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National Uranium Resource Evaluation

GEOLOGY AND RECOGNITION CRITERIA FOR VEINLIKE URANIUM DEPOSITS OF THE LOWER TO MIDDLE PROTEROZOIC UNCONFORMITY AND STRATA-RELATED TYPES

FINAL REPORT

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PREPARED FOR THE U.S. DEPARTMENT OF ENERGY
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SYNOPSIS

General

The discovery of the Rabbit Lake deposit, Saskatchewan, in 1968 and the East Alligator Rivers district, Northern Territory, Australia, in 1970 established the Lower-Middle Proterozoic veinlike-type deposits as one of the major types of uranium deposits. The term "veinlike" is used herein for this type of deposit in order to distinguish it from the classical magmatic-hydrothermal "vein" or "veintype" deposits. The veinlike deposits exhibit distinct geologic features and are now known to include the largest and the richest uranium deposits of the world. At present they account for between a quarter and a third of the Western World's proven uranium reserves.

The veinlike deposits are still in an early stage of geologic description. There continues to be much disagreement on the processes involved in their formation. Studies have established many geologic relations within the principal veinlike districts, including those in Canada, Australia and the potentially related deposits of the Franceville Basin, Gabon. Many detailed aspects of the geology within the various districts remain to be defined. More important, however, are the large apparent differences between districts which have made correlations between them difficult to establish. One approach, preferred by many authors, has been to consider each area separately on the basis of its own geologic characteristics. We believe, however, that the various types of veinlike deposits are probably related by a series of geologic processes, the differences between deposits reflecting differences in host rocks and the types and intensities of the processes they experienced. We believe it is important to attempt to establish what relations exist between the seemingly different types of veinlike deposits.

Lower-Middle Proterozoic veinlike deposits, as discussed in this report, include several subtypes of deposits, which have some significantly different geologic characteristics. These various subtypes appear to have formed from various combinations of geologic processes under a sequence of geologic conditions ranging from synsedimentary uranium precipitation through some combination of diagenesis, metamorphism, metasomatism, weathering, and deep burial diagenesis. Many important aspects of the deposits and their geologic characteristics have not yet been well documented, and the sequence of processes that is inferred to have formed the deposits is based, in many cases, on inadequate and conflicting data. Some of the deposit subtypes are based on only one or two incompletely described examples; hence, even the classification presented in this report may be expected to change. Geologic characteristics of the deposits differ significantly between most districts and in some cases even between deposits within districts. Because of this diversity and complexity, and the lack of a consensus among geologists on the modes of ore formation, emphasis in this report is placed on deposit descriptions and the interpretations of the observers. This permits the reader to better evaluate the conclusions and interpretations presented.

Geographic-Geologic Distribution

The bulk of the known veinlike deposits have been found in Canada and Australia. In Canada, the major districts occur in the province of Saskatchewan, but minor deposits have been discovered in the Northwest Territories and Newfoundland. In Australia, the Northern Territory hosts all the deposits. Some minor occurrences have been found in Sweden. The uranium deposits in Gabon may represent the unmetamorphosed equivalent of the veinlike-type deposits. The locations of the principal veinlike districts and deposits are shown in Figure 1 together with the locations of important uranium deposits of other types.

All the deposits in the Northern Territory and Saskatchewan have certain geologic features in common. They occur in metasediments which were (a) originally deposited upon Archean granitic basement in upper Lower Proterozoic time, (b) metamorphosed between about 1700 to 1900 m.y. ago, and (c) then covered by Middle Proterozoic continental sandstones, in part after a period of strong weathering. The major deposits in Gabon also occur in sediments of upper Lower Proterozoic age, but the sediments are not metamorphosed.

Geologic Characteristics and Classification of Deposits

The veinlike-type deposits can be subdivided according to their geologic characteristics, principally host rock type, stratigraphic and/or structural setting and relations to the Middle Proterozoic unconformity, into two main groups, each with subtypes. A deposit classification is presented below in outline and in a more complete form in Plate I. Definitions of important terms are presented in the Introduction. Deposits of the first group, the strata-related deposits, show an affinity for distinct rock types; and individual deposits may extend to depths of several thousand meters below the surface. Deposits of the second group, the unconformity-related deposits, exhibit an affinity for the same host rocks, but they are restricted to the Middle Proterozoic unconformity from where they extend to depths rarely exceeding 150 m.

A proposed outline for the classification of veinlike deposits is presented below with examples of each deposit subtype and a letter designation used throughout the report:

1. Unmetamorphosed sedimentary host rocks
    - 1.1 strata-related deposits
        - 1.1.1 strata-bound (a) [Oklo, Gabon]
        - 1.1.2 strata-structure-bound (b) [Mounana, Gabon]
2. Metasedimentary (crystalline) host rocks
    - 2.1 strata-related deposits
        - 2.1.1 strata-bound [Kitts (c) and Michelin (d), Labrador and protores (e) of the Wollaston Belt, Saskatchewan, Canada]
        - 2.1.2 strata-structure-bound [deposits of the East Alligator Rivers district (f and g), Australia and Beaverlodge district (h), Canada]
    - 2.2 unconformity-related deposits

2.2.1 structure-bound in basement [in terranes of uraniferous metasediments; Key Lake (j), Canada]
2.2.2 sediment-bound [in unmetamorphosed sediments (l) overlying terrane of uraniferous metasediments; D orebody, Cluff Lake, Canada]
2.2.3 structure-bound in unmetamorphosed uraniferous cover volcanics [Baker Lake (m), South Alligator River (n)]

Deposit Grades and Reserves

The different subtypes of veinlike deposits vary significantly in the tonnages and grades of the deposits. Some are small in area, but of extremely high grade and contained metal value, for example, the D orebody at Cluff Lake. Others have large dimensions but lower average ore grades, and some of the strata-bound occurrences contain considerable uneconomic mineralizations. Typical grades and ore tonnages are presented in Plate I for the various subtypes of deposits. In addition, Table 1 presents the published reserves and grades for many of the deposits. The reader will note that the data in Table 1 are incomplete, because such information is generally held confidential by companies. Also, many of the deposits have been inadequately explored, and reserves can be expected to increase significantly.

Model for Deposit Accumulation

A brief summary of a "state of the art" working model for the evolution of the various types of veinlike deposits would appear to be as follows (see Plate IV):

(1) During late Early Proterozoic time, uranium and other metals became concentrated in pelitic-psammitic, in part calcareous, sediments often adjacent to organic-rich horizons. Possible pre-metamorphic relocalization led to the formation of deposits such as occur in Gabon.

(2) The Hudsonian (in Canada), and time-equivalent orogenies elsewhere, metamorphosed the sediments to the amphibolite and locally to granulite metamorphic facies.

(a) In areas of closed systems, i.e., generally remote from intrusions, metasomatism, and anatexis, the uranium became crystallized, but remained more or less in situ, forming strata-bound deposits of generally subeconomic or marginal size (e.g., Kitts, and the protores of the Wollaston Belt).

(b) In regions of open systems, i.e., regions affected by granitic and perhaps major mafic instrusions, or by anatexis and metasomatism, the uranium was locally mobilized by metamorphic-hydrogenic processes and reconcentrated in structures within the uraniferous strata (e.g., Beaverlodge, Alligator Rivers district).

