to the foliation and appear to postdate the earliest mineralisation. Complex intergrowths in which chlorite exerts its platy habit against uraninite are also common. Rare massive spherules of uraninite up to 0.7 mm in diameter are found at Jabiluka. At Ranger, the disseminated form is particularly common, and "atoll-type" textures occur where only the rims of uraninite cubes take a polish; Ewers and Ferguson (1980) have reported the progressive replacement of these cubes from the core outwards by chlorite, thereby establishing that, at different times uranium has been remobilised. In polished sections, at high magnification and with the aid of oil immersion lenses, the alteration of uraninite to darker varieties is visible and is ascribed to the partial oxidation of U^{4+} to U^{6+} . This alteration occurs along grain boundaries, in fractures, and as isolated patches in massive uraninite. The extent of the alteration is very pronounced in residual uraninite found in sericitised ore-zone rocks at Nabarlek.

Sulphide occurs in minor amounts in all deposits, though it should be added that there is no correlation between the presence of sulphur and the concentration of uranium (Ferguson and Winer 1980; Binns et al., 1980). Galena is most abundant; its relationship to the uraninite and its Pb isotopic composition indicate a radiogenic origin (Hills and Richards, 1976). It usually occurs as disseminated euhedral grains (generally $<5 \mu\text{m}$

across), fracture fillings in uraninite, and as stringers and irregular grains in massive chlorite. Pyrite and chalcopyrite are present and can be replaced by galena. Traces of chalcocite and covellite have been found in all deposits, and bornite, digenite, arsenopyrite, cobaltite, and marcasite have been identified at Nabarlek. Hegge (1977) has reported the rare occurrence of tellurides (altaite, tellurbismuth, and melonite) at Jabiluka. Weathering at Nabarlek has led to the breakdown of copper sulphides and the minor supergene enrichment of native copper and cuprite. Gold has been noted in all deposits except Nabarlek, and occurs in economic quantities in the Jabiluka 2 orebody.

Graphite is found in the ore zones at Jabiluka, Ranger, and Koongarra; however, there appears to be no correlation between the presence of carbon and concentration of uranium, and there is no clear evidence to suggest that the removal of carbon (as say methane and carbon dioxide) produced a widespread reducing environment in which uranium deposition took place. Vein and vug carbonates occur in all deposits, but they are a rare feature at Nabarlek.

While the field relationships and age dating have provided a reasonably coherent picture of the sequence of events on a regional scale (Page et al., 1980), the relationship and timing of the main mineralising event in each deposit and subsequent events in the ore zones to the regional framework is less certain. It seems to be generally accepted, on the basis of field and laboratory work, that mineralisation took place later than the 1800 Ma regional metamorphism, although the evidence indicates that remobilisation has occurred in the ore zones, probably many times. Uraninite and galena ages indicate two main periods of possible mineralisation or mobilisation, namely ~1600 Ma and ~900 Ma (Hills & Richards, 1976; J.H. Hills, R.W. Page, B.L. Gulson & G.H. Riley, pers. comm.). Rb-Sr ages on rocks from the alteration zones associated with uranium mineralisation at Nabarlek and Jabiluka give an average model age of about 1600 Ma, additionally a younger event <920 Ma, is recorded at Nabarlek in both ore and the sericitised ore-zone rocks (Page et al., 1980). K-Ar muscovite ages from altered and unaltered Cahill Formation rocks at Jabiluka are consistent at about 1800 Ma - an indication that the alteration associated with this ore zone took place below the threshold retention temperature at about 350°C (Page et al., 1980).

Stable isotopes

Stable isotope studies of bedded sulfides (dominantly pyrite) in graphitic rocks from the Cahill Formation, adjacent to the major uranium ore deposits (Jabiluka 1 & 2, Koongarra and Ranger 1), have $\delta^{34}\text{S}$ values in the same range as mantle sulfur (Table 3). This indicates that mantle sulfur was the sulfur source for the formation of these sulfides and that Archaean-type conditions (i.e. anaerobic world conditions) prevailed during sedimentation (cf. Skyring and Donnelly, 1982). The sulfides formed from hydrothermal solutions probably derived by volcanogenic processes.

The $\delta^{34}\text{S}$ values of vein or vug sulfides from the uranium deposits mentioned above have, relative to the bedded sulphides, a wide range from -6 to +7‰ (Table 3). The presence of ^{34}S -enriched $\delta^{34}\text{S}$ values, outside the standard deviation limits of mantle sulfur, indicates sulfate was now present (Rye and Ohmoto, 1974) at the time of uranium ore formation. The variable $\delta^{34}\text{S}$ values are best explained as metal sulfide precipitation in organic-rich zones from H_2S which was produced by anaerobic sulfate reducing bacteria.

Bedded carbonates (mainly dolomite) from samples adjacent to the ore zones have $\delta^{13}\text{C}$ values around 0‰, in accord with normal marine carbonate $\delta^{13}\text{C}$ values (Keith and Weber, 1964). Their $\delta^{18}\text{O}$ values, however, range from +13 to +19‰ and are significantly below the range reported for early Proterozoic marine carbonates (Veizer and Hoefs, 1976; +15 to +25‰), indicating some groundwater recrystallisation.

The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of vein or vug carbonate from the ore zones are variable ranging from -20 to 0‰ and +7 to +20‰, respectively (Table 3). The $\delta^{13}\text{C}$ values indicate carbonate formation, at least in part, from organically derived CO_2 , while the $\delta^{18}\text{O}$ values show to a greater degree the effect of groundwater recrystallisation. Vein or vug carbonates show two reasonable correlation lines between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values for the two most extensively sampled deposits (Jabiluka 1 and 2 and Koongarra). These correlations support the argument of in situ reactions in which oxidising groundwaters have recrystallised carbonate and oxidised organic matter. Under the anaerobic conditions within the breccia zones sulfate reducers were active. A greater groundwater reaction is indicated at Koongarra and this is supported by the significantly altered ore zone organic matter $\delta^{13}\text{C}$ values (Table 3).

Table 3: Isotopic compositions of minerals associated with, and from strata adjacent to, major uranium deposits from the Alligator Rivers Area (Ayres and Eadington, 1975; Donnelly and Ferguson, 1980; Ewers et al., 1983)

Location and mineral form	Isotopic Compositions ‰		
	$\delta^{34}\text{S}(\text{CDT})^*$	$\delta^{13}\text{C}(\text{PDB})^*$	$\delta^{18}\text{O}(\text{SMOW})^*$
<u>1. Alligator Rivers Area</u>			
<u>Bedded sulfides in barren Cahill Fm adjacent to:</u>			
Jabiluka 1 & 2) Koongarra) Ranger 1)	+2 ± 1		
<u>Vein or vug sulfides in breccia ore zones Cahill Fm</u>			
Jabiluka 1 & 2) Koongarra) Ranger 1)	-6 to +14		
<u>Bedded carbonates barren Cahill Fm</u>			
		av. 0	+13 to +19
<u>Vein or vug carbonate in breccia ore zones Cahill Fm</u>			
Jabiluka 1 & 2) Koongarra) Ranger 1)		-20 to 0	+7 to +20
<u>Sedimentary organic matter in breccia ore zones</u>			
Jabiluka 1 & 2 Koongarra		-30 to -24 -22 to -15	
<u>Ore zone carbonate Nabarlek</u>			
		-20 to -15	+25 to +29
<u>2. South Alligator Rivers Area</u>			
<u>Bedded sulfide in barren Koolpin Fm</u>			
<u>Sulfides associated with uranium ore</u>			
	-1.6 -6 to +12		
<hr/>			
Mantle Sulfur	+2 ± 2		
Early Proterozoic marine carbonates		0 ± 4	+15 to +25
Sedimentary organic carbon		-25 ± 5	

*International reference standards:
 CDT - Canyon Diablo Troilite
 PDB - Peedee Belemite
 SMOW - Standard Mean Ocean Water

Table 4: Isotopic compositions of minerals from (1) three base metal deposits in the Rum Jungle area, and (2) barren organic-rich sedimentary rocks of the Pine Creek Geosyncline (Donnelly and Roberts, 1976)

Location and mineral form	Isotopic Compositions ‰		
	$\delta^{34}\text{S}(\text{CDT})$	$\delta^{13}\text{C}(\text{PDB})$	$\delta^{18}\text{O}(\text{SMOW})$
1. Woodcutters Pb/Zn sulfide deposit in Whites Fm	av. ~+9	- 3.5 graphite av. -15.7	+10 to +14.7
2. Browns Pb/Zn sulfide deposit in Whites Fm	-5.4 to +9.4	+5.5 to -6.9 graphite -19 to -30	+9.7 to +13.4
3. Mount Bonnie Pb/Zn/Cu sulfide deposit in the Mount Bonnie Fm	+0.2 to +6.0 av. +2.0	av. -11.5 cc. av. - 8.8 do. graphite -22.3	av. +11.6 cc av. + 8.8 do
Massive carbonate			
Coomalie Dolomite (av. of 2 samples)		+0.9	+15.8
Celia Dolomite (av. of 2 samples)		+5.2	+15.0
Disseminated and vein sulfides from carbonaceous-rich sedimentary rocks from various strata			
Kapalga Fm	av. +12.4		
Koolpin Fm	av. + 2.6		
Wildman Siltstone	av. +14.8		
Coomalie Dolomite	av. + 5.0		

Donnelly and Ferguson (1980) showed, using sulfur isotope geothermometry, that bedded or ore zone coexisting sulfides record the same temperature ($T \sim 270^\circ\text{C}$). A similar temperature was obtained from one sulfide pair by Binns et al. (1980). It was suggested in both studies that the temperature event was post-ore, and it was suggested that the event may have been the ~1688 Ma (Page, et al., 1980) emplacement of the Oenpelli Dolerite.

In contrast to the stable isotope studies of the Jabiluka, Ranger and Koongarra deposits, which indicate low temperature ore zone reactions, Ewers et al. (1983) have noted that isotopic compositions of the Nabarlek ore zone carbonate (Table 3) indicate high temperature reactions. A low fluid/rock ratio produced ^{18}O -enriched carbonates. Low fluid/rock ratios were also found in a $\delta^{18}\text{O}$ study of fluid reactions involving the Oenpelli Dolerite

at Nabarlek (Ypma and Fuzikawa, 1980). The Nabarlek ^{13}C -depleted carbonates (to -20‰) indicate incorporation of organically derived CO_2 in their formation.

A wide variety of geochemical studies on deposits of the ARUF have been undertaken; however, they usually relate to a particular orebody and do not permit comparisons between the deposits. For the Jabiluka orebodies, Ferguson and Winer (1980) noted that where wholerock U values exceeded 40 ppm, U correlated with Cu, W, As, Nb, Mo, Pb, Sc and Co and where whole-rock U values were below 30 ppm no correlations existed. Binns et al. (1980) have concluded that altered schists in the broad alteration halo surrounding the Jabiluka orebodies have undergone the following changes compared to their unaltered amphibolite facies equivalents: enrichment in Li and Mg, and to a lesser extent Sc, V, Ga, and Nb; and depletion in Na, Ca, Sr and Ba, and to a lesser extent Cr, Mn, Fe, P, Zn and Pb. In the immediate vicinity of ore (<1 m), K and Rb were also depleted. They also concluded that uraninite at Jabiluka was significantly enriched in Ca, Sc, Y, radiogenic Pb, rare earth elements (REE), Cu, As, Mo, Ag, and Sn. G.A. Cowan (reported in Ferguson et al., 1980) established that uraninite from Jabiluka also concentrates Li, B, Bi, Sb, Ga, Co and Tl. The concentration of REE (heavy REE in particular) has also been reported for ore-zone samples from Jabiluka, Ranger and Koongarra (McLennan and Taylor, 1980). Mercury enrichment has been observed in primary ores from Jabiluka, Nabarlek and Ranger; the highest concentrations being in gold-rich samples from the Jabiluka 2 orebody (Ryall, 1981; Ryall and Binns, 1980). Marked increases have been noted in the U/Th ratios in the ore zones of all deposits when compared to U/Th ratios in intrusives and metasediments throughout the geosyncline (Ferguson and Winer, 1980; Ewers et al., 1983); this has been interpreted as indicating that U rather than Th was transported under oxidising conditions in the hexavalent state to sites of deposition (Ferguson et al., 1980). Ewers and Ferguson (1980) reported that the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio of chlorite appeared to decrease with increasing uranium content in the whole-rock sample, and suggested that redox reactions involving Fe in the chlorite and uranium in solution (transported as uranyl complexes) could lead to uranium deposition.

A study of the groundwater geochemistry near the Jabiluka deposit has indicated that uranium concentrations in these waters

are low and not useful as a prospecting tool (Deutscher et al., 1980). At Koongarra, the distribution of secondary uranium minerals, which form a dispersion fan in the weathered zone above the primary mineralisation, has been interpreted in terms of lateral groundwater movement (Snelling, 1980). Radiometric disequilibrium between uranium and its daughter isotopes has also been shown to result from weathering and the circulation of groundwaters (Dickson and Snelling, 1980). Shirvington (1980) has suggested that the measurement of $^{234}\text{U}/^{238}\text{U}$ activity ratios in soil samples derived from weathered schists associated with uranium mineralisation may be a useful exploration tool.

Fluid inclusion studies have been confined to the Jabiluka and Nabarlek deposits (Ypma and Fuzikawa, 1980) and are restricted to fluid inclusions occurring in quartz and carbonates, mainly in late stage veins. Although uraninite can be associated with such veins and related to the fluids from which they formed, the significance of these fluids in terms of the earlier main mineralising events must be considered to be suspect. It has already been noted that the mineralisation in all deposits is primarily associated with chlorite, a mineral not amenable to fluid inclusion studies. At Nabarlek, quartz is a minor constituent in the ore zone and is unrelated to the primary mineralising event; it is absent from most rocks, although minor amounts occur in breccia fragments, some schists, and in late veins. Ypma and Fuzikawa (1980) have observed two types of fluid inclusions in quartz and calcite associated with mineralisation in the Nabarlek and Jabiluka deposits: type 1 inclusions contain saline brine dominated by CaCl_2 , MgCl_2 , and NaCl , and have homogenisation temperatures between 100° and 160°C ; type 2 inclusions are characterised by low salinities and CO_2 in the vapour phase.

In summary, there are major features common to all deposits in the ARUF to which various authors (Eupene, 1979; Hegge et al., 1980; Ewers and Ferguson, 1980; Needham and Stuart-Smith, 1980) have drawn attention. These are:

- 1) a spatial relationship of the deposits to the Early/Middle Proterozoic unconformity which approximates to the present day land surface,

- 2) the proximity of deposits to the Kombolgie Formation escarpment, and to the contact between Early Proterozoic metasediments and granitoid complexes,
- 3) the stratabound nature of deposits within the Early Proterozoic Cahill Formation,
- 4) with the exception of Nabarlek, the presence of massive bedded carbonates outside ore zones and their disappearance within the ore zones,
- 5) brecciation within the ore zones,
- 6) an intimate association between primary uranium mineralisation (predominantly uraninite) and chlorite,
- 7) an intense and pervasive chlorite dominated alteration halo in host rocks surrounding the mineralisation.

RUM JUNGLE URANIUM FIELD (RJUF)

Uranium was first discovered in northern Australia at Rum Jungle in 1949, and mining and milling continued until 1970.

The Rum Jungle and Waterhouse Complexes are basement highs to the Early Proterozoic sediments (Fig. 15). Both contain schist, gneiss, granite gneiss, and several varieties of granite. Rhodes (1965) divided the Rum Jungle Complex into six units, which in order of decreasing relative age are schist and gneiss; granite gneiss; metadiorite; coarse granite; large feldspar granite; and leucocratic granite. Veins and dykes of pegmatite and amphibolite, and quartz-tourmaline veins are also present. Johnson (1974) recognised the same units in the Waterhouse Complex, and also noted the presence of banded iron formation in both complexes. Richards et al. (1966) determined a Pb-U age measured on zircons of 2550 Ma for the Rum Jungle Complex, and Page (1976) reported a 2400 Ma Rb-Sr isochron for the Waterhouse Complex. Richards and Rhodes (1967) obtained a Rb-Sr whole rock age of about 2400 Ma for the leucocratic granite of the Rum Jungle Complex, which proved that all units of the complex are Archaean. Rhodes (1965) compared the Rum Jungle Complex to a mantled gneiss dome; Stephansson and Johnson (1976) suggest that the Rum Jungle and Waterhouse Complexes were domed by intrusion of late Early Proterozoic granite at depth.

The Namoon Group represents a basal rudite, arenite carbonate assemblage (the Beestons Formation and Celia Dolomite) which make up a conformable sequence encircling both granitic complexes, except north of the Rum Jungle Complex, and west of the Waterhouse Complex, where they pinch out.

Coarse pebbly sandstone and conglomerate of the Crater Formation represents the unconformable base of the Mount Partridge Group, which oversteps onto the complexes in places. The basement complexes formed islands at least until Crater Formation time, as it commonly contains clasts of banded iron formation derived from the Rum Jungle Complex. The Coomalie Dolomite above the Crater Formation is similar lithologically to the Celia Dolomite; both contain common clasts after gypsum and halite indicating a supratidal environment of deposition, and in places extensive algal mats of Conophyton sp. are developed in the Celia Dolomite. Both carbonate units are pervasively altered to magnesite, and a later alteration event is evidenced by abundant development of talc.

Outside the Rum Jungle area most of the Mount Partridge Group is represented by interbanded grey siltstone and black carbonaceous siltstone of the Wildman Siltstone, but at Rum Jungle this is largely represented by shallow-water facies variants; the Coomalie Dolomite is overlain by calcareous carbonaceous shale of the Whites Formation, and it is at or near this contact that all uranium and base-metal mineralisation is found: the Acacia Gap Quartzite Member of the Wildman Siltstone represents a higher-energy phase in the shallow marine to intertidal conditions which persisted in the area almost to the end of Mount Partridge Group time.

The South Alligator Group rocks thin in the Rum Jungle area and are not known further west, where Burrell Creek Formation greywacke and siltstone form an extensive monotonous terrain. Except for some uranium prospects of no economic importance (mainly in the Koolpin Formation east of the Waterhouse Complex) these units are essentially unmineralised in the Rum Jungle area.

During the ~1800 Ma orogeny the depositional dips around the Archaean basement highs were accentuated, and the Early Proterozoic sequence folded along axes trending mostly north to north-

east. Dips are commonly about 60° , and the sediments regionally metamorphosed to low grade. The Giants Reef Fault, a dextral wrench fault, trends northeasterly and displaces the Rum Jungle Complex and Early Proterozoic units by about five kilometres, west block north. The subsequently produced re-entrant of Early Proterozoic metasediments into the area of Rum Jungle Complex is known as 'The Embayment', where most uranium and base metal deposits of the area are located.

The Early Proterozoic sequence is overlain unconformably by the Middle or Upper Proterozoic Depot Creek Sandstone Member. The uranium deposits at Rum Jungle, Adelaide River and George Creek are all near the present eastern limit of outcrop of the sandstone and are at, or immediately below, the unconformity surface. Like the Kombolgie Formation, the Depot Creek Sandstone Member overlies the older rocks and is mostly quartz sandstone with minor pebble conglomerate beds, but there are no interbedded volcanics.

The RJUF contains numerous prospects and significant uranium deposits at Dyson's, White's, Rum Jungle Creek South (RJCS), and Mt Fitch (Table 2; Figs 15 & 16). Over 4300 tonnes U_3O_8 have been mined and treated from the first three deposits, and Mt Fitch has reserves of 1500 tonnes U_3O_8 . Unlike deposits in the ARUF, these deposits contain considerably smaller tonnages of U_3O_8 , may be associated with significant base-metal mineralisation (particularly Cu), and occur in a low-grade regional metamorphic terrain. Geological cross sections for the Dyson's, White's, and RJCS deposits are given in Figure 16 (and can be referred to in relation to the following text).

The deposits all show a strong stratigraphic and lithological control; they occur within carbonaceous, pyritic, and chlorite-rich shale and schist of the Early Proterozoic Whites Formation, which in turn overlies or is in faulted contact with massive carbonate belonging to the Coomalie Dolomite (Berkman, 1968; Fraser, 1975; Berkman and Fraser, 1980). Unlike the other deposits, the RJCS orebody is not localised at a carbonate contact, although dolomite has been intersected in drillholes within 70 m of the orebody. The orebodies are between 30 m and 100 m below the present land surface; a surface which coincides closely with

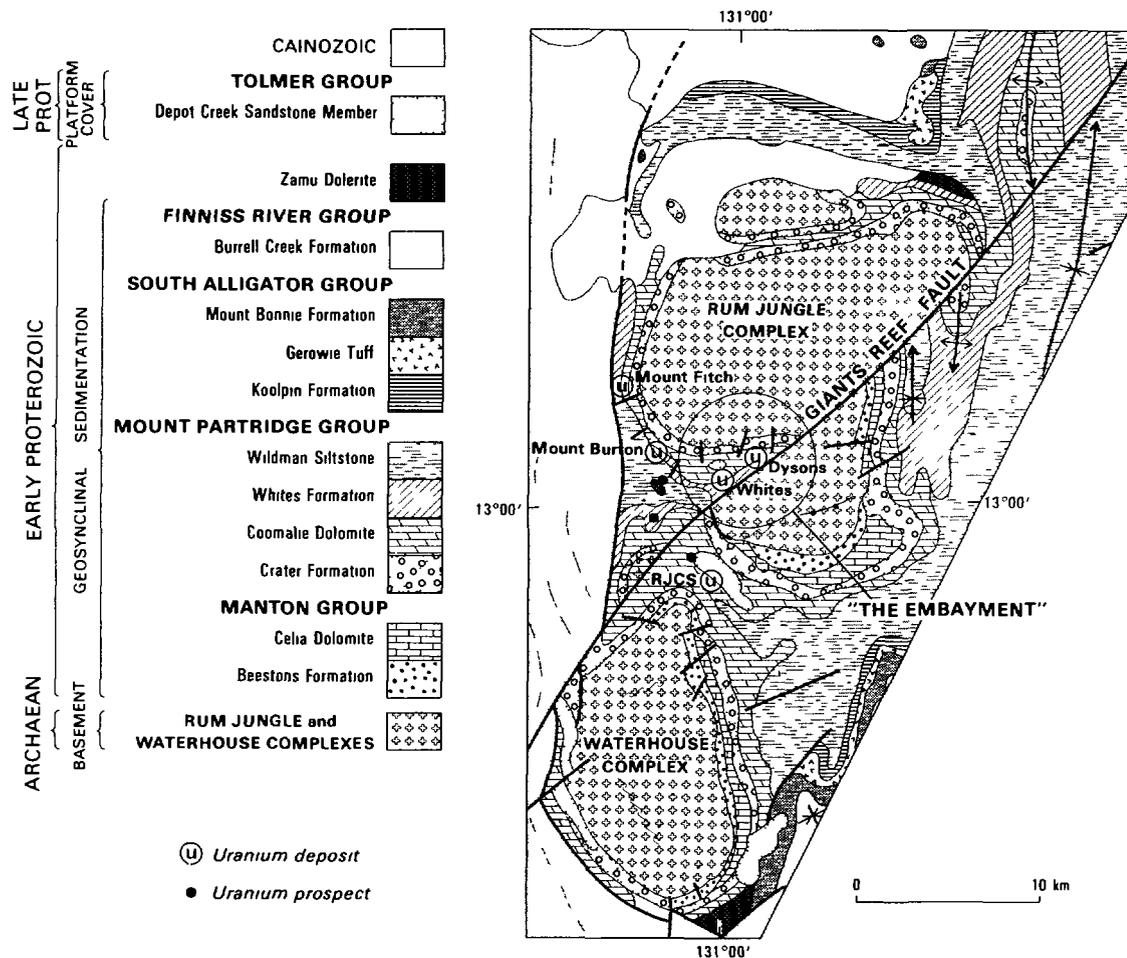


Fig 15. Geology of the Rum Jungle Uranium Field

an unconformity separating the Early Proterozoic rocks from overlying sandstone and hematite-quartz-breccia of probable Late Proterozoic age. The orebodies are typically associated with zones of shearing or brecciation, and as a consequence of their proximity to the surface have been weathered to give a variety of secondary uranium minerals which are predominantly phosphatic.

The uranium mineralisation in the Rum Jungle deposits varies in its mineralogy and association with other metals. At RJCS, the mineralisation is dominantly uraninite (base-metal sulphides are virtually absent) occurring as fine sooty coatings on shears and joints in pyritic and dolomitic shale and schist; some veins and stockworks are developed on a minor scale at the contact with underlying graphitic shale (Berkman, 1968). Several near surface pods of saleeite in the weathered zone were also mined. At Dyson's, saleeite is the dominant ore mineral and occurs throughout the orebody, particularly on cleavage planes, joints, and fractures in graphitic shales. Sklodowskite and autunite are

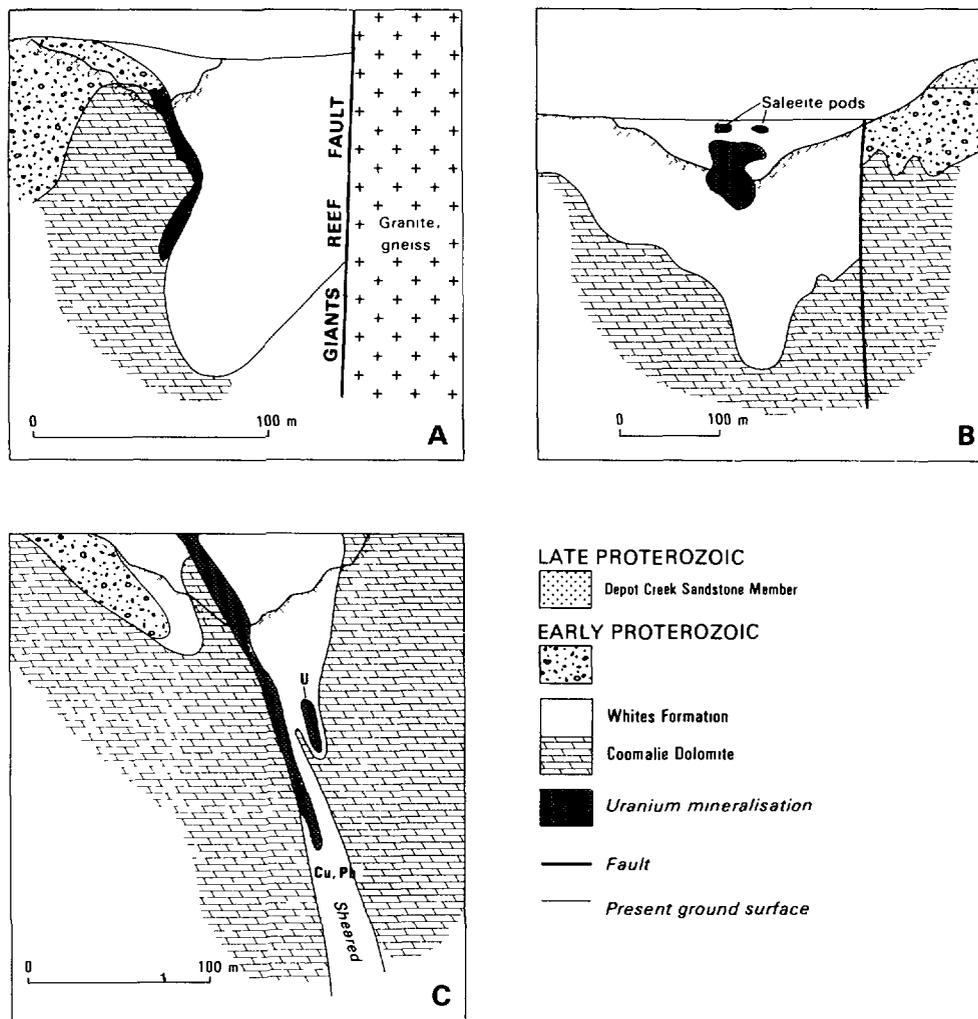


Fig 16. Diagrammatic sections of U deposits at Dyson's (A), Rum Jungle Creek South (B), and White's (C). (Modified after Berkman, 1968 and Fraser, 1980).

minor, and uraninite occurs in graphitic and strongly pyritic shales below the base of oxidation at 25 m. Base metals are again absent. The Mt Burton deposit occurs in graphitic shales interbedded with grey pyritic quartzite and consists of torbernite at the surface grading to uraninite at depth. Malachite, chalcocite and native copper are present in the oxidised zone. Mineralisation in the White's orebody is the most complex and has been described by Spratt (1965) as consisting of two orebodies, a copper-uranium orebody overlain by a base-metal orebody in sheared graphitic, sericitic, chloritic and pyritic shales. The copper-uranium orebody mainly contains uraninite, secondary uranium minerals, chalcopyrite, and bornite. The base metal orebody has been subdivided into three zones: a copper-cobalt zone (mainly

chalcopyrite, bornite, chalcocite, linnaeite and carollite), a cobalt-nickel zone (mainly fine grained linnaeite, carollite, bravoite and gersdorffite), and a cobalt-lead zone (mainly galena with minor carollite and sphalerite). The Mt Fitch copper-uranium deposits are hosted by chloritic, sericitic and graphitic schists, with the main uranium orebody containing fine grained uraninite (Craven, 1983) and confined to a major breccia zone in magnesite. The copper mineralisation is mostly secondary (malachite, native copper, and chalcocite) and confined to residual clays overlying the magnesite (Berkman and Fraser, 1980).

Studies of the petrology, geochemistry and geochronology of the deposits in the RJUF are very minor. Roberts (1960) deduced from mineragraphic studies of ore samples from White's deposit, that uraninite and pyrite mineralisation preceded a period of shearing which was later followed by the introduction of Cu, Co, and Pb sulphides. Richards (1963) obtained a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1015 Ma on a uraninite sample from White's, but concluded from Roberts' work that the uraninite was invariably altered and therefore probably older. No fluid inclusion studies have been undertaken on any of the deposits.

Stable isotopes

To date only limited stable isotopic studies have been carried out in the Rum Jungle area. The following discussion is a summary of a preliminary study (Donnelly and Roberts, 1976) and more recent studies by Donnelly and Crick (in prep.) and Donnelly et al. (in prep.).

Sulfides in Barren Organic Rich Sedimentary Rocks: Sulfides from barren sedimentary rocks (pyrite and pyrrotite) from various stratigraphic units of the Rum Jungle area have a range of positive $\delta^{34}\text{S}$ values (Table 4), which show two distinct distributions. These data are interpreted as indicating two generations of sulfide: one formed during sedimentation, the other was introduced from hydrothermal fluids after consolidation of the sediments. The $\delta^{34}\text{S}$ values of the first generation sulfide are suggested to be similar to that found for bedded sulfides in the Cahill Formation, indicating formation from sulfur of mantle origin. The more positive $\delta^{34}\text{S}$ values of the introduced sulfides indicates their formation from high temperature ($\geq 250^\circ\text{C}$) sulfate

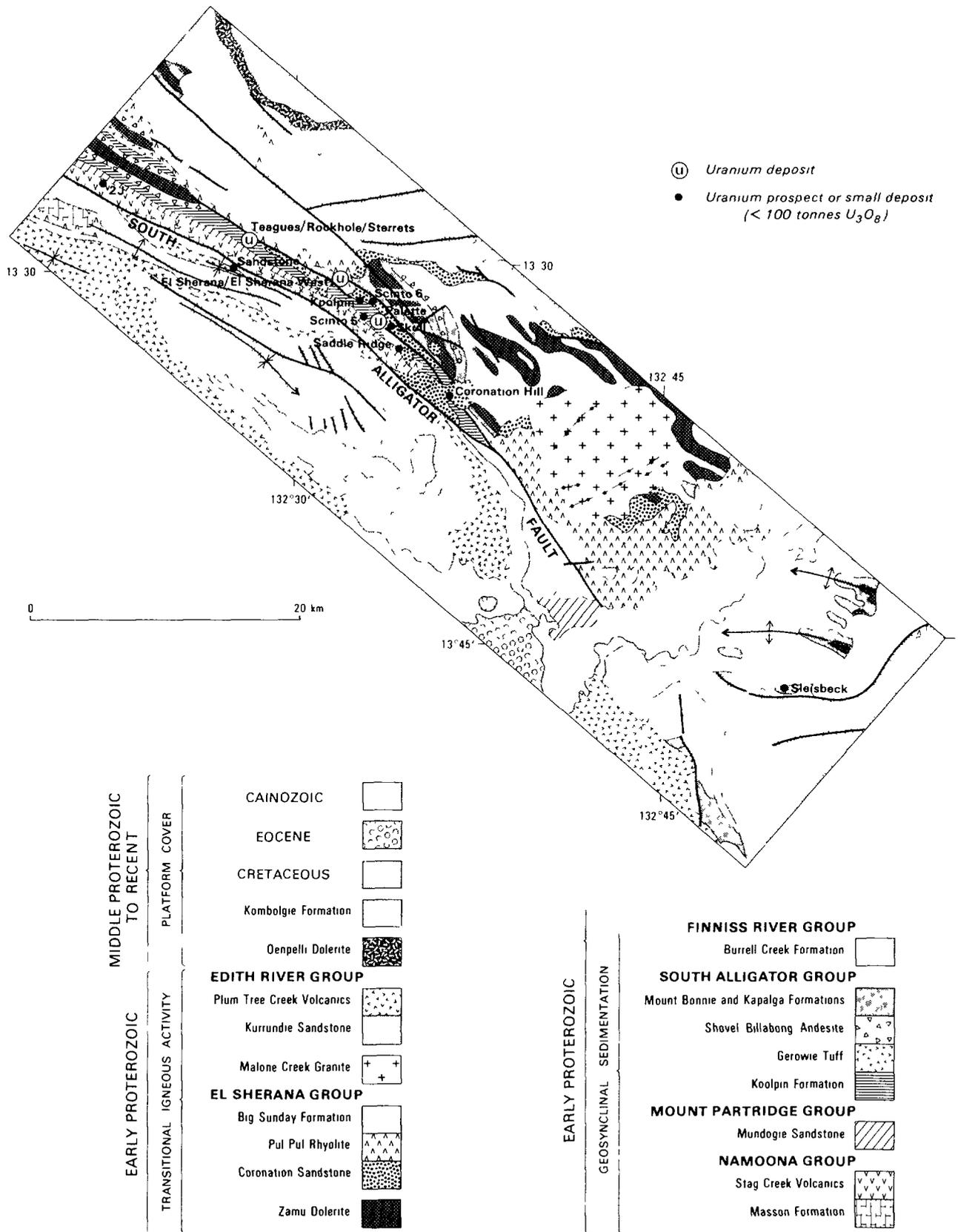


Fig 17. Geology of the South Alligator Valley Uranium Field

reduction. Although there is only limited isotopic data on massive carbonates of the area the fact that their $\delta^{18}\text{O}$ values do not exceed $\sim+15\%$, similar to the values found for the base metal vein carbonate (Table 4), is significant. Within the Alligator Rivers area bedded carbonates have $\delta^{18}\text{O}$ values which range up to $\sim+20\%$, the average value for early Proterozoic marine carbonate. These data suggest that in the Rum Jungle Area significant amounts of carbonates have been recrystallised, or formed, from the hydrothermal fluids; a conclusion in agreement with the extent of introduction of the second generation pyrite or pyrrhotite.

No stable isotopes have been carried out on minerals associated with uranium mineralisation on the RJUF. Three base metal deposits have however been investigated and the stable isotope values presented in Table 4. The significantly positive $\delta^{34}\text{S}$ values found for ore sulfides indicates the presence of sulfate and it is suggested that these deposits are the result of the pervasive hydrothermal fluids moving through the ore zones as well as the country rocks.

SOUTH ALLIGATOR VALLEY URANIUM FIELD (SAVUF)

The upper reaches of the South Alligator River flow along a northwest-trending belt of tightly folded Early Proterozoic geosynclinal metasediments about 60 km long by 10 km wide. These strata are deeply eroded and form strike ridges up to 200 m high in places, the tops of which are commonly capped by late Early Proterozoic to Middle Proterozoic felsic volcanics and sandstone. This area is known as the South Alligator Valley. Basins of the felsic volcanics and sandstone flank this northwest-trending belt, which in its narrowest part contains twelve of the thirteen uranium deposits of the South Alligator Valley Uranium Field. Sleisbeck, the thirteenth deposit, lies 32 km to the southeast (Fig. 17). The deposits were discovered between 1952 and 1954, and mine and milling operations ceased in 1965.

The Early Proterozoic geosynclinal sequence generally youngs eastwards, but forms a complex syncline in the central part where much of the western limb of the structure is concealed by younger rocks. The Masson Formation is the oldest unit and contains mainly carbonaceous shale, siltstone, carbonate, calcarenite and sandstone. The pelitic rocks, particularly the carbonaceous

ones, are strongly iron-stained to brick red shale at the surface, and form low undulating ridges. The calcarenite (porous sandstone at surface) and sandstone form continuous ridges which rarely exceed 60 m in height. The Stag Creek Volcanics is a sequence of poorly exposed altered basalt breccia, flows, tuff, and dark green tuffaceous shale conformably above the Masson Formation, and is about 1000 m thick. It is exposed along the southern flank of a prominent and continuous ridge commonly 100 m high formed by the unconformably overlying Mundogie Sandstone, which contains feldspathic quartzite and conglomerate.

Rocks of the South Alligator Group dominate the geosynclinal sequence in the valley and rest unconformably on older rocks, although owing to the strong folding clear unconformable contacts are seen only in fold hinges north of the area. The basal unit is the Koolpin Formation, interbedded dolomite, siltstone and carbonaceous shale. Its base is marked by a massive chert-banded ferruginous siltstone (carbonaceous shale with carbonate bands at depth), or by massive dolomite with algal structures. Strongly ferruginised or silicified beds form continuous ridges up to 40 m high but other strata rarely crop out. Tuff and argillite of the Gerowie Tuff are interbedded with the upper part of the Koolpin Formation, and thicken upwards as interbeds of Koolpin Formation rocks become progressively thinner. They are probably related genetically to the Shovel Billabong Andesite, a flow of variolitic andesite and microdiorite 100-300 m thick near the base of the Gerowie Tuff. The Mount Bonnie and Kapalga Formations, separated by the South Alligator Fault, form the uppermost part of the group and are similar assemblages of chert-banded ferruginous siltstone and shale, with greywacke, but only the Mount Bonnie Formation contains tuff. The fault may have been active during deposition, so that upward movement on the east side may have led to removal by erosion of any tuffaceous sediments deposited there during South Alligator Group time.

The Fisher Creek Siltstone is the youngest unit in the geosynclinal sequence, and contains a monotonous sequence of siltstone, feldspathic sandstone, phyllite, greywacke and arkose.

The Zamu Dolerite forms extensive sills mainly in the Koolpin Formation. The sills are folded with the geosynclinal sediments

and comprise a tholeiitic differentiated suite of mostly quartz dolerite.

During the 1800 Ma orogenic event the geosynclinal sequence was metamorphosed to low-grade (most sedimentary textures are preserved; pelitic rocks have a well developed slaty cleavage and contain sericite, chlorite and rare epidote, and psammitic rocks are commonly fractured and veined by quartz) and deformed into overturned tight to isoclinal folds with subhorizontal axes.

Following orogenesis, two suites of dominantly felsic volcanics and related volcanoclastics accumulated in a graben-like structure roughly coextensive with the South Alligator Valley. Each is valley-fill in character and strongly unconformable at the base, and they are separated in time by intrusion of the Malone Creek Granite. The older El Sherana Group contains basal coarse sandstone of the Coronation Sandstone, massive rhyolite, ignimbrite and minor tuff of the Pul Pul Rhyolite, and interbedded greywacke and siltstone of the Tollis Formation which are horn-felsed by the granite. These rocks are tightly folded in contrast to the generally gently folded rocks of the younger Edith River Group, which includes basal polymictic conglomerate and sandstone of the Kurrundie Sandstone overlain by an extensive sheet of ignimbrite with minor basalt of the Plum Tree Creek Volcanics. These rocks unconformably overlie granite of similar age to the Malone Creek Granite outside this area.

Earlier workers (Walpole et al., 1968) described volcanic vents in the Pul Pul Rhyolite, including one which hosts a uranium deposit, but more detailed examination indicates that exposure of intrusive centres in the area are confined to small syenite plugs along the South Alligator Fault near the Malone Creek Granite.

The relative age of the Edith River Group volcanism and of intrusion of the Oenpelli Dolerite lopoliths at ~1690 Ma is as yet not known, but the dolerite intrusion probably represents the last event in the period of 'Transitional Igneous Activity' at the end of the Early Proterozoic. The dolerite and both volcanic suites form a very rugged terrain over which sandstone of the Middle Proterozoic Kombolgie Formation was deposited with marked unconformity.