(3) In some regions, the deposits mentioned under (2) became covered by continental sediments (e.g., by the Martin, Kazan, Kombolgie or other Formations)

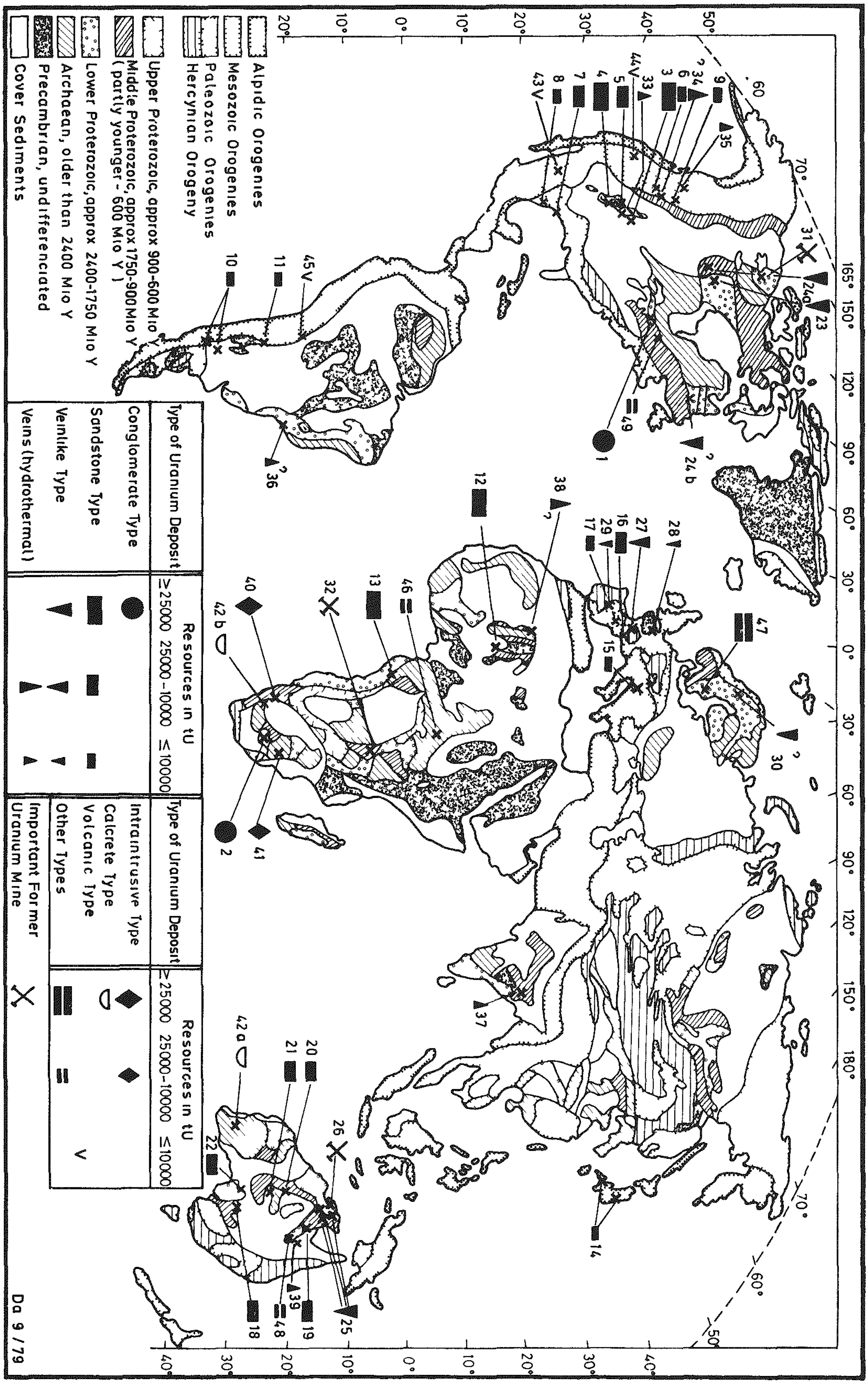

Figure 1. Locations and deposit types for the major deposits and districts in the Western World (from Dahlkamp, 1980).

DISTRICT AND DEPOSIT IDENTIFICATION FOR FIGURE 1

No.	Uranium Deposit/District	Country
	CONGLOMERATE TYPE	
1	Elliot Lake District, Ont.	Can.
2	Witwatersrand	S.A.
	SANDSTONE TYPE	
3	Wyoming District	USA
4	New Mexico District	USA
5	Rest of Colorado Plateau	USA
6	Sherwood, Wash.	USA
7	Gulf Coast District, Tex.	USA
8	Burgos Basin, Nuevo Leon	Mexico
9	Blizzard, B.C.	Can.
10	Malargue, Sierra Pintata	Arg.
11	Salta	Arg.
12	Agades Basin	Niger
13	Franceville Basin[1]	Gabon
14	Ningyô Tôge, Tônô	Japan
15	Zirovski Vhr	Yug.
16	Lodève Basin	France
17	Mazarete	Spain
18	Lake Frome Basin	Aus.
19	Westmoreland District, Qu.	Aus.
20	Ngalia Basin, N.T.	Aus.
21	Amadeus Basin, N.T.	Aus.
22	Roxby Downs, S.A.	Aus.
	VEINLIKE TYPE	
	Lower to Middle Proterozoic Age[2]	
23	Beaverlodge District, Sask.	Can.
24a	Athabasca District, Sask. Rabbit Lake, Horseshoe, Raven, Collins Bay, Cluff Lake, Midwest Lake, Key Lake, Maurice Bay	Can.
24b	Makkovik, Labrador	Can.
25	Alligator Rivers District, N.T. Jabiluka, Koongarra, Ranger, Nabarlek	Aus.
26	Rum Jungle, N.T.	Aus.
	Other Ages	
27	Massive Central	France
28	Vendée	France
29	Iberian Meseta	Spain/Portugal
30	Pleutajokk	Sweden
	HYDROTHERMAL VEINS	
31	Port Radium, NWT	Can.
32	Shinkolobwe	Zaire
33	Schwartzwalder Mine, Colo.	USA
34	Spokane District, Wash. Sunshine Mine (?) Midnite Mine (?)	USA
35	Rexspar, B.C.	Can.
36	Pocos de Caldas Agostinho (?) Cercado (?)	Brazil
37	Singhbum District	India
38	Hoggar (?)	Algeria
39	Maureen, Qu.	Aus.
	INTRA-INTRUSIVE TYPE	
40	Rössing	Namibia
41	Palabora	S.A.
	CALCRETE TYPE	
42a	Yeelirrie, W.A.	Aus.
42b	Langer Heinrich	Namibia
	VOLCANIC TYPE	
43	Sierra Peña Blanca, Chihuahua	Mex.
44	McDermitt, Nev.-Oreg.	USA
45	Cotaje	Bolivia
	OTHER TYPES	
46	Bakouma (U-phosphate in karst)	C.A.E.
47	Ranstad (black shale)	Sweden
48	Mary Kathleen, Qu. (contact-metasomat.)	Aus.
49	Madawasca, Ont. (pegmatite)	Can.

[1]Lower to Middle Proterozoic deposits in unmetamorphosed host rocks discussed in this report.
[2]Lower to Middle Proterozoic veinlike districts and deposits discussed in this report.

Table 1. Grades and reserves for the Lower to Middle Proterozoic strata-related and unconformity-related veinlike uranium deposits.

Deposit Type and Name	Deposit Reserves and Grade: Production Plus Reasonably Assured Reserves mt U_3O_8	Production Plus Reasonably Assured Reserves % U_3O_8	Preliminary Reserve Estimate mt U_3O_8	Preliminary Reserve Estimate % U_3O_8	Announced Total mt U_3O_8	Reference
1. Unmetamorphosed Sedimentary Host Rocks						
1.1. Strata-related						
1.1.1. Strata-bound						International
Oklo	15,500	0.47				Atomic Energy
Okelobondo	4,700	0.3 - 0.4				Agency, 1975
					20,200	
1.1.2. Strata-structure bound						
Mounana	7,000	0.47				International
Boyindzi			3,500	.03 - 0.4		Atomic Energy
Mikouloungou (incl. Kaya-Kaya)			11,500	0.2		Agency, 1975
					22,000	
2. Crystalline Host Rocks						
2.1. Strata-related						
2.1.1. Strata-bound						
Kitts			1,300	0.7		Gandhi, 1978
Michelin			4,200	0.14		Gandhi, 1978
					5,500	
2.1.2. Strata-structure bound						
Jabiluka I	3,484	0.256				Needham & Roarty, 1980
Jabiluka II	203,800	0.39				" " " "
Ranger One	100,350	0.2007				" " " "
Koongara	12,301	0.346				" " " "
Nabarlek	9,550	1.84				" " " "
Rum Jungle	4,300	0.16 - 0.4				" " " "
Beaverlodge	27,000	0.2				Trueman & Fortuna, 1976 and Canadian Mines Handbook, 1978/79
Gunnar	8,700	0.175				Beck, 1969
					369,485	
2.2. Unconformity-related						
2.2.1. Structure-bound (associated with Lower Proterozoic uraniferous metasediments)						
Key Lake						
Rabbit Lake	18,000	0.4				Northern Miner 9/22/77
Collins Bay A & B (may belong to type 2.2.2)	**					Not Published
Cluff Lake N orebody	4,300	0.56				Tapaninen, 1975
Cluff Lake Claude orebody	6,000	0.86				" "
Cluff Lake OP orebody			1,900	0.65		
Cluff Lake R orebody			2,600	0.56		
Midwest Lake*			26,000	1.2		Northern Miner 7/17/80
West Bear*						
Raven, Horseshoe*						
Eagle Point*						
Dawn Lake*						
McLean Lake*						
Lone Gull-Sissons Lake*						
					58,800	
2.2.2. Sediment-bound (superjacent to Lower Proterozoic uraniferous metasediments)						
Maurice Bay-B-Zone (A and Main Zone probably belong to type 2.2.1. but reserves are not split)			680	0.5		Lehnert-Thiel & Kretschmar, 1979
Cluff Lake D orebody	6,600	10.43				Tapaninen, 1975
					7,280	
2.2.3. Structure-bound (associated with Middle Proterozoic uraniferous volcanics)						
Baker Lake region						
South Alligator River (total of all deposits)	795	0.550				Needham & Roarty, 1980
					795	

*Data insufficient to determine with certainty if deposit has been properly classified or if it belongs to a different type of veinlike deposit.
**Reportedly larger than Rabbit Lake

without undergoing a period of strong weathering and regolith formation. The cover sediments are assumed to have acted as a protection against erosion. The presence of magnesium and boron-metasomatism, at least in the Alligator Rivers district, in both crystalline basement and the overlying sandstones, suggests that diagnenetic fluids could have affected any mineralization that might have been present at this unconformity. At Ranger One, for example, such alteration may have recrystallized and further concentrated the uranium in the near-surface portions of the deposits.

(4) In regions where the metasedimentary basement rocks, in the absence of cover rocks, were exposed to a subtropical climate, intense weathering produced a deep regolith. Uranium and other metals must have been liberated and were possibly concentrated in low areas related to structure-controlled valleys, and in lakes or swamps. Organic matter, probably algal, may have accumulated within some of these sites and may have contributed to the accumulation of the uranium and other metals. It is, however, not certain whether these processes operated or, if they did, whether they formed viable orebodies or merely preconcentrations of uranium.

Where uraniferous volcanics (Pitz, Christopher Island Formation in Northwest Territories; Edith River Formation, Northern Territory) overlay the metasedimentary basement, they experienced the intense leaching of paleoweathering while protecting the underlying basement. Locally, small uranium accumulations were formed, but large deposits are lacking, perhaps due to a limited amount of uranium (e.g., Baker Lake region, South Alligator River).

(5) Subsequent to the period of chemical weathering, the exposed and weathered basement was covered by continental, arenaceous sediments (e.g., Athabasca, Thelon Formations). The sediments accumulated to thicknesses of several thousand meters. Diagenetic-hydrogenic processes active along the unconformity may have concentrated uranium and nickel and formed the associated chlorite, kaolinite, and other gangue minerals. If earlier uranium concentrations had formed at the unconformity, they may have been redistributed or upgraded at this time.

(6) Subsequent processes contributed little to improving or upgrading the deposits. Rather, through faulting, fracturing, and ground water movement, they produced local recrystallization (sooty pitchblende, coffinite), redistribution (particularly up into the overlying sandstone), or, in the worst case, destruction of the orebodies.

The various stages of ore formation for the different subtypes of veinlike deposits are presented in Plate IV.

General Recognition Criteria

The geologic diversity of the Lower to Middle Proterozoic veinlike deposits, and uncertainties about the processes which formed them, make it difficult to select geologic characteristics or geologic recognition criteria that are generally applicable to these deposits. Most of the deposits share certain characteristics, however, which are useful in identifying areas generally favorable for veinlike deposits. Other characteristics seem important for only certain subtypes of the veinlike deposits. The characteristics are compiled in Plate II. Continued uncertainties regarding aspects of the geology, ore controls, and formation of these deposits lead to major uncertainties in the selection of more detailed recognition criteria. It seems preferable, therefore, that evaluations concentrate on the more general and better established criteria which are adequate for most resource studies and exploration.

INTRODUCTION

This report reviews the geology, genesis, and controls of the Lower to Middle Proterozoic veinlike uranium deposits for the purpose of identifying those geologic observations, or recognition criteria, which seem most useful for the evaluation of areas with potential for new deposits. The report is a contribution to the National Uranium Resource Evaluation (NURE) program of the U. S. Department of Energy (DOE).

Proterozoic veinlike uranium deposits are a major factor in the western-world uranium industry, constituting as they do between a quarter and a third of known reserves. Intensive exploration activities over the past ten years have led to numerous discoveries, and much has been learned about the characteristics and distribution of these deposits. The high grade of many of the deposits, and the potential for new discoveries, make them vastly more important than the present reserve figures suggest.

The literature on veinlike deposits has grown substantially in the past few years. Available papers present descriptions of aspects of many important deposits and interpretations of their genesis and controls. Nevertheless, there is a paucity of thorough, systematic studies of individual deposits and comparisons between different deposits. Much of the requisite data on the composition, mineralogy, etc., of the host and probable source rocks are lacking, but geological studies are underway in both Canada and Australia.

This project was originally proposed in 1978 as one part of a project to review six major types of uranium deposits considered to have significant potential for discovery in the United States. Six experts, each familiar with one of the deposit types, were engaged to participate in the preparation of the reports. The contract was awarded in November, 1979, and Dahlkamp prepared the majority of the descriptive and interpretive material over the next several months. The manuscript was then compiled and edited and the recognition criteria developed.

Objectives

The NURE program requires improved geologic information on the important types of uranium deposits for the preparation of more reliable and comprehensive uranium reserve and resource estimates for the United States. Preliminary reports (for example, U. S. Department of Energy, 1980a, 1980b) have presented interim estimates of (a) reserves in a series of categories based on estimated forward production costs, and (b) resources for probable, possible, and speculative categories. Reserve estimates are based almost entirely on company data supplied to the Department of Energy. Estimates of undiscovered resources, by contrast, are based upon (1) geologic judgment which compares the geologic characteristics of known uranium districts (control area) with areas perceived to have uranium potential; and (2) assigns to the latter resource potential estimates based upon the general geologic similarities, the comparative sizes of the area and the control area, and the grade and tonnage characteristics of the control area. This report will contribute principally to the geologic data required for the estimation of resources.

The uncertainties associated with resource estimation are considerable, and generally accepted procedures for preparing such estimates are only now being developed. One uncertainty is the selection and interpretation of geologic information. Whereas the subjectivity of comparing geologic characteristics of known deposits and districts to untested areas will never be entirely eliminated, the process might be improved by attempting to identify the most diagnostic geologic observations based on a review of the data and interpretations for the known deposits. This we have attempted to do through the following objectives:

(1) Review the geology of the principal veinlike districts.

(2) Review concepts of genesis and ore control, emphasizing the identification of (a) general processes which reflect the similarities between individual districts and (b) differences which set districts or aspects of districts apart from the typical deposits.

(3) Establish if significantly different types of veinlike deposits exist.

(4) Identify geologic characteristics which can be expressed as recognition criteria, the presence or absence of which most strongly affect the favorability or potential of an area for the occurrence of a veinlike deposit.

In companion reports prepared for five other types of uranium deposits, the relative importances of the recognition criteria were estimated and a method developed for calculating geologic favorability from numerous observations. Because of the diversity and complexity of the veinlike deposits, and the remaining uncertainties as to their geologic characteristics and modes of formation, only general recognition criteria have been chosen, and values of relative importance have not been assigned.

Sources of Information

The descriptive and interpretive material in the report has been taken from published and unpublished reports on the principal veinlike uranium deposits, principally in Canada and Australia. Through discussions with exploration and research geologists, we have attempted to accumulate as much information and informed opinion as possible. In some cases, previously unpublished data were made available to us and are included in the text. In numerous other cases, we found that data simply does not exist, even for the seemingly most basic question such as uranium mineralogy.

Our attempt has been to collect and review well-documented <u>data</u> and <u>observations</u> so as to present a <u>reliable data base</u> for the interpretation of ore genesis and controls and the selection of broadly useful recognition criteria. Attempts to develop more specific and refined criteria have not proved successful, due to both a lack of data and variability among the veinlike deposits.

Terminology and Conventions

Some terms and conventions used in this report have been applied with various other meanings in the literature. To avoid ambiguity, we will use the definitions presented below.