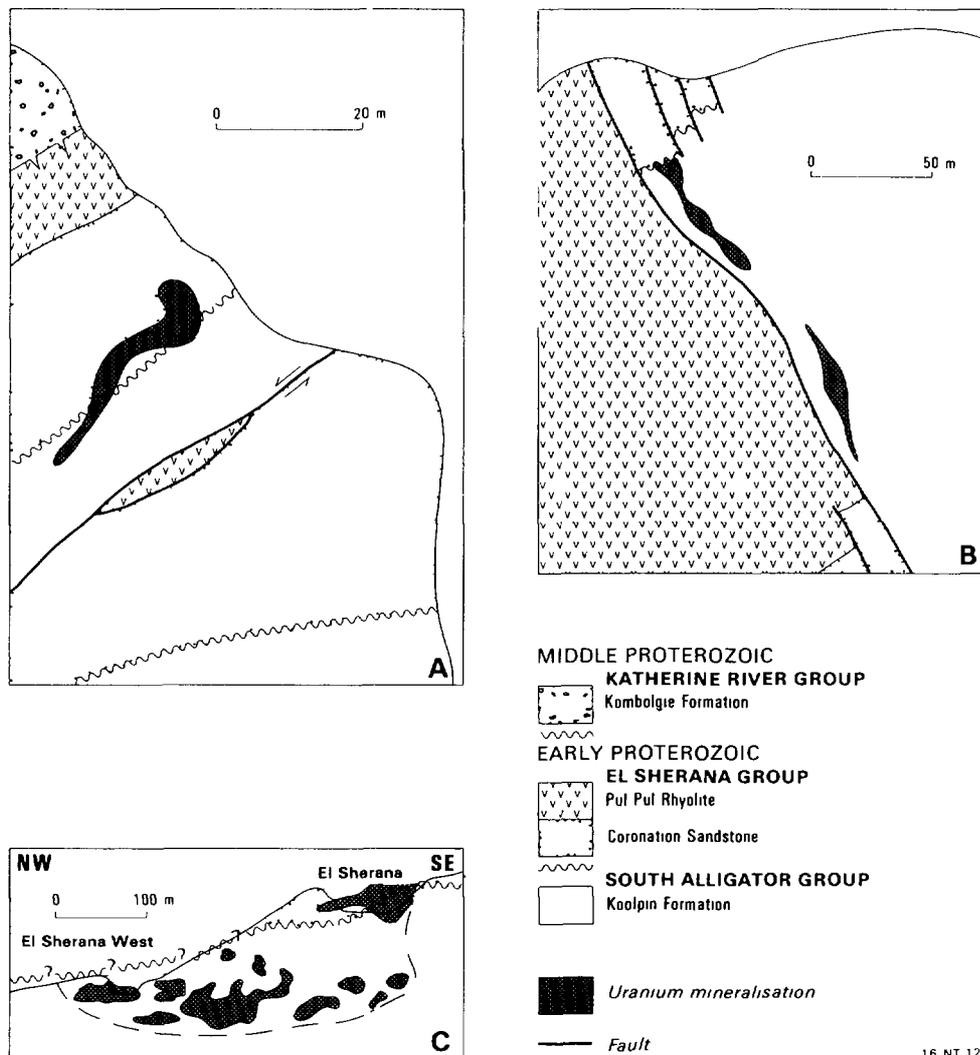


Fig 18. South Alligator uranium deposits. A. Generalised cross section of Palette (after Shepherd, 1967; and Crick et al., 1980). B. Composite cross section of Rockhole (after Hare, 1961; Ayres and Eadington, 1975; and Crick et al., 1980). C. Longitudinal projection of El Sherana and El Sherana West (after Foy, 1975 and Crick et al., 1980).

Faulting took place in the area in the episodes of geosynclinal sedimentation, igneous activity, and platform sedimentation, formed a graben as a depository for the volcanic and volcanoclastic rocks, and probably provided foci for extrusive pipes. Geosynclinal sequence rocks have been thrown against rocks of the volcanic suites and platform cover. Thickened sequences of Mesozoic and Tertiary rocks indicate that faults in the area have remained active until relatively recent geological time.

Deposits in the SAVUF field differ from those in the ARUF and RJUF by their association with Early Proterozoic sedimentary rocks

higher in the sequence, and in some deposits, an association with acid volcanic rocks; however they are similar in that they occur near an Early Proterozoic/Middle Proterozoic unconformity, and like the Rum Jungle deposits, occur in a low-grade metamorphic terrain. Generalised sections through some of the more significant deposits in the SAVUF are illustrated in Figure 18.

An idealised orebody in the South Alligator Valley has the following main features:

- 1) it occurs below the Early Proterozoic/Middle Proterozoic unconformity, usually in fractured cherty ferruginous and, at times carbonaceous, siltstones of the Early Proterozoic Koolpin Formation and adjacent sandstone lenses of the Coronation Sandstone, juxtaposed by faulting,
- 2) the mineralisation does not occur more than 100 m below the unconformity, and does not extend more than a few metres above it (for example refer to cross-sections of the Palette and El Sherana deposits). About 70 percent of the production from the South Alligator Valley deposits has come from the Koolpin Formation and the remainder from the Coronation Sandstone,
- 3) mineralisation is localised by major to minor faults, shears, and fractures,
- 4) uraninite is either massive or occurs as veins and small lenses, and is associated with minor galena, chalcopyrite, pyrite, and native gold. Rutherfordine, niccolite, gersdorffite, clausthalite and coloradite have also been recorded,
- 5) in oxidised ore zones, phosphate-rich secondary uranium minerals predominate and include gummite, metatorbernite, autunite, phosphuranylite, uranophane, and soddyite.

Two of the more significant deposits exhibit some divergence from this idealised orebody; the Coronation Hill deposit occurs in a breccia of unknown origin containing fragments of altered El Sherana Group and blocks of carbonaceous shale; and the Saddle

Ridge deposit consists almost entirely of secondary uranium minerals and is associated with tuff and rhyolite of the El Sherana Group.

Hills and Richards (1972) and Cooper (1973) have reinterpreted U and Pb isotope measurements obtained by Greenhalgh and Jeffrey (1959) on uranium ore specimens from the SAVUF and have indicated an age of 815 to 710 Ma, with a possible remobilisation or further phase of mineralisation at approximately 500 Ma. This is in agreement with the two generations of uranium mineralisation reported by Threadgold (1960) for ores from Rockhole, El Sherana, and Palette.

Apart from a geochemical and petrographic study by Ayres and Eadington (1975) of carbonaceous shales and acid volcanic rocks associated with the uranium mineralisation, there are no further substantive studies of this type reported for deposits in the SAVUF. Ayres and Eadington (1975) concluded that U correlates with Cu, V, and Ga, but not with carbon, even though there is a close association between uraninite and carbonaceous shales.

Stable isotopes

Although only a limited $\delta^{34}\text{S}$ study of barren and ore zone sulfides was carried out there are features in common with similar studies of the major uranium deposits. That is, sulfide in barren carbonaceous shale has a $\delta^{34}\text{S}$ value compatible with derivation from a mantle sulfur source, while introduced ore zone sulfides have a $\delta^{34}\text{S}$ range which the authors interpret as indicating sulfide formation as the result of the actions of sulfate reducing bacteria. The origin of these deposits, the authors suggest, was the result of low temperature fluid transport of oxidised uranium and reduction and precipitation when the fluid reached reduced zones.

CONTROLS OF ORE FORMATION

In the development of any genetic models applying to the uranium deposits of the Pine Creek Geosyncline (PCG) cognisance of a number of features common to these deposits would have to be taken into account. These features include:

- . Stratabound nature of the ore zones.
- . Association of ore bodies with zones of brecciation or shearing.
- . The regional association of most of the mineralisation with carbonate rocks and an antipathetic relationship with carbonate in the ore zones.
- . Shallow depth of the ore deposits.
- . The intense and pervasive chloritisation associated with the ore zones, wall rocks and cover rocks.
- . Absence of mineralisation in the Middle Proterozoic cover rocks despite the sometimes abundant presence of chloritised zones.
- . The spatial relationship of the deposits to the Early/Middle Proterozoic unconformity which approximates to the present-day land surface.
- . High U/Th ratios in mineralised zones.
- . The wide spread of apparent ages of mineralisation.
- . Proximity of the deposits to the overlying Middle Proterozoic cover rocks.

The proposed supergene genetic model for uranium mineralisation which we develop here is not universally accepted and the reader is referred to Binns et al., (1980) and Gustafson & Curtis (1983) for alternative models. The proposed model is based primarily on the deposits in the ARUF which are the most extensively studied. As there are a number of features common to the ore zones within the three uranium fields of the PCG it would seem likely that they share a common origin. Development of breccia zones took place after regional metamorphism. The breccia ore zones associated with carbonate-rich sequences were probably produced during peneplanation of the Early Proterozoic strata and before deposition of Middle Proterozoic cover rocks took place. Solution of these carbonate rocks appears to have produced collapse with the subsequent development of an

insoluble residue of breccia fragments. At Nabarlek and in other deposits from the RJUF and SAVUF, brecciation appears to be tectonically controlled by shear and fracture systems. These breccia zones probably pre-dated the development of the Middle Proterozoic cover rocks. Besides the development of breccia fragments in the solution cavities, other insoluble residues probably included micas, chlorite, clays, quartz and graphite. Textures and lithologies clearly indicate that the breccias developed after the regional metamorphism (Ewers & Ferguson, 1980) and that there was a high percentage of voids between the fragments at times reaching 50 percent by volume. The depth of solution cavity development at Jabiluka, which is thought to extend to 600 m below the Middle Proterozoic cover, was probably facilitated by the presence in the area of a palaeotopographic high of at least 250 m (G.A. McArthur, pers. comm.).

The low grade alteration within the ore zones suggests that the main mineralising event was low temperature and took place after the development of the brecciation and fracturing. The palaeoclimate during the peneplanation of the Early Proterozoic surface with its abundant development of breccia zones was probably arid and oxidising as indicated by the red-bed characteristics of the Middle Proterozoic cover rocks (Gustafson & Curtis, 1983). Lateritic soils were probably developed and clays from these soils could also have contributed to the insoluble material present in the breccia zones. It is also possible that decaying matter, now represented and identified as thucolite in some deposits was washed into these traps. The suggested role of bacterial sulphate reduction and the presence of biogenic carbonates within the breccia zones further supports the presence of organic matter (Donnelly & Ferguson, 1980). The introduced material could have been enriched in uranium, and have been capable of further enrichment through absorption.

Most of the Archaean and Early Proterozoic rocks within the PCG are enriched in uranium relative to world abundances for equivalent rock types (Ferguson & Winer, 1980). The Archaean granitoids within the PCG are thought to be representative of the provenance area for the Early Proterozoic sediments. These granitoids and the later Early Proterozoic high level granitoids and their extrusives are enriched in uranium by 2 to 6 times

world average abundances for granitoids (Ferguson et al., 1980). The uranium in the granitoids is present in the accessory minerals uraninite, monazite, zircon, uranothorite, xenotime and apatite (McAndrew & Finlay, 1980). The accessory uraninite in these granitoids ensured the presence of labile uranium in the provenance rocks. The Early Proterozoic metasedimentary sequence is also a potential source of uranium; however, uranium contents in unmineralised areas of the PCG average no more than 6 ppm and rarely exceed 14 ppm for any given formation or rock type (Ewers, 1982). The syngenetic concentration of uranium was an insufficient concentrating mechanism to produce ore deposits as all of the uranium deposits post-date the regional metamorphic event. There is no apparent concentration of uranium during the main regional metamorphic event (Ferguson & Winer, 1980). The abundant late-tectonic I-type granitoids and extrusive equivalents which developed during the ~1800 Ma regional metamorphic event have slightly higher uranium contents than the Archaean granitoids.

The nature of the ore bodies suggest that there was a downward percolation of the ore-forming solutions. The absence of mineralisation in the cover rocks suggests that the main mineralisation event took place during peneplanation of the Early Proterozoic rocks. Evidence in support of a downward percolation of the mineralising solutions includes ponding effects with uranium enrichment on the upper side of steeply dipping, impermeable barriers in the ore zones, bottoming out of the ore zones against impermeable mafic intrusives as at Jabiluka One, and Nabarlek and limited vertical extent of all the ore bodies. In that photosynthesis probably took place from at least 2500 Ma (Cloud, 1976) it is likely that younger meteoric waters were oxidising to varying degree as suggested by the red bed characteristics of the Kombolgie sandstones. Under these situations it is likely that U was transported as the U^{6+} complex. As Th is diadochic with U^{4+} (Naumov, 1959), the U/Th ratio is a critical parameter in deciding the valence state in which U is being transported. That the uranium was probably transported in the hexavalent state is supported by the marked increase in U/Th ratios within the ore bodies (>500) as compared to the granitoids (<1.1) granitic pegmatites (~12.5) and black shales (~0.3) (Ferguson & Winer, 1980; Ewers, 1982). The presence of

carbonates and micas in the metasediments would buffer groundwater pH to neutral or slightly alkaline. Under these conditions phosphate, carbonate and hydroxy uranyl complexes would be the most important (Langmuir, 1978). With increasing temperature, they are minor species at all pH's at temperatures of 100°C (Langmuir, 1978). Since P is not an important element in any of the rocks associated with the ore zones, whereas the REE's show enrichment in the ore zones and are known to be transported by carbonate complexes (Kosterin, 1959) uranyl carbonate complexes are preferred. That CO₂ was present in the ore zones is supported by the presence of chert after carbonate - a condition resulting from increased P_{CO₂} (von Engelhardt, 1977).

Experimental studies indicate that organic material and clays readily adsorb large quantities of uranium in the pH range 5 to 8.5 (Rozhkova et al., 1959; Muto et al., 1965; Doi et al., 1975). Muto et al., (1965) found that uranium, presumed to be in a metastable state when adsorbed on clays, was released and formed in time a stable uranium mineral and that, in the process, the clays recovered their sorptive capacity. Muto et al., (1965) quote an enrichment factor of 10,000. The experimental work of Giblin (1980) shows that the adsorption capacity of kaolin, known to have the least effective sorption properties of all clay minerals, reached a maximum K_d of 35,000 at 25°C and pH 6.5. In order for desorption to take place the surface charge of the adsorbed uranium ion must be made incompatible with the negative sorbent surface of the clay or clay-sized chlorite. This incompatibility can be brought about by increasing the CO₂ content at constant pH, raising the pH (Langmuir, 1978), or varying the temperature (Giblin, 1980). The accumulation of organic material within the breccia zones would create an anaerobic environment in which CH₄ and CO₂ might be present at a pH between 5 and 7. It is postulated, that while the clays and organic material were accumulating within the breccia zones, the plumbing system of these structures was such that low-temperature CO₂-rich groundwater, carrying uranium as uranyl carbonate complexes, passed through them. It is likely that these meteoric solutions were capable of transporting the other elements that are characteristically enriched in the ore deposits, namely, W, As, Nb, Mo, Li, Sc, Co, Cu, Au, Mg, B and REE's; although the ore zones could have partly inherited this geochemistry from the carbonaceous-rich

residue produced during development of the solution breccias. The main source of U was probably derived from dissolution of uraninite within the Archaean and Lower Proterozoic granitoids and their extrusives with a further contribution from the meta-sedimentary rock pile. The initial Eh and pH of the solutions could have evolved significantly before they reached the sites of uranium deposition in breccia zones. On entering the breccia zones reduction in pH would enhance the adsorption of U onto particulate matter. The reduction of uranyl complexes may have been facilitated by the oxidation of Fe^{2+} in clay, chlorite or other Fe-bearing minerals (Ewers & Ferguson, 1980).

The breccia zones developed during peneplanation, would continue to act as depositional sites for uranium after the onset of Middle Proterozoic sedimentation, provided the following conditions were met:

- . uranium continued to be leached from provenance rocks by groundwater;
- . access of these uranium-bearing waters into the structures remained possible.

Presumably the structures would initially remain open to the introduction of surficial waters and the oxidation-reduction boundary would remain substantially in the same position within the structure. Uranium deposition would only stop once sufficient sedimentation had taken place to result in the following changes:

- . Compaction of the regolith, particularly over the topographic lows which must have overlain the breccias, thereby sealing the structure and preventing further access of uranium-bearing waters.
- . Loading and dewatering of clays within the trap which would reduce permeability and develop chlorites from clays (Rowell and De Swart, 1976).

Uranium could have been added to that already present in the open structures within the Early Proterozoic rocks during the earlier part of the Middle Proterozoic sedimentation. Other authors have suggested that mineralisation could be formed during

the early deposition of the cover rocks (Kalliokoski et al., 1978) and it would seem to be a logical extension of the overall model presented here.

It is suggested that once the deposits were effectively sealed, all subsequent events recorded within the deposits, including the range of isotopic dates and high temperature features, represent reworking in situ. In the ARUF high heat-flow conditions were probably present in the area due to igneous activity associated with the pre-Kombolgie Oenpelli Dolerite at 1,688 Ma and intercalated lava flows in the Kombolgie Formation at 1,650 Ma (Page et al., 1980). It is probable that the heat associated with the latter igneous event resulted in the $\sim 270^{\circ}\text{C}$ temperature recorded in the ore-zone from stable isotope data; additionally, amorphous uranium oxides could have crystallized to a disseminated euhedral form about 1,600 Ma. This euhedral uraninite is particularly well developed at Ranger and Ranger also records the $\sim 1,600$ Ma event very clearly.

Russian studies of hydrothermal uranium deposits (Tugarinov and Naumov, 1969) indicate that the formation of uraninite occurs above 250°C whereas pitchblende, the massive microcrystalline and commonly colloform variety of uraninite, forms at temperatures not exceeding 220°C and probably less than 200°C . The $\sim 1,600$ Ma dates recorded within the ore-zones would belong to this period. It is suggested that the Type II fluid inclusions found at Nabarlek and Jabiluka (Ypma and Fuzikawa, 1980) may represent the original mineralising groundwater.

Petrographic work shows that solution of the disseminated uraninite and its redeposition as stringers and colloform uraninite has occurred in the ARUF deposits (Ewers and Ferguson, 1980; Binns et al., 1980) and it would seem that the conditions required for this to take place may be very mild. The ~ 900 Ma event can be correlated with epeirogenesis and development of Adelaidean (Upper Proterozoic) sedimentation to the south of the Pine Creek Geosyncline. Similarly the ~ 500 Ma dates associated with the SAVUF deposits could be attributed to epeirogenesis associated with the development of the early Palaeozoic Daly River Basin to the south of the PCG. Hydrostatic imbalance at high levels in the crust would be well-developed during periods of thermal activ-

ity associated with epeirogenesis which could subsequently remobilise the uranium.

To preserve these ore-zones it was necessary that impermeable cover rocks develop rapidly. The dominantly coarse-clastics with lesser intercalated volcanic units of the overlying Middle Proterozoic Formations appear to be excellent cover-rock protection once the depth of sedimentation was sufficient to seal the uranium deposits.

DISCUSSION

The events described for the period 2,200-1,700 Ma in the PCG do not appear to be unique to that period and could equally apply to low-temperature vein-type deposits in younger rocks. During the post 2,200 Ma period, the essential requirements of uranium source, transport, deposition and preservation that account for vein-type uranium deposits in Early Proterozoic rocks would appear to apply up to the present. The only apparent post-1,700 Ma variable compared to the 2,200-1,700 Ma period is the hydrosphere, which was progressively evolving an oxygenated atmosphere (Boichenko et al., 1975). The transitional oxidising atmosphere in the period 2,200-1,700 Ma whilst sufficiently oxidising to transport the uranyl ion in the hydrosphere, met rapidly reducing conditions short distances into the lithosphere. This allowed precipitation of UO_2 and, at the same time reducing conditions encountered in the lithosphere stabilised the uraninite. With rapid development of cover rocks the uranium ore-bodies were preserved.

It is suggested that in the post 1,700 Ma period the atmosphere was sufficiently oxidising so that groundwater conditions were generally inadequate for the reduction and precipitation of uranium on any large scale. The ultimate sink for uranium under these circumstances would have been the oceans, where uranium is added to sea-water, altered floor basalts, black shales and other pelagic sediments (Fyfe, 1979). This broad dissemination of uranium in the marine environment did not favour the formation of extensive vein-type uranium deposits in the post 1,700 Ma period.

No uranium deposits have been discovered to date in the Middle Proterozoic cover rocks in the PCG and workers in

Australia have not had the opportunity to study this type of mineralisation. The reader is referred to the companion papers in this volume concerning uranium mineralisation in the cover rocks in some uranium deposits in northern Canada.

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URANIUM MINERALIZATION
AT TUREE CREEK,
WESTERN AUSTRALIA

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Abstract

Uranium mineralisation which appears to be unconformity-related has been discovered at a contact between Middle Proterozoic sandstone and Early Proterozoic shale, greywacke, and dolomite in the Turee Creek area, W.A. The nature of this contact is controversial; it may represent a fault or an unconformity along which there has been minor movement. Although the mineralisation is still being evaluated and the ore controls have yet to be defined, a small uranium deposit consisting of approximately 643 000 tonnes grading 0.124% U₃O₈ has already been delineated. The mineralisation consists of uraninite, carnotite, phosphuranylite, and metatorbernite, and is hosted by clay zones, hematitic and/or carbonaceous shale and their brecciated equivalents, and chert breccias which form a sequence of uncertain age in the contact zone. Relationships are complex due to rapid facies changes within and between drill sections, and a tendency for units to pinch out along strike and down dip.

INTRODUCTION

The Turee Creek area is in the Pilbara region of Western Australia, approximately 1200 km north-northeast of Perth (Fig. 1). Exploration for uranium in this area began in approximately 1973, with the initial target being possible "roll-front" deposits within the Middle Proterozoic sandstones. Although sub-economic occurrences of sandstone-hosted mineralisation were located, the

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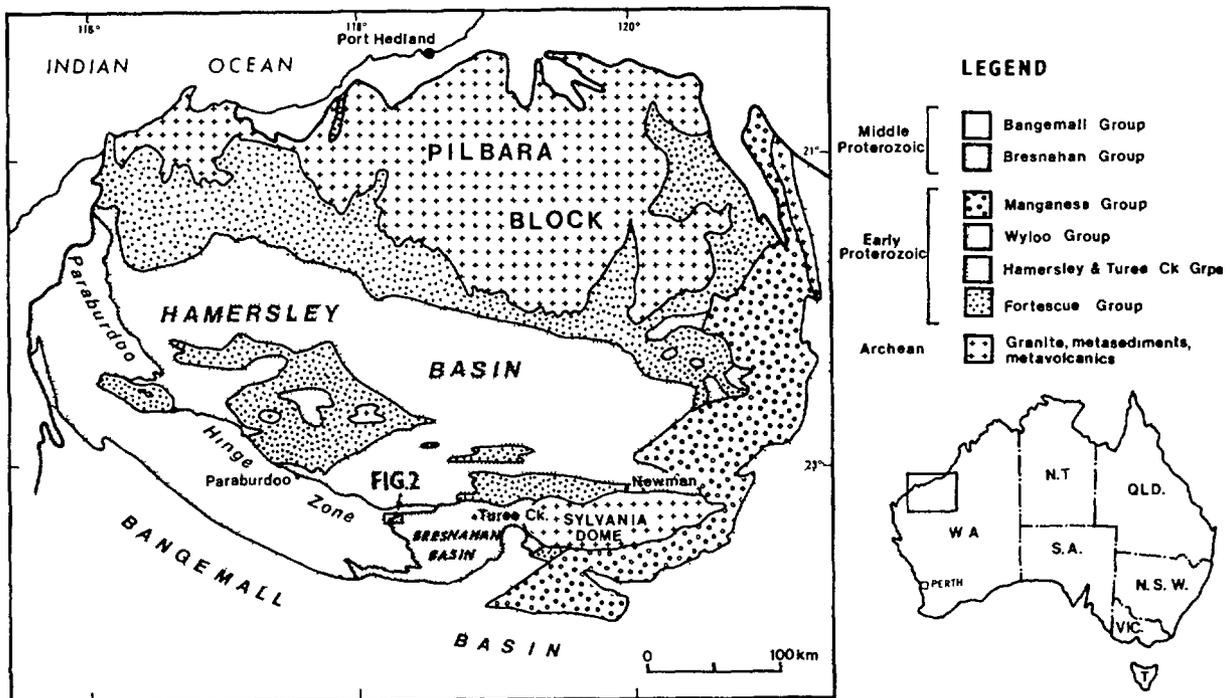


Fig. 1 Geological map of the Pilbara Region (modified after Goode, 1981)

emphasis switched to the Early Proterozoic sediments because of some similarities with the Alligator River region of the Northern Territory.

Initial prospecting involved ground follow-up of airborne radiometric anomalies, with sub-economic uranium mineralisation being located within shales and greywackes of the Early Proterozoic Mount McGrath Formation in the Angelo River area (Fig. 2) west of the Turee Creek homestead marked in Figure 1. The most significant mineralisation was discovered in 1980-81 and, although currently uneconomic, investigations are continuing. These uranium deposits are associated with the contact between the Middle Proterozoic sandstones and the Early Proterozoic shales, greywackes, and dolomites. The BMR's involvement in a petrological, geochemical, and stable isotope study of the Angelo River mineralisation began in late 1982, and the results obtained thus far are of a preliminary nature.

The uranium deposits at Angelo River represent a type of unconformity-related mineralisation, distinctly different from both the Alligator River and Athabasca types of mineralisation. The mineralisation is not clearly located within the overlying sandstone nor the underlying flysch facies sediments, but within a contact unit of disputed sedimentary or tectonic origin. The relationship between this unit and either sequence is uncertain.

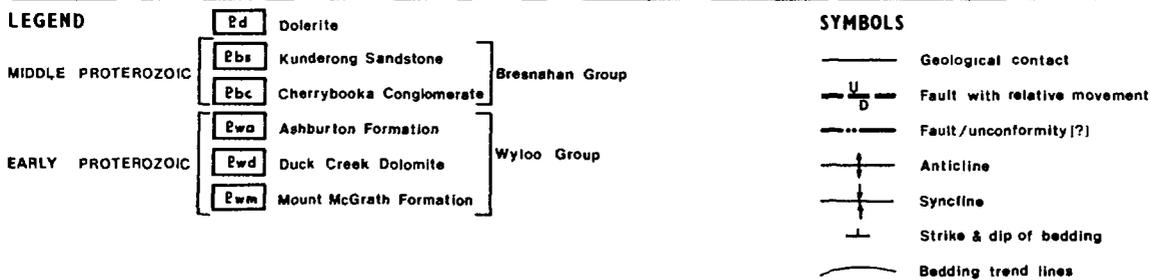
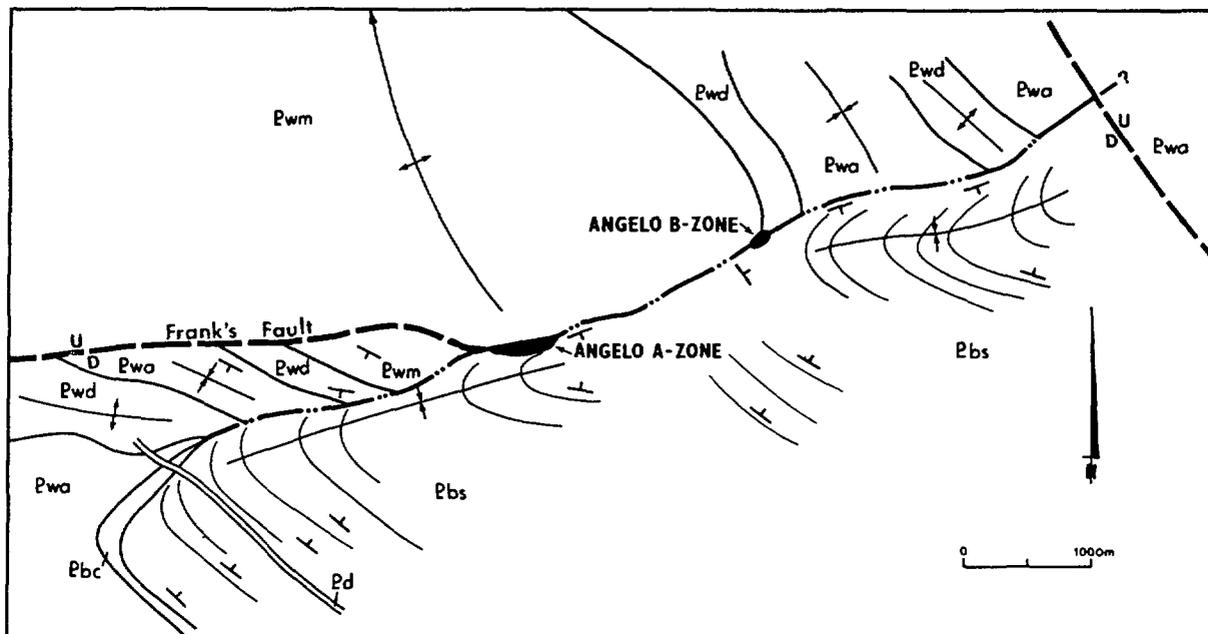


Fig. 2 Regional Geology, Angelo River Area

REGIONAL GEOLOGICAL SETTING

The Turee Creek area is located at the southern margin of the Hamersley Basin (Fig. 1). The area is underlain by Early Proterozoic sediments and minor volcanics of the Wyloo Group, which are unconformably overlain by arenites, feldspathic arenites, and conglomerates of the Middle Proterozoic Bresnahan Group (Daniels, 1968).

The Wyloo Group was deposited in an elongated trough along the south-western margin of the Hamersley Basin (Fig. 1) and is separated from the rest of the basin by an active zone of basement highs referred to as the Paraburdoo Hinge Zone (Goode, 1981). Folding is thought to have controlled the configuration of the basin, and was active both prior to and during deposition.

Wyloo Group sedimentation commenced after a brief period of subaerial exposure, following the dominantly chemical sedimentation of the Hamersley Group. The lowermost clastic units are thought to be terrestrial in origin, with later transgressive

marine deposition. Shallow marine conditions existed during carbonate deposition. The Early Proterozoic sedimentary sequence was subsequently folded and metamorphosed to greenschist facies during the Ophthalmian Orogeny (1700-1800 Ma).

The Middle Proterozoic Bresnahan Group, possibly represents a molasse sequence, deposited in an adjoining basin developed as a result of the Ophthalmian Orogeny.

GEOLOGICAL SETTING OF THE DEPOSITS

Stratigraphy and lithologies

The oldest recognised unit of the Wyloo Group in the Angelo River area has been correlated with the Mt McGrath Formation (Table 1). It consists of a succession of greywacke and shale with minor dolomite, which represents a turbidite sequence, overlain by a sequence of sandstone, dolomite and dolomitic shale, which passes into a thicker sequence of shales with minor dolomite. Near the top of the sequence is a volcanic sedimentary breccia. The overlying Duck Creek Dolomite occurs at several locations within the area, and consists of dolomite, chert breccia and minor carbonaceous shale. The dolomites are frequently silicified at surface, and ironstones have been developed on many outcrops. The Ashburton Formation forms the uppermost unit of the Wyloo Group and consists of interbedded shale, mudstone, siltstone and greywacke. The greywackes are micaceous, a feature which appears to be particularly diagnostic of this formation.

The clastic sediments in the Wyloo Group are characterised by fine grained assemblages of quartz, chlorite, K-mica, possibly clay minerals, and minor opaques. Variations in the relative abundance of any of these minerals can give rise to laminations. The opaques may contain carbonaceous material but usually consist of hematite with some limonite staining along fractures. Very fine grained pyrite and chalcopyrite are rare, as are accessory minerals such as tourmaline and zircon. Brecciation of Wyloo Group lithologies in the Angelo River area is common.

The Bresnahan Group sediments, which unconformably overlie the Wyloo Group, consist of a basal conglomerate belonging to the Cherrybooka Conglomerate passing upwards into a unit known as the Kunderong Sandstone. The Cherrybooka Conglomerate occurs at the western end of the Angelo River area and contains cobbles

Table 1 - Stratigraphic units of the Turee Creek Area.

AGE		STRATIGRAPHIC UNIT		LITHOLOGY
CAINOZOIC	QUATERNARY			Colluvium, alluvium
	TERTIARY			UNCONFORMITY Colluvium, calcrete, ironstone, silcrete, sandstone.
MIDDLE PROTERO-ZOIC (Carpentarian)		BRESNAHAN GROUP	KUNDERONG SANDSTONE	Quartz arenite, sub-arkose, arkose
			CHERRY-BOOKA CONGLOM.	Conglomerate
EARLY PROTERO-ZOIC		WYLOO GROUP	ASHBURTON FORMATION	Greywacke, siltstone, shale
			DUCK CRK. DOLOMITE	Dolomite, dolomitic shale, chert
			MT. McGRATH FORMATION	Greywacke, siltstone, shale, sandstone, carbonaceous shale, dolomite.

and coarse pebbles of quartz, quartzite, hematitic chert, jaspilite and banded iron formation occurring within a coarse sand matrix. The Kunderong Sandstone is the dominant Middle Proterozoic unit within the Turee Creek area. It consists of a sequence of medium to coarse grained, and sometimes pebbly, arenite, feldspathic arenite, and arkose. Coarse cross-bedding is common. The feldspar is mainly microcline and is either pale pink, due to fine grained hematite, or buff white where sericitised. The matrix usually contains fine K-mica, chlorite and minor opaques, and detrital tourmaline is common. Hematitic, chloritic, and kaolinitic alteration are widespread suggesting a complex redox history and resulting in some rocks developing a mottled appearance.

At the Angelo B-zone (Figs 2, 4), the contact between the Kunderong Sandstone and Mt McGrath Formation is marked by a thick silicified breccia which has been alternately described as a silicified fault breccia, a Middle Proterozoic silcrete, or silicified Kunderong Sandstone. The interpretation of this unit is controversial and is largely dependent on whether the Bresnahan-Wyloo boundary is viewed as a faulted contact or an unconformity. The silicified zone is underlain by a clay zone.

At the base of the Kunderong Sandstone in the Angelo A-zone (Figs 2, 3) a sequence of shale/breccia units consisting of hematitic and/or carbonaceous shale, their brecciated equivalents, and mixed breccias containing chert, shale, silicified dolomite (?) and sandstone fragments in a silty matrix are developed.

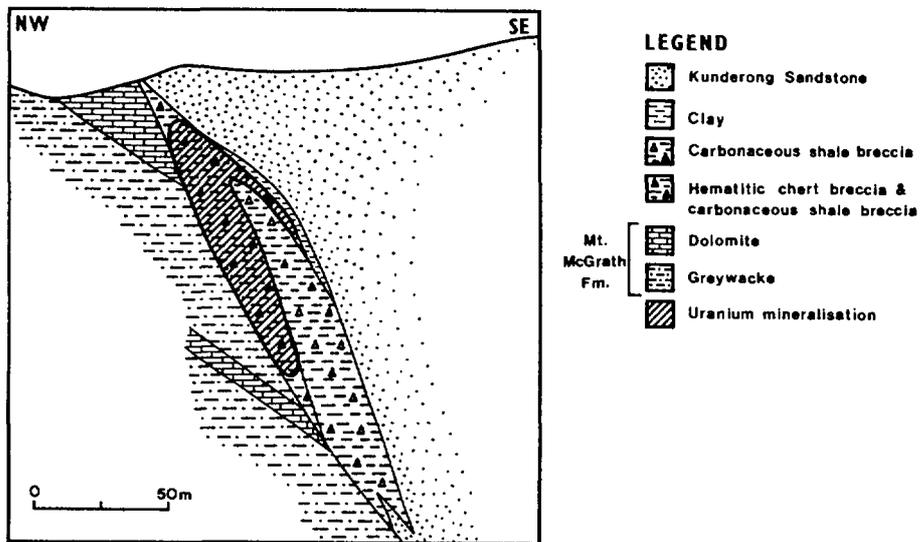


Fig. 3 Generalised cross-section of Angelo River A-Zone

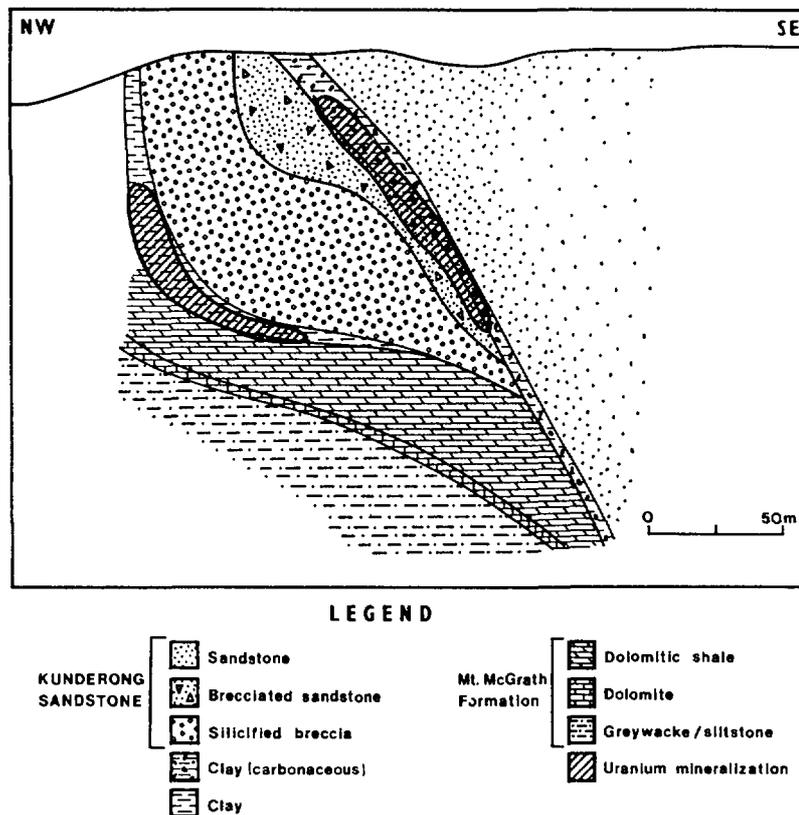


Fig. 4 Generalised cross-section of Angelo River B-Zone

Relationships are complex with rapid facies changes within and between drill sections, and a tendency for units to pinch out along strike and down dip. These units have been considered to be part of the basal Bresnahan Group, or alternatively as Wyloo Group sediments within a fault zone. Some of the brecciation appears to be tectonic, but other breccia units are clearly of sedimentary origin.

Structural Geology

The dominant structure within the Angelo River area is the contact between the Middle Proterozoic Bresnahan Group, and the Early Proterozoic Wyloo Group (Fig. 2). Initial mapping in the Turee Creek area (Daniels, 1968) has shown this contact as a fault. Subsequent work by Pancontinental geologists has led to varied opinions. Some have considered the contact to be an unconformity, with minor movement along the unconformity surface. Curtis (1982) concurred with this interpretation, and felt that the carbonaceous unit associated with mineralisation at the contact represents restricted marine embayments existing at the time of initial alluvial sedimentation in the Bresnahan Basin. Hirono and Suzuki (1983) have interpreted silicified sandstone breccias that occur at several locations along the contact as evidence of post-Kunderong faulting.

The contact is a focus of intense shearing and brecciation within the Wyloo Group sediments, and angular relationships exist between the unconformity/fault surface at several locations. The regional strike of the Kunderong Sandstone is approximately at right angles to the Angelo River contact, but the strike commonly swings to a sub-parallel orientation within 100 to 300 m of the contact (Fig. 2).

A prominent east-west oriented fault, locally known as "Frank's Fault" intersects the main Early Proterozoic-Middle Proterozoic contact west of the mineralised "A-Zone". The fault dips at approximately 70 degrees to the south and has downthrown the southern block relative to the northern block.

The Early Proterozoic sequence has been folded into a broad, northwesterly plunging anticline, that is cored by the Mt McGrath Formation. Folding in the Bresnahan Group occurs near the contact which has resulted in synclinal anticlinal structures parallel to the contact. A large northeasterly plunging syncline within the Kunderong Sandstone is present at the eastern end of the Angelo River area.

Uranium Mineralisation

Although there is mineralisation within the Wyloo Group sedimentary rocks away from the contact, most of the known uranium mineralisation is within the contact zone. As stated previously the nature of this contact is somewhat controversial, and there-

fore some uncertainties about the stratigraphic position of the mineralisation exist. Along the contact there are two main mineralised zones, the Angelo A-Zone and the Angelo B-Zone (Fig. 2).

The Angelo A-Zone (Fig. 3) is a small uranium deposit consisting of approximately 643 000 tonnes grading 0.124% U_3O_8 . The deposit is approximately 400 m long, with a maximum thickness of approximately 30 m. Uranium mineralisation is hosted by hematitic and/or carbonaceous shale, their brecciated equivalents, and chert breccias that form a sequence of uncertain age within the contact zone. Uranium mineralisation is irregular in distribution and commonly neither the mineralisation nor the host rocks can be correlated from hole to hole.

The Angelo B-zone was discovered in 1980, and due to severe drilling problems has been incompletely delineated. Mineralisation has a maximum width of 8.5 m with a grade of 0.047% U_3O_8 and is associated with clay (which is in part carbonaceous) and brecciated Kunderong Sandstone. The lower horizon has a maximum intersection of 10.5 m averaging 0.438% U_3O_8 and mineralisation is associated with cross-cutting iron oxide veins within a clay zone which underlies a silicified breccia of disputed origin. U-Pb isotope data indicate that the age of U mineralisation from this lower zone is approximately 1015 ± 30 Ma (Pigeon, 1981).

Uraninite, carnotite, phosphuranylite and metatorbernite have been identified from the Angelo A-zone and B-zone. Autoradiographs of thin sections prepared from core containing >100 ppm U indicate the following features. In brecciated Wyloo Group sediments, U occurs finely disseminated throughout shale fragments and matrix material. The breccia fragments are not always mineralised, but the fact that some are enriched is clear evidence to suggest a syngenetic concentration in the Early Proterozoic sequence. In mineralised zones, U is usually distributed as secondary minerals either in late fractures or as isolated grains. Uranium also occurs in fractures and disseminated form associated with opaques. In many instances, these opaques are secondary iron oxides which have either scavenged U or have associated secondary U minerals, though some may represent as yet unconfirmed uraninite concentrations. Although sulphides are not generally related to the U distribution, the concentration of U around the margins of some

Table 2 - Correlations on trace element data at 99 percent confidence limits for samples containing >50 ppm U (*denotes sample population too small, <10 samples). The most significant correlations (i.e. where $|r| > 0.70$) are underlined.

<u>ELEMENT</u>	<u>CORRELATES WITH</u>
Ba	Sr
Li	<u>F</u> Zn Rb Zr U Ga
Rb	<u>B</u> <u>Zr</u> Li Ga F U Sc Zn Nb Th
Sr	Ba
Pb	As U Ce Nd La
Th	<u>Nb</u> <u>Zr</u> Ga B Rb
U	As Rb Co Pb Li
Zr	<u>Nb</u> <u>B</u> <u>F</u> <u>Th</u> <u>Rb</u> <u>Ga</u> Li
Nb	<u>Zr</u> <u>Th</u> <u>F</u> Ga B Rb V
Y	-
La	<u>Ce</u> <u>Nd</u> F Pb
Ce	<u>La</u> <u>Nd</u> F Pb B
Nd	<u>Ce</u> <u>La</u> F Pb
Sc	<u>B</u> Ga Rb Cu Ni
V	Ga B Nb
Co	<u>Ni</u> As U
Ni	<u>Co</u> Sc
Cu	Sc
Zn	Li Rb
Sn	-
Mo	*
Ga	<u>B</u> <u>Zr</u> Nb Sc Th Rb F V Li
As	U Co Pb
S	-
F	<u>Zr</u> <u>Li</u> <u>Nb</u> Ce Nd La Rb Ga
B	<u>Sc</u> <u>Ga</u> <u>Zr</u> <u>Rb</u> Nb Th V Ce

sulphide grains indicates that localised reducing conditions may have exerted some influence.