Uranium Oxide Phases. Uraninite is defined as the macro-crystalline cubic form of UO_{2+x} with a lattice constant greater than about 5.42 angstrom. The magnitude of the lattice constant reflects the pressure and temperature conditions under which the uraninite forms. Uraninite can, but does not necessarily, contain thorium and rare earth elements (REE), depending upon the availability of these elements at the time of formation. Uraninite crystallizes at medium to high temperatures (150° to 200°C and upwards). It is commonly found in metamorphic rocks, reflecting greenschist and higher metamorphic facies, in which uranium was a primary rock constituent. Other typical environments are katathermal and pegmatitic veins and magmatic rocks such as granites. Pitchblende, in contrast, does not exhibit a macro-crystalline habit but forms botryoidal and colloform shapes. The lattice constant is less than about 5.42 angstrom, hence pitchblende cannot accommodate thorium and REE. Pitchblende is the uranium oxide phase typically formed at low temperatures (below approximately 150°C).

The tetragonal $\alpha\, U_3O_7$ phase also occurs in the veinlike deposits and has been described, for example, at Key Lake. It was referred to as "tetra uraninite" by Clasen and Voultsidis (1980). Laboratory tests suggest it forms at temperatures of about 137°C.

Open and Closed Systems. Field observations suggest, but do not prove, that pre-metamorphic concentrations of uranium in some stratigraphic settings were relatively immobile during metamorphism, whereas concentrations in other settings appear to have moved. Even under seemingly comparable host rock metamorphism, local geologic conditions appear to have produced different results, which are designated herein as closed and open systems. Although this division is arbitrary and oversimplified, it may help to describe and present the complexity of geologic settings which apparently reflect the behavior of uranium during metamorphism.

In geologic settings where uranium does not appear to have moved during metamorphism it is assumed the system was relatively closed. The impact of metamorphism on the primary sedimentary uranium is limited to recrystallization forming uraninite that is characteristic of strata-bound deposits (for example, subtype c, Kitts deposit, in Plates I, II, and IV). In the open system the primary sedimentary uranium is at least partly redistributed into structures within or adjacent to the uraniferous metasediments. The deposits are typically strata-stucture-bound (types f to i, Jabiluka, Beaverlodge, etc., in Plates I, II, and IV). The deposits formed in open systems seem to occur in close proximity to late orogenic intrusives and/or migmatitic complexes and in terranes where Na and/or K metasomatism affected the host rocks. Felsic and mafic dikes and pegmatites are relatively abundant. It is uncertain, however, if these metamorphic and intrusive features produced the uranium mobilization.

Units of Measure. The metric system is used almost exclusively in this report. Where other conventions are used, they are specified; unspecified measurements should be interpreted as metric.

Protore. Strata-bound concentrations of uraninite within preferred lithologies in the Lower to Middle Proterozoic sediments of, for example, the Wollaston Domain, are referred to as protore. Whereas these anomalous concentrations are not known to be upgraded to ore strictly in place, we believe the redistribution of this uranium by a variety of processes contributed to the formation of several subtypes of veinlike deposits.

Deposit Classification. Three conventions are used in the presentation of subtypes of veinlike deposits: (a) in the text and plates the deposit classification is presented as an enumeration (1., 1.1, 1.1.1, etc.) to indicate types and subtypes of deposits; (b) fourteen lowercase letters (a through n) are assigned to examples of the important subtypes of uranium occurrences; (c) descriptive names are assigned to the principal deposit subtypes. These names are used as follows:

strata-related	deposits that show a strong affinity for particular strata.
strata-bound	deposits that are restricted to particular strata without other controls.
strata-structure-bound	deposits that are jointly restricted to structures and particular strata.

Selected References. The geologic discussions of most districts and deposits are preceded by references to publications which deal with the general geology. Not all of these references are cited in the text for specific data, thereby avoiding excessive referencing of the more general sources.

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DESCRIPTION OF INDIVIDUAL DEPOSITS

Canada

Veinlike-type uranium deposits have been discovered in Canada in Saskatchewan, Northwest Territories, and Newfoundland. The principal areas of Lower to Middle Proterozoic rocks with veinlike occurrences, or potential for occurrences, are shown in Figure 2. Saskatchewan hosts the largest individual deposits and the greatest ore reserves.

Saskatchewan

The uranium province around and within the Athabasca Basin in northern Saskatchewan is one of the major uranium regions of the world with respect both to the size and grade of individual deposits and total uranium resources. The province can be subdivided into two districts: the Beaverlodge district north of Lake Athabasca and the Athabasca Basin district south of Lake Athabasca (Plate III).

The uranium province lies in the subarctic climatic zone between 102° and 110° of western longitude, and between 55° and 60° of northern latitude. The infrastructure consists of all-weather roads from La Ronge to Rabbit Lake, from Pine House to Key Lake, and another to Cluff Lake. On the Alberta side of the Athabasca Basin, a road and railroad connect Edmonton with Fort McMurray from where a boat services Uranium City. All other locations can be reached only by aircraft, canoe, or, in winter, by winter road.

Regional Geology of Northern Saskatchewan

Alcock, 1936; Beck, 1969; Burwash et al, 1962; Fahrig, 1961; Hoeve and Sibbald, 1978a; Lewry and Sibbald, 1978; Money et al, 1970; Ramaekers and Hartling, 1978; Sibbald et al, 1976; Stockwell, 1962; Tapaninen, 1976; Tremblay, 1972, 1978a; Tyrrell, 1896; Wanless et al, 1966.

The Athabasca region is part of the Churchill structural province of the Canadian shield as defined by Stockwell (1962). It comprises Archean basement of predominantly granitic rocks and some greenstone belts. They were affected by the Kenoran orogeny at about 2500 m.y. (Wanless et al, 1966).

The Archean basement forms northeast-southwest elongated troughs which are filled with Aphebian (middle to upper Lower Proterozoic, older than 1800 m.y.) sediments and volcanics. The Hudsonian orogeny (about 1700 to 1800 m.y.) metamorphosed and folded all these rocks creating northeast to southwest-trending mobile belts. Such belts contain the Tazin metasediments of the Beaverlodge district to the west, the Wollaston Fold Belt along the eastern margin of the Athabasca Basin, and the Virgin River Fold Belt in between.

During the waning stages of the Hudsonian orogeny, in the region north of Lake Athabasca, the Martin Formation, composed of continental sediments (conglomerates, arkoses, siltstones, etc.) and intercalated volcanics (basaltic and andesitic lavas, gabbroic sills; age: 1630 ± 180 m.y.; Wanless et al, 1966), was deposited immediately on the Hudsonian crystalline basement apparently without the intervening development of a weathering (regolith) horizon (Fig. 3). The Martin sediments were slightly folded by Late Hudsonian movements producing fold axes that strike northeast to southwest, approximately parallel to those of the subjacent metasediments. Diabase dikes (1490 m.y.; Wanless et al, 1966) cut the Martin Formation. Based on geologic position and age dates for the volcanics, the Martin Formation must have been deposited between 1490 and 1740 m.y.