At the time of writing, only trace element data are available and the interpretation of this data is at an early stage. The results of a correlation matrix calculated for those samples where U concentrations are in excess of 50 ppm are summarised in Table 2. Correlations at the 99 percent confidence limit (for

48 samples, $r \approx 0.37$) have been ranked in descending order according to the absolute value of the correlation coefficient. The most significant correlations (i.e. where $|r| > 0.70$) are underlined. Uranium correlates, though not strongly, with elements having different geochemical affinities (i.e. some are chalcophile, others are lithophile). The absence of strong correlations involving U, particularly with respect to Pb, probably reflect the mobility of U in a deeply weathered environment as indicated by the widespread development of secondary U minerals and both a primary and radiogenic source for the Pb. Surprisingly, no element correlates with S. Of these 48 samples containing >50 ppm U, 39 samples are either breccias or have been brecciated, and they encompass the full range of lithologies represented at Turee Creek, though shale breccias predominate. Twenty-five samples are either known or suspected to be carbonaceous and 24 are hematitic.

CONTROLS ON ORE-FORMATION

For a variety of reasons, an ore genesis model for the mineralisation at Turee Creek cannot be advanced at this stage. The true nature of the Bresnahan-Wyloo contact (i.e. whether it is a fault or unconformity) has not been resolved, and the mineralisation is associated with lithologies which are complex and are of uncertain age. Petrological, geochemical, and stable isotope studies are also at an early stage.

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UNCONFORMITY-RELATED URANIUM DEPOSITS IN THE ATHABASCA BASIN REGION, SASKATCHEWAN

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Abstract

Uranium deposits related to the sub-Athabasca unconformity contain large tonnages of high grade uranium resources. Their distribution is structurally and lithologically controlled by the unconformity, steep faults, pelitic rocks in the crystalline basement and clastic sedimentary rocks in the cover. The deposits contain monomineralic or polymetallic mineralizations, which are surrounded by alteration haloes. The deposits formed 1050 to 1300 Ma ago under hydrothermal conditions.

INTRODUCTION

Discoveries of uranium deposits related to the sub-Athabasca unconformity in the late 1960s triggered intense exploration activity and extensive geological studies not only in Saskatchewan and Canada but also around the world.

Economic importance of this deposit type attracted in the late 1970s more than 60 companies which operated more than 150 exploration projects with a total annual budget exceeding 60 million Canadian dollars.

As of the end of 1982 uranium resources of the Athabasca region constituted almost a half of Canada's uranium endowment in the Reasonably Assured and Estimated Additional low price resource categories.

GEOLOGY OF THE ATHABASCA REGION

The Athabasca region is a part of the Churchill Geological Province of the Canadian Shield. It is built up of Archean and Apehbian crystalline basement and younger, Helikian, supracrustal rocks.

The crystalline basement

Lewry and Sibbald (1979) subdivided the crystalline basement complex into lithostructural domains and these domains were grouped in major crustal units designated from northwest to southeast as Western Craton, Cree Lake Mobile Zone and Rottenstone Complex (Fig. 1).

The **Western Craton** was interpreted as a relatively stable foreland bordering in the northwest the Hudsonian orogenic belt. This craton is built up of mainly Archean katazonally metamorphosed rocks with some remnants of Aphebian supracrustal rocks. It is bounded north and northwest of the Athabasca Basin region by the Macdonald Fault and the Thelon Front and in the southeast by the Virgin River Zone. During the Hudsonian Orogeny the craton was affected by intense brittle to ductile deformation and by retrograde metamorphism.

The **Cree Lake Mobile Zone**, which is part of the Hudsonian orogenic belt, comprises a core of Archean granitic gneisses and Aphebian shelf to miogeosynclinal metasedimentary rocks including graphitic and pyritic metapelites. It consists of Wollaston, Mudjatic and Virgin River domains.

The Wollaston domain, which is the southeastern marginal part of the Cree Lake Mobile Zone, contains elongated Archean granitic domes flanked by Aphebian metasedimentary rocks including quartz conglomerates, quartzites, aluminous, graphitic, pyritic and non-graphitic pelites and semipelites, calc-silicate rocks, banded iron formation, volcanic arkoses and greywackes. The lowermost horizon in the metasedimentary sequence, the Wollaston Group, are graphitic metapelites. They are fine- to medium-grained rocks consisting chiefly of quartz, feldspars, biotite and graphite (Sibbald, 1979). Garnet, tourmaline and pyrite are present in lesser amounts. This horizon underlies for example Collins Bay 'A' and 'B' uranium deposits. The Wollaston Group contains several such pelitic horizons, which usually contain graphite. These horizons are intercalated in the vicinity of several uranium deposits commonly with calc-silicate rocks containing locally scapolite and albite. These scapolite/albite rocks in the Wollaston domain are interpreted by some geologists (e.g. Ray, 1978; Chandler, 1978) as having been formed by evaporitic processes.

The most common rocks of the Mudjatic domain are Archean granitoid gneisses locally containing pegmatitic intercalations.

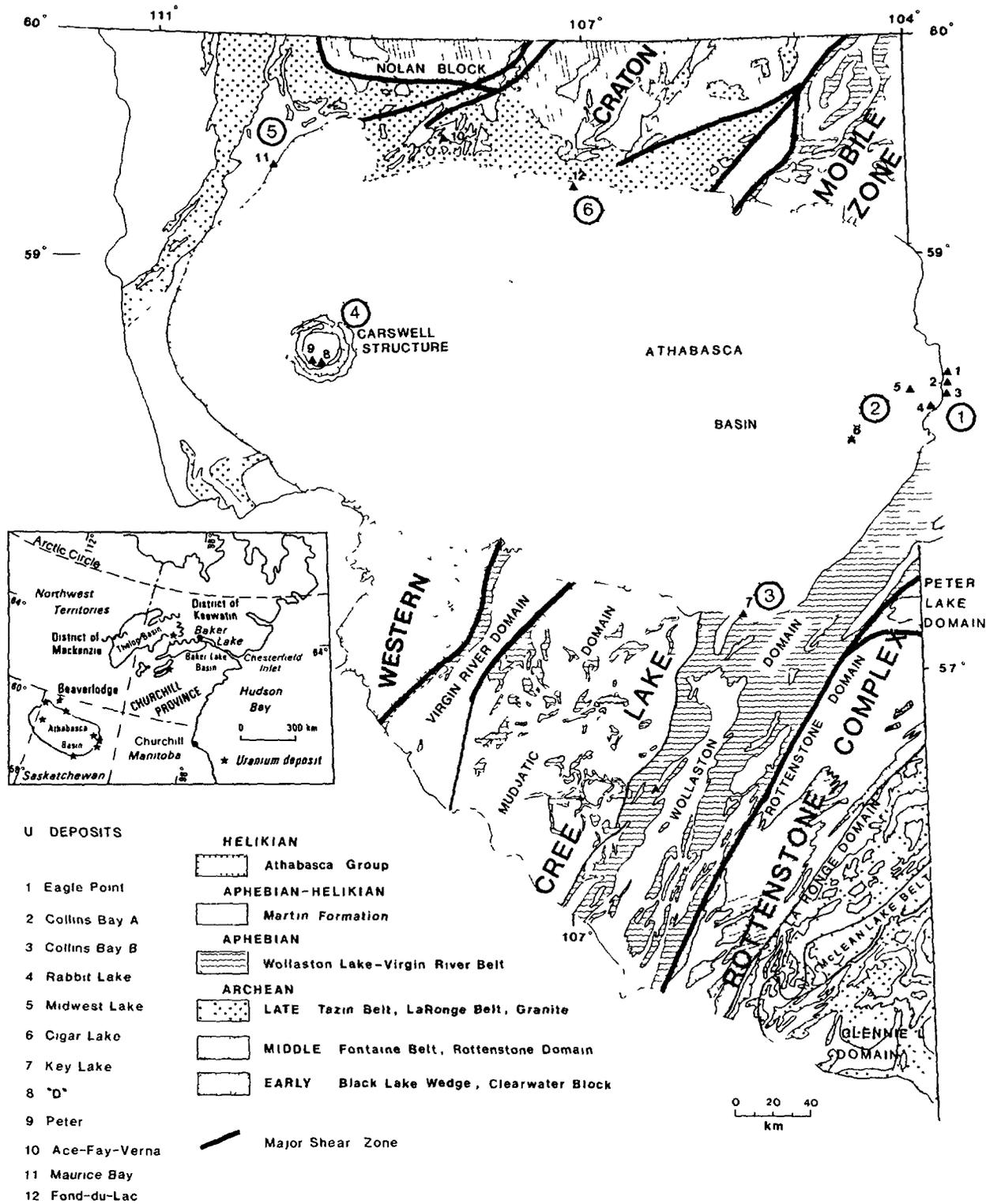


Figure 1. Major crustal units and lithostructural domains of the Athabasca region (modified from Lewry and Sibbald, 1979). Circled numbers:

- (1) Rabbit Lake – Collins Bay area
- (2) McClean Lake – Midwest Lake – Waterbury Lake area
- (3) Key Lake area
- (4) Carswell Structure
- (5) Maurice Bay area
- (6) Fond-du-Lac area

The Virgin River domain is a mobile belt of Archean granitoid cores and Aphebian supracrustal rocks; it is bounded in the northwest by the Virgin River - Black Lake Shear Zone. It represents a major Hudsonian mobile front, analogous to the Grenville Front at the southeast margin of the Superior Structural Province (Lewry and Sibbald, 1979).

The **Rottenstone Complex**, which borders the Cree Lake Mobile Zone to the southeast, comprises a broad belt of plutonic rocks of mainly Hudsonian age (Lewry and Sibbald, 1979) and older intrusive rocks. The Wathaman Batholith, which is a major intrusive body in this complex, originated during a tectonic event, which took place about 1880 Ma (Bell and Macdonald, 1982). The Peter Lake domain, separated from the Wollaston domain by the Needle Falls Shear Zone, comprises a variety of granitic to basic plutonic rocks; the basic rocks represent the oldest intrusive suite in the complex (2177 ± 110 Ma; Ray and Wanless, 1980).

Geochronology of the crystalline basement

Bell and Macdonald (1982) summarized and interpreted results of geochronological studies on the Precambrian in Saskatchewan and concluded, that: (a) the major plutonic events took place in four periods: at about 2510 Ma (e.g. intrusion of 'Wollaston Inliers'); 2,180 Ma (e.g. formation of Donaldson Lake gneiss); 1,880 Ma (e.g. intrusion of Wathaman batholith); and 1740 Ma (the "main" Hudsonian event); (b) the felsic hypabyssal rocks were emplaced at about 1580 Ma; (c) the three main metamorphic episodes culminated at 1875 ± 20 Ma; 1762 Ma; and especially 1680 - 1655 Ma; the latter episode represents an important and distinct anatectic event; (d) the supracrustal rocks of the Wollaston Group were deposited 1875 - 2500 Ma ago; and (e) the intrusion of lamprophyre dykes took place at about 1740 Ma ago.

The Helikian supracrustal rocks

Prior to deposition of the Helikian sedimentary rocks in the Athabasca Basin the crystalline basement complex underwent chemical weathering in a warm, moist climate (Macdonald, 1980). This weathering produced a regolith similar to modern lateritic soils up to several tens of metres thick (Ruzicka, 1975). The Helikian supracrustal sequence (Athabasca Group) was deposited on this regolith or locally, where the regolith was eroded, on the unaltered basement. The sedimentation took place in three structural sub-

Table 1: Lithostratigraphic units of the Athabasca Group
(After Ramaekers, 1979 and 1980).

	Formation	Maximum Thickness metres	Lithology
Subgroup	Carswell	500	Dolomite, some chert
	Douglas	2000(?)	Psammites, pelites
River	Tuma Lake	80	Pebbly sandstone
	Otherside	350	Sandstone, siltstone
	Locker Lake	120	Pebbly sandstone, conglomerate
William	Wolverine Point	700	Psammites, pelites, phosphorites
	Lazenby Lake	118	Pebbly sandstone, sandstone
	Manitou Falls	1400	Sandstone, basal conglomerate
	Fair Point	300	Conglomeratic quartz- rich sandstone with clay matrix

basins (Ramaekers, 1980) and reflected a general uplift in the Wollaston Fold Belt and perhaps along some of the faults in the eastern portion of the Athabasca Basin (Ramaekers, 1979). Therefore the eastern part of the basin, i.e. that in the vicinity of the uplifted area, contains mainly fluviatile deposits of detritus, whereas the distal (i.e. western) part contains lacustrine or shallow marine sediments. The Athabasca sedimentary sequence resembles a typical molasse assemblage which, after deposition underwent, severe diagenetic changes (ibidem).

The Athabasca Group has been subdivided (Ramaekers, 1979 and 1980) into nine formations (Table 1). In the eastern part the basal unit, the Manitou Falls Formation, is made up of quartz sandstones with variable amounts (up to 20 percent) of interstitial clay. The source of the detritus was apparently to the northeast or to east. The Manitou Falls Formation has a maximum thickness of about 1400 m.

The basal rocks of the Athabasca Group in the western part of the Athabasca Basin were designated as the Fair Point Formation. This formation, about 300 m thick, is built up of conglomeratic sandstone with clay-rich matrix. The detritus was derived from a nearby source and deposited in, apparently, lacustrine or shallow marine environment.

The Manitou Falls Formation is overlain by the Lazenby Lake Formation and the Wolverine Point Formation, which consist of pebbly quartz sandstone and of pelitic sedimentary rocks respectively with a maximum thickness about 700 metres.

The Locker Lake Formation which overlies the Wolverine Point Formation in the western portion of the Athabasca Basin consists of pebbly poorly sorted sandstone, which is about 120 m thick.

The uppermost members of the Athabasca Group, namely the Otherside, the Tuma Lake, the Douglas and the Carswell Formations were deposited apparently in a paralic environment. Most of them consist of sandstone with abundant interstitial clay; in the Carswell Formation carbonate prevails. The combined maximum thickness of these members exceeds 600 metres.

The sedimentation within the Athabasca Basin was intermittently accompanied by explosive volcanism; ash beds occur, for instance, in the Wolverine Point Formation (Ramaekers, 1980)!

Locally the clastic sedimentary rocks contain substantial amounts of phosphates (e.g. in the upper part of the Wolverine Point Formation; Ramaekers, 1980), organic substance, such as kerogen (e.g. in the basal part of the succession; Ruzicka, 1975; Ruzicka and LeCheminant, 1984) or layers of sulphides (e.g. in the Beartooth Island area).

The deposition of the Athabasca Group rocks took place probably during the 1340 to 1450 Ma period (Bell and Macdonald, 1982) as indicated by the Rb-Sr isochron on tuffaceous shales from the Wolverine Point Formation and diabase dykes cutting the Athabasca Group sedimentary rocks.

Structural features of the Athabasca region

The structural pattern of the crystalline basement is dominated by northeasterly trending geological units, most of which are bounded by major faults or shear zones. The Virgin River Shear and Black Lake Fault Zones separate the Western Craton from the Cree Lake Mobile Zone. The Needle Falls Shear Zone separates the Cree Lake Mobile Zone from the Rottenstone Complex. The northeasterly striking fault system is complemented by northwesterly and northerly striking fault sets.

Basic intrusive rocks, which were emplaced after the deposition of the Athabasca Group sedimentary rocks, heal some of the northwesterly and northerly trending faults.

A multi-ring structure, the Carswell Structure (Currie, 1969), occurs in the western part of the Athabasca Basin. The origin of this structure is not unanimously explained: it is interpreted either as having been formed by a meteoritic impact (Innes, 1964) or as a

cryptovolcanic feature (Currie, 1969); the latter interpretation appears to be more reasonable.

URANIUM METALLOGENY OF THE ATHABASCA REGION

Two major important episodes dominate the uranium metallogeny of the Athabasca region: (1) Mineralization associated with the Hudsonian orogeny about 1740 Ma; and (2) mineralization associated with the tectonic events about 1240 Ma.

Processes associated with the first episode were active mainly within the crystalline basement rocks whereas the mineralization of the second episode was spacially related to the sub-Athabasca unconformity. Uranium deposits of the first episode occur in the Beaverlodge area, north of the Athabasca Basin (Tremblay, 1972). Mineralization in deposits of the second period occurs in the altered crystalline basement rocks below, within the altered sedimentary rocks above the unconformity or, most commonly, within the altered interface between the crystalline basement rocks and overlying clastic sediments, i.e. along the sub-Athabasca unconformity.

The first episode in uranium metallogeny

Tremblay (1972) recognized four stages in formation of the Beaverlodge uranium deposits, which are hosted by crystalline basement rocks of the Western Craton: (i) Deposition of uranium-bearing sediments; (ii) mobilization of uranium and its concentration during granitization; (iii) remobilization of uranium and its concentration during mylonitization (about 1750 Ma ago) and (iv) remobilization and concentration during late fracturing (about 1240 Ma and later). He regarded the granitic and argillaceous rocks of the Archean Tazin Group as the ultimate source of uranium in the Beaverlodge deposits.

Bell and Macdonald (1982) recognized two periods of prominent mineralization in the crystalline basement rocks in Saskatchewan: (1) Syngenetic mineralization in pegmatites with absolute age of uraninite about 1860 Ma (which would correspond with Tremblay's second stage) and (2) epigenetic mineralization in pitchblende veins with absolute age about 1740 Ma, (which is identical with Tremblay's third stage of mineralization in the Beaverlodge area). These two periods coincide with igneous and metamorphic events in the region namely: the syngenetic mineralization with the "Wathaman Plutonism" (c. 1880 Ma) and "Wathaman Peak" of metamorphism in metasediments (1875 ± 20 Ma); the epigenetic mineralization with the emplacement of

"Younger Granites" along with lamprophyre dykes (1740 Ma) and with the second ("Main") peak of metamorphism (c. 1762 Ma). The second period, i.e. the epigenetic mineralization, represents a major metallogenic event associated with magmatic and post-magmatic processes of the Hudsonian orogeny. These processes included extensive mylonitization (Tremblay, 1972), feldspathic (commonly sodic) metasomatism (Robinson, 1955), carbonatization and hematitization of the rocks hosting uranium and/or polymetallic deposits (Ruzicka, 1971). Similar processes as those associated with the "Younger Granites" or the "Main" peak of (Hudsonian) metamorphism are recognizable in other regions of the Canadian Shield. Langford (1977), however, speculated that the Beaverlodge pitchblende deposits originated from uranium-bearing meteoric and near-surface ground water.

Uranium mineralization of the first period of Bell and Macdonald is widespread in Churchill Structural Province, but the mineralized pegmatites and mineralization in them are very irregularly distributed and, as a rule, of low grade.

Uranium mineralization of the second period of Bell and Macdonald occurs in fractures in certain lithostratigraphic units (e.g. Fay Complex of Tremblay, 1972) which were affected by metasomatic and hydrothermal processes. The main mineral assemblages are either pitchblende and U-Ti phases ('brannerite') or (rarely) uranium-polymetallic associations. The ultimate source of uranium in these deposits is unknown: it might be deep-seated fluids, granitized and mylonitized uranium-bearing sediments (Tremblay, 1972), residual evaporitic brines, connate fluids or crystalline basement rocks.

Unaltered crystalline basement rocks underlying the Athabasca Group locally contain elevated amounts of uranium and associated elements, such as nickel, cobalt and molybdenum (Table 2). These rocks might be sources not only of the Hudsonian epigenetic mineralization, but also of the mineralization associated with the sub-Athabasca unconformity.

The second episode of uranium metallogeny

The main ore-forming processes of the second episode of uranium mineralization took place after deposition of the Athabasca Group rocks, i.e. during their diagenesis, under elevated thermal conditions. They were accompanied by retrograde metamorphism of the host rocks (e.g. argillization, depletion of graphite), magnesian metasomatism and redistribution of iron, silica and aluminum oxides.

Table 2: Some elemental constituents from crystalline basement rocks, Athabasca Basin.

Element	Sample analyses in ppm		
	1	2	3
Ca	730	17000	340
Na	329	>10000	720
Mg	>20000	>20000	>20000
Ti	9000	10000	6900
Mn	110	2600	510
Ag	<5	<5	<5
As	<2000	<2000	<2000
B	98	53	62
Ba	130	140	680
Be	6	5	3
Ce	500	<200	200
Co	20	52	57
Cr	170	140	120
Cu	14	18	180
La	240	<100	<100
Mo	<50	<50	<50
Ni	190	110	220
Pb	<700	<700	<700
Sb	<500	<500	<500
Sn	<200	<200	<200
Sr	300	150	89
U	48	14	17
V	330	210	320
Y	41	50	<40
Yb	7	<4	<4
Zn	<200	<200	<200
Zr	380	200	210

Sample 1: Graphitic pelite from the footwall of the Deilmann ore body.

Sample 2: Unaltered garnetiferous gneiss from the footwall of the Midwest Lake deposit.

Sample 3: Unaltered graphitic pelite from the footwall of the Midwest Lake deposit.

Analytical method: Optical emission spectroscopy using 12B-DR spectroscope (samples 1-3)

As a rule illite and/or chlorite form haloes around the mineralization, whereas kaolinite occurs in a greater distance from the mineralization. The host rocks in the vicinity of the mineralization are hematitized and higher up in the sandstone limonitized. Graphite in the pelite immediately below the mineralization is usually depleted. The sandstone above the zone of limonitization is often silicified (Fig. 2).

Distribution of the ore bodies is, as a rule, structurally controlled by intersections of strike faults with the unconformity

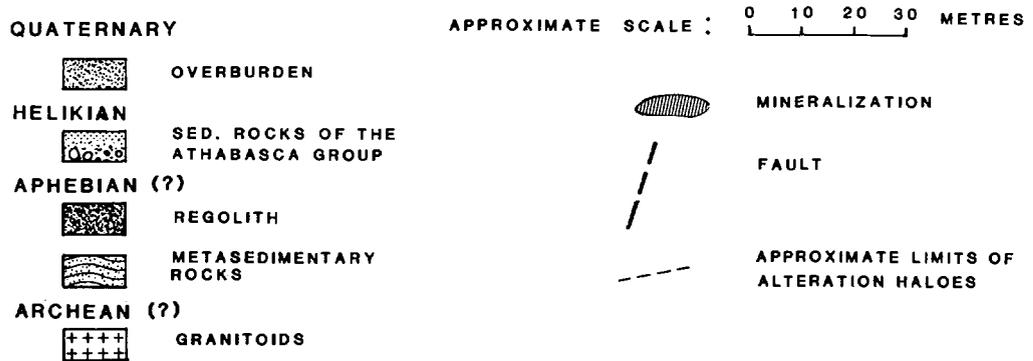
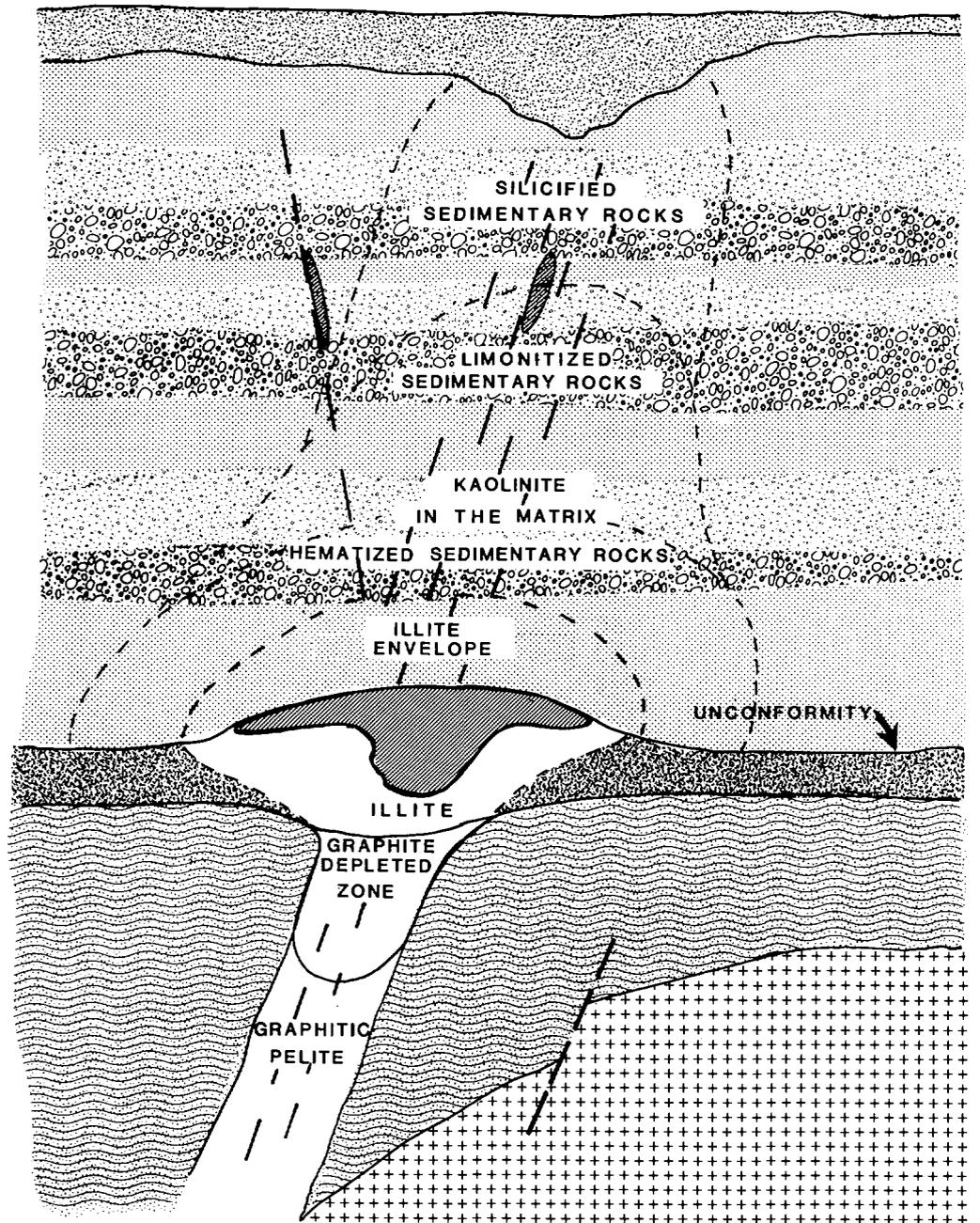


Figure 2. A generalized cross section through a mineralized body associated with the sub-Athabasca unconformity.

and lithologically by graphitic pelite or semipelite horizons in the crystalline basement.

Age of mineralization, as determined on seven pitchblende samples (Tremblay, 1982), spans an interval from 1075 to 1320 Ma. The mineralization is either monomineralic (pitchblende) or polymetallic (U, Ni, Co, Bi, Cu, Pb, As, Y, Zn, Mo, Ag, Au in various proportions).

Mineralogical geothermometric analyses of samples from the Key Lake deposit indicate (Dahlkamp and Tan, 1977; Pechmann and Voultsidis, 1981; Ruzicka and Littlejohn, 1982; Ruzicka, 1982) that the uranium minerals crystallized at temperatures from 135° to 150°C. Pagel (1975) and Pagel et al. (1980) on the other hand determined, on the basis of fluid inclusion studies on samples from the Cluff Lake area, that temperature of mineralization was probably in the range from 60° to 260°C.

URANIUM DEPOSITS

The uranium deposits related to the Aphebian-Helikian unconformity at the base of the Athabasca Basin occur beneath a cover of rocks of the Helikian Athabasca Group or, where these rocks were eroded, under unconsolidated Quaternary deposits. The cover rocks above the known deposits vary in thickness from nil at Rabbit Lake to 10 metres at Collins Bay and Key Lake, 165 metres at McClean Lake, 210 metres at Midwest Lake and 450 metres at Cigar Lake.

Individual deposits contain resources comprising tonnages of uranium from a few hundred to several ten thousands tonnes in ores grading from 0.2% to more than 10% U (Table 3).

Areal distribution of the deposits is controlled by structural and lithological features of the crystalline basement and the sedimentary cover.

The Athabasca region has been subdivided in this paper into areas as follows (Fig. 1): (1) *Rabbit Lake - Collins Bay; (2) McClean Lake - Midwest Lake - Waterbury Lake; (3) Key Lake; (4) Carswell Structure; (5) Maurice Bay; and (6) Fond du Lac.

RABBIT LAKE - COLLINS BAY AREA

The most important deposits in this area are: Rabbit Lake, Collins Bay 'A', Collins Bay 'B' and Eagle Point. In addition to these deposits the Raven, Horseshoe and West Bear deposits contain identified uranium resources.

*Numbers in brackets refer to circled numbers in Figure 1.

Table 3: Published uranium resources in selected uranium deposits associated with the sub-Athabasca unconformity.

Area/Deposit	Ore Tonnes	U %	U Tonnes	Reference
Rabbit Lake - Collins Bay area				
Rabbit Lake	5 655 000	0.34	19 230	1) Clark et al., 1982
Collins Bay B	N.A.	N.A.	11 293	Denner and Reeves, 1981
West Bear	N.A.	N.A.	425	Tremblay, 1982
McClellan Lake - Midwest Lake - Waterbury Lake area				
McClellan Lake	353 800	1.53	5 384	Saracoglu et al., 1983
Midwest Lake	1 200 000	1.60	19 250	Canada Wide Mines (1980)
Key Lake area Key Lake	3 277 800	2.12	69 228	Saskatchewan Mining Development Corporation (1983)
Carswell Structure D	123 000	4.25	5 211	Bayda (1978)
Maurice Bay area Maurice Bay	N.A.	<0.42	577	Lehnert-Thiel and Kretchmar, 1979
Fond-du-Lac area Fond-du-Lac	N.A.	<0.21	385	Tremblay, 1982

N.A. Information not available

1) Production has not been excluded.

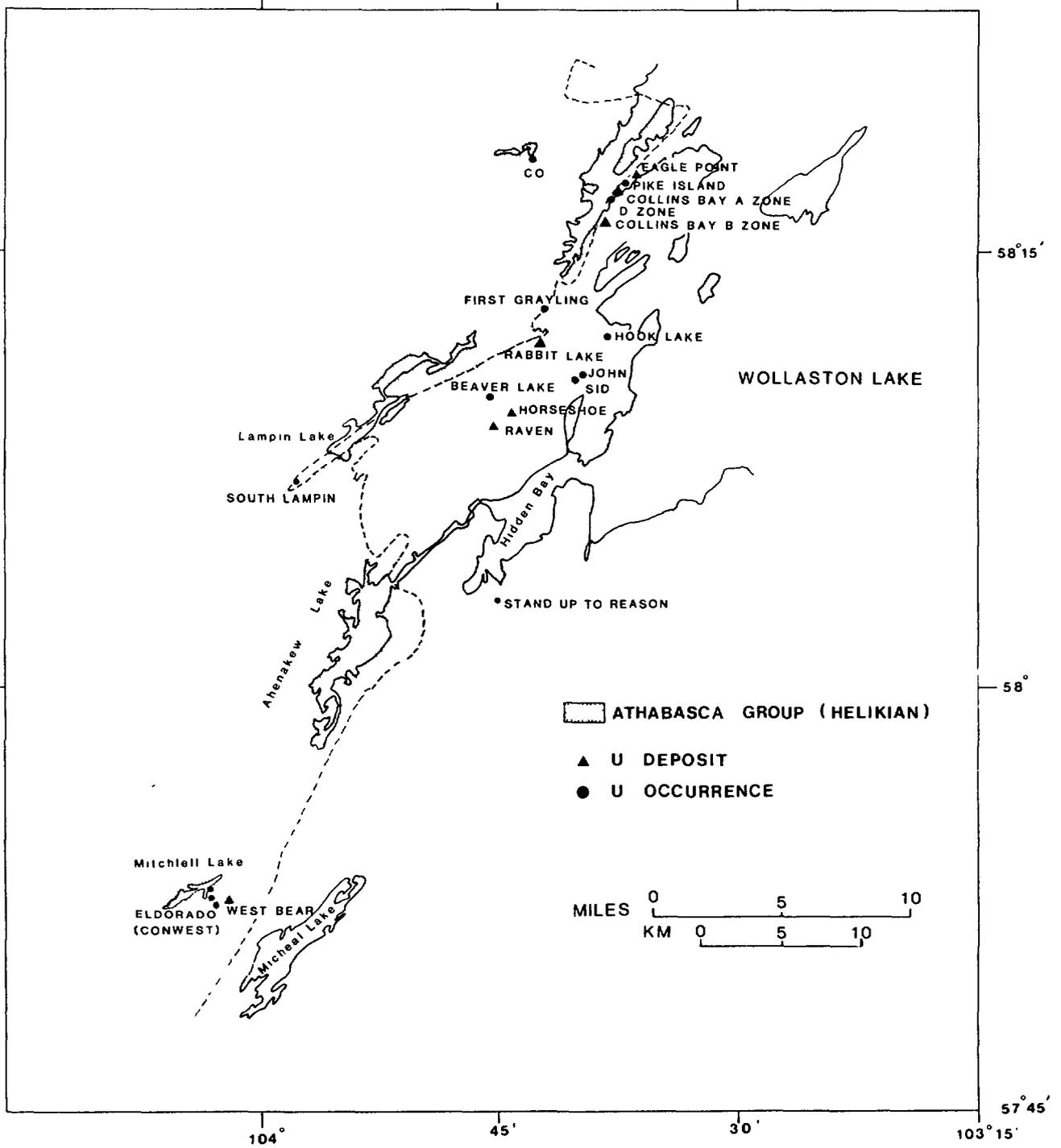


Figure 3. Uranium occurrences in Rabbit Lake - Collins Bay area.

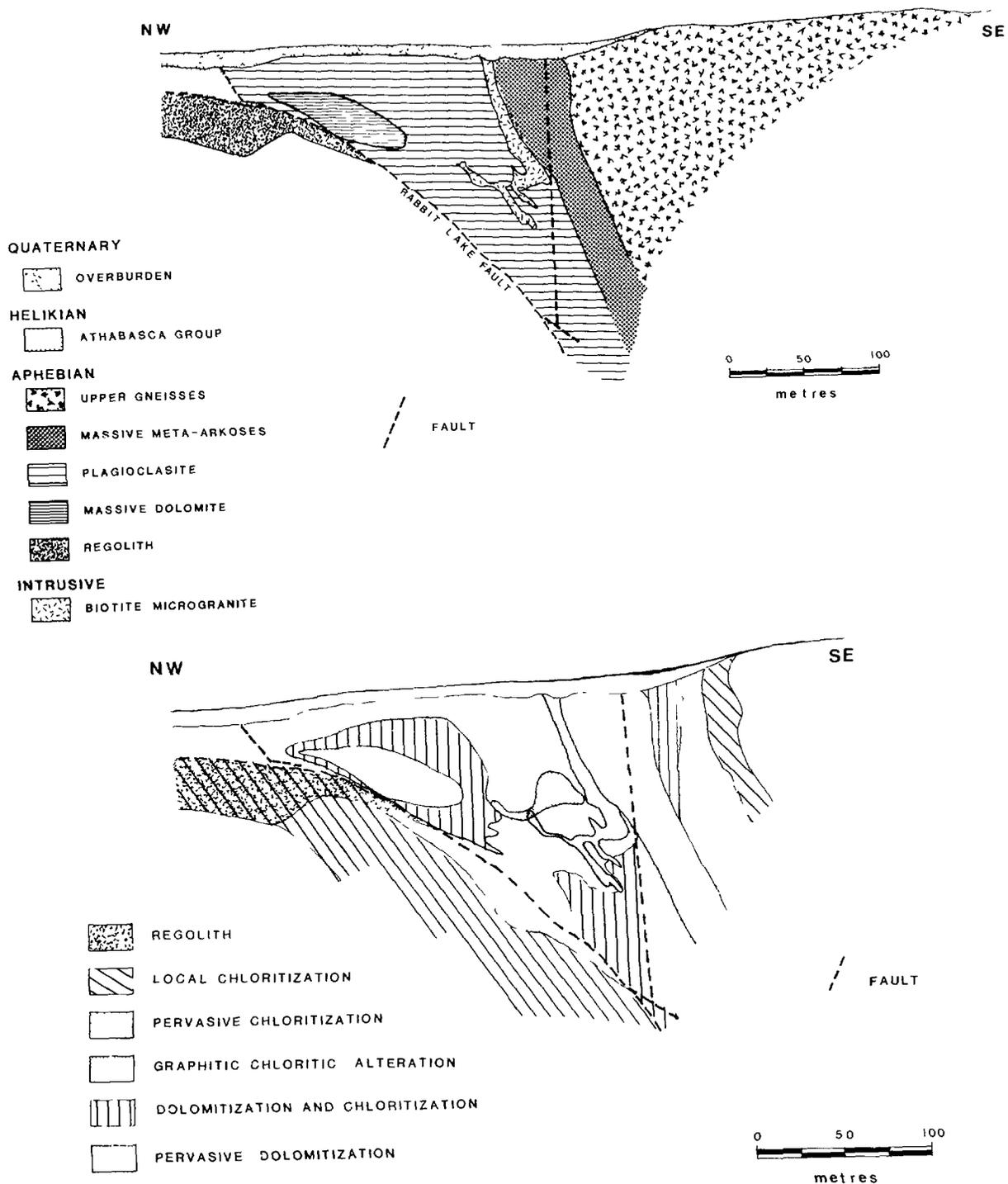


Figure 4. Geological section through the Rabbit Lake deposit; (a) lithology; (b) alteration. After Sibbald in Heine (1981).

The Rabbit Lake deposit

This deposit is located about 5 km west of the west shore of Wollaston Lake and 354 km north-northeast of La Ronge (Fig. 3).

Uranium mineralization in the Rabbit Lake deposit is hosted by a suite of Aphebian rocks of the Wollaston Group (Hoeve and Sibbald, 1978). Sibbald (1978) recognized in this suite three rocks



Figure 5. Radiating crystals of sklodowskite in quartz; Rabbit Lake deposit, Saskatchewan. Transmitted light.

units: (1) soda-rich feldspathic quartzite at the base; (2) an assemblage of calc-silicate rocks, feldspathic quartzite, marble and graphite-bearing rocks; (3) layered gneiss made up of quartzofeldspathic rocks intercalated with amphibolite. This suite is intruded by fine-grained granites (microgranite), (Fig. 4).

In the area of the deposit the Aphebian rocks trend northeasterly (065°) and dip southeasterly (65°); the host rocks represent a northwestern limb of a major syncline. They are dislocated by the 065° -trending and 30° SE-dipping Rabbit Lake Fault.

The host rocks are strongly altered. Chloritic alteration took place in the pre-mineralization period during the late stages of Hudsonian Orogeny, kaolinization and illitization during the mineralization period and argillization mainly due to weathering during the post-mineralization period until present time (Tremblay, 1982).

The ore body is cigar-shaped and in its longest dimension 550 metres long. In the horizontal plane projection the ore zone is 215 to 365 metres long and 90 to 125 metres wide; it extends to a depth of 150 metres.

The mineralization consists mainly of pitchblende and coffinite, but sklodowskite ($\text{Mg}(\text{UO}_2)_2(\text{SiO}_3)_2(\text{OH})_2 \cdot 5\text{H}_2\text{O}$) is a common secondary mineral (Fig. 5) along with minor amounts of kasolite, woelsendorffite, uranophane and boltwoodite.

Minor amounts of other metallic minerals are associated with uranium mineralization: galena, pyrite, rutile, nickeline and marcasite. Calcite and phyllosilicates are most common gangue minerals.

Elemental assemblages associated with uranium in the Rabbit Lake deposit include vanadium, molybdenum, nickel, copper, lead, barium, boron, magnesium and phosphorus in amounts exceeding the clarkes of these elements.

The minimum absolute age for the pitchblende mineralization has been determined by U-Pb method as 1281 ± 11 Ma (Cumming and Rimsaite, 1979); however uranium has been later rejuvenated several times.

Decrepitation tests on dolomite, which accompanied uranium mineralization as a gangue in the Rabbit Lake deposit, indicated temperature of crystallization at 245°C and on fluid inclusions in euhedral quartz at 135° to 160°C and allowing for effects of pressure at 180° to 225°C (Little, 1974).

A similar type of mineralization was noticed about 21 km northeast of Rabbit Lake on Spurjack Island (Chandler, 1978).

The Collins Bay 'A' Zone

The Collins Bay 'A' Zone is located about 10.5 km north of the Rabbit Lake deposit near the eastern edge of the Athabasca Basin (Jones, 1980; Tremblay, 1982). Its uranium-polymetallic mineralization occurs in the hanging wall of the Collins Bay Fault under overburden and a small remnant of a sandstone layer of the Athabasca Group rocks. The ore body is enclosed in clay, which gradually changes with depth to clay-altered Aphebian rocks (regolith) fresh graphitic and/or biotitic paragneiss and Archean (?) granitoid gneiss (Fig. 6). The Aphebian rocks are folded into a northeasterly trending anticline. Distribution of the mineralization is structurally controlled by intersections of the northeasterly trending and southeasterly dipping Collins Bay Fault, the altered zone along the sub-Athabasca unconformity, and by northwesterly trending cross faults. The high grade core of the Collins Bay 'A' Zone has a lensoid shape; it is about 50 metres long, up to 30 metres wide and up to 22 metres thick. Some drillhole inter-

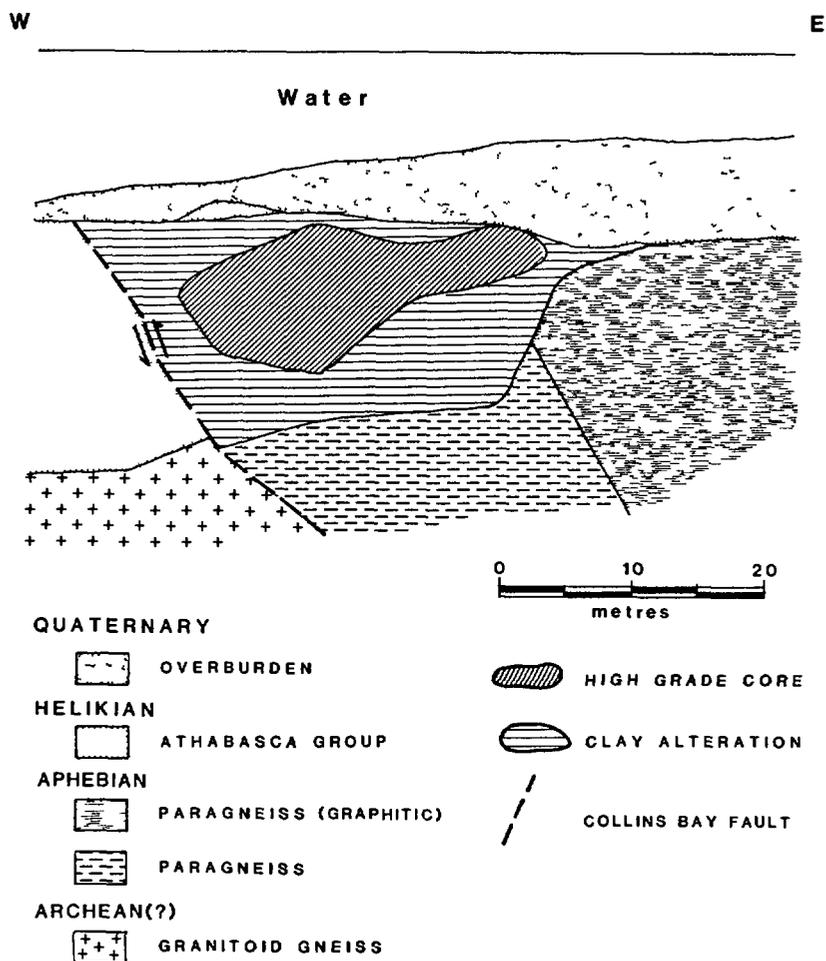


Figure 6. Generalized cross section through the Collins Bay 'A' Zone. After Jones (1980).