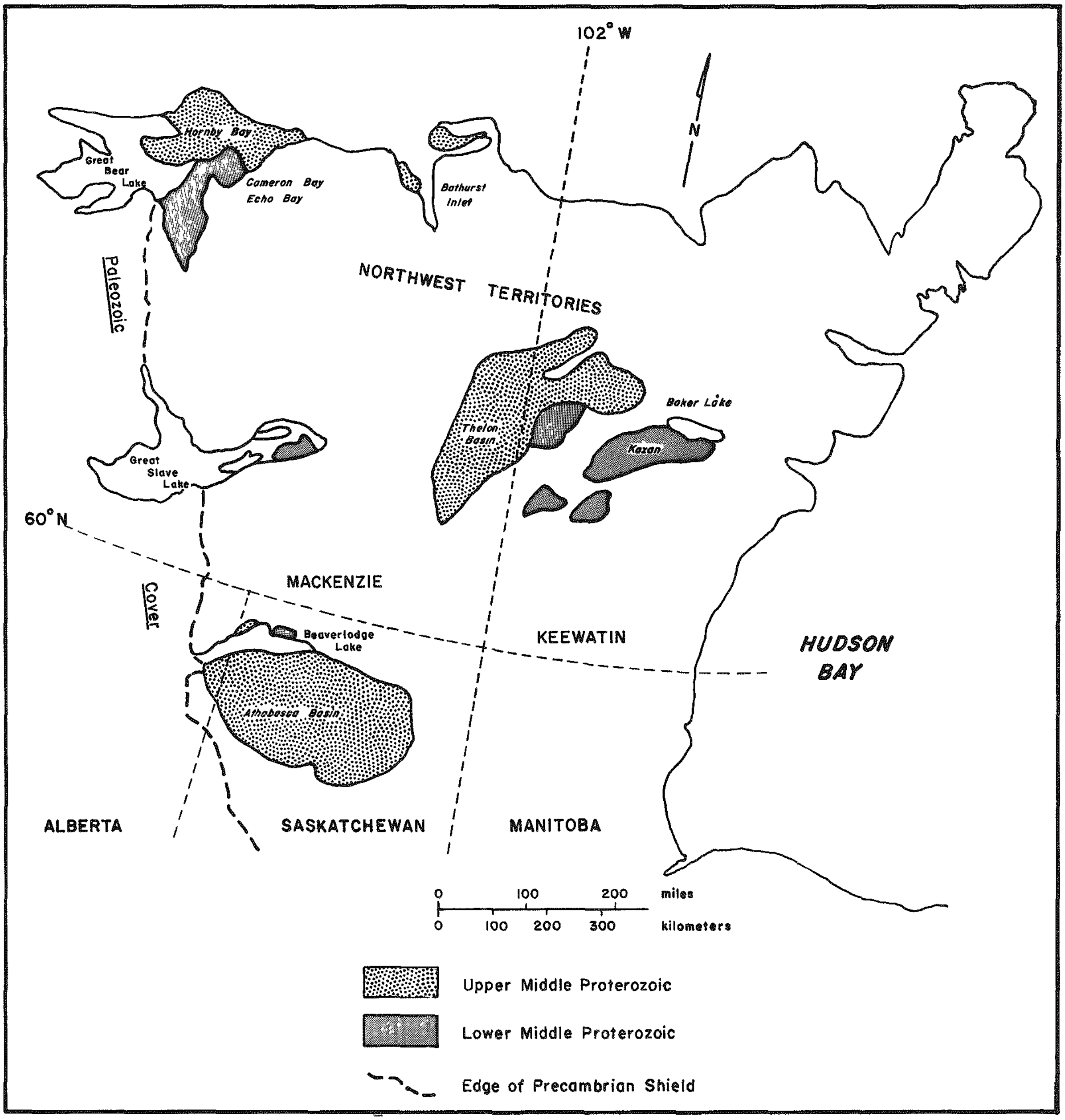


Figure 2. Location map for the Middle Proterozoic sedimentary basins and veinlike uranium districts of northern Saskatchewan and Northwest Territories, Canada (modified from Bundrock and Fuchs, 1980).

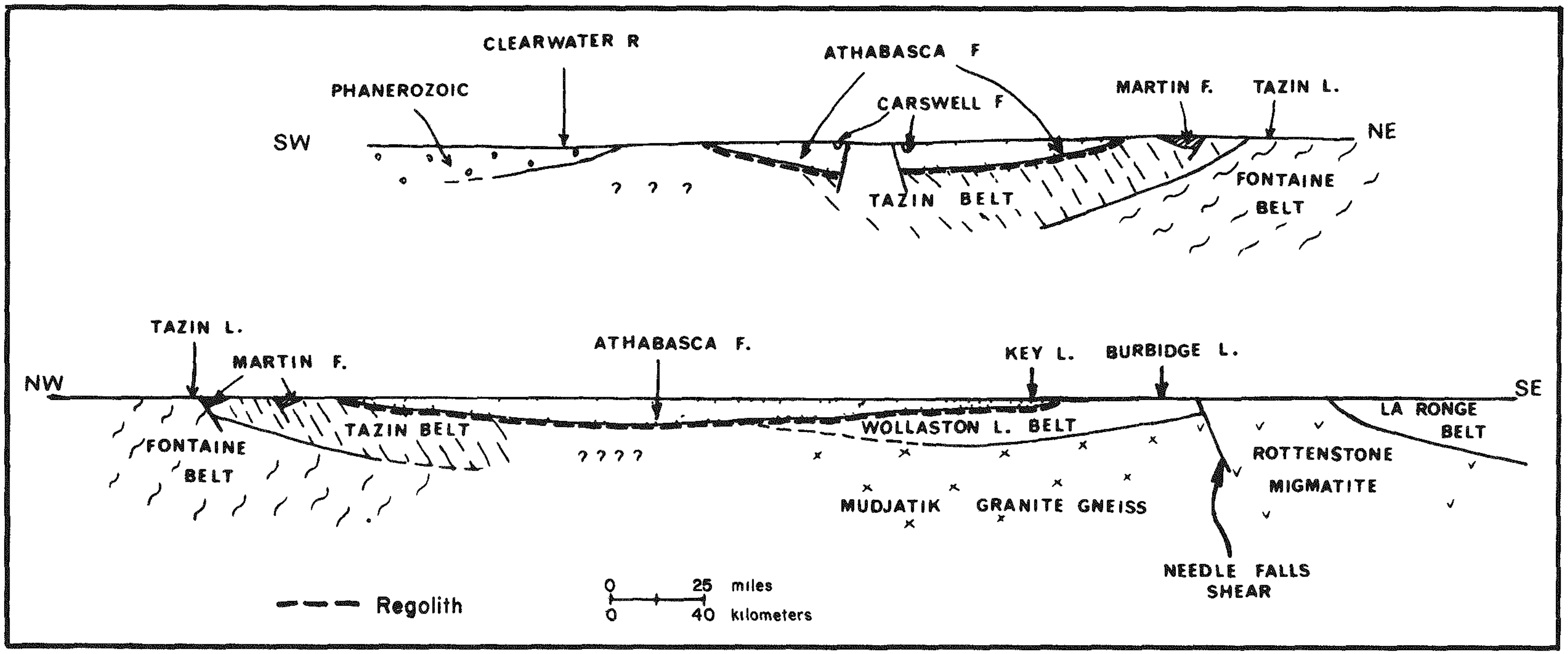


Figure 3. Schematic cross sections through the Beaverlodge district and the Athabasca Basin (modified from Tremblay, 1978c).

To the south of Lake Athabasca, a longer period of weathering produced a deep chemical alteration of the metasediments forming a saprolite (referred to as a regolith in Canada). Subsequently, the Athabasca Formation was deposited over the older rocks and the regolith.

The Athabasca Formation is comprised of continental sandstones with some conglomerates and argillaceous intercalations. Diabase dikes dated at 1230 m.y. (Burwash et al, 1962) cut the sediments. The age of the Athabasca Formation is given as 1350 $\pm$ 50 m.y. by Ramaekers and Dunn (1977). Near Cluff Lake, the Athabasca Formation is overlain by siltstone of the Douglas Formation and dolomites of the Carswell Formation.

According to Tapaninen (1976), the Athabasca depositional basin is divided into southwest-trending zones by horst and graben structures. The controversial Carswell circular structure is located in the west-central part of the basin.

Within the structure, which has a diameter of about 40 km, crystalline basement is found lying overturned on Athabasca sandstone. The origin of the structure is still uncertain, but one theory considers it to be the result of a meteoric impact. The age of the event is dated at 470 m.y.

Finally, glacial deposits of variable thickness cover wide areas of northern Saskatchewan and create a major obstacle to exploration.

Beaverlodge District

Beck, 1969, 1970; Dawson, 1956; Eldorado, 1964; Koeppel, 1968; Krupicka and Sassano, 1972; Lang et al, 1962; Murphy, 1948; Robinson, 1955a; Sassano, 1972; Sassano et al, 1972a, 1972b; Smith, 1974; Tremblay, 1958a, 1970, 1972, 1978a, 1978b; Trueman and Fortuna, 1976; Turek, 1965; Wanless et al, 1967.

The Beaverlodge district with its main settlement, Uranium City, is located on the north side of Lake Athabasca about 730 km northeast of Edmonton and about 800 km north-northwest of Saskatoon. Regular air services are provided from these two cities. During the summer, boats can reach the area from the railhead at Fort McMurray, a distance of about 550 km.