Table 4: Analyses of selected drill core samples from the Collins Bay 'A' Zone!

Sample No	Constituents				
	U	Ni	Pb	Ag	Au
1	2.33	0.56	0.20	3.77	0.03
2	59.78	1.07	9.18	29.14	10.63
3	64.87	0.96	9.11	30.51	24.31
4	61.22	1.20	8.89	25.37	33.46
5	13.40	5.09	1.18	23.66	1.92
6	53.17	1.69	6.16	43.54	15.94
7	35.19	3.66	7.08	1,349.8	10.35

Samples 1 to 5 were:

- randomly collected from the central portion of the 'A' zone;

Sample 6 and 7 were:

- randomly collected from the northeastern portion of the 'A' zone;

sections contained uranium in excess of 50 percent U over more than 10 metres.

The ore consists of pitchblende associated with rammelsbergite, pararammelsbergite, some galena, sphalerite and traces of silver and gold. (Table 4).

Collins Bay 'B' Zone

The Collins Bay 'B' Zone is located about 8 km north of Rabbit Lake deposit (Jones, 1980; Tremblay, 1982).

Uranium mineralization occurs mainly in clay altered sandstone of the Athabasca Group, which unconformably overlies highly altered Archean granitic gneiss. The Aphebian paragneiss, which is locally graphitic, occurs mainly to the east of the mineralization and only at the northern end of the deposit is with it in contact. The ore bodies of the 'B' Zone follow the trend of the Collins Bay Fault.

The ore body is about 1200 metres long, up to 150 metres wide and in average 17 metres thick. It contains high grade pods in the northern, central and southern part of the deposit with ore grades exceeding 20% U and 20% Ni over 2 metres.

In addition to pitchblende and coffinite the mineralization includes gersdorffite, skutterudite, nickeline, millerite, galena, chalcopyrite and pyrite (Fig. 7). Elemental assemblages in the Collins Bay 'B' zone include Ag, As, Co, Cr, Cu, Ni, Pb, Ti, V and Zr (Table 5).

Several small ore bodies occur between the Collins Bay 'A' and 'B' Zones. Their distribution is controlled by intersections of the Collins Bay Fault with the sub-Athabasca unconformity. These ore bodies are called Collins Bay 'D', 'E' and 'F' Zones. Their mineralization is similar to the 'A' and 'B' Zones (Fig. 8).

Eagle Point deposit

The Eagle Point deposit occurs about 2 km northeast of the Collis Bay 'A' Zone (Fig. 3). Its host rocks are Aphebian metasediments such as feldspar-cordierite-biotite gneiss, pyritic garnetiferous gneiss, feldspathic quartzite and graphitic paragneiss, which are intercalated with granitic pegmatoids. The host rocks exhibit monoclinial layering and faulting and strong argillization and hematitization or limonitization which follow faults, bedding-planes or foliation.

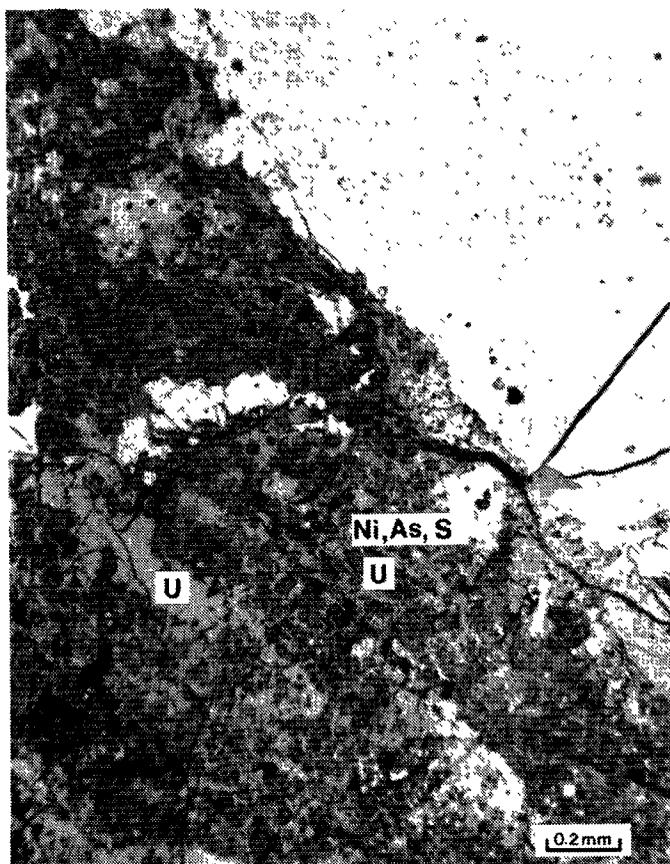


Figure 7. Photomicrograph of pitchblende associated with gersdorffite and nickeline; Collins Bay 'B' Zone. Reflected light.

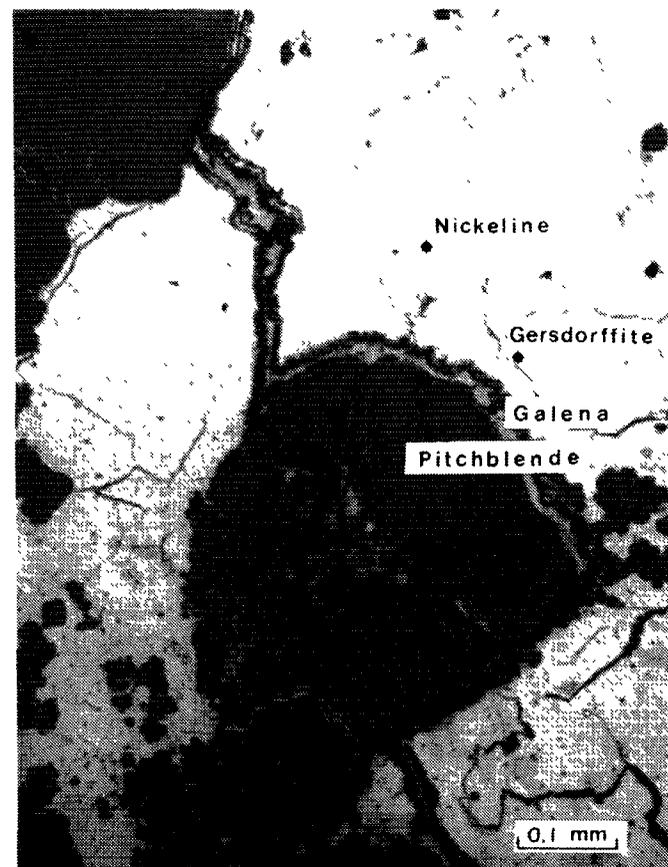


Figure 8. Photomicrograph of pitchblende, partly coated by galena, associated with gersdorffite and nickeline. Collins Bay 'D' Zone. Reflected light.

Table 5: Selected elemental constituents in selected drill core samples from the Collins Bay 'B' Zone. (From: Ruzicka and Littlejohn, 1981).

Element	Constituents in Percent						
	Sample 1	2	1) 2	1) 3	1) 4	1) 5	2) 6
Ag							0.015
As	< 10.0	< 0.0005	< 0.0005	< 0.0005	< 0.0005	< 0.0005	> 10.0
B	n.a.	0.55	0.023	0.078	0.0098	0.014	n.a.
Ba	n.a.	0.0083	0.014	0.003	0.0089	0.0089	n.a.
Be	n.a.	< 0.0003	< 0.0003	< 0.0003	< 0.0003	< 0.0003	n.a.
Co	0.1	0.0062	0.0044	0.001	< 0.001	< 0.001	0.1
Cr	0.01	< 0.0005	0.001	< 0.0005	< 0.0005	< 0.0005	0.01
Cu	> 0.3	0.058	0.0034	0.001	< 0.0007	< 0.0007	0.2
MO	n.a.	0.0062	0.0091	< 0.005	< 0.005	< 0.005	n.a.
Ni	> 0.7	0.37	0.32	0.0039	0.010	0.010	> 0.7
Pb	2.0	< 0.07	< 0.07	< 0.07	< 0.07	< 0.07	5.0
Sr	n.d.	0.026	0.11	0.0093	0.0039	0.0039	n.d.
Ti	0.15	0.31	0.84	0.13	0.17	0.17	0.2
U ³)	21.4	0.004	0.046	0.005	0.009	0.009	17.6
V	0.02	0.004	0.16	< 0.002	< 0.002	< 0.002	0.05
Zn	n.d.	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	n.d.
Zr	< 0.005	0.11	0.30	0.035	0.10	0.10	< 0.005

N.A. - analysis not available

N.D. - not detected (i.e. below the detection limit)

Th was not detected in any sample

1) Analyzed in G.S.C. laboratory using 12B-DR

2) Analyzed in G.S.C. laboratory using 5Q-23

3) Analyzed by Atomic Energy Canada Ltd. using Neutron Activation

Location of Samples:

1. DDH 241 (CAB): regolith with pitchblende

2. DDH 253 (CAB): altered sandstone

3. DDH 241 (CAB): regolithic clay

4. DDH 241 (CAB): regolith

5. DDH 241 (CAB): altered gneiss

6. DDH 253 (CAB): regolith with pitchblende

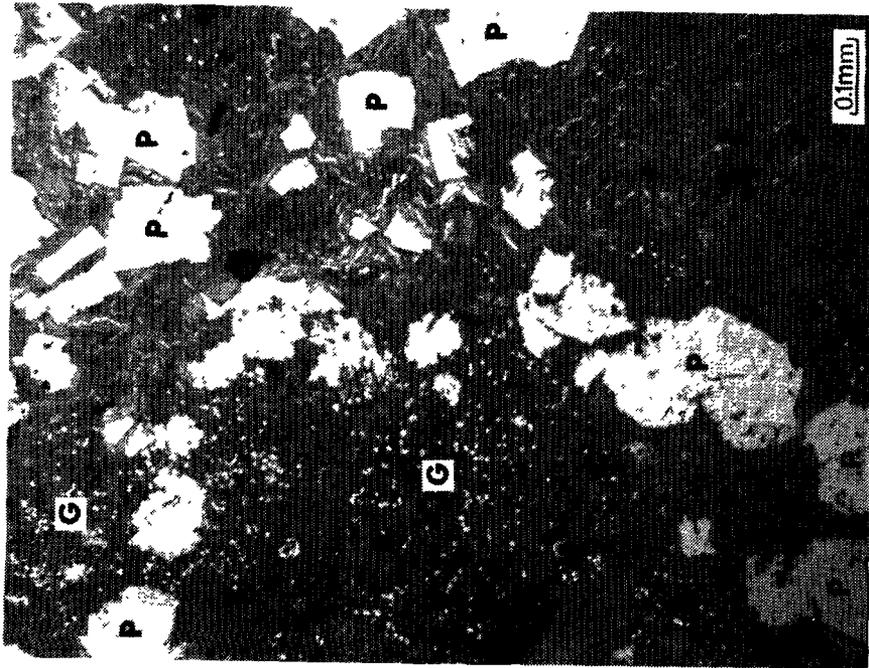


Figure 9. Photomicrograph of pitchblende (P) and finely disseminated galena (G – small light grey specks) from Eagle Point deposit. Reflected light.

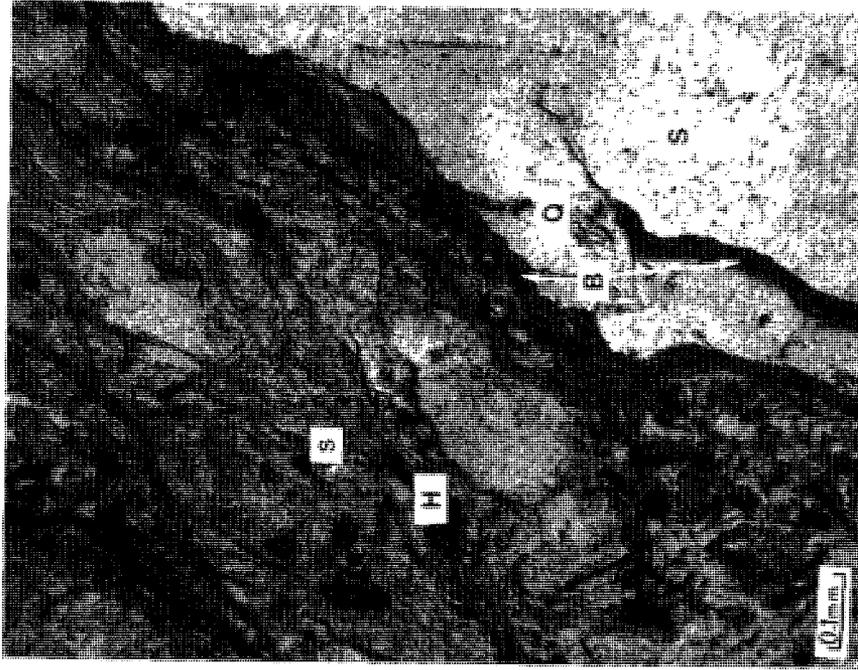


Figure 10. Boltwoodite (B) rimming grains and filling fractures of quartz (Q) and associated with hematite (H) and sericite (S) in ore from Eagle Point deposit; transmitted light.

Table 6: Elemental assemblage in a weakly mineralized part of the Eagle Point deposit.

	Sample	
	1	2
SiO ₂	74.0	84.0
Al ₂ O ₃	12.0	8.5
Fe ₂ O ₃	0.4	0.4
CaO	0.25	0.15
K ₂ O	3.4	1.7
Na ₂ O	‡	0.2
MgO	2.5	1.9
TiO ₂	0.38	0.16
P ₂ O ₅	0.05	0.04
MnO	0.06	NF
As	NF	NF
Ba	340	100
Co	10	NF
Cr	90	50
Cu	10	40
Nb	10	10
Ni	20	20
Pb	ppm	410
Sr	NF	NF
U	10	12
Y	20	10
Zn	80	10
Zr	180	210
Rb	200	80
F	900	500
Cl	200	400

N.B.: N.F. - not found
 Samples 1 and 2 collected from drill core and analyzed using 12B-DR

Uranium mineralization occurs in lenses arranged in narrow zones and consists mainly of pitchblende, which occurs in small cubes, veins, botryoids or associated with carbon, coffinite, uranophane and boltwoodite (Figs. 9 & 10). Its distribution is controlled by the alteration zones. Gersdorffite, millerite, chalcocite and galena occur locally in small amounts. Elemental assemblage in a weakly mineralized part of the deposit includes Cr, Pb, Ni, Zr, Rb, F and Cl (Table 6).

Unlike the Collins Bay zones the Eagle Point deposit occurs entirely in the altered Aphebian basement rocks below the sub-Athabasca unconformity, is stratabound and its mineralization is confined to at least fifteen sheet-like zones. The general strike of the rocks and mineralized zones is east-northeast and dips are 40° to 70° SE. The mineralization has been so far identified along a distance of about 2000 m, up to 200 m width and to 450 m depth down the dip.

Other deposits of the Rabbit Lake – Collins Bay area

In addition to the Collins Bay zones and Rabbit Lake and Eagle Point deposits, the Rabbit Lake – Collins Bay area includes the West Bear, Raven and Horseshoe deposits and several small uranium occurrences (Fig. 3).

The West Bear deposit occurs about 43 km southwest of the Rabbit Lake mine. Distribution of the mineralization in the deposit is controlled by the sub-Athabasca unconformity, which is beneath overburden and 15 to 20 metre thick sandstone of the Athabasca Group. Most of the mineralization is in the altered pyritic and graphitic semipelites of the Wollaston domain just below the unconformity. Some mineralization occurs in the sandstone immediately above the unconformity and within the clay alteration zone at the unconformity. In addition to uranium the mineralization contains higher amounts of arsenic, lead, nickel, vanadium, zirconium and silver (Table 7).

The Raven and Horseshoe deposits occur about 5.5 km southeast of the Rabbit Lake mine (Fig. 3). The host rocks of both deposits are mainly altered graphitic quartzites and biotite gneisses with minor amphibolites and calc-silicate rocks of the Wollaston Group. The pitchblende and uranophane mineralization is irregularly distributed in fractures and disseminated in the altered host rocks.

MCCLEAN LAKE – MIDWEST LAKE – WATERBURY LAKE AREA

Deposits with identified uranium resources in this area are: McClean Lake, Dawn Lake, Midwest Lake and Cigar Lake. In addition several occurrences, such as JEB and Mallen Lake near the McClean Lake deposit and BJ near McArthur River, occur in this area (Fig. 11).

The McClean Lake deposit occurs about 11 km northwest of the Rabbit Lake mine (Brummer et al., 1981; Saracoglu et al., 1983; Tremblay, 1982; and Fig. 11). The deposits contains three east-

Table 7: Spectroscopic analyses of selected samples from the West Bear deposit.

Constituent	Sample		
	1	2	3
Si	>2.0	>20.0	15.0
Al	1.5	2.0	2.0
Fe	>2.0	>3.0	>3.0
Ca	0.033	0.3	0.5
Na	0.0054	N.F.	N.F.
Mg	0.67	0.1 - 0.5	0.2 - 0.5
Ti	0.11	1.0	1.0
P	N.A.	N.F.	N.F.
Mn	0.031	0.2	0.1
Ag	<5	100	70
As	19 000	10 000	15 000
Bi	N.A.	2 000	700
Ce	<200	N.F.	N.F.
Co	360	1 000	700
Cr	91	200	150
Cu	570	1 500	500
La	<100	N.F.	N.F.
Nb	<50	N.F.	N.F.
Nd	N.A.	N.F.	N.F.
Ni	1 700	2000 - 5000	1000 - 3000
Pb	>100 000	20 000	15 000
Sb	<500	N.A.	N.A.
Sc	N.A.	100	100
Su	<200	N.A.	N.A.
Sr	24	1 000	1 000
U	70	85 700	125 000
V	<20	2 000	5 000
Y	67	100	200
Yb	<4	N.A.	N.A.
Zn	15 000	N.F.	N.F.
Zr	100	3 000	1 500

N.A. - not available

N.F. - Not found

Sample 1: analyzed using 12B-DR

Sample 2 & 3: analyzed using SQ23

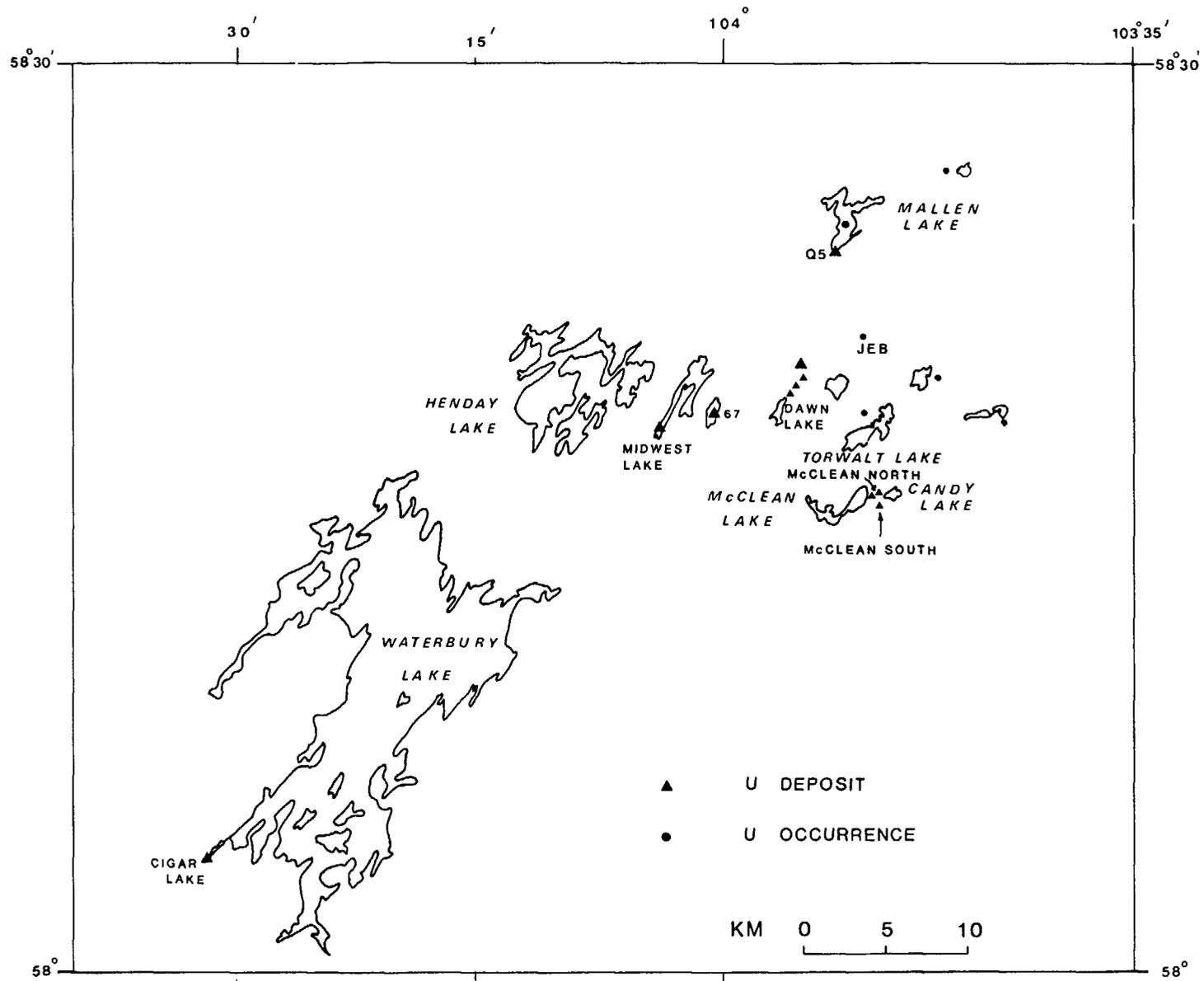


Figure 11. Uranium occurrences in McClean Lake - Midwest Lake - Waterbury Lake area.

north-east trending mineralized zones, each of which consists of several ore lenses. These zones occur at the sub-Athabasca unconformity which is about 165 metres below the surface. The footwall of the zones consists of Aphebian rocks including graphitic and pyritic metapelites, feldspathic quartzite and amphibolite. The hanging wall consists of coarse or pebbly sandstone of the Manitou Falls Formation. Uranium mineralization, pitchblende and coffinite, is commonly associated with illite, chlorite and metallic minerals such as pararammelsbergite, nickeline, gersdorffite, safflorite, chalcopyrite, siderite, hematite, goethite, bravoite and pyrite (Brummer et al., 1981).

The Dawn Lake deposit is located about 20 km west of the Rabbit Lake mine (Clarke and Fogwill, 1981; Tremblay, 1982; and Fig. 11). Its four mineralized zones are designated as 14, 11, 11A and 11B (Fig. 12). The mineralization, consisting mainly of pitchblende (massive, botryoidal and sooty), some uranoan carbon and secondary uranium minerals, is accompanied in one of these zones with cobalt and nickel arsenides and copper sulphide, whereas in the other zones the uranium mineralization is monomineralic. The mineralization occurs in the altered basement rocks (Zone 11B), within the argillized interface along the unconformity (Zones 11A and 14) and within the sedimentary rocks of the Manitou Falls Formation (Zone 11). The basement host rocks are chloritized pelites with variable amounts of disseminated graphite, biotite, pyrite and locally cordierite; calc-silicate rocks and granitic pegmatites locally contain tourmaline. The argillized interface along the sub-Athabasca unconformity includes weathered zone of the basement rocks (saprolite or regolith) and products of diagenetic alteration. The rocks of the Manitou Falls Formation include basal and intraformational conglomerate, sandstone and clay intercalations. Distribution of the mineralization is structurally controlled by intersections of the sub-Athabasca unconformity with strike- and cross-faults (Fig. 12).

The Midwest Lake deposit is situated 25 km northwest of the Rabbit Lake mine (Fig. 11; Scott, 1981; Tremblay, 1982).

The deposit occurs along the sub-Athabasca unconformity, which is about 195 metres below the surface at the centre of the deposit, and extends along an intersection of this unconformity with a northeasterly trending fault zone (Figs. 13 and 14). It is about 900 metres long, up to about 110 metres wide and 36 metres thick.

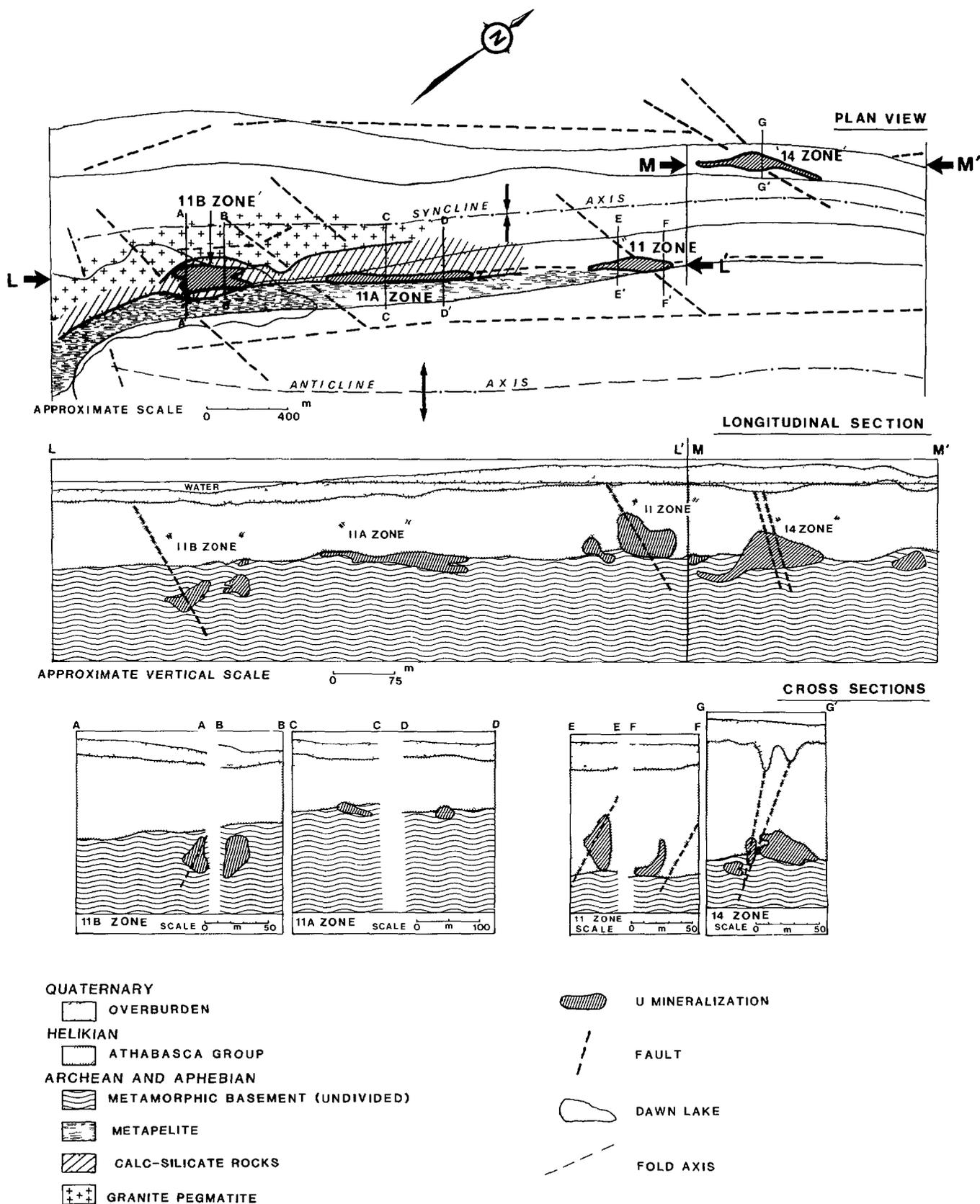


Figure 12. Dawn Lake deposit. Modified after Clarke and Fogwill (1981).

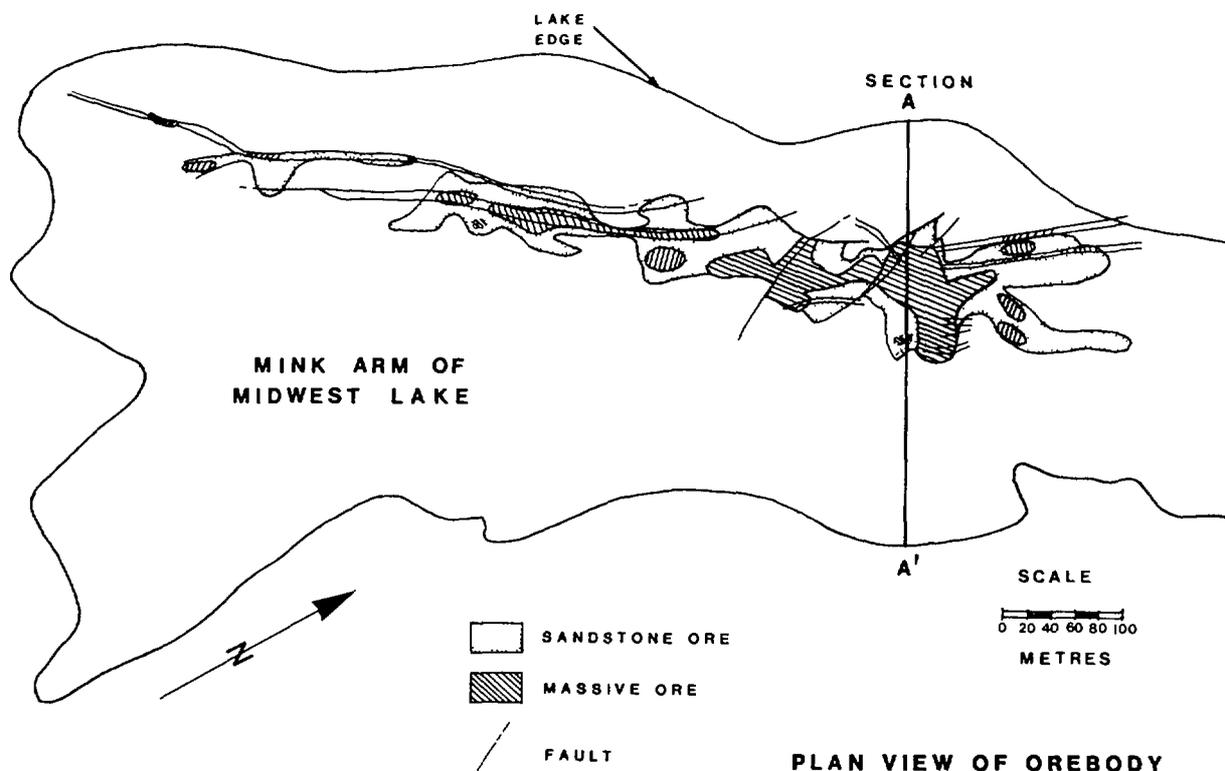
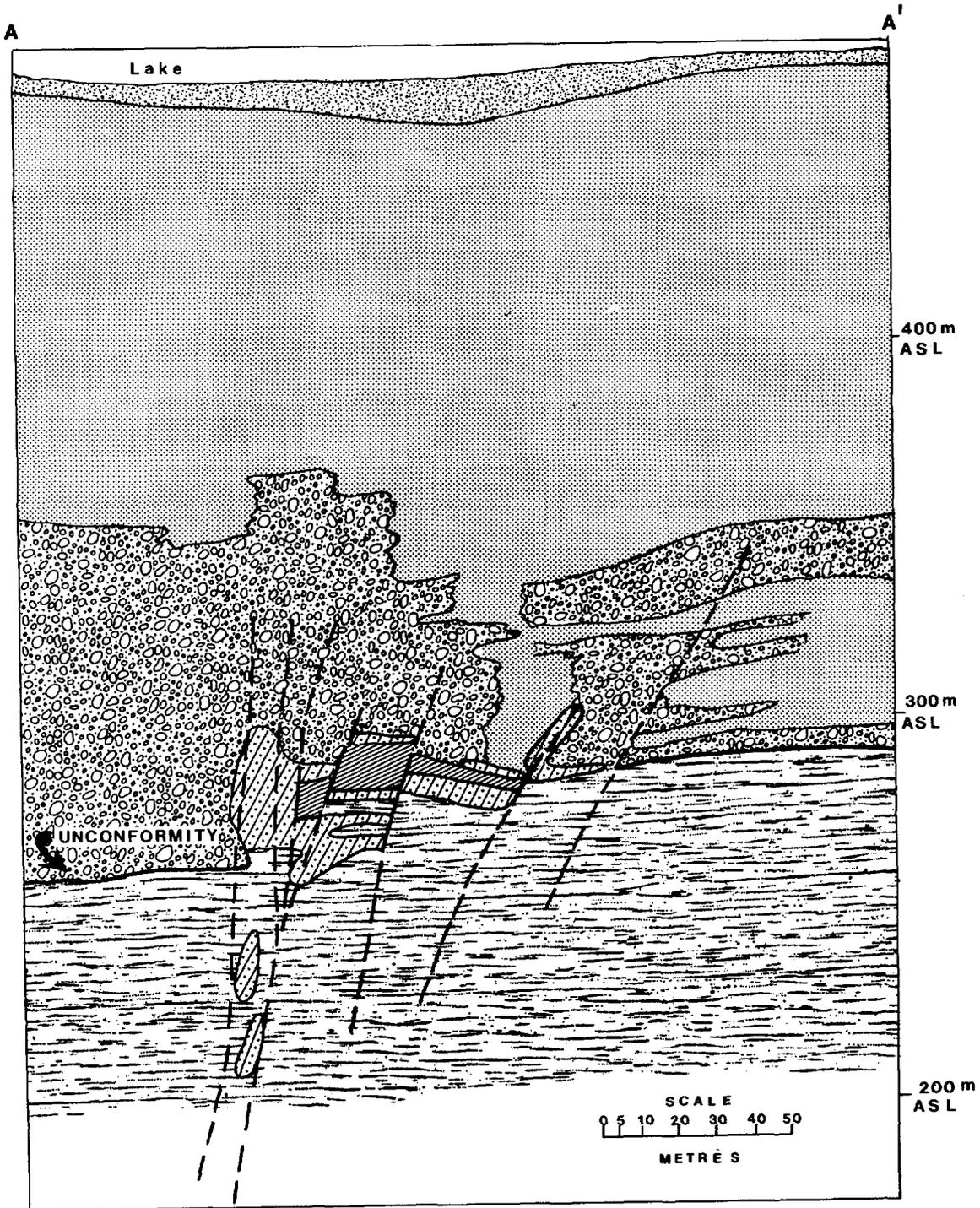


Figure 13. Plan view of Midwest Lake deposit.
 (After 'Canada Wide Mines - Midwest Lake Uranium Project';
 Canada Wide Mines, 1980).

The uranium mineralization occurs (i) in a massive or spherulitic form (Fig. 15); (ii) in a mixture of pitchblende with coffinite; and (iii) in a sooty form (Ruzicka and Littlejohn, 1981). Associated nonradioactive minerals are nickeline, millerite, maucherite, rammelsbergite, gersdorffite, nickelhexahydrate, retgersite, calcite, chlorite, halloysite, hematite and goethite. Mineralization in the sandstone consists mainly of massive and sooty pitchblende occurring interstitially or as fracture filling in quartz grains (Fig. 16).

A generalized conceptual mineral succession postulates five stages of mineralization (ibidem; Fig. 17): (1) massive or spherulitic pitchblende; (2) first generation of nickel arsenides and sulphides; (3) second generation of nickel arsenides and sulphides and pitchblende-coffinite assemblage; (4) sulpharsenides and sooty pitchblende; (5) gangue and post-ore minerals. The main elemental constituents in the Midwest Lake deposit are, in addition to uranium, nickel, cobalt, arsenic, molybdenum, titanium, vanadium and zirconium (Table 8).

In addition to concentrations in the main ore bodies at the unconformity some mineralization was deposited in fractures connecting the ore bodies with the surface and later incorporated in



QUATERNARY

 OVERBURDEN

HELIKIAN

 ATHABASCA GROUP-SANDSTONE

 ATHABASCA GROUP-CONGLOMERATE

ARCHEAN

 GNEISS
(BIOTITE, FELDSPAR, CHLORITE, GRAPHITE)

 SANDSTONE ORE

 MASSIVE ORE

 FAULT

Figure 14. Cross section through Midwest Lake deposit. (After 'Canada Wide Mines - Midwest Lake Uranium Project', Canada Wide Mines, 1980).

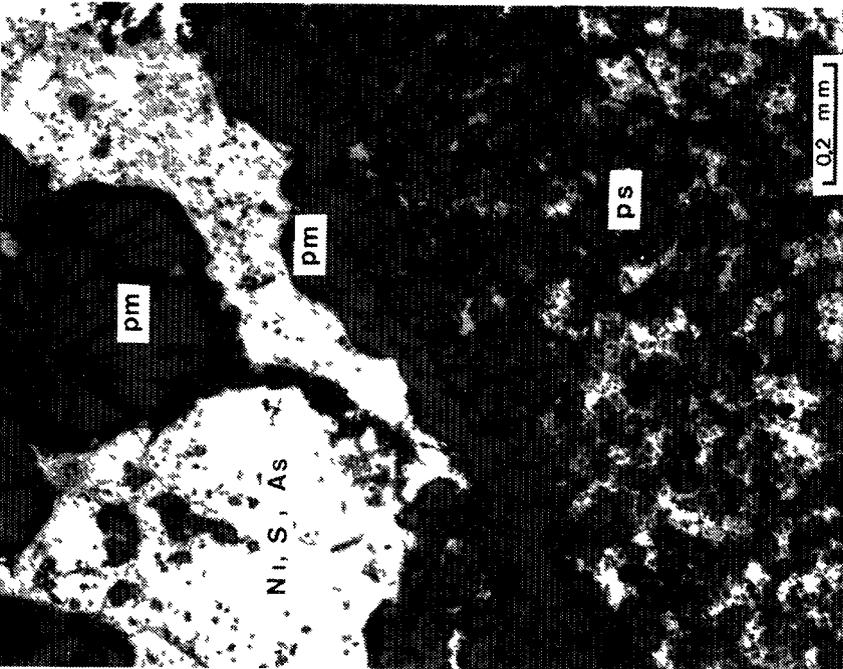


Figure 15. Photomicrograph of massive (pm) and spherulitic (ps) pitchblende associated with nickel sulpharsenides (Ni, S, As) from Midwest Lake deposit. Combined transmitted and reflected light.

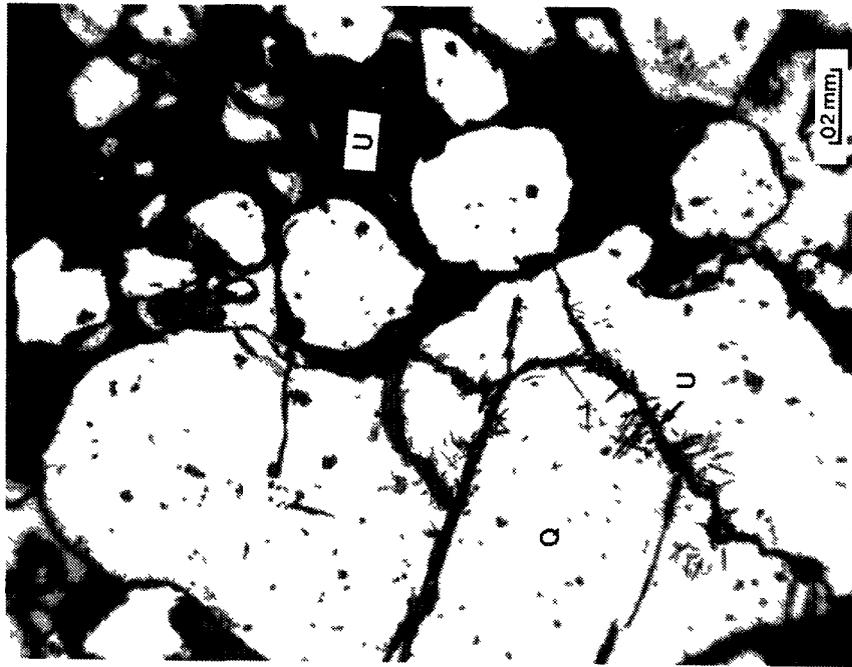


Figure 16. Pitchblende occurring interstitially and as fracture filling in quartz grains. Sandstone ore, Midwest Lake deposit. Transmitted light.

MINERAL ASSEMBLAGE	STAGE				
	1	2	3	4	5
Pitchblende	█		█	█	
Nickeline		█	█	█	
Millerite		█	█	█	
Maucherite		█			
Rammelsbergite			█		
Pitchblende and Coffinite			█		
Gersdorffite			█	█	
Pitchblende (sooty)				█	
Calcite, Hematite, Chlorite, Goethite, Halloysite, Røtgersite, Nickel-hexahydrate					█

Figure 17. Generalized mineral succession in the Midwest Lake deposit. Dashed line (- - -) indicates replacement process; dotted line (.....) indicates that the younger mineral has been derived from another mineral(s).

glacial drift. In this way the surficial dispersion haloes indicated presence of concealed ore bodies and thus exploration targets.

K-Ar analyses of sericitic and chloritic clay collected from the mineralized zone indicated absolute age of 1212 ± 33 Ma (Stevens et al., 1982), which can be considered as the main age of the Midwest Lake deposit.