Uranium was first reported by Alcock in 1936. The major orebodies were discovered between 1945 and 1958. During this period, numerous uranium showings had been found, 36 deposits had been explored underground, and 16 reached production. The first mine opened in 1953. The most important deposits are: Eldorado's Ace, Fay, Verna, and Bolger Mines near Uranium City, and the Gunnar Mine at the southwest end of the Crackingstone Peninsula. At present, Eldorado is the major producer. Minor production comes from the Cenex Mine at Cinch Lake. Gunnar, discovered in 1952, was closed in 1963. The Eldorado and Gunnar deposits accounted for about 90 percent of the total production of about 32,000 t of U_3O_8 to 1975 (Table 2).

Geologic Setting of Mineralization. Tremblay (1978c) describes the general geology of the Beaverlodge district as comprising the metamorphic rocks of the Tazin Group, the sediments of the Martin Formation (Fig. 4), and gabbro dikes.

Table 2. Uranium production for the major uranium mines of the Beaverlodge area (from Trueman and Fortuna, 1976).

	Uranium Mine	Production (pounds U_3O_8)
1.	Eldorado Ace and Fay	31,250,000
2.	Gunnar	19,250,000
3.	Eldorado Verna and Bolger	12,844,000
4.	Eldorado Hab	2,100,000
5.	Rix Smitty	1,132,000
6.	Cinch Lake	739,000
7.	Cayzor Athabasca	485,000
8.	Lorado	232,000
9.	Eldorado Eagle	220,000
10.	Rix Leonard	200,000
11.	Nicholson	106,000
12.	National Exploration	78,000
13.	Nesbitt Labine	61,000
14.	Eldorado Fishhook	40,000
15.	Eldorado Martin Lake	28,000
16.	Uranium Ridge	25,000
	Total	68,790,000

The Tazin Group belongs to the crystalline basement and is overlain unconformably by the Martin Formation and, near the north shore of Lake Athabasca, by the Athabasca Formation. Granite and pegmatite dikes and sills have been mapped within the Tazin rocks and are regarded as having been mobilized from the granitized host rocks. The Martin and Athabasca Formations do not occur in contact, but, from geologic considerations, the Athabasca Formation is assumed to be the younger. Diabase dikes cut Tazin rocks, the Martin Formation, and the Athabasca Formation south of Lake Athabasca. In the Beaverlodge area, uranium has been found in all rock types, but ore occurrences are essentially limited to rocks of the Tazin Group. The past and producing mines in the area are shown on a simplified geologic map in Figure 5.

Crystalline Basement. In the vicinity of the Fay-Ace-Verna deposits, the crystalline rocks of the Tazin Group are at least 10,000 m thick and comprise, from oldest to youngest, four main units (Tremblay, 1978c):

(1) Foot Bay Gneiss - Granites and amphibolites of Archean age (2300 m.y. to 3200 m.y.).

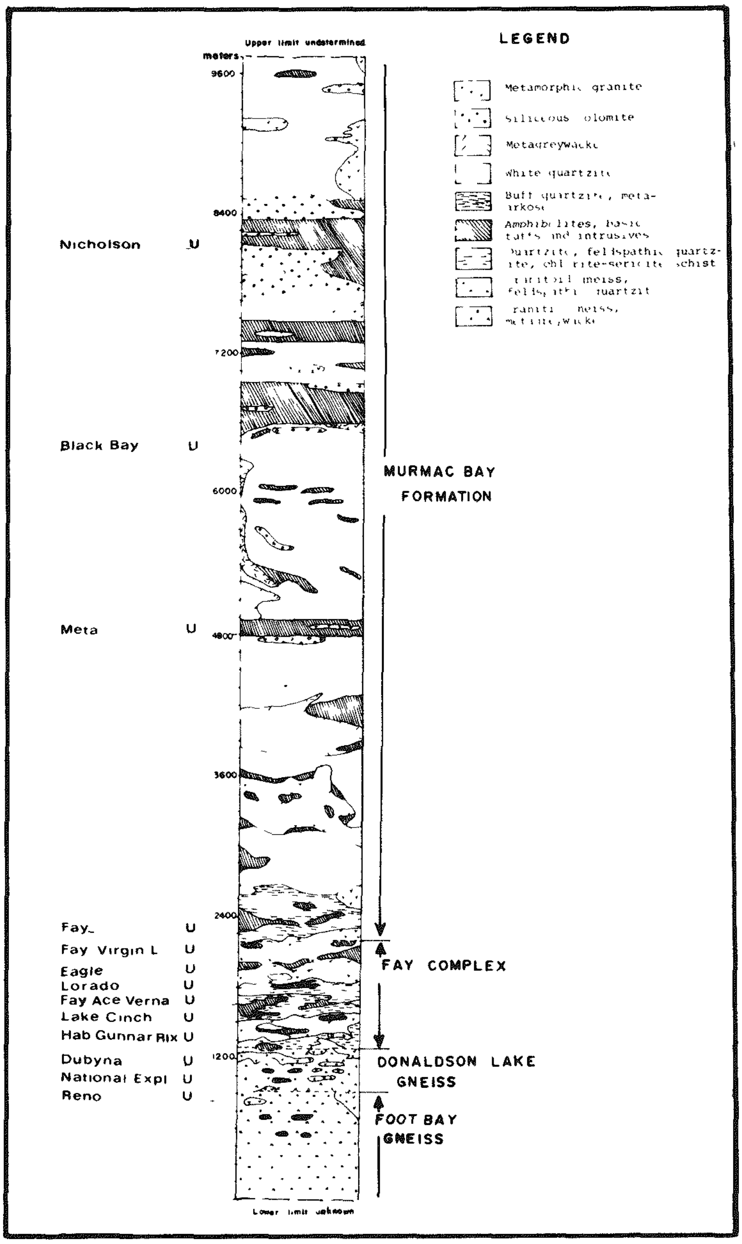


Figure 4. Schematic section for the metasedimentary rocks of the Beaverlodge district showing the interpreted positions of known uranium deposits (modified from Tremblay, 1978c).

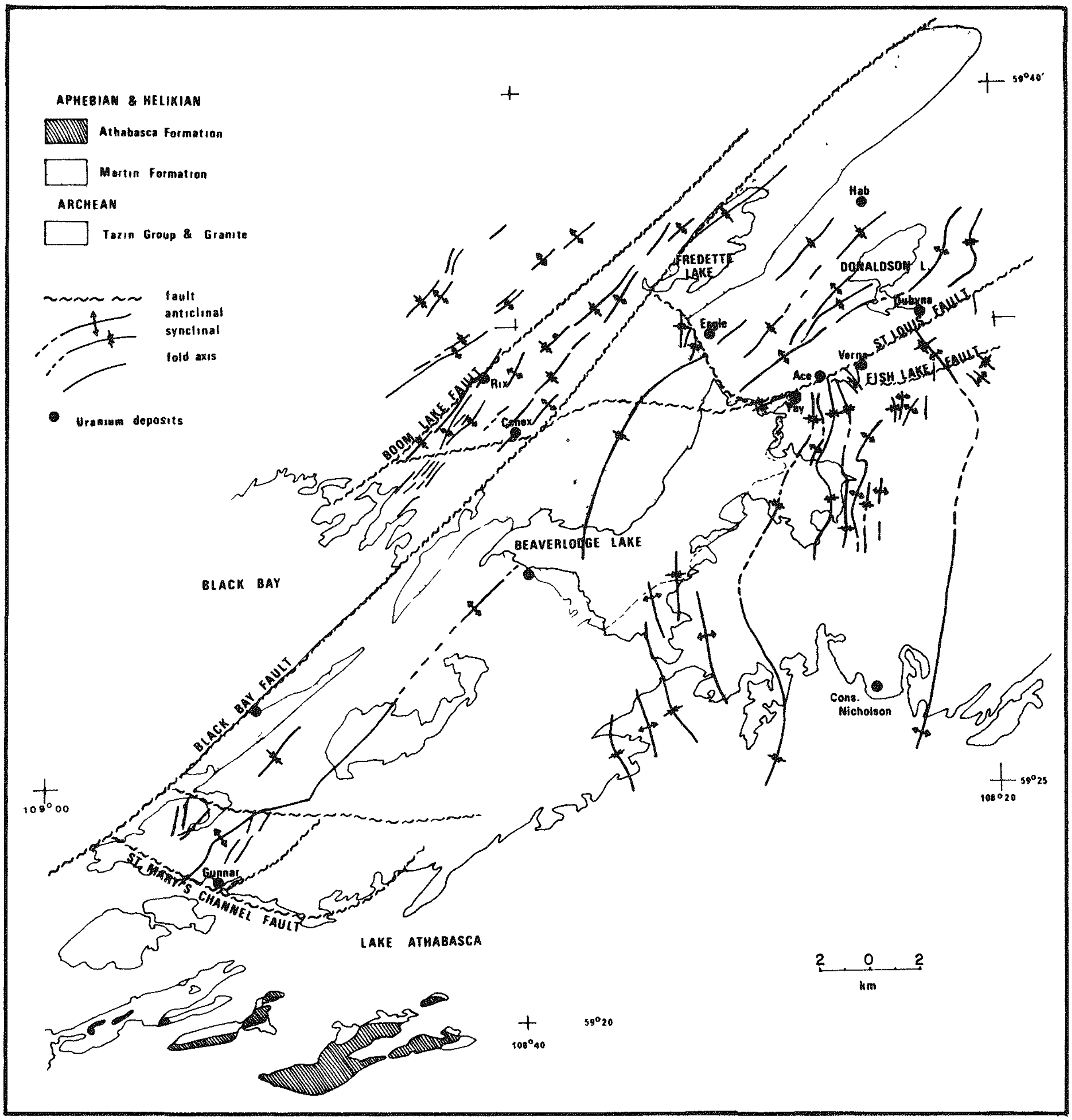


Figure 5. Simplified geologic map of the Beaverlodge district showing the past and producing mines (modified from Tremblay, 1978c; Trueman and Fortuna, 1976).

(2) Donaldson Lake Gneiss - Alaskites, adamellites, granodiorites, and amphibolites, of Lower Proterozoic age (2200 m.y.) (Beck, 1969). Small amounts of uranium are found in the Donaldson Lake Gneiss. Beck (1969) refers to granitic rocks of both the Foot Bay and Donaldson Lake Gneisses as the "old" granites. He regards them as Archean in age and interprets the divergent age-datings as caused by rejuvenation during the Hudsonian orogeny or a post-Archean hydrothermal event.

(3) Fay Complex - Quartzo-feldspathic gneisses with variable mafic content, containing amphibolites, chlorite-sericite-argillite-schists, hornblende schists, quartzites, and other rock types. The schists and gneisses are locally graphitic. These metasediments are believed to have been derived from a pelitic to psammitic sedimentary sequence of middle to upper Lower Proterozoic age. Beck (1969) combined the Fay Complex and the Murmac Bay Formation into the Tazin Metasediments. These metasediments host almost all of the important uranium occurrences. Figure 6 provides a correlation between these rocks and the terminology for their equivalents where encountered in the mine workings.

(4) Murmac Bay Formation - Clean white glassy quartzite, amphibolites, graywacke or impure feldspathic quartzite, and siliceous dolomite. Graphitic horizons are locally present at the white quartzite-amphibolite contact. Minor uranium mineralization is known at at least three levels in the Murmac Bay Formation, where it is closely associated with siliceous dolomites and graphitic rocks.

Metavolcanics and pegmatites and granites, ranging in composition from quartz diorite to alkali granite, occur within the metasediments of both the Fay Complex and Murmac Bay Formation. Beck (1969) refers to the latter as "young" granites. The rocks of the Tazin Group were regionally metamorphosed during the Hudsonian orogeny (1930-1780 m.y.) to the granulite facies, producing local granitization, and later retrograded to the amphibolite facies.

The sequences were then strongly folded along dominant northeast-trending axes. Repeated deformation and metamorphism produced upper greenschist assemblages and locally sodium metasomatism and "hydrothermal" alteration. These rocks, and the important uranium deposits, occur in a linear belt in which two main phases of faulting are recognized. The earlier phase occurred toward the end of the main period of Hudsonian folding and granitization, and it is represented by east- and northeast-striking mylonite and breccia zones up to several hundred meters in length. The second important phase of faulting produced fractures that trend northeast, east, north-northwest, and northwest (St. Louis, Black Bay, ABC).

The geology in the vicinity of the Gunnar deposit (Evoy, 1961; Jolliffe and Evoy, 1957) consists of well-banded, fine-grained paragneisses, ranging in composition from quartzite to amphibolite, that strike north 70 degrees east and dip 45 degrees to the south. These are conformably overlain to the south by coarse-grained granitized gneisses and metasomatic granite referred to as Gunnar granite. Quartz-microcline pegmatites intruded the gneisses. The Gunnar deposit is situated close to the Zeemel and Iso-Fraser faults, just north of the regional St. Mary's Channel Fault.

Martin Formation. The crystalline basement is locally covered by the Martin Formation, a sequence of continental clastic sediments including arkoses, silts, sandstones, and conglomerates believed to be about 4500 m in thickness. The sediments are dominantly red due to dispersed matrix hematite. Locally interbedded volcanic flows, gabbroic sills, and dikes are present in the formation. The flows have been dated at 1630 ± 100 m.y., and the sills at 1410 ± 180 m.y. (Fraser et al, 1970).

ERA	Period	Orogeny	Age Dates (m.y.)		
				MARTIN FORMATION	
PROTEROZOIC	Helikian	HUDSONIAN	1490 (1)	Diabase(1)	
				Siltstone and Shale	
			1779 (2) 1630 (3)	Andesite, Porphyry(2), Basalt(3)	
				Arkose and Sandstone	
			(1800)	Conglomerate	
	Aphebian			TAZIN GROUP	
				Metasediments	
			1975 (1)	Pegmatite(1), Pegmatitic Alaskite	Mylonitic Mica Schist - Para Gneiss, Meta-Argillite
				Orange Mylonite, Feldspar rock	Migmatite
				Argillite, Paraschist	Siliceous Argillite, Ultra Mylonite
				Epidotic Argillite, Greenschist, Phyllonitic Amphibolite	Silica, Siliceous Mylonite
				Quartzite	Dolomite
				Diopside, Calc-Silicate rocks	
				Donaldson Lake Gneiss	
			2100 (1)	Alaskite(1), Leucocratic Gneiss (Mafics 15%)	
				Amphibolite	
ARCHEAN		KENORAN	(2200)	Mylonite (40% Silica)	
				Foot Bay Gneiss	
				Granite crush rock	
			2300 (1) 3200 (2)	Cataclasite(1), Augen Gneiss(2)	
				Ultra Mylonite	
				Amphibolite	
				( ) Indicates rock type sampled for age date	

Figure 6. Rock types recognized in the mines of the Beaverlodge district and selected age dates (modified from Eldorado Nuclear Limited, 1976).

The Martin sediments were deposited in the region north of Lake Athabasca in several fault-bounded sedimentary basins. The sediments rest with pronounced angular unconformity on a rugged paleotopographic surface of the Tazin Group. Tremblay (1972) states that, in contrast to the southern Athabasca region in the vicinity of the Rabbit Lake, Key Lake, and Cluff Lake deposits, no paleosol of weathered basement is developed in the underlying metasediments. The unconformity is marked only by a thin layer of locally derived detritus. Tremblay (1972) regards the source of the Martin as an area of unweathered Tazin rocks to the northeast. Erosion was mainly mechanical, and stream transportation rapid, due possibly to steep relief produced by local faulting.

During the final stages of Hudsonian tectonism, the Martin sediments were slightly folded along southwest-trending axes and intruded by andesitic and basaltic dikes. Faults which displaced basement and Martin rocks were commonly reactivations of pre-Martin structures.

Host Rock Alterations. In the Fay-Ace-Verna and adjacent areas the Tazin metasediments were altered including (a) hematitization, (b) chloritization, (c) epidotization, (d) silicification, (e) carbonatization, and (f) albitization.

Disseminated and vein-related hematite is widespread in the crystalline rocks of the Beaverlodge area, particularly near uranium mineralization where it may become so intense as to mask the original nature of the rock.

Chlorite is also widespread, occurring in veinlets and seams that crisscross all types of rocks. It is particularly abundant in the proximity of uranium mineralizations and mylonitic and breccia zones, where the mafic minerals of the wall rocks are almost entirely chloritized.

Epidote occurs on a regional scale as widely spaced veinlets in most rock types, but it is more abundant in amphibolites and hornblende schists where it forms irregular patches. Epidote alteration does not seem to be ore related in that these rock types tend to be chloritized near uranium deposits.