The Cigar Lake deposit occurs near the southwestern shore of Waterbury Lake (Fig. 11). Its mineralization is structurally controlled by a mylonite zone in the basement rocks, by an altered zone at the sub-Athabasca unconformity and by graphitic metapelites of the Wollaston Group (Ruzicka and LeCheminant, 1984). The mylonite zone has been subjected to faulting and cross-faulting. Retrograde metamorphism resulted in extensive clay (kaolinite, illite and chlorite) alteration of the host rocks. Two phases of uranium mineralization occur in the deposit: (i) a polymetallic, which

Table 8: Selected elemental constituents in selected drill core samples from the Midwest Lake deposit.
(From: Ruzicka and Littlejohn, 1981 and Canada Wide Mines Limited, 1980).

Sample Element	Constituents in Percent										
	1) 1	1) 2	2) 3	2) 4	2) 5	1) 6	2) 7	2) 8	1) 9	4) 10	4) 11
Ag	0.0068	<0.0005	0.015	n.d.	0.003	<0.0005	0.0015	n.d.	<0.0005	tr.	0.0068
As	7.2	<0.20	>10.0	n.d.	3.0	0.23	5.0	n.d.	0.35	1.68	9.62
B	0.0068	0.024	n.a.	n.a.	n.a.	0.068	n.a.	n.a.	0.0085	n.a.	n.a.
Ba	<0.0005	0.0082	n.a.	n.a.	n.a.	0.0078	n.a.	n.a.	0.0033	n.a.	n.a.
Be	<0.0003	0.0004	n.a.	n.a.	n.a.	0.0016	n.a.	n.a.	<0.0003	n.a.	n.a.
Bi	n.a.	n.a.	n.a.	n.d.	0.1	n.a.	0.15	n.d.	n.a.	0.017	0.057
Co	0.22	0.013	1.0	0.3	0.5	0.003	0.2	< 0.05	0.29	0.19	0.11
Cr	<0.0005	0.019	0.015	0.003	0.015	0.033	0.01	0.02	<0.0005	0.019	0.023
Cu	0.033	0.0024	0.15	0.007	0.007	0.0014	0.15	0.02	0.00073	0.08	0.42
Mo	0.49	<0.005	n.a.	n.a.	n.a.	<0.005	n.a.	n.a.	<0.005	0.023	0.136
Ni	>2.0	0.02	> 0.7	0.2	>1.5	0.35	> 1.5	< 0.005	0.12	0.94	4.80
Pb	0.082	<0.07	3.0	n.d.	n.d.	<0.07	n.d.	n.d.	<0.07	0.04	1.19
Sr	0.0028	0.0052	n.d.	n.d.	0.007	0.0029	0.003	n.d.	<0.001	n.a.	n.a.
Ti	0.24	0.93	0.2	0.05	2.0	0.66	1.0	0.7	0.066	0.79	0.73
U ³)	0.02	0.007	27.2	4.8	2.2	0.14	14.4	17.3	0.009	0.25	11.79
V	0.014	0.062	0.3	0.015	0.3	0.49	0.3	0.1	0.0055	0.11	0.34
Zn	<0.02	<0.02	n.d.	n.d.	n.d.	<0.02	n.d.	n.d.	<0.02	0.11	0.52
Zr	0.025	0.032	< 0.005	0.03	0.3	0.02	0.5	0.15	0.014	n.a.	n.a.

tr. - trace
n.a. - analysis not available
n.d. - not detected (i.e. below the detection limit)

1. Analyzed using 12B-DR
2. Analyzed using 5Q-23
3. Analyzed by Neutron Activation
4. Analyzed by a commercial laboratory

Location of Samples:

1. DDH 78-40: sandstone
2. 58 18'N, 104 06'W: chloritized
3. DDH 78-42: regolith
4. DDH 78-40: sandstone
5. DDH 78-18: regolith
6. DDH 78-18: regolith
7. DDH 78-18: sandstone
8. DDH 78-70: sandstone
9. DDH 78-15: sandstone
10. Typical sandstone ore
11. Typical massive ore

includes, in addition to uranium, Ni, Co, Pb, C, Mo, As, Zr and Zn; this phase prevails at the base of the ore bodies; (ii) a monomineralic, which consists of pitchblende in botryoidal, massive, granular, brecciated or finely disseminated forms; this phase usually occurs in the upper portions of the mineralized bodies, i.e. in the sandstone.

The main mineralized zone occurs about 450 metres below the surface, but lesser amounts of mineralization were encountered about 100 metres below the present surface.

KEY LAKE AREA

The Key Lake area is located about 240 km north of La Ronge and about 180 km south-southwest of the Rabbit Lake mine (Fig. 1). The uranium mineralization occurs in two ore bodies: Gartner and Deilmann (Gatzweiler et al., 1981; Tremblay, 1982; and Fig. 18). The ore bodies are closely associated with the sub-Athabasca unconformity, basement tectonic features, such as several layers of graphitic metasedimentary pelitic rocks and a major reverse fault zone. The fault zone is parallel with the foliation of the basement rocks, i.e. 060° to 070° , dips 40 to 60 degrees to the north-west and dislocates both the basement and cover rocks vertically up to 30 m. The graphitic pelites are part of the Aphebian Wollaston Group, comprising biotite-plagioclase-quartz-cordierite gneiss, garnet-quartz-feldspar-cordierite gneiss, amphibolite, calc-silicate rocks, migmatite and granite pegmatite. The Wollaston Group rocks unconformably overlie Archean granitic rocks, which occur as north-easterly elongated domal structures. The Aphebian sediments are at the sub-Athabasca unconformity, are strongly altered and contain chlorite and illite. Some of the alteration is, apparently, regolith, but some is diagenetic hydrothermal or related to tectonic movements along the fault zone. The sedimentary rocks of the Athabasca Group rest unconformably on the basement rocks and are up to 60 metres thick in the area of the deposits. They are conglomeratic sandstone at the base and quartz sandstone in the rest of the sequence. The sedimentary rocks are altered with hematite, kaolinite and chlorite.

The uranium mineralization occurs in at least four main generations (Ruzicka and Littlejohn, 1981): (i) as thorium-free euhedral crystals of a alpha U_3O_7 compound; (ii) as massive, commonly botryoidal, pitchblende; (iii) as pitchblende-coffinite aggregates; and (iv) as sooty pitchblende. The most common mineral assemblages of the deposits consist of pitchblende-coffinite aggregates with

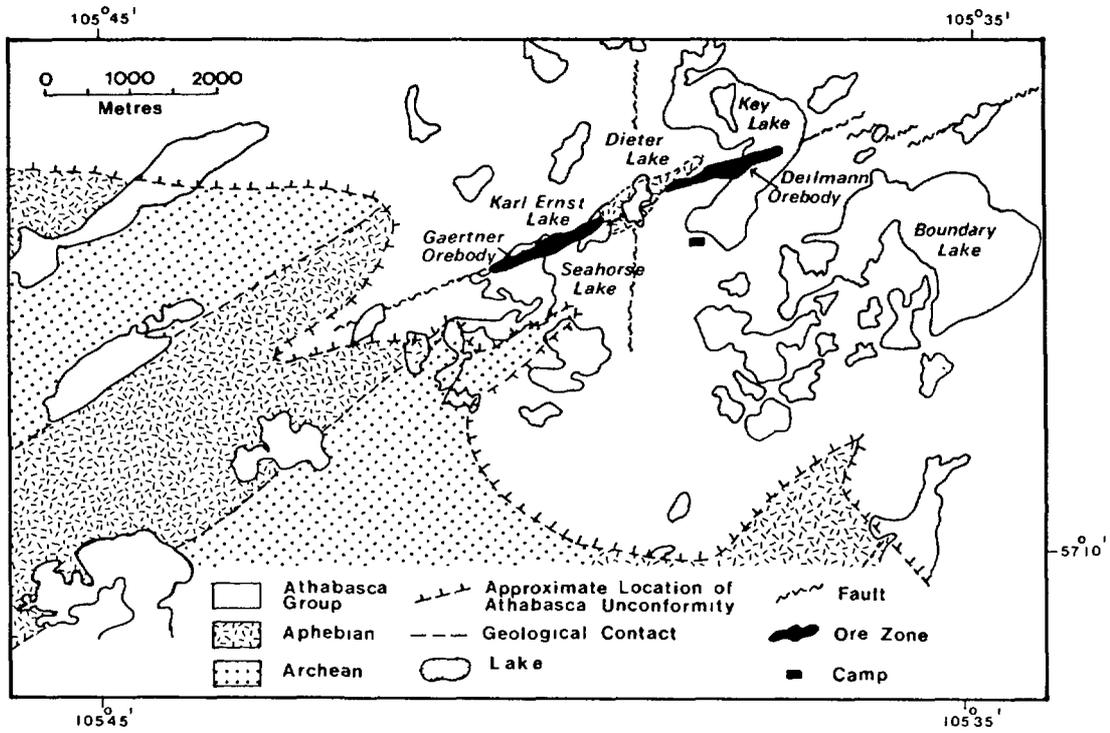


Figure 18. Geological setting of the Key Lake deposit. (After Tremblay, 1982).

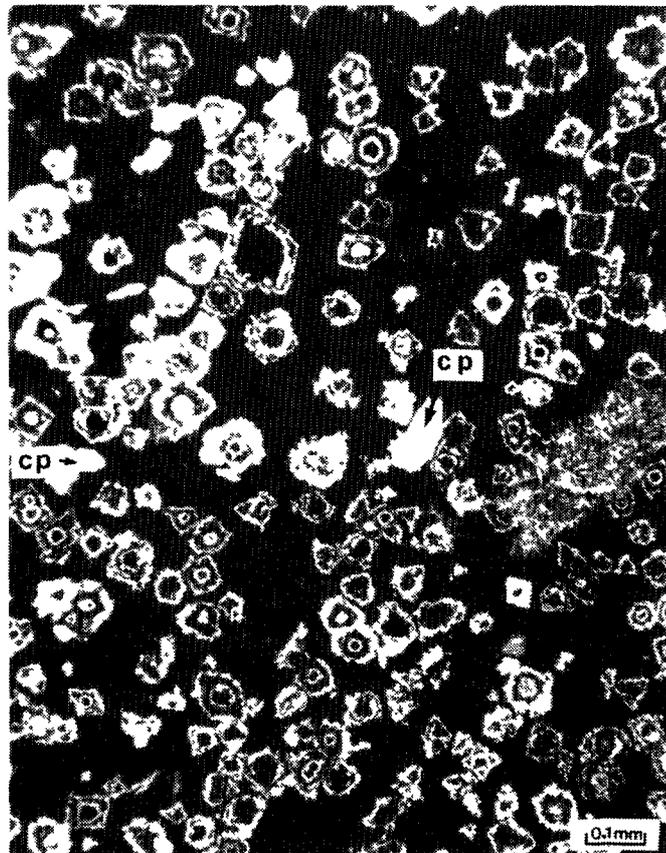


Figure 19. Snowflakes of gersdorffite with dark cores of bravoite from Deilmann ore body, Key Lake deposit. Reflected light; cp = chalkopyrite.

gersdorffite and sooty pitchblende. In addition to clay, calcite and/or siderite are the main gangue minerals. Associated with the uranium mineralization are also millerite, nickeline, bravoite (Fig. 19), rammelsbergite, chalcopyrite and galena. According to analyses of selected samples the elemental assemblages of the mineralization consist of arsenic, cobalt, copper, nickel, lead, titanium and vanadium (Table 9).

U-Pb isotope analyses on 34 samples of pitchblende from the Key Lake deposit indicated three main ages of mineralization: ~1,228 Ma; ~960 Ma; and ~89 Ma (Gatzweiler et al., 1979); Wendt et al. (1978) reported an age of 1270 Ma also on pitchblende. The ~1,228 Ma age fits well with the absolute ages of the mineralizations obtained on other sub-Athabasca unconformity related deposits.

The associations of pitchblende/bravoite and pitchblende/alpha-triuranium heptaoxide, found in the Key Lake deposits, indicate a temperature of crystallization between 135° and 150°C (Dahlkamp et al., 1977; Pechmann and Voultsidis, 1981; Ruzicka and Littlejohn, 1982).

The Gartner and Deilmann deposits are 1450 and 1200 metres long respectively, their horizontal width is up to 100 metres and their vertical dimension is up to 150 metres.

CARSWELL STRUCTURE

The Carswell Structure is located in the western part of the Athabasca Basin, about 140 km southwest of Uranium City (Fig. 1). The central core of the structure comprises Aphebian gneisses and granitoids, classified by Alonso et al. (in press) into two groups: an older Earl River Complex (2005 to 1960 Ma) and a younger Peter River Gneiss. This core is surrounded by Helikian sedimentary rocks of the Athabasca Group: William River Subgroup, consisting of conglomerate, sandstone and pelite; Douglas Formation with sandstone, siltstone and mudstone; and Carswell Formation consisting mainly of dolomite (ibidem). These rocks are intruded by diabase dykes (dated by Wanless et al., 1979, as 949 ± 33 Ma). The youngest, volcanic-like rocks, are Cluff Breccia, dated on two samples by a K-Ar method as 486 ± 55 Ma and 469 ± 28 Ma (Currie, 1969).

The known deposits occur in the south-central part of the Carswell Structure, in the vicinity of Cluff Lake (Fig. 20). To date, uranium resources have been identified in the following deposits: D, N, R, OP, Claude and Peter River (Fig. 21).

Table 9: Selected elemental constituents in selected drill core samples from the Key Lake deposit.
(From: Ruzicka and Littlejohn, 1981).

Element	Sample	Constituents in Percent							
		1) 1	1) 2	2) 3	2) 4	2) 5	2) 6	2) 7	2) 8
Ag		< 0.0005	< 0.0005	n.d.	< 0.001	0.03	0.03	0.03	0.02
As		< 0.20	< 0.2	2.0	0.7	3.0	> 10.0	> 10.0	> 10.0
Ca		0.073	0.017	10.0	3.0	10.0	1.5	1.5	10.0
Co		0.002	< 0.001	0.1	0.2	0.07	0.3	0.3	0.1
Cr		0.017	< 0.0005	< 0.001	< 0.001	< 0.001	< 0.001	0.03	< 0.001
Cu		0.0014	< 0.0007	0.05	0.02	0.07	0.2	0.07	0.03
Mn		0.011	0.002	0.5	0.3	0.3	0.05	0.02	0.2
Mo		< 0.005	< 0.005	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni		0.019	0.0022	> 0.7	> 0.7	> 0.7	> 0.7	> 0.7	> 0.7
Pb		< 0.07	< 0.07	2.0	1.0	3.0	3.0	1.5	5.0
Sr		0.03	0.005	0.1	0.03	0.07	0.02	< 0.001	0.15
Ti		0.90	0.029	0.2	0.15	0.2	0.2	0.15	0.17
U ³)		0.0048	0.0155	23.0	20.4	31.6	30.8	32.1	26.9
V		0.033	< 0.002	0.1	0.07	0.1	0.07	0.15	0.07
Zn		< 0.02	< 0.02	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Zr		0.058	0.0055	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005

n.a. - analysis not available

n.d. - not detected (i.e. below the detection limit)

Th was not detected in any sample

1. Analyzed using 12B-DR
2. Analyzed using 5Q-23
3. Analyzed by Atomic Energy Canada Ltd. by Neutron Activation

Location of Samples:

1. DDH 1962 (Deilman): graphitic schist
2. DDH 1967 (Deilman): sandstone
3. DDH 5052 (Gartner): regolith with pitchblende
4. DDH 5052 (Gartner): regolith with pitchblende
5. DDH 5057 (Gartner): regolith with pitchblende
6. DDH 5062 (Gartner): regolith with pitchblende
7. DDH 5050 (Gartner): regolith with pitchblende
8. DDH 5057 (Gartner): regolith with pitchblende

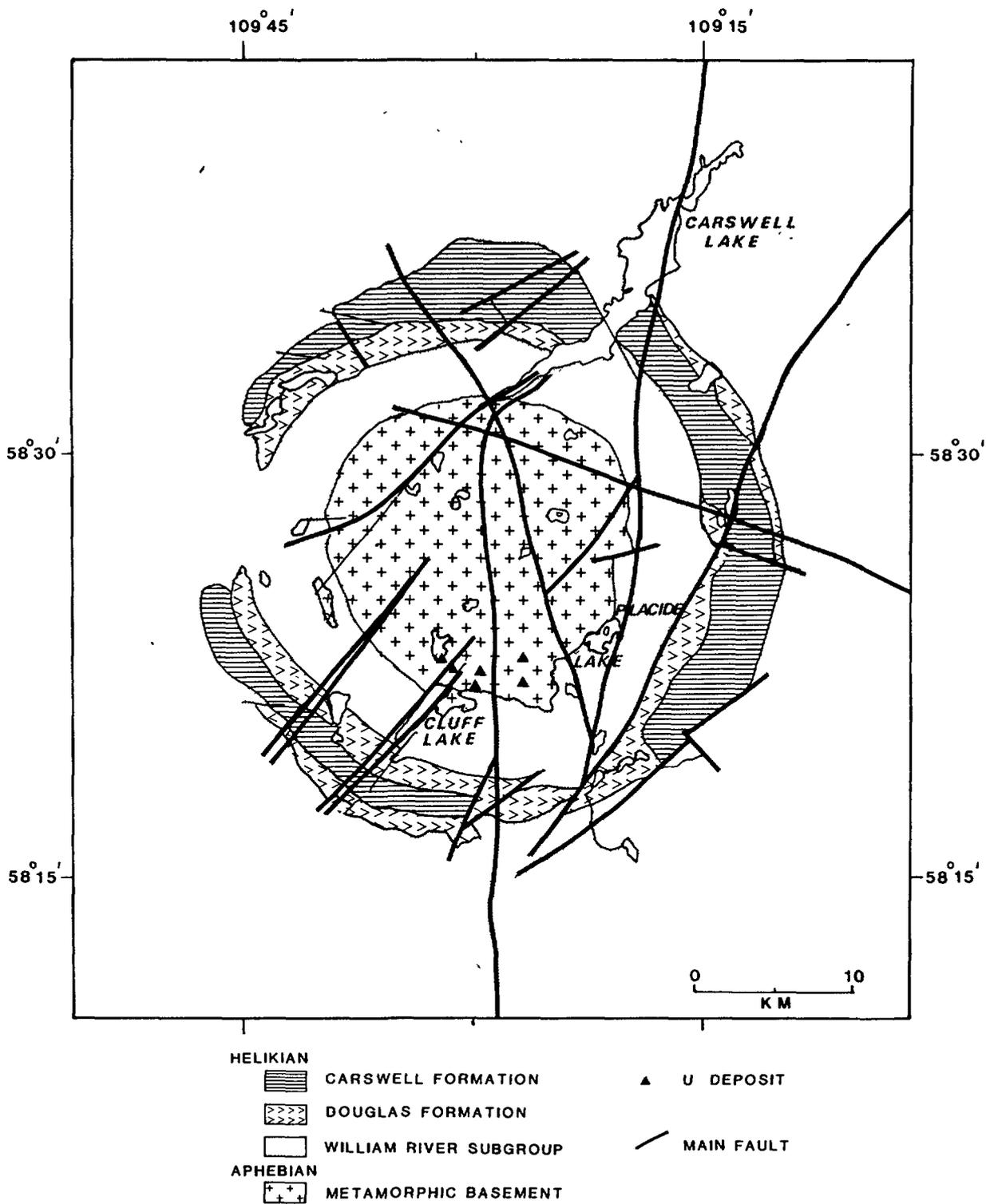


Figure 20. Geology of Carswell Structure. (Simplified after Alonso et al., in press).

The D deposit occurs along the sub-Athabasca unconformity (Ruzicka, 1975). The whole sequence is overturned so that the rocks of the Peter River Gneiss Formation rest upon the sedimentary rocks of the William River Subgroup. The paleosurface of the basement rocks is deeply weathered and has a thick regolith. The highest uranium concentration occurs in the basal sequence of the Athabasca Group. It is confined almost entirely to bituminous pelite, which

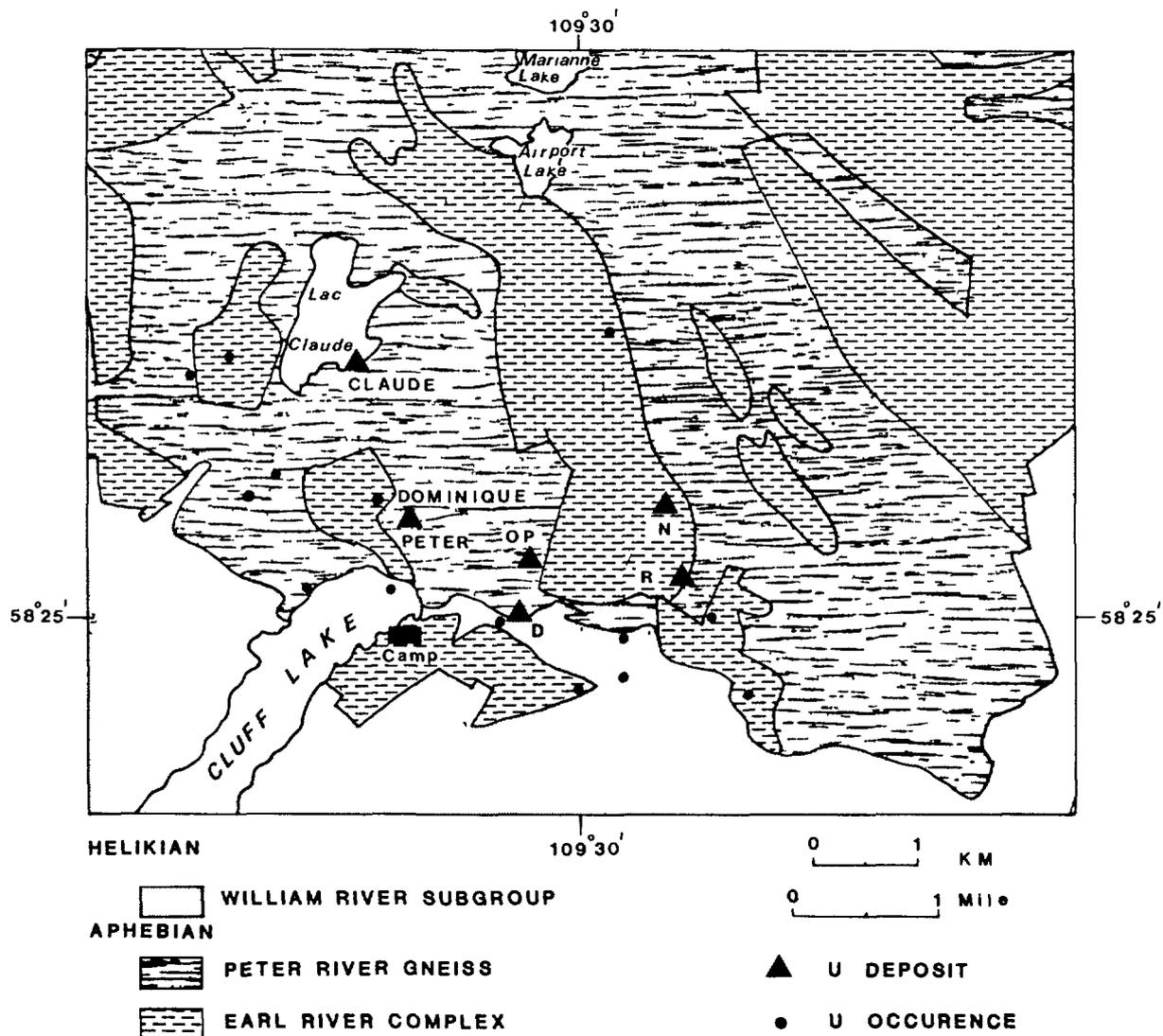


Figure 21. Geology and distribution of uranium occurrences in a part of Carswell Structure in the vicinity of Cluff Lake. (After Alonso et al., in press).

grades transitionally to sandstone. The main uranium ore mineral is pitchblende; coffinite and uranoan carbon occur in lesser amounts. The associated polymetallic mineralization includes pararamelsbergite, native selenium and, selenides of lead, bismuth, nickel and cobalt, native gold, altaite, galena, chalcopyrite, pyrrhotite and pyrite.

U-Pb isotope analyses indicate absolute age of the 'D' deposit as 1100 Ma (Tapaninen, 1975), but Gancarz (1979) using U-Pb and Pb-Pb methods suggested two main phases of mineralization (1050 Ma and 800 Ma) and a remobilization phase (234 Ma); the remobilization phase coincides with the range of the Hercynian uranium metallogenic epoch in Europe (Ruzicka, 1971; Ball et al., 1982).

The D deposit has been depleted. It was a high grade ore body (Table 3), 140 metres long, 12 metres wide and 12 metres thick.

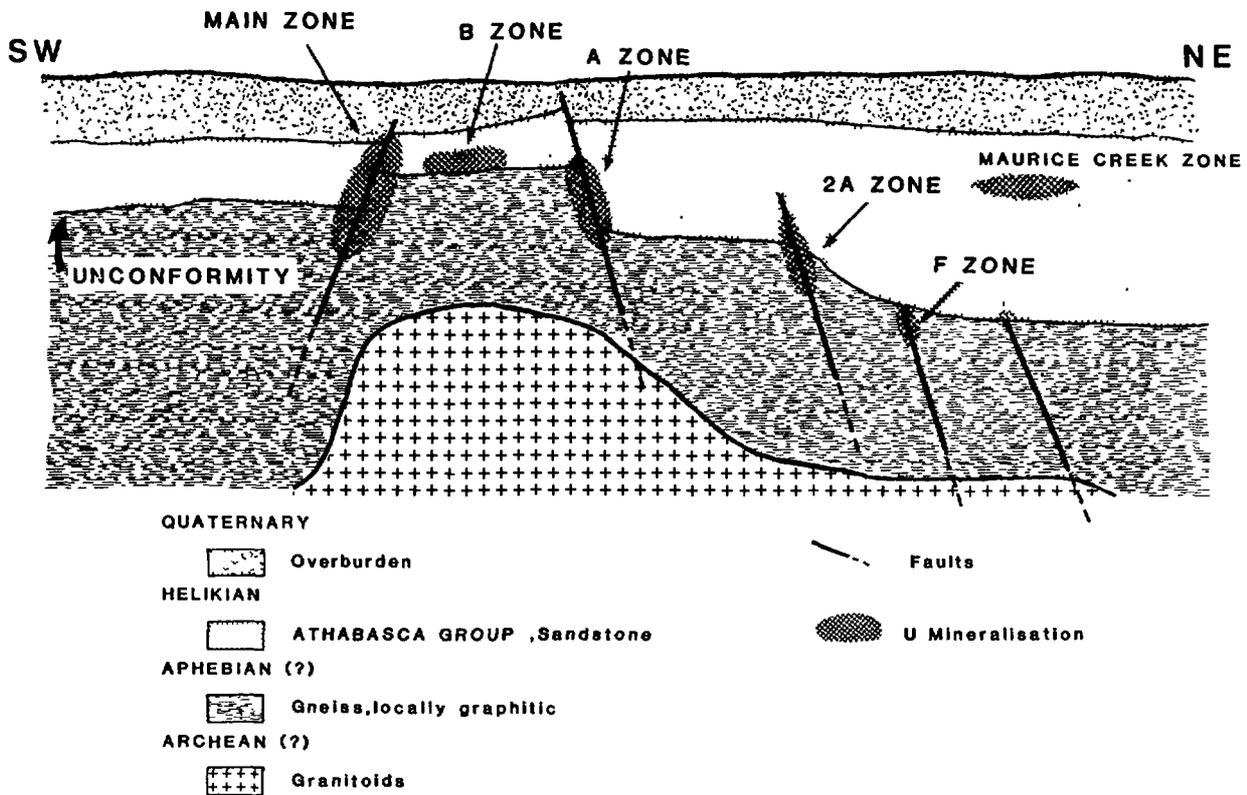


Figure 22. A sketch (not to scale) showing distribution of mineralized zones in Maurice Bay area. Modified from Lehnert-Thiel et al., 1981 and Uranerz Exploration and Mining Limited, personal communication.

The remaining deposits in the Carswell Structure are monometallic and consist mainly of pitchblende and coffinite. The N, R, OP, Claude and Peter River deposits occur in quartzo-feldspathic gneiss, metapelite and quartzite of the Peter River Gneiss Formation (Fig. 21). Their mineralization is structurally controlled by steeply dipping faults and subhorizontal mylonite zones.

MAURICE BAY AREA

The Maurice Bay area is located about 80 km west-southwest of Uranium City on the north shore of Lake Athabasca and northwest rim of the Athabasca Basin (Fig. 1).

Uranium mineralization occurs in the Main Zone, the A Zone, the B Zone, and in a few additional zones. All the mineralized zones are spatially related to the sub-Athabasca unconformity (Lehnert-Thiel and Kretschmar, 1979; Lehnert-Thiel et al., 1981; Tremblay, 1982).

The basement rocks in the Maurice Bay area are granitized metasediments, apparently a part of the Tazin Belt (Tremblay, 1982), which are the main host rocks of the Beaverlodge uranium deposits. The basement rocks were affected by Hudsonian Orogeny and are locally albitic and some are graphitic. The tops of the basement rocks at the unconformity (regolith) are strongly hematitized and chloritized

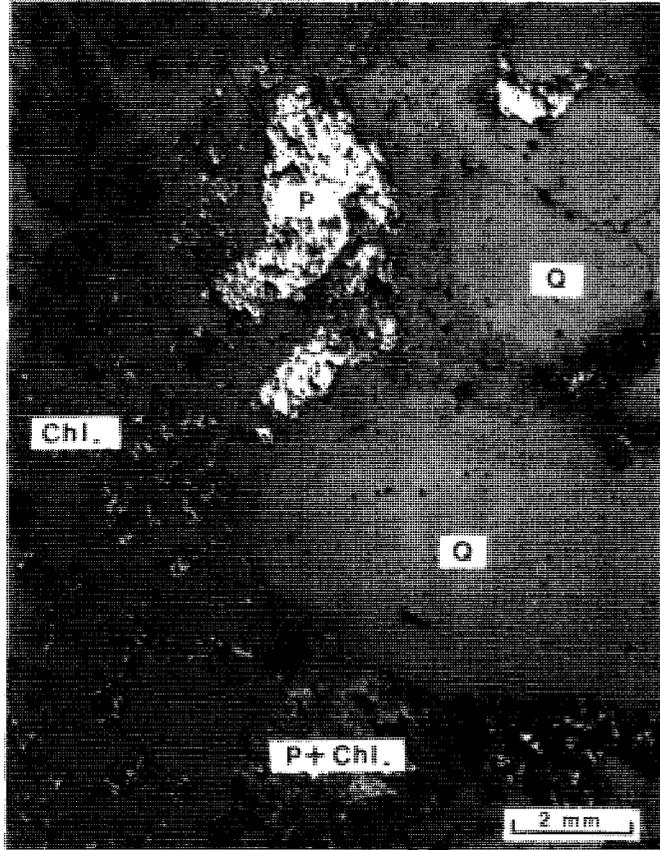


Figure 23. Photomicrograph of pitchblende (P) associated with chlorite (Chl) and pitchblende-chlorite mixture ($P \pm Chl$) in sandstone, Maurice Bay deposit (Main Zone) (Q) = quartz grains. Reflected light.

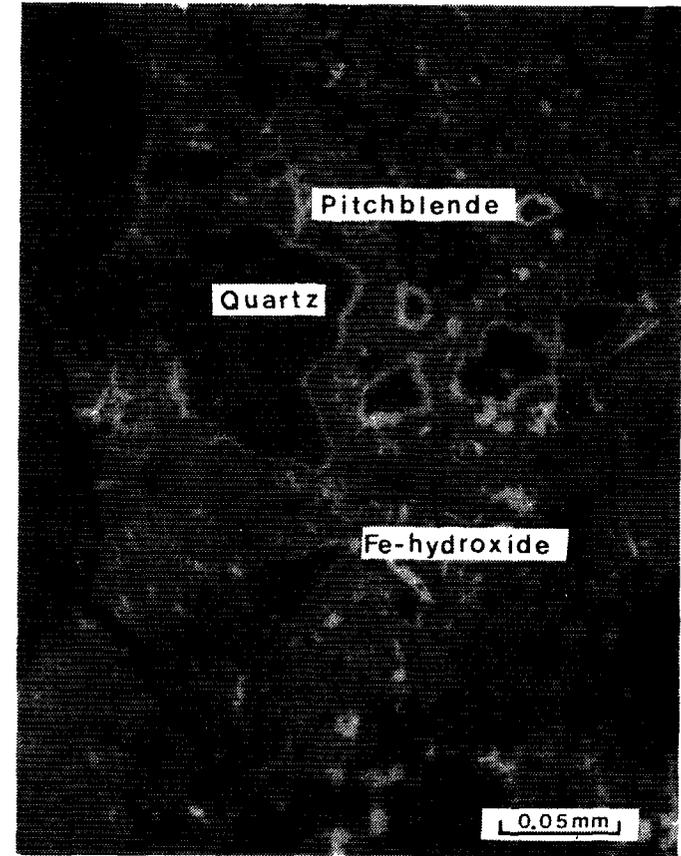


Figure 24. Photomicrograph of mineralization from Fond-du-Lac deposit. Q = quartz, Fe = limonite, P = pitchblende. Reflected light.

(Fig. 22). The sedimentary rocks of the Athabasca Group which overlie unconformably the basement rocks, are at the unconformity chloritized and limonitized, brecciated and, further upward, silicified.

The mineralization in the Main Zone is controlled by a steeply dipping fault and occurs in both the altered basement rocks and in the altered sandstone. In the A Zone the mineralization occurs along fractures and disseminated in the basement rocks and the sandstone. In the B Zone the mineralization occurs entirely in the altered sandstone. In one of the additional small zone mineralization occurs as subhorizontal lens in the sandstone near the surface. The largest resources (Table 3) are in the Main Zone, which is 1500 metres long, up to 200 metres wide and up to 10 metres thick. Pitchblende and coffinite are the main ore minerals (Fig. 23); they are commonly associated with chlorite and/or limonite (Table 10).

Uranerz Exploration and Mining Limited reported (verbal communication) absolute age of most of the uranium mineralization (determined by U-Pb method in W. Germany) as 1,200 Ma, but some of the pitchblende from the Main Zone reportedly yielded 2500 Ma. Absolute age of mineralization in one of the small zones was reported by Uranerz as 250 Ma.

Table 10: Selected elemental constituents in selected drill core samples from the Main Zone, Maurice Bay deposit. (From: Ruzicka and Littlejohn, 1981).

Element	Sample	Constituents in Percent				
		1) 1	1) 2	2) 3	1) 4	1) 5
Ag		n.d.	n.d.	< 0.005	n.d.	n.d.
As		n.d.	n.d.	< 0.2	n.d.	n.d.
Co		n.d.	n.d.	< 0.001	n.d.	n.d.
Cr		0.01	0.03	< 0.0005	n.d.	n.d.
Cu		< 0.001	0.05	< 0.007	0.005	0.007
Mo		n.a.	n.a.	< 0.005	n.a.	n.a.
Ni		0.02	< 0.0015	< 0.001	0.02	< 0.0015
Pb		0.2	1.5	< 0.07	n.d.	n.d.
Sc		n.d.	< 0.0007	n.a.	n.d.	n.d.
Ti		0.3	0.3	0.48	0.1	0.1
U ³⁾		5.84	32.5	0.14	7.70	11.1
V		0.01	0.07	< 0.002	0.005	n.d.
Zn		n.d.	n.d.	0.11	n.d.	n.d.
Zr		0.015	< 0.005	0.0096	n.d.	n.d.

n.a. - not available
n.d. - not detected
(i.e. below the detection limit)

Th was not detected in any sample
1. Analyzed using 5Q-23
2. Analyzed using 12B-DR
3. Analyzed by Neutron Activation

Location of Samples:
1. DDH MB-21: sandstone
2. DDH MB-87: regolith
3. DDH MB-24: altered sandstone
4. DDH MB-46: regolith
5. DDH MB-98: regolith

FOND-DU-LAC AREA

The Fond-du-Lac area is located at the south shore of the Athabasca and at the northern rim of the Athabasca Basin (Fig. 1). The Fond-du-Lac deposit, the only known deposit in this area, occurs about 90 km east-southeast of Uranium City (Homeniuk et al., 1980; Tremblay, 1982).

Most of the uranium mineralization of the Fond du Lac deposit occurs in the sandstone of the Athabasca Group within 35 metres above the sub-Athabasca unconformity (Homeniuk et al., 1980). The host rocks, which contain carbonate cement, are hematitized, limonitized and chloritized. The main ore mineral, pitchblende, occurs as coating on quartz grains or in the sandstone matrix as a mixture with limonite (Fig. 24). Coffinite is less abundant. According to Homeniuk et al., (1980) the main mineralization took place 1100-1200 Ma ago and its rejuvenation at 215 Ma and 80 Ma.

A CONCEPTUAL GENETIC MODEL FOR THE SUB-ATHABASCA UNCONFORMITY-RELATED DEPOSITS

Conceptual genetic models for the sub-Athabasca unconformity-related deposits have been proposed by several authors (e.g. Knipping, 1974; Little, 1974; Morton, 1977; Langford, 1977; Hoeve and Sibbald, 1976, 1978; McMillan, 1978; Dahlkamp, 1978; Munday, 1979; Ruzicka, 1979, 1982; Kirchner et al., 1979; Pagel et al., 1980; Ramaekers, 1980; de Carle, 1981; Clark et al., 1982; Tremblay, 1982). Some of the authors consider that the concentration of uranium took place in several stages and that several processes were involved in formation of the deposits.

Taking into account similarities and dissimilarities among these deposits, field and laboratory observations, and studies on similar deposits outside Canada (e.g. Ferguson, et al., 1980; Crick and Muir, 1980; Binns et al., 1980; Brookins, 1980) the following factors for establishing a conceptual model are recognized:

- (1) The main episode of uranium mineralization in all the sub-Athabasca unconformity-related deposits took place from 1050 to about 1300 Ma ago;
- (2) most of the pitchblende, the main ore-forming mineral, was deposited under temperatures between 130° and 260°C;
- (3) the mineralization was associated with retrograde metamorphism, which commonly resulted in clay alteration; tourmalinization of the host rock and magnesian metasomatism were common companions of these processes;

- (4) deposition of the mineralization was structurally controlled by the sub-Athabasca unconformity and steep faults intersecting this unconformity; the host rocks were, as a rule, dislocated along these faults;
- (5) at least one additional period of uranium mineralization (remobilization ?) took place about 200 to 300 Ma ago, i.e. during the time of Hercynian Orogeny;
- (6) uranium might have been derived from several sources. Some unaltered basement rocks, such as granitoids and metapelites, contain above normal amounts of uranium and associated elements which constitute the ore bodies; these elements could have been incorporated into mineralizing solutions by leaching. Altered sedimentary rocks of the Athabasca Group are depleted of some elements, such as U, Ni, As and Co; these elements might have been incorporated in connate waters or residual brines and thus might become another possible source for the mineralization;
- (7) hydrothermal solutions associated with diagenetic, tectonic or deep seated processes acted as an important factor in the formation of the ore;
- (8) remobilization and redistribution of the mineralization due to hydrodynamic conditions are continuing processes, which have caused modification of the deposits and development of dispersion haloes in their vicinity.

Therefore formation of the uranium/polymetallic deposits associated with the sub-Athabasca unconformity should be classified as polygenetic.

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URANIUM GEOLOGY BEAVERLODGE AREA

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Abstract

A brief summary is presented of the geology of the Beaverlodge Area with particular emphasis placed on the uranium mining properties of Eldorado Resources Limited. The deformed meta-sedimentary and volcanic rocks within the area are of Aphebian and Helikian age. These rocks have undergone at least three periods of orogeny, namely, the Kenorian (~2560 m.y.), Hudsonian (~1750 m.y.) and Grenvillian (~1000 m.y.). The final phase of the Hudsonian Orogeny caused the activation of major faults with initial emplacement of epigenetic pitchblende deposits taking place and with probable widespread remobilisation during the Grenville Orogeny. Dates as recent as 200 m.y. have also been recorded for the uranium mineralisation.

Genesis of the numerous uranium deposits in the Beaverlodge Area remains uncertain. It is generally considered that the deposits are related to metamorphic events and are the result of remobilisation within and from donor metasediments.

INTRODUCTION

The purpose of this paper is to provide a brief summary of the geology of the Beaverlodge area of northern Saskatchewan with particular emphasis on the uranium mining properties of Eldorado Resources Limited (formerly Eldorado Nuclear Limited). An attempt has been made to accentuate some of the more controversial aspects of the geological record and to summarize as briefly as possible the concepts of various proposed genetic models.

Only the most recent and major publications on the Beaverlodge area have been included in the selected references and the reader is referred to those publications for a more complete record. All geological maps and records of the Eldorado mining

operations are maintained in storage in the National Archives, in Ottawa.

Total production of uranium from the Beaverlodge district over a lifetime of 32 years, commencing in 1950 and terminating in June 1982, has exceeded 30,500 tonnes of U_3O_8 , of which in excess of 21,000 tonnes were produced from the mines of Eldorado Resources. Although this volume of production is comparable to the reserves of many of the more recent discoveries associated with the Athabasca Basin, the long production life coupled with the large number of geologists who have been associated with the Beaverlodge area has resulted in the accumulation of a considerably greater technical data base. As a consequence there may be a tendency to assume that the geology of uranium deposits of the Beaverlodge area is more complex than that associated with the Athabasca Basin.

GENERAL GEOLOGY OF THE AREA

The Beaverlodge area is located within the Canadian Shield, north of the northwest edge of the Athabasca Basin and north of Lake Athabasca in the province of Saskatchewan. The area is situated in the western Craton subdivision of the Churchill Structural Province. The rocks within the area have been subdivided into three groups (Tremblay 1972) which include the folded and metamorphosed Archean meta-sedimentary rocks of the Tazin Group, Archean meta-sedimentary rocks of the Murmac Bay Formation and Helikian sedimentary and volcanic rocks of the Martin Formation (Fig. 1).

Rocks of the area have undergone at least three periods of orogeny. The earliest was the Kenoran (about 2560 m.y. ago), which was followed by the most prominent the Hudsonian (about 1750 m.y. ago) and finally by the Grenville (about 1000 m.y. ago). The Kenoran orogeny is considered to have resulted in metamorphism to produce Archean gneiss domes and granulites plus syngenetic uranium in pegmatites. The Hudsonian orogeny resulted in widespread metamorphism and mylonitization of the Tazin Group and Murmac Bay Formation with the later stages having marked a period of active mountain building, the deposition of the Martin Formation sediments, and eruption of the Martin volcanic rocks. The final phase of the Hudsonian also caused the activation of the major faults including the St Louis, Black Bay and ABC faults.

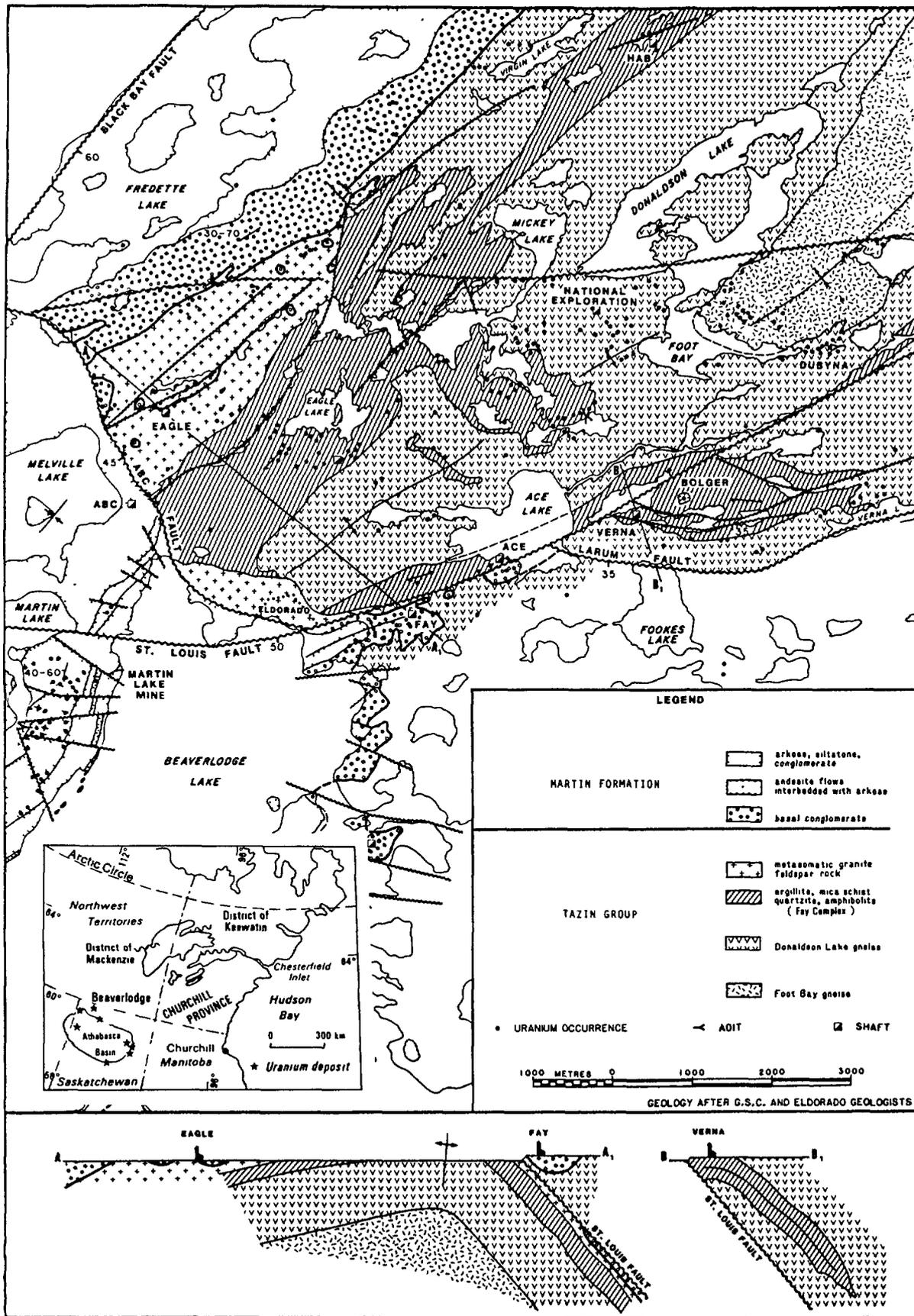


Fig. 1 Generalized geology of the Beaverlodge Area

Initial emplacement of epigenetic pitchblende deposits occurred at this time while, the Grenville orogeny is credited for further widespread remobilisation.

HISTORICAL REVIEW

During the gold rush in the 1930's, pitchblende was discovered at the property of Nicholson Mines Ltd, on the north shore of Lake Athabasca. The occurrence remained a mineralogical curiosity until Eldorado Mining and Refining (now Eldorado Resources) staked mineral claims in the Fish Hook Bay region immediately east and north of the Nicholson property. Eldorado then commenced prospecting for uranium throughout the area and succeeded in identifying hundreds of uranium showings, which led to the driving of an exploration adit near Martin Lake in 1948 and the sinking of two prospect shafts in 1949, the Eagle and Ace shafts (Fig. 1).

The greatest success from underground exploration and development was achieved from the inclined Ace shaft situated parallel to, and in the footwall of the St Louis Fault. After a decision was made to go into production the Ace shaft was deepened to a vertical depth of approximately 240 m and a vertical production shaft (Fay) was collared in 1951, approximately 1200 m west of the Ace shaft. Further underground shaft development included the Verna shaft approximately 900 m east of the Ace shaft in the hanging wall of the St Louis fault and two Winze shafts to develop the Fay and Verna orebodies at depth. The Fay Winze shaft achieved a vertical depth of approximately 1.8 km below surface. Lateral underground development from these shafts totalled in excess of 136 km by the time the mine closed.

Several satellite mines were developed on the Eldorado holdings and provided supplementary ore at various times throughout the life of the property. These included the underground Hab, Dubyna and Martin Lake mines and small open pits in the Verna, Eagle, West Fay, and Dubyna areas, the largest pit being the Bolger pit located east of the Verna shaft. Increasing production costs coupled with declining market prices and ore reserve grade necessitated the termination of production from the area in June 1982.

Production for the Eldorado properties is summarised in table 1. If production is included from other operations the

TABLE 1
 ALL TIME MINE PRODUCTION
 ELDORADO RESOURCES LIMITED
 BEAVERLODGE OPERATION

Mine	Average grade (% U ₃ O ₈)	Tonnes U ₃ O ₈
Fay	0.28	12,305
Verna	0.19	6,934
Hab	0.43	934
Open Pits	0.20	657
Dubyna	0.22	195
Martin Lake	0.30	7
Eagle	0.10	1
Total	0.25	21,033

total for the district becomes 33,713 tonnes U₃O₈ with most of the additional production coming from the Gunnar Mine at the south end of the Crackingstone peninsula and from small underground orebodies located west of the Black Bay Fault.

REGIONAL GEOLOGY AND STRATIGRAPHY

Figure 2 is a stratigraphic column of geology and stratigraphy of the area containing uranium deposits of Eldorado's mining operations. Most of the rock nomenclatures used throughout the history of the operations have been included for cross reference purposes.

The Tazin Group comprises a large variety of metamorphic granulite, sedimentary and volcanic rocks. The major uranium host rocks are contained within this group and in a broad zone of mylonitization and faulting. Although significant in surface exposure, the Murmac Bay Formation did not contribute in a significant way to the uranium production for the area. The Martin Formation is made up of the remnants of a Helikian supra-crustal basin lying unconformably on the Tazin Group. The rocks consist of a succession commencing with a basal angular conglomerate through a rounded upper conglomerate grading into an arkosic sandstone which in turn grades into a sequence of red-bed siltstones. The Formation also contains andesites and basaltic flows. A small amount of uranium production was achieved from

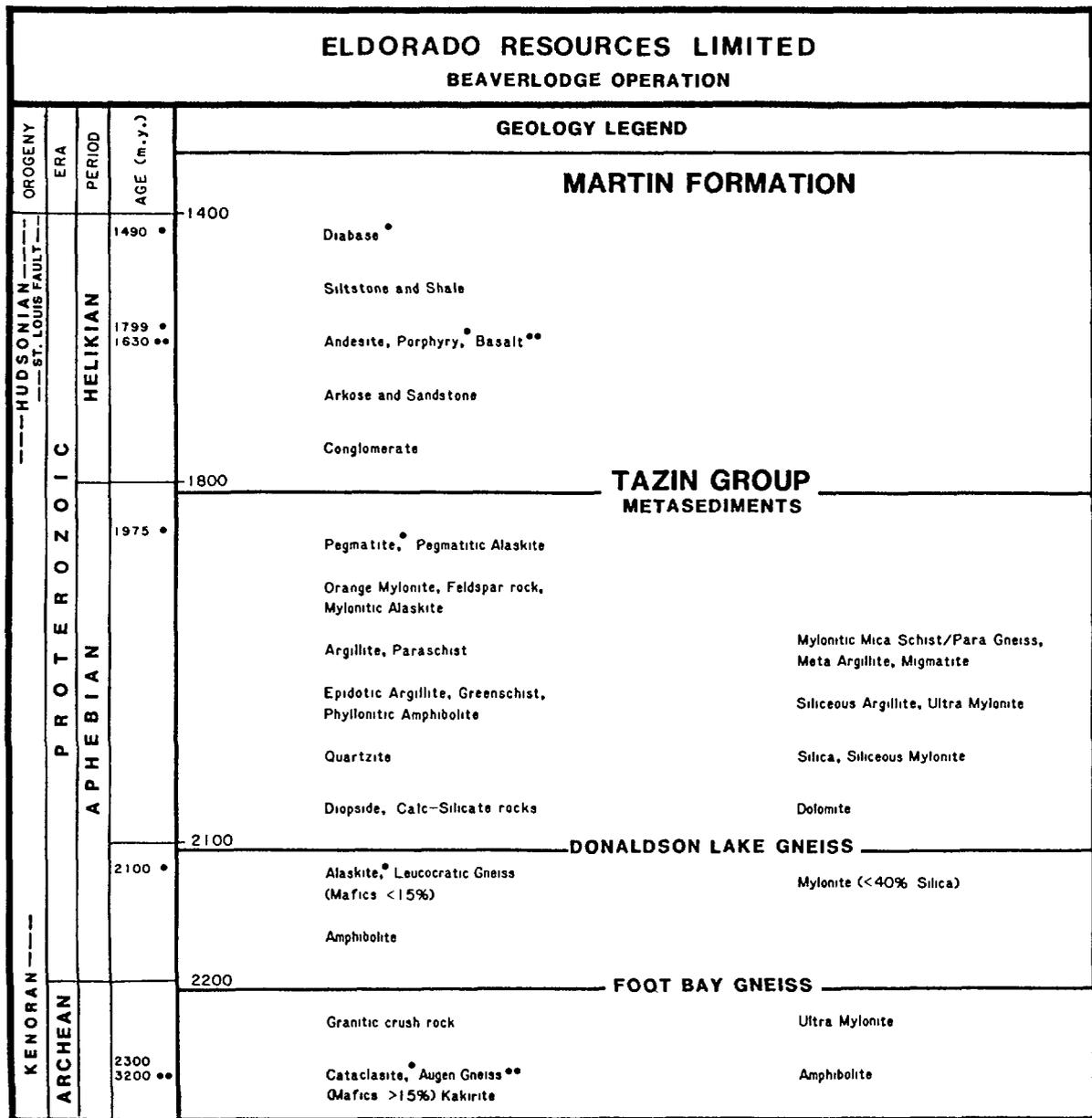


Fig. 2 Stratigraphic column

the basaltic-flows and from within the basal conglomerates, at topographic lows in the unconformity.

Structural features of the area include the St Louis Fault (Fig. 1) which strikes northeast and dips 50° to the southeast and along which the Tazin host rocks for the major uranium producing deposits are distributed. North of the St Louis fault is the Donaldson Lake anticline, a broad fold structure which plunges gently to the southwest with its southeast limb lying parallel to the St Louis fault and its northwest limb being offset by the Black Bay fault (Section A-A1, Fig. 1). The Black Bay fault also strikes northeast, is situated 6 km west of the St Louis fault, and is slightly offset by the St Louis fault. These two fault

structures are connected by the ABC fault which dips approximately 45° to the southwest, abuts the Black Bay Fault at the southwest end of Fredette Lake and splays off the St Louis fault in the vicinity of the old Eldorado townsite. The other major structural feature of the area is the Martin Lake syncline which is a synclinal trough with maximum dips up to 75° and which plunges to the north where it is offset by the ABC fault.

Although uranium mineralisation occurs in nearly all Tazin and Martin rocks, the major concentrations lie within meta-sediments of the Tazin Group distributed along the St Louis fault. Lesser amounts of uranium ore production has been achieved from basal Martin rocks west of the Fay Mine shaft and very minor amounts from volcanic rocks of the Martin Group.

ST LOUIS FAULT AREA

The majority of rocks seen underground and on surface in the immediate vicinity of the St Louis Fault are part of the Tazin Group. Figure 3 shows generalised sections of geology and uranium mineralisation on both sides of the fault. In general terms the section commences with the Foot Bay Gneiss. This unit, which forms the core of the Donaldson Lake Anticline, is represented in the lower levels of the Fay Mine in the extreme footwall of the fault, as an augen gneiss, whose texture is primarily a result of cataclastic deformation. It varies in grain size with plagioclase augen ranging up to 3-4 cm in diameter set in a fine quartzo-feldspathic matrix. The unit does not host any significant uranium mineralisation and due to its distance from the fault is not often encountered in the mine workings.

The second member of the Tazin Group is known as the Donaldson Lake Gneiss. This unit has also undergone severe cataclastic deformation and within the mine is represented by a fine grained highly laminated mylonite of granite composition. The laminations tend to be relatively flat lying where they are encountered in the extreme footwall of the fault but tend to steepen as they approach the fault. Only occasionally do these mylonites host uranium mineralisation and then usually at the contact with overlying units. Near surface and away from the St Louis fault however, this unit is not so highly mylonitised and

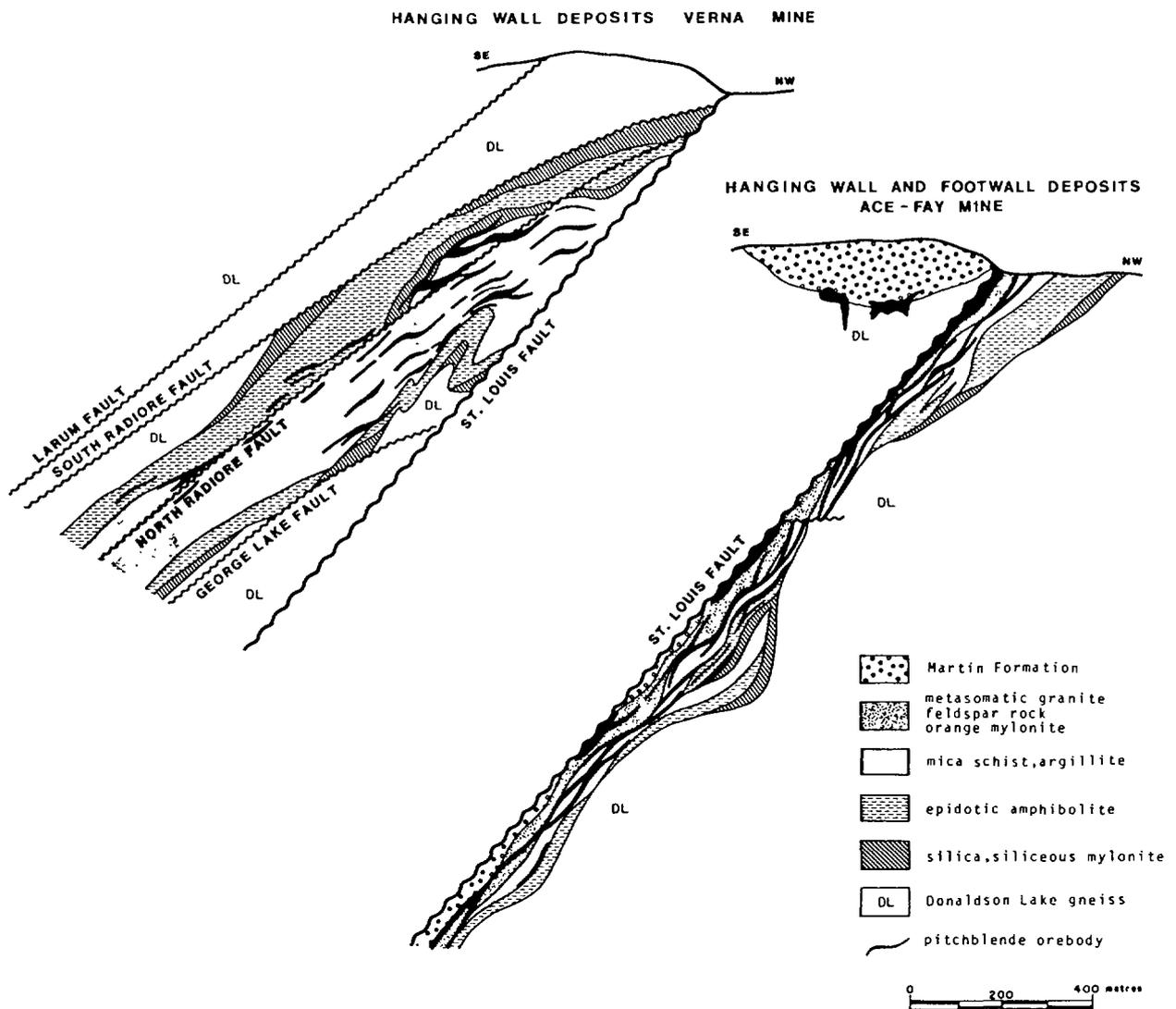


Fig. 3 Sections showing generalized geology in hanging wall and footwall of St. Louis Fault

hosts the Dubyna deposit, the 38 zone of the Hab Mine, and the deposits of National Exploration.

The next series of rocks is a complex sequence which hosts the majority of the uranium deposits. It occurs for a considerable distance (>5 km) along the footwall of the St Louis fault where it hosts the deposits of the Fay Mine and in a wedge located in the hangwall of the fault, which is formed by the St Louis, and Larum faults, where it hosts the Verna mine and related deposits. The sequence consists mainly of what is generally referred to as a mylonitic mica schist. It is composed primarily of albite feldspar with accessory chlorite and muscovite and has been intensely mylonitized. By far the greatest quantities of uranium occur in this rock as branching networks of veins usually displaying cymoidal structural patterns. Near the base of the sequence there usually occurs an amphibolitic unit which is thought to be

metavolcanic rock. It is represented by dark green to black phyllonitic and epidotic amphibolite or chlorite-epidote rock. The unit is characteristically laced with a network of fine epidote veinlets, is associated with relatively large bands of silica or siliceous mylonite, and is the second most productive rock for uranium mineralisation. Although it provides an excellent marker horizon for the base of the uranium producing sequence it does occasionally occur well up within the mylonitic mica schist especially in the hanging wall of the fault.

The uppermost unit of the Tazin Group in the vicinity of the St Louis fault is a controversial rock indeed. It occurs as a mylonite which is granitic in composition and frequently difficult to distinguish from the mylonites of the Donaldson Lake Gneiss. It contains megascopic porphyroclasts of plagioclase lying in a fine grained quartzo-feldspathic matrix, in which the feldspar contains fine inclusions of hematite giving the rock a characteristic orange colour. Due to this characteristic colour and texture, the rock has been referred to as feldspar rock or orange porphyroclastic mylonite by mine geologists and as a metasomatic quartz feldspar granite by others. The unit is much more brittle than the underlying mylonitic mica schist and therefore tends to host uranium deposits in lens-shaped stockworks consisting of tiny cross cutting fractures or breccia zones. Controversy exists as to whether the unit is an alteration of underlying units resulting from metasomatism or albitization of the underlying units adjacent to the fault, or is perhaps an ancient paleoweathering of the underlying units. Uranium deposits occurring in this unit tend to be low grade, irregular in shape and extremely erratic in mineral content. Most of the production from the very deepest levels of the mine, along the footwall of the fault was derived from this unit.

Martin Formation rocks also occur on surface and in the underground workings in the St Louis Fault area. The most common occurrence are the coarse angular basal conglomerates which occur in the hanging wall of the St Louis Fault, west of the Larum Fault. Uranium was mined from the conglomerate in topographic lows generally formed by down faulted blocks, which, within the limits of the underground workings, extended to a depth of 150 m. At one location uranium was mined adjacent to a Martin amygdaloidal basalt dyke in the footwall of the fault at a

depth of approximately 240 m. In access crosscuts driven south from the Fay Shaft toward the main footwall ore zone, porphyritic andesite dykes of the Martin Formation are exposed. This intrusive unit appears to occur as a single narrow dyke extending up to within 840 m of surface and branches at depths into several dykes at approximately 1060 m from surface, which is the limit of the exposure. In the immediate footwall and adjacent to the fault plane, Martin rocks have been seen to occur to depth in excess of 1.8 km. Considerable controversy exists as to whether these rocks actually are Martin or a tectonic breccia. However large blocks of polymict conglomerate and bedded and cross bedded arkosic sandstone containing lenses of siltstones have been mapped from surface to the deepest levels of the mine. Uranium has been known to occur in close proximity to the Martin rocks in the footwall of the fault but rarely within the rocks themselves.

Uraninite is the most abundant and widespread uranium bearing mineral in most of the host rocks. In the mylonitic mica schist and associated amphibolites, and especially in the lower levels of the Fay Mine minor uranium depleted brannerite occurs as the extremities of the ore bearing structures. In the uppermost unit of the Tazin Group (orange mylonite-feldspar rock) brannerite is the most abundant ore bearing mineral where it occurs in networks of Mg-chlorite veins at the core of the ore bearing structures. At the ends of the structures the brannerite gives way to a uranium depleted variety of brannerite and uranium becomes enriched in a siliceous pitchblende rock, while the extremities of the structure are relatively brannerite free.

ORE GEOLOGY

With the exception of surface production from the Eagle area, from Hab Mine and from Dubyna Mine all uranium production for the Eldorado Beaverlodge operation has been achieved from mylonitised metasediments and granitic rocks located within 400 m of the St Louis Fault. Figure 4 is a simplified stratigraphic section indicating the proportion of total production plus remaining drill indicated resources for major rock units.

Upon termination of production from the operation an estimate was made of remaining reserves and resources. Reserves are classified as all uranium bearing rock from which production was

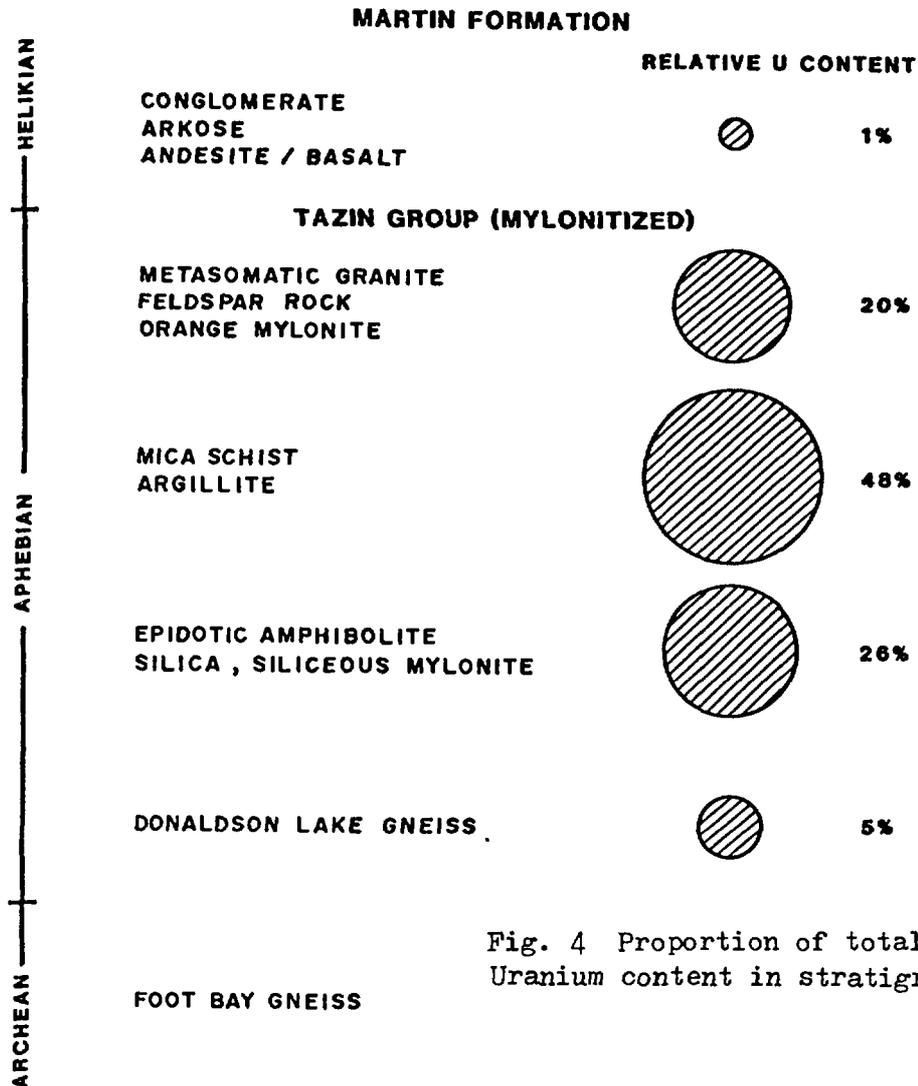


Fig. 4 Proportion of total Uranium content in stratigraphic column

being achieved and for which mining development had been completed at the time of closure. Resources, on the other hand includes reserves plus all drill indicated uranium, whether under development or having been mothballed for possible future development, should economics warrant it. Therefore, in order to provide an estimate of the quantities of uranium within each unit of the stratigraphic section, production plus resources has been used.

By far the greatest amount of uranium was contained within the top 3 units of the Tazin Group. The largest producers were the vein type deposits occurring in the mica schist and at the base of the mica schist within the metavolcanics (epidotes argillites) and associated silica units. The veins generally displayed branching cymoidal structural patterns both longitudinally and vertically, with those located in the footwall of the St Louis Fault being the most elongated, continuous and of highest grade. Individual ore veins ranged from less than 0.1 m to more than 1.5 m in width.

A considerable amount of uranium was produced from the upper unit of the Tazin Group, the mylonitized metasomatic granite or orange mylonite. Due to its more brittle nature this unit tended to provide a stockwork of tiny cross cuttings fractures hosting uranium mineralisation rather than the more continuous vein of the mica schist units. This unit generally lies stratigraphically below the Martin-Tazin unconformity in the footwall of the St Louis Fault both on surface and at depth. Production from the upper unit of the Tazin therefore also includes some of the material from the base of the Martin rocks west of the Fay Shaft, in the hanging wall of the fault, where the stockworks or breccias occurred in downfaulted topographic lows in the Martin-Tazin unconformity.

Most orebodies distributed along the St Louis fault plunged to the west and displayed a remarkable continuity with depth. At the time of closure the deepest production was being achieved from a stockwork breccia deposit in the footwall of the St Louis Fault at a vertical depth in excess of 1800 m.

FACTORS CONTROLLING MINERALISATION

Many factors have been reported to have a major controlling influence on uranium mineralisation in the Beaverlodge area. The most dominant of those factors are listed as follows:

- A. All Tazin Group host rocks are highly mylonitized but retain a recognisable stratigraphic order.
- B. All uranium deposits are spacially related to major faults and occur in secondary structures.
- C. Uranium bearing structures are confined to elongated zones that are both stratiform and crosscutting and form cymoidal fracture patterns.
- D. Wall rocks of uranium bearing structures are hematitised.
- E. All uranium deposits are spacially related to the Martin-Tazin contact.
- F. Rocks in the vicinity of uranium deposits have been subjected to some late stage soda-metasomatism in the form of albitization.

Although graphite is an important association with uranium deposits in the Athabasca basin, its presence in the Beaverlodge deposits does not appear to be as significant. First it is

characteristically associated with ore bearing structures at the base of the mylonitic mica schists, within and adjacent to the epidotic amphibolite. Secondly, at one known location, it occurs within an ore-bearing shear zone immediately below the Martin Formation west of the Fay Shaft. The third notable occurrence is in ore bearing fractures in the uppermost unit (mylonite) of the Tazin Group in the Eagle Mine area, situated on the crest of the Donaldson Lake anticline. In all cases the graphite occurs on slickenside faces but is not considered to be sufficiently ubiquitous to be a major factor in the control of uranium mineralisation in the Beaverlodge area.

In addition to the above, geochronology of uranium deposits in the Beaverlodge area has been the subject of considerable work by a number of geologists. To address this subject in detail is well beyond the scope of this paper. In summary therefore, age dates of epigenetic pitchblende mineralisation are highly discordant. The earliest dates that have been recorded are in the order of 1700 to 1800 m.y. and coincidental with the Hudsonian orogeny. Age determinations have also suggested clusterings in the 900 to 1100 m.y. area and as recent as 200 m.y.

Statistics, group summaries with corresponding histograms, for a total of approximately 120 age determinations were made by Robinson (1955), Koepfel 1968 and Slater 1982 using Pb206/U238, Pb207/U235 and Pb207/Pb206 isotopic compositions. Histograms illustrate the suggestion of the above-mentioned clusterings, while the statistical summaries and plots suggest that the two methods using the uranium-lead isotopes are comparable but the lead-lead isotopes do not correlate as well with the other two and on the average indicate considerably older ages. The effects of episodic lead loss, and consequently the discordancy of the uranium ages, are therefore illustrated.

Fluid inclusion studies in an attempt to determine temperature of formation have also been quite extensive and wide ranging in reported results. Temperatures have ranged from greater than 400°C to as low as 60-70°C. Sassano (1972) suggested that deposition may have occurred over a long period of time and perhaps that temperatures of formation have gradually decreased over that time. It was not uncommon in the deeper levels of the Fay Mine in particular to encounter pockets of highly saline

(CaCl) water under extremely high pressure. It was generally felt that these waters represented remnants of original formational waters or hydrothermal fluids.

CONCEPTS OF GENETIC MODELS

Genetic Models proposed for uranium deposits in the Beaverlodge area have ranged from exclusively hypogene to exclusively supergene, depending largely what factors controlling mineralisation are considered to be significant. Neither geochronological nor fluid inclusion studies have been able to provide a definitive guide to a specific genetic model. Age dates of uranium mineralisation have, however, defined possible periods of remobilisation of uranium, the oldest coinciding roughly with the late stages of the Hudsonian orogeny, and the most recent being within the last 200 m.y. Fluid inclusion studies also have provided a wide range of results, which for any single period could be interpreted to be a result of either deep-seated hydrothermal fluids or of relatively cooler surface water heated purely by diagenesis.

What is most common to nearly all models is that uranium probably originated from weathering of the pre-existing Archean terrane which contained uranium in granitic and pegmatitic rocks. The uranium was concentrated syngenetically in Aphebian pelites and was then mobilised during subsequent metamorphic events. Genetic models vary at this point with respect to how and during what metamorphic event the major period of mobilisation occurred to bring the uranium to its present site of deposition. Proposals range from uranium being moved during and immediately following metasomatism via deep thrust faults produced by wide and deep zones of mylonitisation, to during the mylonitisation.

If the uranium was deposited syngenetically in Tazin sediments, the present vein systems might reflect old stream channels or shore lines in the Tazin sedimentary sequence. This would help to explain the remarkable continuity down plunge of the stratiform vein systems along the St Louis Fault as shown in figure 3.

If the uranium was moved up via deep thrusts associated with mylonitisation, the fault association and specific alteration halos would be explained.

A supergene model would have uranium released through weathering of the Aphebian metasediments and older Archean rocks probably during Hudsonian times. Uranium solutions would migrate downwards via open fractures in Tazin meta-sediments immediately below elongated fracture controlled basins or valleys on the Martin-Tazin unconformity. Late tectonic activity during the Hudsonian orogeny and related to faulting, folding and subduction of Martin rocks along the northeast trending St Louis and related faults, resulted in the remobilisation of uranium downwards in tensional fracture zones to its present depositional site.

The greatest amount of remobilisation would occur in the immediate vicinity of the fault resulting in the greatest concentration and greatest preservation of the uranium mineralisation at this location.

Areas away from the fault such as across the west of the Donaldson Lake anticline would contain erratic mineralisation in fractures which tend to accumulate in elongated zones parallel with the axis of the pre-Martin valleys. Most mineralisation seen at the present surface in these areas would therefore represent roots of eroded deposits, explaining the lack of structural continuity.

In summary the complete genesis of the numerous uranium deposits in the Beaverlodge area remains uncertain. Most workers agree however, that the deposits are related to metamorphic events and are the result of remobilisation within and from donor metasediments.

CONCLUSIONS

The Beaverlodge mining district has played a major role in the history of Canadian uranium mining. Had the richer deposits associated with the Athabasca Basin been discovered first, the Beaverlodge story might never have occurred. However, greater bedrock exposures of mineralisation has naturally attracted attention to the Beaverlodge area and it was this attention that lead to discoveries in the Athabasca Basin. It appears that through mining and continuing discovery of new deposits in the Athabasca Basin that the interpretation of the geology of the associated deposits is becoming increasingly more complex. Therefore, what might have initially been interpreted as substantial

geological differences between the Beaverlodge deposits and the Athabasca deposits will very likely be interpreted as being similar and indeed merely as variations within a common geological environment.

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**GEOLOGY AND DISCOVERY
OF PROTEROZOIC URANIUM DEPOSITS,
CENTRAL DISTRICT OF KEEWATIN,
NORTHWEST TERRITORIES, CANADA**

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Abstract

Proterozoic supracrustal successions, Central District of Keewatin, are similar to the Proterozoic basins of northern Saskatchewan which contain economic uranium deposits. Because of the geological similarities, this district experienced a dramatic increase in uranium exploration during the 1970's. Deposits of varying type were discovered in this new uranium province indicating a potential comparable to the Northern Saskatchewan uranium province. In this paper, examples of three of the more important uranium deposit types are described.

Early Aphebian shallow marine pelitic to psammitic meta-sediments of the upper Amer group host subeconomic uranium concentrations. Mineralisation interpreted as syngenetic to early diagenetic is restricted to drab to red fine clastic sediments that display a moderate magnetic susceptibility.

Late Aphebian structurally controlled depressions, Baker Lake Basin, Yathkyed Lake and Angikuni Lake subbasins, are

filled with continental sediments and volcanics of the Dubawnt Group. Structurally controlled uranium mineralisation is most common adjacent to the margins of these basins. The Lac Cinquante deposit located in the northeastern Angikuni Lake subbasin is hosted in Archean metasedimentary and metavolcanic rocks immediately adjacent to the Dubawnt unconformity. Mineralisation is localised in or in close proximity to a highly fractured and brecciated unit consisting of interbedded chloritic tuffaceous and sulphide + graphite metasediments. In the eastern Baker Lake Basin uranium mineralisation is localised in thermal altered Kazan Formation arkose near alkaline dyke complexes.

Conglomerate and sandstone of the Helikian Thelon Basin lie unconformably on a highly weathered basement complex. The Lone Gull deposit is hosted in retrograded and altered psammitic to pelitic metasediments and undeformed granite near the erosional edge of the basin. Mineralisation is structurally controlled and associated with zones of intense K- and Mg-metasomatism. These features parallel those of the unconformity-related deposits of N. Saskatchewan.

INTRODUCTION

The Baker-Thelon uranium district lies within one of the most remote areas of Canada, in the Districts of Keewatin and Mackenzie, Northwest Territories. This is a subpolar region, beyond the northern limit of forest cover, marked by subdued topography and extensive lake and river systems which can be ice covered for nine months of the year. Existing transportation infrastructure is minimal, comprising only float aeroplane access, a single land air strip at the village of Baker Lake, and barge access 280 km inland from Hudson Bay through Chesterfield Inlet and Baker Lake. The village of Baker Lake is situated 640 kilometres north of the port and railway terminal Churchill, Manitoba.

In spite of the remote location and high costs of exploration, the region has been subjected to several periods of intense uranium exploration by both private and government-owned mining companies. The most recent exploration period dating from 1974 to the time of writing, is largely the result of the recognition

of marked regional geological similarities to the productive Athabasca Basin (700 kilometres to the southwest) and the Pine Creek Geosyncline region in the Northern Territory of Australia (Curtis and Miller, 1980), and the fierce competition for land in the Athabasca Basin, which forced companies with a commitment to uranium exploration but a restricted land position northward. Earlier discoveries in the Baker-Thelon area, made during the period 1968 to 1970, had demonstrated that uranium mineralisation was present, though not as economically viable deposits, and together with the rapidly accumulating data from discoveries in Saskatchewan and Australia, set the stage for a major effort in the region and the establishment of a new camp (Bundrock, 1981).

This paper outlines the igneous and sedimentary record of Proterozoic successions in this district and uses this record as the framework to outline the exploration history and geology of the most important uranium prospects and deposits. The geology and uranium metallogeny are presented in three sections:

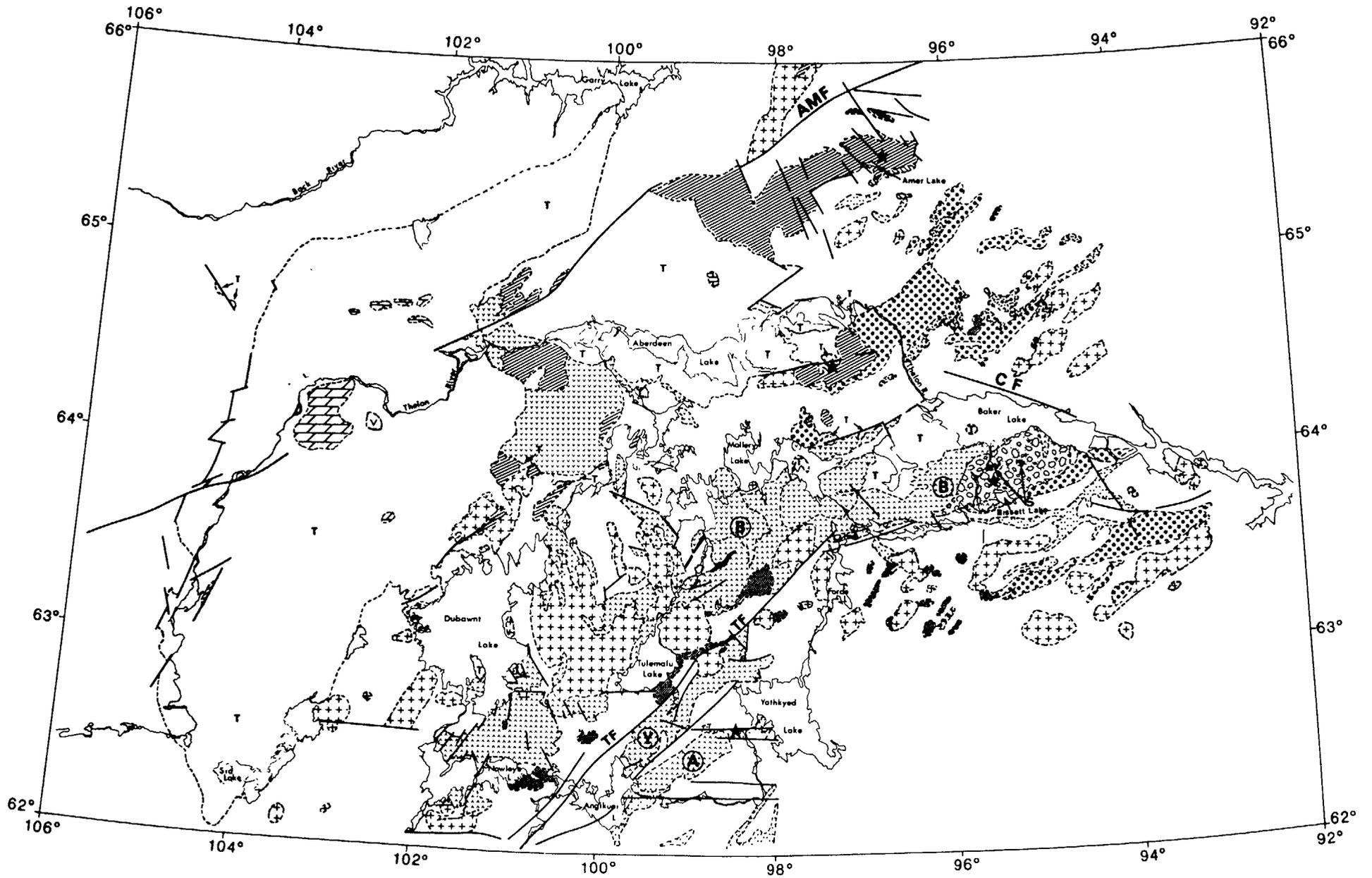
A) Early Aphebian metasedimentary belts: i) Amer group consisting of shallow marine to continental deposits and ii) undifferentiated metasedimentary belts; B) Late Aphebian Baker Lake Basin and subbasins: Dubawnt Group continental sedimentary and volcanic rocks; C) Helikian Thelon Basin: Dubawnt Group continental and shallow marine sedimentary rocks.

A) Early Aphebian Metasedimentary belts

Amer group

Early Aphebian metasedimentary belts are principally found in the region bounded by the Baker, Aberdeen and Amer lakes (Figure 1). These belts are largely confined to the Armit Lake Block (Heywood and Schau, 1978) which is bounded to the north by the Amer-Meadowbank Fault and to the south by the Chesterfield Fault Zone (Schau et al., 1982).

The Amer group is preserved in a west-southwest trending southwest plunging synclorium that is covered in the southwest by the Helikian Thelon Formation. The belt is exposed for more than 120 km with an average width of about 50 km. The Amer group is interpreted as early Aphebian based on its correlation with the Hurwitz Group of southern Keewatin (Bell, 1969, 1971). However the age of the Amer group is poorly bracketed between



ORDOVICIAN

 Fossiliferous limestone

HELIKIAN

 Basalt

 Dolostone, siliceous dolostone

 Thelon Formation: sandstone, pebbly sandstone, conglomerate

APHEBIAN

 Porphyritic diorite-gabbro (includes McRae Lake dyke)

 Granite: in part fluorite bearing and rapakivi textured

 Syenite: quartz syenite; includes Martell intrusive suite

 Pitz Formation

 Christopher Island and Kunwak formations

 South Channel and Kazan formations

} Dubawnt Group

 Amer group and equivalents

APHEBIAN and/or ARCHEAN

 Orthoquartzite, quartz pebble conglomerate, muscovite schist and phyllite,

 Basic metavolcanics, metapelites, calc-silicate rocks, graphitic schists, metagreywacke, iron formation

 Migmatite, irregularly layered granitoid gneiss, paragneiss; amphibolite, cataclastic augen gneiss

ARCHEAN

 Ultramafics: komatiites, serpentinites

 Basic metavolcanics, massive and pillowed flows, pyroclastics, tuff, and agglomerate; metagreywacke, mixed basic and intermediate metavolcanics, amphibolite, carbonate iron formation, calc-silicate rocks; quartzite, quartz pebble conglomerate, black slate, includes some gabbro

 Fault

 Baker Lake Basin

 Yathkyed Lake sub basin

 Angikuni Lake sub basin

TF Tulenalu Fault

AMF Amer-Meadowbank Fault

CF Chesterfield Fault Zone

★ Uranium deposit, prospect

Location of the Thelon and Baker Lake Basins, Districts of Keewatin and Mackenzie, Northwest Territories, Canada

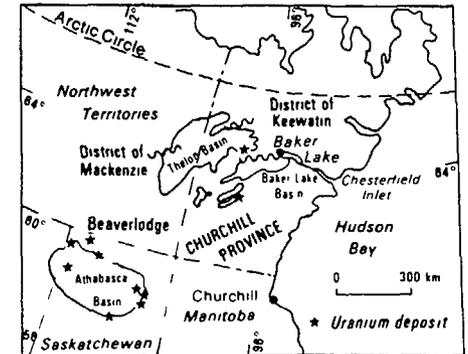


Fig 1. Geology of Central District of Keewatin, N.W.T. (from Miller and LeCheminant, in press)

Table 1. Stratigraphic column of the Amer group, Central District of Keewatin

Lithology	Remark
quartz arenite, arkose, maroon sandstone, shale and siltstone with rare stromatolitic dolostone.	preserved only at the western end of the belt
upper clastic sequence	fine grained pink feldspathic arenite, interlaminated arenite and siltstone, calcareous trough-cross bedded arenite, local conglomeratic breccia; capped by massive to laminated siltstone
cyclic with overall upward fining trend; main uraniferous unit at interface between arenite and siltstone	
grey black, green and maroon shales and siltstone, interbedded fine grained feldspathic and quartz arenite, thin stromatolitic dolostone.	upward coarsening trend
transitional sequence	laminated and locally stromatolitic dolostone, with minor intercalated shale, fine-grained quartz arenite, chert and conglomerate; very local vesicular mafic flows and sills.
pyritic grey to black carbonaceous siltstone and shale, interbedded chert and fine grained quartz arenite.	
lower clastic sequence	basal thick quartz arenite and quartz-pebble orthoconglomerate with minor shale and iron formation.
fluvial to near shore marine	

2801±24/-21 Ma (U/Pb, zircon) from the basement complex adjacent to the Amer group (Miller and LeCheminant, in press) and 1849±18 Ma (U/Pb zircon) from an undeformed quartz syenite that intrudes Amer metasediments (Tella and Heywood, 1978).

Stratigraphy and sedimentology of the Amer group have been described by Heywood (1977), Tippett and Heywood (1978), Knox (1980), Patterson (1981) and Tella et al. (1983); see Table 1. The group consists predominantly of two clastic sequences, a lower white orthoquartzite and an upper interbedded sequence of feldspathic sandstone, siltstone, mudstone and arkose. These two sequences are separated by a transitional sequence that includes thin discontinuous dolomitic limestone at the base and intercalated mudstone-siltstone at the top. Minor mafic igneous units occur along the fold belt at approximately the same stratigraphic level as thin locally conformable flows (Patterson, 1981) and as gabbroic sills (Tella et al., 1983).

Metamorphic assemblages in the northeast segment of the fold belt indicate upper greenschist-lower amphibolite facies regional metamorphism (Patterson, 1981) with the grade decreasing to sub-greenschist in the south-western end of the belt (Knox, 1980, Tella et al., 1983). Deformational events affecting the meta-sedimentary sequence are: i) west trending folds and northerly verging thrust faults, ii) southwest trending folds, and iii) northwest trending normal faults (Tippett and Heywood, 1978; Knox, 1980; Patterson, 1981; Tella et al., 1983).

Exploration for and geology of uranium mineralisation in the Amer group

The discovery of economic uranium deposits in Wollaston Group metasedimentary rocks adjacent to the Athabasca Basin, N. Saskatchewan in 1968, prompted Aquitaine Company of Canada to conduct reconnaissance airborne surveys in other geologically similar regions. Reconnaissance airborne radiometric and magnetic surveys were conducted over the northeastern portion of the Amer belt because of the abundant outcrop compared to the southwestern portion. Radiometric anomalies were identified which initiated a program of ground radiometric surveys, prospecting, soil geochemistry and diamond drilling (Aquitaine Company of Canada, 1970; Laporte, 1974). Re-evaluation of the northeast Amer belt by Cominco in 1977 involving detailed mapping, radiometric

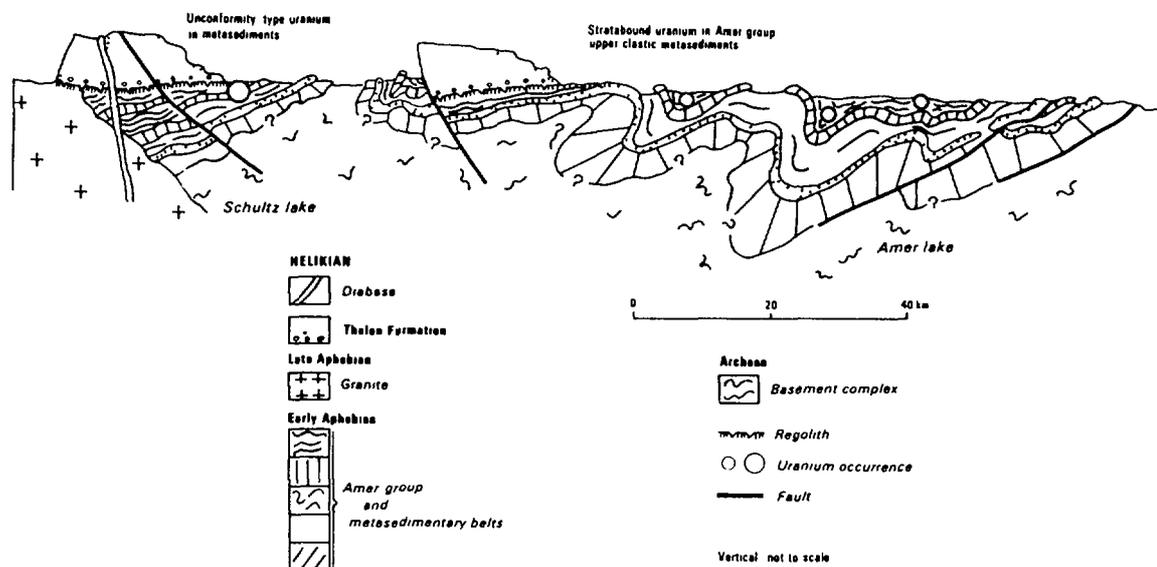


Fig 2. Schematic cross section, Schultz and Amer Lakes, Northeast Thelon Basin

surveys and diamond drilling indicated subeconomic uranium concentrations. The discovery of uranium mineralisation by Westmin Resources Ltd in the southwestern portion of the Amer group has influenced the exploration for unconformity-related mineralisation in that region.

Stratiform and stratabound uranium with minor base metals is hosted by several lithologies within drab and red fine clastic units situated near the boundary of the transitional and upper units of the Amer group (Figure 2). Much of the uranium mineralisation is restricted to this stratigraphic position along the length of the synclorium (Miller and LeCheminant, in press). Mineralised zones, lenticular in plan and section, are comprised of stacked discontinuous concordant psammitic and pelitic beds. These zones may have a composite strike length to 1000 m and thickness of 3-5 m. Mineralised zones show variable grades of 0.05 to 0.18% U_3O_8 over 1-2 m (Laporte, 1974; Lord et al., 1981).

Mineralisation is contained in a wide variety of lithologies of the upper Amer group: siltstone, sandy siltstone, feldspathic sandstone and calcareous equivalents (Knox, 1980; Taylor, 1978; Curtis and Miller, 1980). Rapid lateral and vertical lithological variations of the interstratified mudstone-siltstone-feldspathic sandstone are interpreted to have been deposited in a tidal flat-restricted bay environment. Mineralisation localised within siltstone, along silt-sand interfaces or within sandy beds exhibits a consistency of both macro- and microscopic features,

alteration assemblages and elemental associations along the entire length of the Amer group. The mineralised lenses have an elevated magnetic susceptibility and a red coloration which contrasts with drab hues common in adjacent strata. Uraninite, coffinite and subordinate U-Ti-Si compounds occur as ultra fine (1-10 microns) disseminated grains replacing framework feldspar and interstitial to quartz-feldspar framework grains in psammitic beds and as disseminated and spheroidal aggregates in pelitic beds (Curtis & Miller, 1980). Disseminated pyrite, galena, chalcopyrite, bornite, molybdenite, trace arsenopyrite and cobaltite are associated with uranium mineralisation. Radioactive strata are characterised by goethite and celadonite interstitial to and replacing feldspar framework grains, hematite, disseminated authigenic subhedral to euhedral magnetite and interstitial iron-chlorite and quartz. Complex metal assemblages and early diagenetic alteration support the interpretation that the stratiform mineralisation is comparable to sandstone-type mineralisation which is controlled by initial porosity, permeability and redox barriers.

Mineralised zones explored to date do not constitute economic ore bodies because of i) remote location, ii) size, form and grade of the lenses, and iii) geometry of the stratiform lenses due to multiple deformation. However potentially economic zones of uranium mineralisation may occur in fold closures where mining thickness could be created due to recumbent folding.

Exploration concepts

The following exploration concepts have been useful in prospecting and delineating the stratiform mineralisation in the Amer group: a) recognition of the mineralisation to be restricted to a specific lithostratigraphic position and environment, b) recognition of a primary sedimentologic control, and c) coincidence of mineralised strata with moderate magnetic susceptibility.

Undifferentiated metasedimentary belts

Several discrete sedimentary and volcanic-bearing sequences containing orthoquartzite strata are recognised south and south-east of the Amer group (Ashton 1981, 1982; Schau et al., 1982) and are termed Archean and/or Aphebian (Figure 1). Polyphase

Table 2. Stratigraphy of the Dubawnt Group, Baker Lake Basin and subbasins

Unit	Lithologies	Remarks
Mackenzie Diabase	medium to coarse grained gabbro and quartz gabbro	NW trending: 1204 Ma (Rb/Sr)
Thelon Formation	conglomerate, sandstone, pebbly sandstone	
Basic Intrusions (McRae Lake dyke)	porphyritic leucogabbro; medium grained gabbro and quartz monzonite	NE trending dyke-like intrusions: 1735 Ma (K/Ar)
Granite	alkali-feldspar granites; porphyritic biotite-hornblende, biotite and biotite-muscovite granites	circular to multilobate; fluorite-bearing; granophyric, miarolitic to rapakivi textures
Basalt	black amygdaloid basalt	intercalated with laminated green siltstone
Pitz Formation	rhyolite, minor rhyodacite and dacite; rhyolite breccia and conglomerate, red lithic sandstone and siltstone	fluorite and topaz-bearing; interflow quartz-rich sediments represent debris flow and stream channel deposits
Kunwak Formation	conglomerate, lithic sandstone, siltstone, and mudstone; minor amygdaloidal dacite	alluvial fan, braided river and lacustrine deposits
Christopher Island Formation and related alkaline intrusive complexes (includes Martell Syenites)	trachybasalt, trachyandesite and trachyte; volcanoclastic conglomerates, wacke, sandstone and siltstone	subaerial potassic alkaline lavas and pyroclastics with interflow fluvial deposits: 1786 Ma (Rb/Sr) to 1830 (K/Ar)
	medium to coarse grained syenite-quartz syenite; minor biotite pyroxenite; biotite lamprophyre	small stocks, sills and dykes: 1832 Ma (K/Ar)
Basal clastic successions (Kazan Formation, South Channel Formation, Angikuni Formation)	polymictic conglomerate, red to grey arkose and arkosic wacke, siltstone and mudstone	alluvial fan and braided fluvial deposits, minor eolian deposits; clastic wedges derived from east and southeast.

folding, northerly directed thrusting and lithological differences have made stratigraphic correlations with the Amer group tentative. Some of these sequences may be equivalent to the Archean Prince Albert Group, Melville Peninsula (Schau et al., 1982). Scattered uranium occurrences are known throughout these sequences however their position in the stratigraphy, alteration and associated minerals is poorly known (Curtis & Miller, 1980).

B) Late Aphebian Baker Lake Basin and subbasins

Sedimentary and volcanic units of the Dubawnt Group were divided into six formations by Donaldson (1965) and two formations of more local extent were established (Blake, 1980; LeCheminant et al., 1979a; see Table 2). The most complete record of the Dubawnt Group is preserved in the Baker Lake Basin. This complex graben, 50 km in average width, can be traced more than 300 km from eastern end of Baker Lake to Tulemalu Lake (Figure 1). Isolated Dubawnt Group successions west of Tulemalu Lake and southeast of Dubawnt Lake may be faulted remnants of a southwestern extension of the basin. West of Forde Lake, the Baker Lake Basin is bounded by Tulemalu Fault. To the northeast the basin extends across the projection of this fault. East of the Tulemalu fault the boundaries of the Baker Lake Basin are generally parallel to earlier structural trends in the basement and are defined by unconformities or steep normal faults. Here the basin has a generally asymmetric cross-section with northwest dipping basal red beds sequences overlain by a thin veneer of alkaline volcanic rocks (Donaldson, 1965, 1967; Blake, 1980).

Two smaller intracratonic basins, the Yathkyed Lake subbasin (Curtis and Miller, 1980) and the Angikuni Lake subbasin (Miller and LeCheminant, in press) are southeast of the Tulemalu fault. Structurally and stratigraphically these subbasins are similar to eastern parts of the Baker Lake Basin (Eade and Blake, 1977; Blake, 1980).

Initial development of the Baker Lake Basin and subbasins was strongly influenced by the pre-existing tectonic framework particularly major faults. Basal redbeds of the South Channel and Kazan formations were deposited in response to faulting and shedding of debris from adjacent highland areas. These formations are interpreted as alluvial fan-braided river deposits

having a source area to the south and southeast (Donaldson, 1965, 1967).

Redbed sedimentation was succeeded by widespread voluminous subaerial volcanic eruptions that produced potassic alkaline lavas, pyroclastics and comagmatic stocks, sills and plutons of the Christopher Island Formation. Alkaline flows are interbedded with debris flows and fluvial deposits which display the complex interaction between volcanism, faulting and fluvial deposition. The Christopher Island Formation is not diachronous (Curtis and Miller, 1980) as it is probably the only valid time-stratigraphic event in the Baker Lake Basin, instead its relationship to a wide variety of underlying units reflects the relatively independent histories of deposition in the various subbasins of the Baker Lake Basin (Blackwell, in prep.). Volcanic rocks of the Christopher Island Formation are alkaline, with shoshonitic affinities (Blake, 1980) and are characterised by high $K_2O + Na_2O$, $K_2O:Na_2O > 1$, low Fe, Ti contents, high Ba and P contents and erratic but high U and Sr contents. Covering an area of $5 \times 10^5 \text{ km}^2$, the Christopher Island constitutes the largest alkaline province in the world. Whole rock Rb/Sr and mineral K/Ar radiometric dating indicate a minimum age for alkaline volcanism of about 1830 Ma (LeCheminant et al., 1979b).

Continued block faulting following the waning of alkaline volcanism created local subbasins that were infilled with Kunwak Formation red clastic sediments. Depositional environments range from alluvial fan to braidplain to lacustrine (LeCheminant et al., 1981).

Large scale magmatism resumed with rhyolitic eruptions and emplacement of epizonal granite plutons. Pitz Formation is comprised of high-K, silica-rich, topaz-bearing rhyolite lavas, lithic-crystal tuffs with intercalated quartz-rich volcaniclastic rocks. This sequence records a history of contemporaneous silicic volcanism, mass wasting and stream-channel deposition. Pitz volcanic rocks are comparable to topaz rhyolites as defined by Burt and Sheridan (1980) and Burt et al., (1982). Elongate multilobate plutons of rapakivi granite intrude Dubawnt Group rock west of Tebesjuak Lake. Northeasterly trending bodies of porphyritic leucogabbro-quartz monzonite, including the McRae Lake dyke, intrude the latter rocks and have yielded a whole

rock K/Ar date of 1735 ± 52 Ma. The youngest intrusions in the area are regionally extensive MacKenzie diabase dykes (whole rock Rb/Sr 1204 ± 39 Ma, Patchett et al., 1978) which intrude isolated cappings of Thelon Formation west of Tulemalu Fault (Figure 1). In summary the Baker Lake Basin and subbasins developed in a continental extensional regime at about 1.9-1.8 Ga.

Uranium mineralisation has been recognised in each formation of the Dubawnt Group and basement complex to the Baker Lake Basin and subbasins (Miller and LeCheminant, in press). Zones of brittle failure are potentially the best exploration targets and have yielded the largest number of occurrences (Miller, 1980) with the highest uranium concentrations. Structurally controlled mineralisation is spatially related to: i) faulted margins of the basins, ii) fault and cataclastic zones cutting or adjacent to the basal unconformities, iii) specific lithologies in the Archean-Aphebian basement and Dubawnt Group, and iv) structures that have suffered repeated movement. The most significant fracture controlled uranium deposit discovered to date, Lac Cinquante deposit, is situated near the northeastern rim of the Angikuni Lake subbasin.

Exploration and Geology of the Lac Cinquante deposit, Angikuni Lake subbasin

The Lac Cinquante deposit contains drill indicated reserves of 5.3 million Kg U_3O_8 (Northern Miner, 1982). The initial discovery of mineralisation on the property was made by Pan Ocean Oil Ltd. in 1974 during a reconnaissance airborne radiometric prospecting program. At the time of discovery, only 1:1,000 000 scale maps were available in the region of Yathkyed-Angikuni lakes; however the rims of these subbasins were targeted based upon the success of Pan Ocean's exploration along the eastern margin of Baker Lake Basin in the late 1960's. Uranophane-bearing conglomerate was detected during the airborne survey and provided the impetus for ground acquisition. Follow-up work included regional airborne magnetic and electromagnetic surveys and detailed ground scintillometer, magnetic and VLF surveys. On the Lac Cinquante property, detailed ground prospecting revealed numerous fracture controlled uraninite-hematite-carbonate veins within Archean metavolcanic rocks which are basement to the Dubawnt Group on the property. The key to ongoing exploration

was the recognition by Pan Ocean personnel of the association between VLF conductors and uraninite-bearing vein systems.

The northeast terminus of the Angikuni Lake subbasin is underlain by an Archean greenstone belt which on a regional scale is subordinate in volume to granite gneiss and granodiorite. This greenstone belt is correlated with the Henik Group of southern Keewatin (Eade, 1980). Fault and mylonite zones trending E-W, NE and NW transect this basement complex and control the distribution of Dubawnt Group rocks (Eade, 1980).

The deposit is hosted in a sequence predominantly of propylitized pillowed and massive basic metavolcanics, meta-gabbros and subordinate massive and fragmental felsic metavolcanics with related metasediments. Few lithological markers are apparent in this sequence, the one exception to this generalisation is a thin, 1-2 metre, tuffaceous chert and chert-graphite-sulphide unit which occurs discontinuously through the principal zone of mineralisation. This zone is termed the Main Zone. Similar cherty carbonate and graphitic metasediments of possible exhalative affinity have been noted in outcrop and in drill core elsewhere in the district.

Greenschist grade basaltic to andesitic volcanics consist of chlorite, epidote, relict plagioclase (An_{30-35}) with minor quartz, clino-amphibole, albite, carbonate, pyrite, sphene, anatase and sericite. Interbedded tuffaceous metasediments contain quartz, chlorite, sericite and carbonate with minor pyrite and Fe-Ti oxides. The chert-sulphide marker unit, sometimes associated with U-Mo mineralisation, consists of chlorite, quartz, a carbonaceous chlorite mix, sericite, pyrite and rare chalcopyrite and sphalerite.

The contact between the greenstone and overlying Dubawnt Group is marked by an increase in hematite and to a lesser extent carbonate. This hematite-carbonate paleo-weathering profile is up to 5 metres thick with pronounced variations that reflect pre-Dubawnt paleo-topography.

Coarse grained conglomerate of the late Aphebian Dubawnt Group overlies the basement complex. Boulder to pebble sized granitic to granodioritic gneiss framework clasts characterise the conglomerate although lithologies of the greenstone terrain

are present. Basal conglomerate is overlain conformably and gradationally by pink to red arkosic grits, siltstone, mudstone and conglomerate.

Minor clasts of Dubawnt mafic volcanic rocks in the basal red bed succession indicate alkaline volcanism accompanied alluvial fan-braided river sedimentation. Because of this minor volcanic component, the basal redbeds have been mapped as Christopher Island Formation (Eade, 1980) but they occupy the same stratigraphic position and display essentially the same lithological relationships as South Channel and Kazan formations in the Baker Lake Basin (LeCheminant et al., 1976, 1977, 1979a,b; Donaldson, 1965). Christopher Island Formation phlogopite-phyric lavas, lapilli tuff and intercalated volcanic-rich sediments overlie the redbeds (Blake, 1980). The alkaline volcanics display elevated U, Th, Ni, Cr, Ba, and Sr contents. Lamprophyres and sill-like intrusions comagmatic with volcanic rocks occur throughout the stratigraphy.

In the vicinity of the deposit, major penetrative faults and shears are subparallel to WNW foliation. The principal conductive zones, one of which coincides with the ore deposit, also strike in this direction. Extensive shearing sub-parallel to foliation is indicated by transposition of pillows and locally extreme stretching of pillows. Although the Main Zone direction is indicated by VLF conductor axis at 290° - 300° , most of the surface mineralisation spatially associated with the Main Zone is controlled by a set of cross fractures, termed gash veins, trending 040° - 060° . These vein systems composed of carbonate + hematite + uraninite with subordinate chalcopyrite, pyrite and rare arsenopyrite are discontinuous and of variable width, 1-15 cm.

The Main Zone structure, approximately 1100 m long, coincides with a band of volcanogenic and volcanoclastic meta-sediments ranging from 1 to 8 metres and averaging 2.5 metres in thickness. Mineralisation occurs within this stratigraphic unit or in very close proximity to it and has the form of plunging pods of uraninite veins (Miller et al, in press). The ore zone is 300-400 m long with an average width of 1 metre and has been drill tested to 270 m depth. Extensive fracturing and localised cataclastic textures characterise the Main Zone and brecciation is typical of the cross-cutting 'gash veins'.

A complex metal assemblage, U + Mo + Ag + Pb + Cu + (Zn) characterises the Lac Cinquante Main Zone ore body. This type of mineralisation is similar to structurally controlled occurrences in the Baker Lake Basin (Miller, 1980). U, Mo and Ag are potentially economically recoverable in the deposit. Hematite, chlorite, Fe-carbonate and albite are the commonest gangue minerals forming diffuse envelopes around veins and filling veins. Uraninite occurs as vein and fracture fillings in brecciated metavolcanics and metasediments, as selvages to hematitised volcanic fragments in breccias and disseminated in pervasively altered wall rock. Very fine grained felty molybdenite accompanies uraninite and occurs with minor quantities of chalcopyrite. The mineral containing silver has not been identified.

Summary and Genesis of the Lac Cinquante Deposit

The deposit is a structurally controlled vein system containing complex U + Mo + Ag + Pb + Cu + (Zn) mineralisation. The cherty, sulphidic and graphitic interflow sediments may well have influenced the localisation of the host structures and created a local reducing environment for the precipitation of mineralisation. These earlier sediments may have contained traces of primary pyrite + sphalerite + chalcopyrite mineralisation.

The Main Zone mineralisation has been emplaced in a WNW striking structure which intersected the late Aphebian unconformity. Cross-cutting NE and ENE veins were also mineralised during the main event. The mineralising fluids were oxidising and characteristically CO₂-rich and were enriched in U, Mo, Ag, Cu, Pb and to a lesser extent As, and Na.

Explorationists in this region have observed the preferential association of uraninite veins in greenstones near the basal Dubawnt Group unconformity as compared to granite and granite gneiss and this has been used as an empirical exploration guide in the region. One of the genetic implications of this observation could be that the ultimate source of the uranium is the overlying Dubawnt Group volcanics and clastic sediments, which as previously noted are high in uranium and also coincidentally contain U-Mo mineralisation. Basic metavolcanics and interflow sediments appear to be more favourable hosts than granites or

granite gneisses and this may signify a redox effect which is not yet understood. The mineralisation and its structural setting has invited comparisons between the Lac Cinquante deposit and the Beaverlodge vein-type deposits in Northern Saskatchewan (Tremblay 1972, 1978; Miller, 1980; Miller and LeCheminant, in press).

Exploration Concepts

The following exploration concepts have proved useful in prospecting and outlining the deposit: (a) recognition that a late Aphebian unconformity truncates a sequence of Archean meta-volcanic and metasedimentary rocks; (b) evidence of enrichment in uranium in the overlying late Aphebian sequence; (c) recognition of dominant structural control; (d) coincidence of VLF conductors with mineralised structures; and (e) some lithological (redox?) control of mineralisation by cherty-sulphide and graphitic interflow sediments. These same units may also have exerted an influence on the localisation of structures.

Exploration and geology of epigenetic stratabound mineralisation, Baker Lake Basin

In 1974-75 Cominco Ltd entered a joint venture with Pan Ocean Oil Ltd to explore the eastern Baker Lake Basin (Laporte et al., 1978). Radiometric anomalies detected by airborne surveys were followed up with regional and detailed geological mapping, prospecting, geochemical surveys, a variety of geophysical surveys and diamond drilling.

Uranium mineralisation in Kazan Formation arkose and South Channel conglomerate has been described in detail by Stanton (1979) and Miller (1980). Mineralisation comprising disseminated uraninite, coffinite, U-Ti-Si compounds, digenite, covellite, chalcopyrite, bornite, native copper and native silver occurs within laminar and cross-bedded arkose, arkosic siltstone and conglomerate peripheral to crosscutting xenolithic lamprophyre dykes. The outer portion of the thermally altered sediments commonly grey, mottled pink to cherry red contain the highest grades of uranium-copper-silver mineralisation: uranium, to 0.31%, copper to 3.5%, silver to 15 ppm and anomalous concentrations of V, Mo, and Ba (Miller, 1980; Stanton, 1979). However the epigenetic cross-cutting mineralised zones are small, irregular, discontinuous along strike and confined to arkose and

conglomerate beds having higher porosity and permeability. Alteration assemblages include albite, hematite, anatase, carbonate minerals and quartz. Miller (1980) considered the mineralisation process to be a two-stage event. Metallic, sulphide influx and precipitation occurred due to convective flow of groundwater accompanying dyke emplacement and thermal and Eh gradients in the outer portion of the thermal aureole. Later, uranium was precipitated from oxygenated groundwater in zones of pre-existing sulphides. Stanton (1979) considered mineralisation to occur entirely during dyke emplacement and resulted from redox reactions between the lamprophyre dyke and heated metal-bearing groundwater.

Exploration concepts

The following concepts proved useful in prospecting for epigenetic mineralisation within redbeds: a) distinctive colour changes; b) localisation of mineralisation to specific porous horizons in the arkosic sequence; and c) proximity of alkaline intrusive bodies.

C) Helikian Thelon Basin

The Thelon Formation as outlined by Wright (1967) and Donaldson (1969), is largely preserved in an arcuate northeast trending basin which lies principally to the west and northwest of the early Aphebian belts and late Aphebian basins (Figure 1).

Thelon sediments lie unconformably upon a diverse basement complex of Archean tonalitic to granitic gneisses, Aphebian metasediments of the Amer group and interpreted equivalents and late Aphebian continental sediments and volcanics of the Dubawnt Group. Basement lithologies at and adjacent to the perimeter of the Thelon Basin display intense hematization and argillization and record a period of lateritic weathering prior to and during initial Thelon sedimentation (LeCheminant et al., 1983). Depth of weathering is variable based on lithology but feldspathic metasediments and granitoid gneiss can be weathered to depths greater than 50 m.

Sedimentology of the Thelon Basin has been studied by Donaldson (1969) and Cecile (1973). Cecile (1973) subdivided the basin on the basis of various physical and sedimentologic parameters into four 'facies' that broadly mirror the preserved

form of the basin. The basal 'facies' of the Thelon Formation is commonly conglomeratic and interstratified with pebbly arkose and siltstone. Basal coarse to medium grained siliciclastics can be cemented by authigenic clay + quartz or syngenetic to early diagenetic uraniferous fluorapatite, goyazite and illite. Uraniferous phosphates have been found throughout an extensive stratigraphic interval in the Thelon Basin, from the sub-Thelon saprolite to more than 300 metres above the basal unconformity (Westmin Resources private reports). A minimum age for the Thelon Formation of 1660 Ma (Pb/Pb, fluorapatite) was determined from a phosphate-cemented pebbly arkose overlying the weathered basement complex (Miller, 1983). Ninety percent of the basin is characterised by mature sandstone, quartz arenite and lithic subarenite which are interpreted as continental to nearshore marine in origin (Donaldson, 1969). This thick sandstone sequence corresponds to the upper three 'facies' of Cecile (1973). Multicoloured siltstone-sandstone intercalate with and increase in abundance near the top of the sandstone sequence. These fine clastics are overlain by shallow marine stromatolitic and oolitic dolostone-siliceous dolostone. Basalt is spatially associated with the upper most lithologies, however, its stratigraphic relationship is uncertain.

Exploration and geology of the Lone Gull deposit

In 1973, Urangesellschaft Canada Ltd began a grassroots uranium exploration program in the Central District of Keewatin for unconformity-related mineralisation based on the available 1:1,000,000 map of Wright (1967) and on then current concepts pertaining to this deposit type. Geochemical lake water and lake sediment surveys and a helicopter-mounted airborne system were undertaken on permits obtained in 1974 (Bundrock, 1981). A significant airborne uranium anomaly was located in highly glaciated and drift covered terrain near the erosional edge of the southeastern Thelon Basin, south of Schultz Lake. Ground followup detected a uraniferous mudboil. In addition the drainage geochemical survey disclosed anomalous radon in a lake, 3 km south of the deposit. This led to an intensified exploration program in 1975 and 1976 that incorporated prospecting, detailed mapping, geomorphology surveys, soil geochemistry, scintillometer, magnetometer, VLF and IP surveys. Exploration diamond drilling, initiated in 1977, intersected ore grade

mineralisation of 1.0% U_3O_8 over 33 m (Northern Miner, 1978). Since then the deposit, called Lone Gull, has undergone extensive exploration drilling to 1983. Exploration has been focused on targets that display multiple coincidences of VLF, gravity, resistivity, radiometric and EM-16 anomalies in altered meta-sediments. The Lone Gull deposits contain 17 million kg U_3O_8 at the present stage of exploration (Hilger et al., 1982).

The Lone Gull deposit is hosted by clastic metasedimentary rocks, of the informally called Judge Sissions Lake belt, and unmetamorphosed fluorite-bearing granite which is intrusive into this metasedimentary sequence (Miller and LeCheminant, in press). In the immediate area, shallowly north dipping metasedimentary rocks can be subdivided into a lower group characterised by immature clastic sediments and an overlying group comprising supermature orthoquartzite that resembles orthoquartzite of the Amer group. The lower immature metasedimentary sequence is dominated by drab green to green-black sulphide-bearing biotite + muscovite feldspathic wacke, lithic feldspathic wacke and epidote-bearing equivalents. Pelite and lean oxide facies iron formation intercalate with the psammitic units and increase proportionally eastward through the deposit area. Metamorphic assemblages indicate upper greenschist-lower amphibolite regional metamorphism followed by retrogression to lower greenschist facies. Phlogopite-phyric lamprophyres, syenitic dykes, and non-foliated, medium grained, sulphide- and fluorite-bearing sub-porphyrific to porphyritic granites intrude this metasedimentary sequence. Differences in the structural style and in the lithological assemblage of the immature metasedimentary sequence compared to the Amer group to the north suggest that these meta-sediments are older than the Amer group, and could be Archean.

Basal silicified conglomerate and sandstone of the Helikian Thelon Formation rest unconformably on weathered orthoquartzite, approximately 2 km north of the mineralised zone. In this area hematized orthoquartzite reflects pre-Thelon paleo-weathering. Northwest trending Mackenzie diabase dykes intrude all of the above lithologies.

Potential uranium ore, occurring as a series of three pods having a combined strike length of 1900 m (Fuchs et al., in press), is controlled in part by a well defined east-northeast

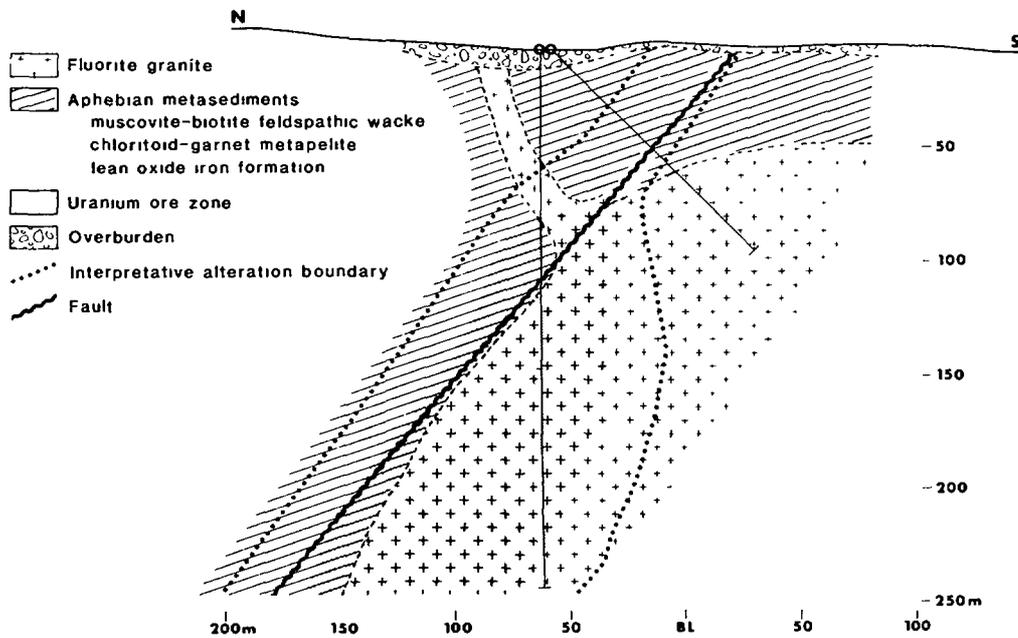


Fig 3. Interpretative drill section through the Lone Gull uranium deposit (from Miller and LeCheminant, in press)

trending steeply north-dipping normal fault and psammitic lithologies that are highly susceptible to alteration. Alteration, present as an envelope about the major structure, is characterised by a pervasive illite, Mg- and Fe-chlorite, minor smectite group clays, hematite and limonite (Miller and LeCheminant, in press; Figure 3). Mineralisation is most commonly present as fractures cross-cutting altered metasedimentary layering and granite and disseminations through intensely clay altered rocks. Multi-generation uraninite and coffinite are associated with minor and variable galena, molybdenite, pyrite, chalcopyrite, clausthalite and nickel, bismuth and bismuth-silver tellurides. Anomalous contents of boron and vanadium are associated with mineralisation.

Summary of Exploration concepts

The Lone Gull deposit exhibits several features in common with unconformity-related deposits in Northern Saskatchewan (Tremblay, 1978; Hoeve, 1978) except for the absence of graphitic metasedimentary host rocks (Miller and LeCheminant, in press). Thus the following concepts have proved useful in delineating and exploring the Lone Gull deposit: i) position near the erosional edge of a Helikian sandstone basin; ii) spatial association of mineralisation with reactivated major structures; iii) a comprehensive geophysical program to

delineate the response of each system and coincidence of various methods;

Southwestern Amer group

The southwestern portion of the Amer group and overlying Thelon Formation sediments have been the focus of continued uranium exploration utilizing unconformity-related models because this region possesses many features similar to the southeastern Athabasca Basin and East Alligator River uranium field, Australia. This region of the Thelon Basin has been extensively faulted by NE trending structures as the Amer mylonite zone and parallel faults (Geol. Surv. Can. Maps 1566A, 1567A) and NW trending faults. Kirchner et al. (1980) suggested that lower Proterozoic pelites syngenetically enriched in uranium are an important component in the generation of unconformity-related deposits in the Athabasca region. Stratiform mineralisation in upper Amer group pelites-psammites may represent a similar favourable situation. Carbonaceous/graphitic mudstone and siltstone in this same sequence may represent reduced strata that could react with oxidised uraniferous solutions. Numerous fracture-controlled occurrences with a uraninite-illite signature have been found in this region and these suggest similarities to the unconformity-related environment present in Northern Saskatchewan.

CONCLUSION

Numerous factors interact to determine area selection by the exploration geologist, however the Baker-Thelon region represents a target selection based almost exclusively on geological criteria. The region is remote, did not have the benefit of early prospecting discoveries, but did have a reliable geological base of maps and reports by officers of the Geological Survey of Canada (Wright, 1967; Donaldson, 1965, 1966). The importance of having an established geological framework cannot be overstated, and coupled with interpretative papers such as those by Donaldson (1967) and Fraser et al (1970), provided the analogical link to the Athabasca Basin in Saskatchewan and the East Alligator River area in northwestern Australia. The discovery of the Rabbit Lake, Cluff Lake and Key Lake deposits in Saskatchewan, and the Jabiluka, Koongarra and Ranger deposits in Australia allowed geologists to focus in on areas where higher metamorphic rank Lower Proterozoic supra-

crustal rocks are overlain with profound unconformity by undisturbed Middle Proterozoic fluvial quartz arenite units, with that unconformity surface marked by intense regolithic alteration. That relationship exists in the Baker-Thelon region, witnessed by the relative distributions of the Thelon Formation overlying the Amer Group and the informally named Judge Sissons Lake belt supracrustal rocks in the Shultz Lake area.

The discovery of the unconformity-related Lone Gull deposits confirm the validity of exploration by geological analogy within this geological setting. Notwithstanding the fact that an unconformity-type deposit occurs where it was predicted to be (and deposits of this type, with their higher grades and large tonnages represent the prime exploration target), other aspects of the Baker-Thelon region add strength to this area being selected as a prime exploration target.

1. The presence of moderate to high metamorphic rank "basement rocks" of Archean and Lower Proterozoic ages, with preserved belts of Lower Proterozoic supracrustal sequences containing stratabound uraniferous horizons provide a "protore" situation for subsequent upgrading at the Lower-Middle Proterozoic unconformity.

2. The presence of numerous vein-type occurrences in adjacent basement terranes and regional relationships to those in Saskatchewan with the uranium veins in the Beaverlodge area immediately adjacent to the lucrative Athabasca Basin camp (Miller, 1980) suggest widespread uranium mobility.

3. The presence of uranium-enriched subaerial volcanic rocks such as the Christopher Island and Pitz formations, or the uraniferous fluorite-bearing granites of the Nueltin-type, which during lithification and subsequent weathering provided a source of labile uranium for subsequent remobilization and re-deposition.

4. The multiple episodes of weathering and saprolite development recorded in the Dubawnt Group stratigraphic record, and the flat-lying nature of this rock package, provides larger, areally extensive tracts of prospective ground.

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THE RIO PRETO URANIUM OCCURRENCES, GOIÁS, BRAZIL

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Abstract

The pre-Arai (\pm 1,200 Ma) discordance is interpreted as a surface from which uranium was leached from older (3,200 - 2,500 Ma) granites and gneisses, and transported by surface and ground waters. Prior to their metamorphism, the graphitic schists of the Ticunzal Formation possessed the oxi-reduction conditions necessary to fix the uranium available at that time.

The Basal Complex consists of Archaean and lower Proterozoic rocks (3,200 - 2,500 Ma) including gneissic granites and orthogneisses. The Ticunzal Formation (2,000 Ma) which overlies the Basal Complex consists of paragneisses and biotite-muscovite graphite schists. The Basal complex and the Ticunzal Formation are in contact with granitic bodies, and together these underlie discordantly the metasediments of the Arai and Bambui groups which are likewise separated by a discordance. The Arai and Bambui groups are of Upper Proterozoic age and are sterile with respect to uranium.

INTRODUCTION

Aerogamaspectrometric surveys carried out in 1983 over approximately 46,000 km² of the northeastern part of the State of Goiás revealed hundreds of radiometric anomalies in basement rocks. The morphology of the region is characterized by a dissected plateau and ranges of Proterozoic quartzites and metaconglomerates attributed to the Arai Group. These anomalies were evaluated during geological reconnaissance, regional and local geological mapping, geophysical surveys and geological drilling. A number of uranium occurrences in Proterozoic metamorphic and metasomatic rocks were found, the ages of which vary from 1,700 to 2,200 Ma. During the Uruassuan (1,400 - 1,000 Ma) and Brazilian (1,000 - 500 Ma) cycles the rocks were rejuvenated isotopically.

Various types of uranium mineralization in veins have been identified. These include the classical types of occurrence such as those associated with pegmatites, with rocks attributed to hydrothermal

origin and with tectonic structures, along with mineralization types associated with unconformities such as those defined in the classification of Mc Millan (1978) for Canadian deposits and by Ferguson and Rowntree (1980) for the Alligator River uranium occurrences.

This paper summarizes the regional geological panorama of the Campos Belos-Cavalcante-Rio Preto areas of the State of Goiás covering some 10,000 km² of the state, and comments on the small uranium deposits around Rio Preto which are interpreted as being of the "unconformity" type.

GEOLOGICAL SETTING

Geomorphology

The regional uplift which initiated the present erosional cycle of the basins of the rivers Paranã and Preto in the northeastern part of the State of Goiás began after the Lower Cretaceous. According to Bruni and Schobbenhaus Filho (1976), this surface can be equated to the Gondwana Surface of King (1956), the remnants of which include the Chapada dos Veadeiros and the Serra Geral do Paranã. This regional uplift has a NE-SW trending axis with outcrops of the Archaean and Lower Proterozoic basement preserved in a number of inliers at elevations of between 400 and 500 m, surrounded by the Upper Proterozoic quartzite uplands of the Serra do Santana which attain altitudes of 1,000 m to the north and 1,700 m to the south.

The most significant of these inliers are those of Campos Belos Cavalcante and Rio Preto (Figure 1). The former is drained by the Rio Paranã while the latter through the Rio Preto system drains into the Rio Maranhão to the northwest of the area before it receives the waters of the Rio Paranã.

The orientation of the inliers shows a distinct northeasterly trend, the eastern border being controlled by large scale thrust faults and the northwestern one by broad synclines and anticlines with axes trending N-S. In the more eroded westerly areas of Campos Belos, the Paranã River flows over older rocks, leaving isolated relicts of quartzitic rocks.

Within the eroded parts of both the Campos Belos-Cavalcante inlier as well as that of Rio Preto, there occur four types of geomorphological structures: (1) alignments of crests of the older faults, whether fault scarps or fault-line scarps with elevations between 500 and 600 m; (2) elevated and rounded forms composed of granitoids attaining heights of 800 m; (3) hogbacks of quartzites which protect the relict hills attaining altitudes of about 700 m; (4) the

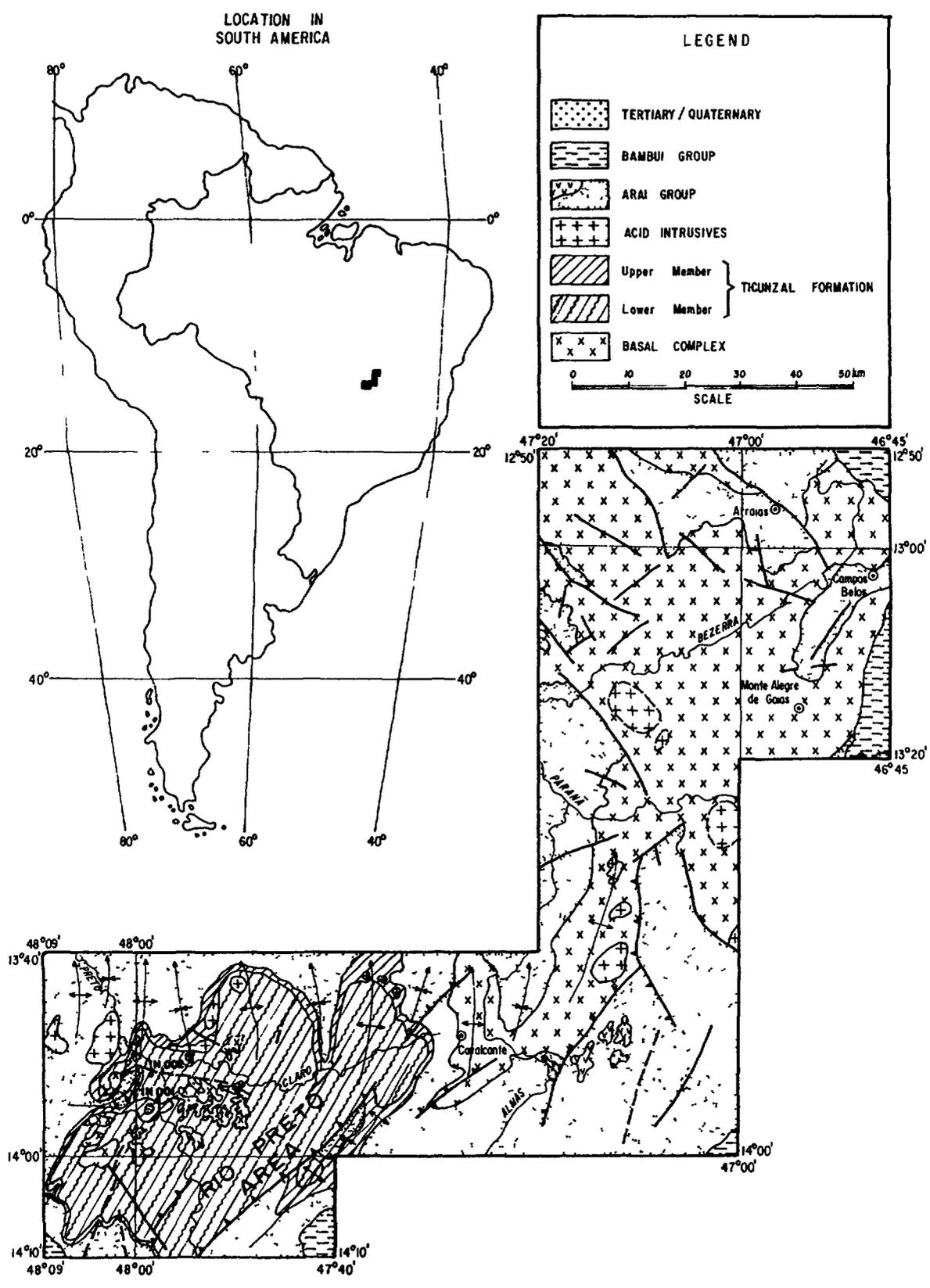


Fig. 1 - REGIONAL GEOLOGY OF THE RIO PRETO-CAVALCANTE-CAMPOS BELOS AREAS STATE OF GOIÁS, BRAZIL

Tertiary surface composed of detritus and laterite mapped by Sousa et al. (1980).

Regional Geology

The principal elements of the Precambrian geology and stratigraphy of Goiás were defined by Barbosa et al. (1969). The regional mapping of the Cavalcante-Rio Preto area of Goiás by Sousa et al. (1980) was based on this work and the stratigraphy was accordingly adapted. The mapping of Sousa et al. (1980) has served as a base for more recent studies and specifically those related to uranium prospection and exploration.

The oldest rock unit in the area is the Basal Complex which contains rocks of Archaean and Lower Proterozoic age. Sousa et al. (1980) included within this the coarse grained granite gneisses which are grey in colour, with K-feldspar porphyroblasts as well as orthogneiss of granodiorite-tonalite composition, (typically coarse grained and leucocratic with a slightly conspicuous foliation). Ages of this complex vary from 3,200 to 2,500 Ma (Reis Neto, In: Andrade et al. 1981). Subordinately, there occur nuclei of migmatites and veins of pegmatite. According to Figueiredo and Oesterlen (1981), the uranium mineralization which occurs to the west of Campos Belos is associated with rocks of the Basal Complex.

Of the principal groups of rocks comprising the Basal Complex Marini et al. (1978) and Sousa et al. (1980) drew attention to a new unit of metasedimentary rocks which was named the Ticunzal Formation, divisible into two members. The lower member is composed of fine grained biotite paragneiss which is light grey in colour, garnetiferous, finely foliated, generally cataclastic and intercalated with biotite-muscovite schist (which can be graphitic). Amphibolites also occur as well as pegmatite veins and basic dykes. Minerals such as chlorite, garnet and tourmaline usually occur. The most common accessory minerals are zircon, rutile, apatite, goethite and opaques. The upper member, separated from the underlying unit by a gradational contact, is composed of muscovite-biotite schist, generally graphitic; schist containing garnet and tourmaline and usually quartzose, passing to quartz-schist vertically. Secondary minerals include epidote, chlorite and sericite while the more common accessories include zircon, apatite and opaques. Also present in this member are veins of pegmatite and quartz. This Ticunzal Formation is the host of the uranium mineralization in the Rio Preto region. This formation is dated at about 2,000 Ma (Reis Neto, in Andrade et al., 1981).

Normally, two schistositys are clearly visible. S_1 is marked mainly by lenses of quartz, sericite/muscovite and biotite derived, probably, by metamorphic segregation. This surface may coincide with the stratification plane of the original rock (S_0), an hypothesis which is reinforced by the tectonics of isoclinal folds which gave rise to this S_1 .

The S_2 surface indicates the most recent foliation plane. On many occasions, various stages of crenulation development can be observed with reorientation of the micaceous minerals and graphite to the extent that, in some places, there has occurred a total transition of the older schistosity (S_1). In many cases S_2 is defined in thin section by narrow zones of opaque minerals.

The rocks of the Ticunzal Formation have been metamorphosed to biotite facies. Indicators of partial retrograde metamorphism are common. These include: chloritization of the biotite, alteration of the garnet to biotite and chlorite and sericitization of the plagioclase. This retrograde metamorphism is attributed to generalized cataclasis which affected the whole area.

The rocks of the Basal Complex and the Ticunzal Formation are cut by bodies of granitic composition which Sousa et al. (1980) referred to as "acid intrusives". These include bodies which have been intruded only into the Basal Complex as well as younger bodies which cut the Ticunzal Formation. The older intrusives can be separated into those which contain tin mineralization and those which do not.

The rocks associated with the tin mineralization are restricted to certain bodies such as those of Sucuri, Mangabeira, Pedra Branca and Riacho dos Cavalos. These are light grey in colour, fine to medium grained and composed of quartz, feldspar and biotite. The rocks are of porphyroblastic texture and contain porphyroblasts of blue quartz and euhedral as well as subhedral crystals of feldspar. Hydrothermal pneumatolytic alteration phenomena are observed. The rocks occur in the form of greisens mineralized with cassiterite and to a lesser extent with tantalite. According to Urdininea (1977), there is likely to exist a relationship between the tin and tantalite mineralization and the gold which occurs throughout the area. Attention was drawn to geochemical samples with anomalous uranium values suggesting a probable association of this element and its remobilization with the same mineralizing phenomenon.

The granitic bodies which do not contain tin mineralization include the Teresina Granophyre, the Caldas Granite, the Morro da Mangabeira, Serra dos Mendes and the Serra do Mocambo. According to

Reis Neto (In: Andrade et al., 1981), some radiometric datings suggest an age of 2,500 Ma for the Teresina Granophyre. Urdininea (1977), found anomalous uranium values in stream sediments derived from these areas.

The younger "acid intrusives" are those which cut the Ticunzal Formation and have a granitic-granodioritic composition. According to Andrade et al. (1981), the emplacement of these bodies was related to diapiric processes. They have been attributed an age of 1,600 Ma by Reis Neto (In: Andrade et al., 1981).

The rocks of the Basal Complex, the Ticunzal Formation, and the acid intrusives are separated from the metasediments of the Arai Group by an unconformity representing an erosional phase. The Arai Group has been divided into two formations: The Arraias Formation and the Trairas Formation. The Arraias Formation consists of fine-grained quartzites, well stratified and laminated. Fine to medium-grained quartzites and medium to coarse-grained quartzites with cross bedding and ripple marks and a level of calcareous quartz schist also occur. In several places a basal conglomerate having a schistose quartz matrix with pebbles of quartz and quartzite has also been observed. Volcanic rocks of acid to intermediate composition and represented by rhyolites, dacites and andesites are intercalated in the sequence, especially in the region of Cavalcante.

The Trairas Formation consists of quartz-schists with lenses of friable quartzite and beds of metamorphosed siltstone. The Arai Group is about 2,240 m thick and the youngest date determined from the volcanic rocks is 1,200 Ma (Sousa et al., 1980).

The Arai Group constitutes a sedimentary cover overlying the unconformity under which the uranium occurrences are found in the areas of Rio Preto as well as Campos Belos. These sediments are responsible for the topography of the Chapada dos Veadeiros, Chapada de Água Doce, the serras of Caldas, Forquilha, Ticunzal and others, as well as for the spurs which occur at the margins of the inliers under consideration.

Metasediments of the basal formation of the Bambui Group overlie unconformably the rocks of the Arai Group. However, the occurrence of the former is restricted throughout the region under study.

Deposits of detritus and laterite of probable Tertiary age occur on the eroded parts of the Basal Complex forming terraces and plateaus of small extension as well as on the tablelands composed of quartzite of the Arraias Formation.

The recent sediments are composed of bedded fine - to medium-grained loose sands which are white in colour. These form deposits

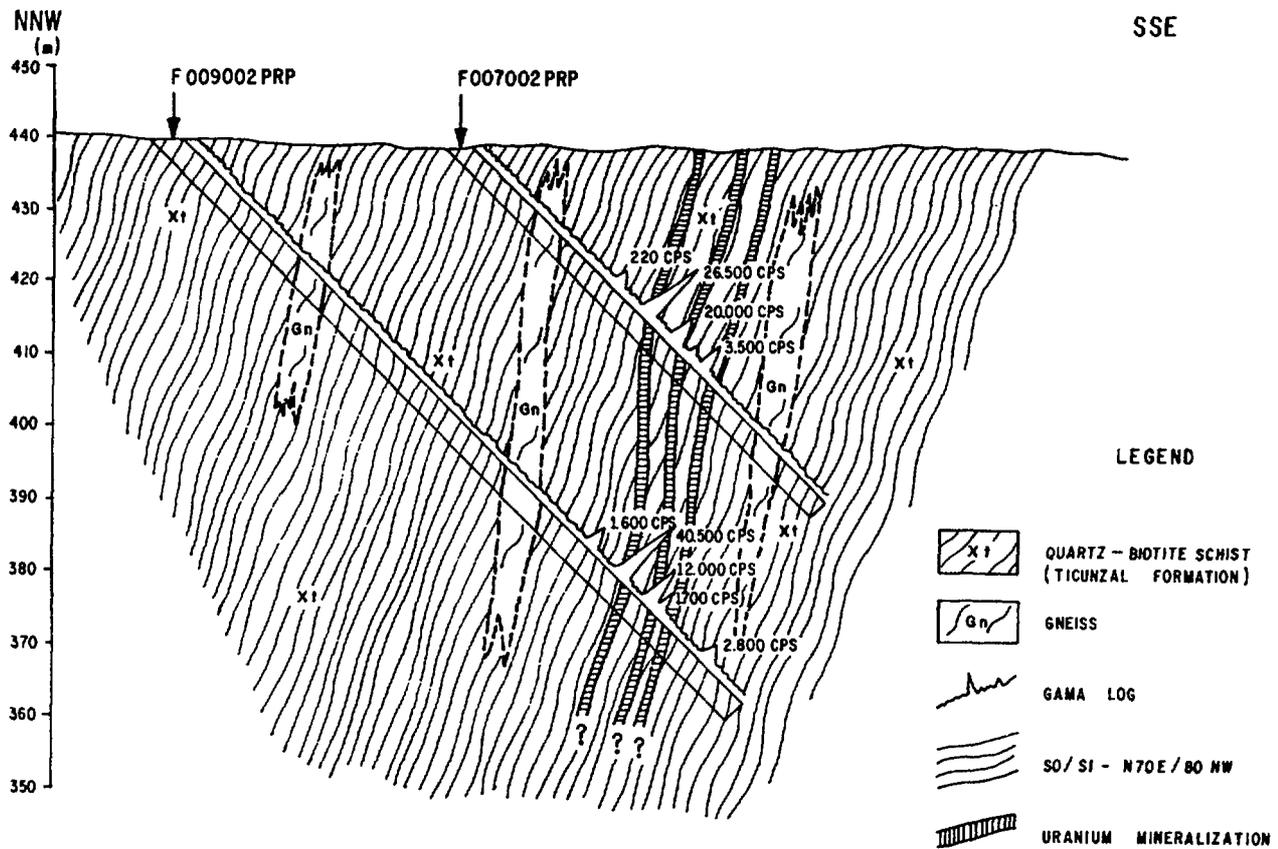


Fig. 2-SCHMATIC SECTION OF THE MODE OF OCCURRENCE OF URANIUM ORE IN INO02, RIO PRETO PROJECT, GOIAS, NUCLEBRAS-SUPPM

on the bed and margins of some stretches of the Preto, Claro, das Pedras, das Almas and Parana rivers (Sousa et al., 1980).

GENERAL CHARACTERISTICS OF THE URANIUM MINERALIZATION

Features of the uranium mineralization in the Rio Preto area have been summarized by Figueiredo Filho et al. (1982) as follows :

Lithological Controls

The uranium mineralization occurring in the Rio Preto area is restricted to the Ticunzal Formation.

This mineralization is found most commonly in quartz-muscovite biotite schist which may be graphitic. The levels of schists contain little biotite are sterile with respect to uranium. However, this does not mean that the biotite-rich schists necessarily contain uranium. Quartz veins, composed generally of smoky quartz, are found frequently adjacent to the mineralization.

Another type of uranium mineralization is that which occurs in the contact between a biotite schist of metasomatic origin and a gneiss belonging to the lower member of the Ticunzal Formation.

Structural Controls

The principal control over the mineralization verified in surface studies is the schistosity plane S_0/S_1 (Figure 2) since nearly all the radioactive bands follow this trend. Besides this form of occurrence, subsurface studies have revealed that mineralization is present frequently in fractures.

Another important structural control is the contact zone between the metasomatic rocks and the gneisses of the Ticunzal Formation.

Mineralogical Association

Biotite, pyrite, chalcopyrite, chlorite and hematite nearly always accompany the uranium mineralization. However, it can not be stated that these minerals are always present along with significant uranium grades.

Grades, Thickness and Radioactivity

The best occurrences in the area of the Rio Preto Project are occurrences 001 and 002. These are small deposits less than 1,000 tonnes of U_3O_8 each. On the basis of drilling results, the grades vary from 600 to 2,000 ppm U_3O_8 and less than 100 ppm ThO_2 . The mineralized thicknesses are about 0,85 m. The radiometric values of gamma logs of these two occurrences are generally high with maxima of 20,000 cps at occurrence 001 and 40,000 cps at occurrence 002.

MINERALIZATION MODEL

The eleven most promising uranium occurrences in the Rio Preto area are associated with two distinct lithological contexts which fall into the same metamorphic rock domain. These consist of graphitic schists and paragneisses of the Ticunzal Formation, described by Sousa et al. (1980).

In the first case the uranium concentrations are conditioned by the presence of schistose rocks, grey to dark grey in colour in the form of a dyke. These rocks possess sharp contacts and are enclosed in the paragneisses referred to above. In many cases, both rock-types have been affected by cataclasis. At depth, the uranium mineralization in this lithological context is very irregular and discontinuous. It occurs exclusively in the form of uraninite as small fracture fillings in the contact zone with the gneiss country rock. This rock is the product of metasomatic alteration of the country rocks. Recent petrographic and chemical studies carried out on surface samples and drill cores have shown this to be a biotite

schist, sometimes containing abundant hornblende and apatite. Biotite, present as a major constituent is neoformed.

The second and more usual lithological context is invariably a biotite-muscovite schist, generally graphitic and cataclastic. This schist encases pegmatite injections and veins of quartz which is nearly always of the smoky variety. In this rock-type, the uranium mineralization occurs as uraninite, sometimes in fractures and at other times, distributed along the schistosity planes. In both contexts (metasomatic rocks and graphitic schists), autunite and more rarely renardite, torbernite, rutherfordine and sabugalite are the secondary uranium minerals which occur at the surface.

According to Marini (1978), the controls over the uranium mineralization are essentially stratigraphic in the graphitic schists. This contrast with earlier views developed during the initial stages of evaluation which considered that the uranium mineralization was controlled structurally by faults. However, this author did not comment on the origin of the uranium although its concentration was attributed to tectonic mechanisms and folding in which graphite played the role of a chemical barrier for mineralized solutions. Rodrigues (1978) proposed an epigenetic origin for the uranium which may have migrated through intensely cataclased zones in the graphitic schists.

As a result of the integration of the various phases of the Rio Preto Project, it is reasonable to consider the hypothesis that the pre-Arai unconformity (1,200 Ma) was a surface over which uranium leached from the older gneisses and granites (2,500 Ma) was transported by surface and ground waters. The anomalous geochemical uranium values adjacent to the older granites and gneisses described by Urdininea (1977) support the hypothesis that these rocks were the source rocks of the uranium.

The graphitic schists possessed the physical and chemical characteristics which permitted redox reaction and the fixation of any free uranium available at that time. The Ticunzal Formation is the host rock of the uranium mineralization while the paragneisses and quartzose schists are mineralized only slightly.

Another possibility worth considering involves the contribution of fluids having hydrothermal characteristics in the phase of uranium concentration. This view takes into account the frequent occurrence of hematite and the argillization of the mineralized sections having significant uranium grades along with sulphides (pyrite) associated with uraninite.

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PROTEROZOIC UNCONFORMITY AND STRATA-BOUND URANIUM DEPOSITS

Epilogue

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No detailed attempt is made to synthesise the diverse styles of mineralisation found in the Proterozoic rocks which are presented in this collection of papers. It appears to me unlikely that a common thread would link all these deposits into a single genetic framework. Although a number of these deposits appear to have a similar history of development when viewed in the gross aspect.

The question could be asked as to why the Proterozoic was such a favourable time period for the development of uranium ore bodies, in particular the high-grade ones, as well as a number of other mineral commodities. The sceptic may reply that the Proterozoic covers a large time span amounting to a third of earth's history and nearly half of the geological record. The Early to Middle Proterozoic period appears to have been essential to the development of the high-grade unconformity related uranium deposits. Further exploration is needed before it can be established whether the Zambia-Zaire, Labrador and Olympic Dam stratiform types of uranium deposits should be restricted to a particular era of the earth's history. The uranium deposits covered by this collection of papers group themselves into two main types, being:

- a) dominantly stratiform types
- b) stratabound and unconformity-related types

I have chosen to look at these two groupings separately. The notable absence of a paper on the Franceville Region, Gabon, in this treatise is unfortunate and stems from the difficulty in communicating with authors in remote parts of Africa. Fortunately reference can be made to a range of published material on these deposits and this is included in the discussion presented here.

STRATIFORM TYPES

Regional Setting

A number of regional contrasts are offered by the three stratiform provinces, namely, Zambia-Zaire, Aillik Group-Labrador, and Olympic Dam Deposit-South Australia. The Labrador deposits are hosted in Lower Proterozoic rocks whereas the other two occurrences are hosted in Middle Proterozoic rocks. The rocks range from undisturbed and unmetamorphosed as in the Olympic Dam Deposit to highly deformed and metamorphosed as is the case for the Labrador Province. The Zambia-Zaire Province offers an interesting contrast in that the individual deposits range from an unmetamorphosed condition grading through to deposits occurring in lower amphibolite grade.

Contrasting rock types host the uranium mineralisation in the three provinces, they span the compositions from felsic volcanoclastics, argillites, arenites, rudites and calcareous rocks. In all three provinces the uranium mineralisation occurs in the basal sections which unconformably overlies high uranium granitoids of the basement complexes. In these provinces there is no relationship to a major unconformity with the overlying rocks. Dolerite dykes cut the mineralised zones in two of the deposits and additionally lamprophyres are found in the alkaline igneous province of the Aillik Group, Labrador. Pre-Adelaidean lamprophyric rocks are found at the Cattle Grid, Cu-deposit, Mt Gunson area some 85 km from the Olympic Dam deposit (J. Knutson pers. comm.).

The rocks hosting the uranium mineralisation in the three provinces occur in anorogenic environments related to extensional tectonics with rifting having been identified in two cases.

Geological setting of deposits

In all three situations the initial uranium concentration, that in some places produced protore and elsewhere ore-grade, appears to have been stratiform and syngenetic with some development of epigenetic mineralisation. The epigenetic mineralisation was usually accompanied by upgrading of uranium values. This transgressive epigenetic uranium appears in the post-lithification situation in the Labrador and Zambia-Zaire Provinces and appears to have been developed shortly after the syngenetic mineralisation. The transgressive mineralisation is

related to fractures, faults, breccias, joints, shears and mylonites. In all situations the main primary mineralisation is low thorium uraninite; minor coffinite, brannerite and soddyite are present in some situations. In the Zambia-Zaire and Olympic Dam Deposit multi-element mineralisation is present, in particular Cu, rare earth elements, gold ± silver - these deposits are all characterised by high U/Th ratios.

The role of metamorphism in concentrating uranium appears to have been insignificant as evidenced by the Zambia-Zaire Province where no marked change is discernable within the different metamorphic grades encountered. It is suggested that if uranium mobilisation occurred it could only be over short distances and may account for the resetting of uraninite ages.

Source, Transport and Deposition

In all three situations the deposits have a close spatial relationship with the basement and initial mineralisation is thought to have been syngenetic. It would appear likely that the syngenetic mineralisation, developed in the Lower Katanga System of the Zambia-Zaire Province, was derived from uranium enriched basement. A likely source for the uranium is the granitoids whereas the copper probably owes its origin to mafic rocks within the basement complex. The mineralisation associated with both the Labrador and Olympic Dam Deposit appear to be related to alkaline igneous activity which is identified in the Aillik Group by the mineralisation being contained in or adjacent to alkaline felsic volcanogenic rocks. In the case of the Olympic Dam Deposit, these alkaline igneous rocks have not been identified but the high uranium granitoid basement rocks at the nearby Cattle Grid copper deposit, Mt Gunson area, contain lamproitic rocks (pers. comm. J. Knutson). Alteration has played a significant role in the mobilisation of uranium at the Olympic Dam and Aillik Group Deposits being characterised by alkaline metasomatism; K being dominant in the former and Na in the Aillik Group Deposits. In both situations this alkaline metasomatism is probably related to the alkaline igneous activity with the possibility of a meteoritic interaction. The resetting of uranium isotopic values is a feature of most uranium deposits, particularly those that have undergone metamorphism, orogenesis, epeirogenesis and alteration produced by

groundwaters. This holds for Labrador and, in the case of the Zambia-Zaire Deposits is pertinent to those that have undergone metamorphism.

It is suggested that the copper, iron and gold at the Olympic Dam Deposit probably originated from a mafic source. The uranium was probably transported in the oxidised state as uranyl complexes as the ore deposits are characterised by low thorium contents.

In the Labrador and Zambia-Zaire situation carbonaceous matter and sulphides, which may have acted as reductants, are present in the host rocks. Evans (1980) also suggests absorption of uranyl complexes onto Fe^{2+} , Mn and Ti hydroxides with redox reactions causing precipitation of uraninite. The absence of reductants at the Olympic Dam Deposit suggests that the mechanism of precipitation of the oxidised uranium may have been brought about by oxidation of ferrous to ferric iron. Later circulation by mineralising fluids in these deposits also resulted in transgressive uranium being deposited.

Discussion

The role of alkaline igneous activity seems a likely mechanism for the development of uranium mineralisation in the Olympic Dam and Labrador Deposits, but is not obvious in the Zambia-Zaire Province. Although the structural setting of these deposits is very different, they share the aspect of having been developed in a continental regime during anorogenic periods. For the development of uranium deposits of this type the following appears to be essential:

- 1) Establishment of a uranium province either by an enriched basement complex or association with U-enriched alkaline igneous activity.
- 2) Transport as uranyl complexes.
- 3) A suitable environment for syngenetic concentration.
- 4) Mobilisation of syngenetic uranium mineralisation producing some transgressive zones of epigenetic uranium enrichment.
- 5) Sealing of deposit so that present-day oxidising ground and surface waters do not disperse the uranium by solution and transport.

STRATABOUND AND UNCONFORMITY-RELATED TYPES

Regional Setting

In most situations the unconformity, when present, separates the Lower Proterozoic from the Middle Proterozoic as is the case for the extensive Alligator Rivers Uranium Field and those of the Athabasca Basin Region. Others that share this time break are the Beaverlodge Deposits, Brazilian Deposits, Turee Creek and Thelon Basin Deposits. Elsewhere the unconformity separates the Archaean and Lower Proterozoic; for example, the Late Aphebian Basin mineralised zones and the Lianshanguan Deposit. Stratabound deposits that appear to have no spatial relationship to unconformities include those of the Dripping Spring Quartzite, Amer Group, and the Franceville Deposits (Diouly-Osso & Chauvet, 1979). In fact the Amer Group Deposits more correctly belong to the stratiform type but because the other two types of deposits in the Central District of Keewatin fall within this category they have been included here.

Mineralisation occurs in diverse lithologies which display varying degrees of metamorphism and alteration. In all situations the host rocks are either Lower or Middle Proterozoic in age, except for the Late Aphebian Basins, here the mineralisation is present not only in the Lower Proterozoic rocks but also in metastrata of the Archaean basement.

In the unconformity-related situations, the mineralisation is either restricted to the lower sequences of rocks or, alternatively, present in rocks both above and below the unconformity. Examples of the first type include the deposits of the Pine Creek Geosyncline, the Brazilian Deposits and the Thelon Basin. Examples of the cover rocks containing mineralisation include Late Aphebian Basins, Beaverlodge area, Athabasca Basin Region and Turee Creek.

With the exception of the stratiform and stratabound Amer Group mineralisation, the economic grades of uranium occupy prominent dislocation features, for example, fractures, faults, schistosity planes, breccias, shears and mylonitised zones. Metamorphic grade in the hosting rocks is generally greenschist to amphibolite facies, although notable exceptions include zeolite facies in the Franceville and Dripping Spring Quartzite Deposits. Additionally, the Amer Group uranium mineralisation

is contained in rocks ranging from zeolite through greenschist to lower amphibolite grade. The uranium is usually stratabound and in some local situations also has a stratiform disposition. In most of these deposits the mineralisation post-dates the metamorphism and deformation. However, a notable exception is the Lianshanguan Deposit where the early syngenetic uranium mineralisation has been migmatized.

The host rocks to these uranium deposits are dominantly meta-terrigenous rocks that are usually carbonaceous. Other rock types include metavolcanics, granitoids, volcanoclastic rocks, metaregolith and carbonates.

Basement granitoids have a close spatial relationship with most of these uranium deposits and furthermore, where present, display anomalously high uranium content. In a number of deposits there is a spatial association of uranium mineralisation with dolerite intrusives and alkaline igneous rocks. In all situations the uranium deposits occur in tectonic regimes developed during anorogenic periods produced by extensional tectonics where continental and/or marine sequences dominate.

Geological Setting of Deposits

In some of these deposits there was initial syngenetic concentration of uranium in terrigenous sediments (Franceville, Amer Group, Beaverlodge, Lianshanguan) or volcanoclastic rocks as in the Dripping Spring Quartzite Deposits. This syngenetic uranium does not produce economic grades. However, diagenetic processes have upgraded some of the syngenetic concentrations. Epigenetic processes superposed on post-lithification syngenetic mineralisation is the main factor responsible for upgrading these uranium deposits to economically viable grades. Most of the deposits are characterised by multiple resetting of the uranium mineralisation ages. Generally these mineral resetting ages correspond to periods of metamorphism, igneous events and epeirogenesis. Uraninite is the main primary uranium mineral in all situations, with some deposits containing minor coffinite and brannerite.

A feature of these uranium deposits is that uranium can either occur with other economically viable elements or in the mono-element situation. Even within a single province it is possible to find both situations. Common associated economic

elements can be any of a combination of the following: Cu, Ni, Pb, Mo, As, Co, Ag, Au, Nb, Zn, U, Sn, Bi and Li.

Within the ore zones metasomatism is usually present and is usually accompanied by the introduction of one or more of the following major elements: Na, K, Mg and Fe.

The gangue mineralogy in these uranium deposits is widely diverse, chlorite and iron oxides and hydroxides (mainly hematite and limonite) are common to most of these deposits but can also be mutually exclusive within individual deposits. Other relatively common minerals include clays, graphite (and carbonaceous matter), alkali feldspars, chert, quartz, carbonates and tourmaline. Common opaques include galena, pyrite, chalcopyrite, covellite, and sundry nickel sulphides.

In the unconformity-related uranium deposits the depths to which mineralisation is found below the unconformity is usually shallow, being less than 300 m. The Beaverlodge Deposits are an exception as here mining has taken place to depths of 1800 m.

Source, Transport and Deposition

Most of these deposits are juxtaposed with crystalline basement rocks and where information is available, these rocks are shown to be enriched in uranium and appear in most circumstances to be the primary source of uranium found in the deposits. In all occurrences the high U/Th ratios present within the mineralised zones suggest that uranium was transported in the oxidised state. The labile uranium extracted from the granitoid basement rocks usually results in mild syngenetic enrichment of the sediments and regoliths derived from these sources. In the case of the Amer Group deposits, the syngenetic enrichment approaches economic grades, but this is the exception rather than the rule. Elsewhere it has been necessary to upgrade the initial syngenetic mineralisation in order to achieve economic grades. In most syngenetic situations uranium appears to have been precipitated by reduction in the presence of carbonaceous matter. Diagenetic upgrading of some deposits has also taken place. Ore grade concentration of uranium has in general been brought about by epigenetic remobilisation with deposition having taken place in zones of disruption. The low temperature epigenetic movement of uranium generally appears to have been generated by surface and groundwater flow initiated by epeiro-

genesis. The higher temperature epigenetic solutions appear to have been mobilised by metamorphism, granite intrusion, migmatism and other igneous events. In some situations stable isotope data suggest the reductant appears to have been biogenic carbonaceous matter and/or bacterial sulphate. In a few occurrences it has been suggested that the absorption of uranium onto clays or Fe²⁺-Mn-Ti hydroxides was coupled with later redox reactions involving these minerals resulting in the precipitation of uranium.

Fluid inclusion and stable isotope data suggest a wide variation of temperatures recorded by the mineralising solutions in the general range 60-300°C. Temperatures at both these extremes have been recorded within individual deposits. There is a wide variation in uraninite ages within individual deposits, within a province ages can range from Middle Proterozoic to Mesozoic.

Discussion

It would appear that once a province has been enriched in uranium that all the succeeding sedimentary rocks derived from the basement rocks are also uranium enriched, although sometimes only mildly so. This feature also generally applies to the later development of igneous rocks within the province. The labile nature of uranium in the post-2200 Ma period is very evident judging from syngenetic and epigenetic upgrading found in most of these Proterozoic uranium deposits. In the syngenetic situation psammitic, pelitic and volcanogenic rocks host the mineralisation. In these situations there is a close spatial relationship with carbonaceous matter. The large compositional variety of rock types that host the epigenetic uranium deposits at first suggest a wide spectrum of depositional controls. In these situations structure appears to be the main control of uranium mineralisation rather than the primary host rock lithology. All the epigenetic mineralisation zones share the feature of being associated with low temperature parageneses apparently brought about by wall rock-solution reaction. Ore zones are usually characterised by the presence of chlorites, clays, iron oxides, graphite and carbonaceous matter. It could be argued that in situations where graphite/carbonate matter is absent that this material was initially present and has sub-

sequently been consumed. The alternative suggestion to uranium being precipitated by organic reduction is one of absorption of uranium from solution onto particulate matter with redox reaction involving Fe causing deposition of uraninite.

The generally shallow depths to which mineralisation is encountered in the unconformity-related deposits has led to the suggestion that these deposits were produced by surface-related supergene processes. The Beaverlodge Deposits are the exception as mining has proven ore to depths of 1800 m. The fact that the Beaverlodge Deposits are spatially related to major faults may account for the great depths of mineralisation encountered. If one is to adopt a supergene model it could be argued that this mineralisation could be brought about by downward percolation of uranium solutions via deep tensional fractures related to major faults. An alternative interpretation could account for this mineralisation to be produced as a result of remobilisation of syngenetic uranium during metamorphic events.

The grade of metamorphism does not always play a significant role in the location of these deposits as hosting terranes range from zeolite to amphibolite facies. Within single geological provinces uranium deposits occur in rocks that have undergone metamorphic grades ranging from greenschist to upper amphibolite. In the case of the Pine Creek Geosyncline uranium movement does not appear to be related to this metamorphic gradient. It is to be remembered that in a number of deposits the uranium mineralisation post-dates the regional metamorphism being contained in zones of dislocation. In some terranes metamorphism does appear to have played a role in the generation and activation of solutions that may have been responsible for the scavenging of uranium with precipitation taking place in traps under epigenetic conditions. Metasomatism can also result from the solutions associated with those metamorphic processes.

In all situations the high U/Th ratios recorded in the ore zones strongly suggest that the uranium was transported in the oxidised state.

The multiple ages recorded in the ore mineralisation of these deposits indicates high mobility of uranium under a number of geological conditions. This feature is the norm rather than the exception and evaluation of the timing of ore-forming events

should be treated with great caution. Uraninite dissolution and re-precipitation under low temperature groundwater situations possibly related to epeirogenesis is a common feature. The large range of temperatures deduced from fluid inclusion and stable isotope data equally has to be treated with great caution as most of these deposits occupy open systems. It is imperative to identify which gangue minerals are related to uranium mineralisation and to identify the geological events. The range of temperatures deduced from fluid inclusion and stable isotope data is simply reflecting different periods of activity only some of which might be related to uranium mineralisation. Unfortunately stable isotope data is presently limited; where sulphur isotopes are available there is the suggestion of bacterial sulphate reduction as well as sedimentary source input. In the Alligator Rivers Uranium Field biogenic carbonaceous matter has also been identified.

Any account of the behaviour of uranium transporting solutions would also have to take account of the frequent association of other economic elements found in zones of uranium mineralisation. Where experimental work is available it would appear that most, if not all, of these elements can be transported in oxidising solutions. Where determined, the lead is radiogenic which explains the correlation of this element with uranium.

The role of the unconformity in the development of these deposits is a tantalising one. This enigma is caused mainly by the fact that uranium mineralisation is either confined to rocks below the unconformity or is found both above and below the unconformity. A few workers have suggested that the cover rocks are the main source of the uranium mineralisation. Other interpretations see the unconformity surface serving as an aquifer along which uranium-rich solutions were transported to produce the ore grades encountered. Yet other workers regard the rocks above the unconformity as having acted as a passive impervious cap shielding uranium deposits from subsequent weathering and transport. Those who argue for the protective role of the cover rocks explain the situation where there is mineralisation within these rocks as having resulted from remobilisation from below the unconformity. In this model it

is necessary for faulting and brecciation to have taken place in the cover rocks, these zones of dislocation then acted as avenues for solutions which derived their uranium content from the ore zones below the unconformity. It is also necessary to fix the uranium in the cover rocks, the absence of a suitable reductant in the Kombolgie cover rocks of the Alligator Rivers Uranium Field may explain why there is chloritisation of the Kombolgie but no associated uranium.

CONCLUDING REMARKS

The high solubility of uranium in oxidising environments appears to be responsible for the diverse styles of mineralisation outlined in this collection of papers. What has to be answered is whether there is a real time dependency in the distribution of these Proterozoic uranium deposits. In order to make this assessment it is as well to look at the uranium cycle.

During the 3800-3000 Ma period, the continental crust developed by generation of sodic plutonism characterised by tonalitic and frondhjemitic magmas derived from a peridotitic upper mantle source (Glikson, 1979; Sutton, 1979). These Na-rich and uranium-depleted sialic rocks occur in close association with the early greenstone belts. In southern Africa, the potassic-rich volcanic and plutonic rocks developed at 3000 Ma, whereas in most other areas this development took place at 2700 Ma, corresponding to a major global thermal peak. With the advent of the development of K-rich granitoids in the period 3000-2700 Ma, uranium, owing to its incompatible behaviour, was partitioned into these magmas by partial melting and fractionation of an undepleted upper mantle source. Some K-rich granitoids are richer in uranium than others, so it would appear that the upper mantle source peridotites were probably inhomogeneous, at least in their uranium content. Where the uranium content of these granitoids exceeded 6 ppm, they represent potential provenance areas for the quartz-pebble conglomerate deposits. In that K-rich granitoids were developed at an earlier stage in southern Africa (i.e. at 3000 Ma), it is not surprising that the uraniferous quartz-pebble conglomerates of the Dominion Reef and Witwatersrand Systems fall into the older time slot of about 2800-2600 Ma (Pretorius, 1975)

whereas the Blind River deposits developed between 2500-2200 Ma (Robertson, 1974). The low oxidation state of the atmosphere at this time would have allowed detrital transport of uraninite in the reducing environs of the bedload of streams to produce the quartz-pebble conglomerate uranium deposits.

The development of red beds in the post-2200 Ma era (Cloud, 1976) indicates uranium, readily leached from the enriched provenance rocks, could be transported as the uranyl ion in the near-surface oxidizing atmosphere. A feature of the Proterozoic unconformity and stratabound uranium deposits are the large U/Th ratios, which are generally greater than 100 and in the high-grade ore zones can exceed 1000. These high ratios support the uranyl transport concept as Th is diadochic with U^{4+} .

The high-grade unconformity-related uranium deposits were developed in the post-2200 Ma period being either hosted in Lower or Middle Proterozoic rocks. It would appear from known discoveries that this time constraint is valid in the production of these deposits.

In order to account for this time constraint it could be argued that earlier detrital uraninite was concentrated in pre-2200 Ma sediments, as is the case for the quartz-pebble conglomerates, and that this syngenetic mineralisation was later mobilised and concentrated by oxidising solutions related to tectonic processes. An alternative hypogene argument would be to suggest that igneous activity in the Lower and Middle Proterozoic was U-enriched. However, some of these U-deposits lack a time and spatial association with igneous events. If a supergene model is adopted the following argument could be advanced to account for the skewed time distribution of unconformity-related deposits (Ferguson & Rowntree, 1980; Robertson et al, 1978).

As continental crustal development in post-2200 Ma times appears mainly to follow uniformitarian lines, the only variable which could explain the concentration of vein-type uranium by supergene processes in the 2200-1400 Ma period appears to be a steadily evolving atmosphere. It is suggested that during these times the hydrosphere was sufficiently oxidising for uranyl transport, but that rapidly reducing conditions were met short distances into the lithosphere. Reduction resulted in precip-

itation of uranium as UO_2 from meteoric water into suitable structural traps, which were largely developed during periods of prolonged erosion. The structural traps may also have been active during the early sedimentation of the Middle Proterozoic cover rocks. Rapid development of impermeable cover rocks preserved the uranium deposits from subsequent weathering and transport. In the post-1400 Ma period the atmosphere was sufficiently oxidizing so that reduction in groundwater situations was generally inadequate for the precipitation of uranium on any large scale other than in restricted continental sandstone situations. The ultimate "sink" for uranium under these circumstances would have been the oceans where it is found to concentrate in sea-water, altered floor basalts, black shales and other pelagic sediments. This broad dissemination of uranium within the marine environment did not allow any extensive uranium deposits to form in the post-1400 Ma period.

A similar supergene genetic argument could be advanced for the dominantly stratiform U-deposits to explain their distribution in Lower and Middle Proterozoic rocks. A hypogene process can also be advanced for the Aillik and Olympic Dam Deposits; if this genetic model is correct then it is difficult to understand why uranium associated with alkaline igneous rocks should not in fact occur throughout the geological time scale. The apparent time skewness shown for these deposits may only be a reflection of yet undiscovered younger occurrences.

It is clear that once a province has been enriched in uranium - whether these are basement rocks or alkaline igneous rocks that all rocks post-dating this event in the province are usually anomalously enriched in uranium. This later enrichment results from the highly labile behaviour of U under oxidising conditions whether they be hypogene or supergene. What is required in exploration to locate ore bodies is identifying the structural traps which can be either syngenetic or epigenetic.

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