Silicification, as cherty or fine-grained replacements, is reportedly a major alteration type in the rocks in the uranium deposits near the St. Louis-ABC faults and elsewhere. Silica is also present as crypto-crystalline fracture fillings and thin quartz veinlets in rocks of both the Tazin Group and the Martin Formation.

Carbonate alteration is not extensive and is best developed as replacements along fractures in granite and granitized rocks. Carbonate-altered rocks are generally slightly more radioactive than the ordinary granites, and in many localities carbonate alteration is cut by veins of pitchblende, suggesting a relation may exist between uranium mineralization and carbonate alteration. Furthermore, carbonate veins, sometimes pitchblende-bearing, cut most rock types.

Albitization is represented by narrow veinlets of albite that are most abundant in altered areas, particularly adjacent to major faults such as the St. Louis-ABC and Black Bay structures and in fracture zones. No direct relationship to uranium mineralization has been established.

At the Gunnar deposit, a pipelike zone within the host granite has been altered to a rock type locally referred to as "syenite" through the removal of quartz and the apparent introduction of albite and calcite. Albite now comprises about 60 percent of the "syenite", and the balance is comprised of equal amounts of quartz, carbonate, and chlorite. Portions of the "syenite" are now a porous, altered rock, possibly formed by the removal of calcite, that persists to a depth of at least 500 m. Similarities have been suggested between the "syenite" and the "episyenites" associated with uranium deposits in the Massif Central and Vendee in France. The ore at Gunnar occurs within a zone of mylonitized "syenite".

Mineralization. Two types of uranium mineralization occur in the Fay-Ace-Verna area. The first type of mineralization is not economic but may represent, at least in part, the source for the later economic deposits. It consists of uranium in the form of uraninite, uranothorite, monazite, zircon, and other complex minerals, in various pegmatitic rocks, metasediments, and granites (Robinson, 1955a; Tremblay, 1978c). Koeppel (1968) established two principal ages for this type of uranium mineralization, the oldest at a minimum age of 2200 m.y. and the younger at 1930 m.y. These periods can be related to the emplacement of the "old" and "young" granites of Beck (1969, 1970). Beck also considers the possibility that the pegmatitic rocks represent stages of the transformation or granitization of country rock to granite. This may well be true for the younger (1930 m.y.) pegmatitic generation.

The second type of uranium mineralization includes the economic deposits and can be subdivided into simple, essentially monometallic and polymetallic deposits. Over 90 percent of the deposits are monometallic, including all major orebodies such as the Fay, Ace, Verna, Bolger, and Gunnar deposits. The principal ore mineral is pitchblende which contains negligible amounts of thorium and rare earth elements. It is accompanied by hematite, pyrite, and minor amounts of chalcopyrite, bornite, and galena. Calcite is the dominant gangue mineral, but dolomite, quartz, and chlorite, generally penninite, are also present. Locally brannerite (Fay Mine) and thucholite have been reported. Pitchblende is described as predominantly colloform and massive in habit, but euhedral shapes have also been reported. Several generations of ore and gangue are present (Fig. 7), and at least five generations of carbonate were distinguished by stable isotope and mineralogic studies (Sassano et al, 1972b).

Polymetallic occurrences of mineralization were discovered in a narrow belt within the Beaverlodge area. They form only small deposits, such as the Consolidated Nicholson Mine with original reserves of about 60 t U_3O_8, and consist of pitchblende accompanied by Co-Ni arsenides and sulfides, Co-Ni-Pb-selenides, and native platinum, gold, silver, and copper.

The lithologic and structural controls of both types of deposits appear to be similar. The ore minerals are described as occurring in subsidiary structures on both sides of major faults in the form of massive veins or veinlets, as well as disseminated in breccia zones within the crystalline basement. For example, the Ace-Fay deposits are found in the footwall and within 100 m of the St. Louis Fault that strikes north 70° east and dips 50° southeast. The Verna orebody, located about 1 km to the northeast and along strike from the Ace-Fay deposits, occurs 150 m or more into the hanging wall of the St. Louis Fault (Figs. 8, 9, 10).

In the Fay-Ace Mines, the bulk of the mineralization seems to prefer a graphite- and sericite-bearing chloritic rock, locally referred to as "mica schist", which is in contact with a hematitic, silicified, feldspathic rock referred to as "orange mylonite" (see Fig. 6). The country rock of the Verna Mine consists mainly of meta-argillites.

Locally, uranium mineralization also occurs in the Martin Formation. In the basal conglomerate, and in volcanic rocks near the northeast end of Martin Lake, concentrations were found along fractures and disseminations in the adjacent wall rocks. Mineralization in the basal conglomerate occurs above the Fay orebody. Mineralization in the volcanic flows lies on the possible extension of branch faults connected with the St. Louis Fault. These structural settings suggest that the uranium may have been remobilized from older deposits in basement rocks, possibly with the reactivation of the faults with which the pre-Martin deposits are commonly associated (Tremblay, 1978c). Mineralization within the Martin Formation is of the complex type and has been dated at about 1100 m.y. (Koeppel, 1968).

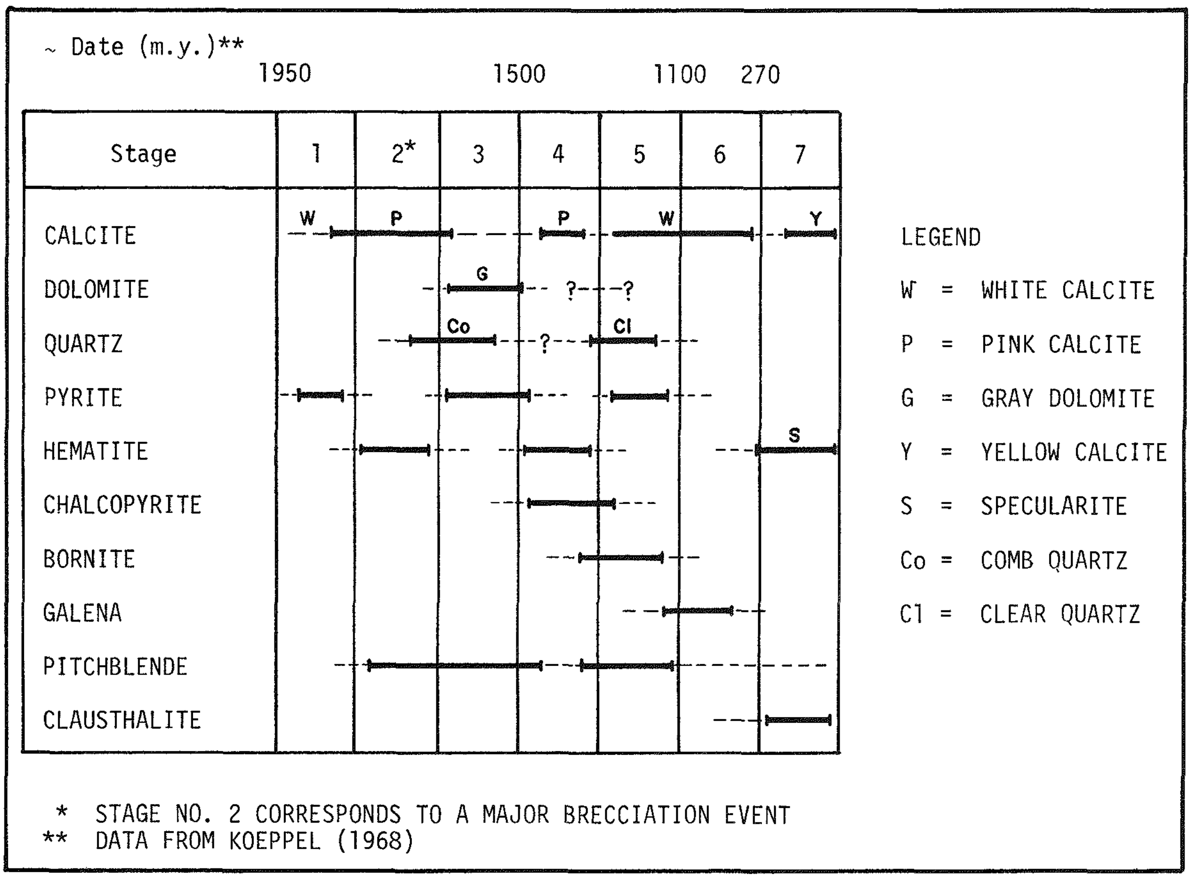


Figure 7. Paragenetic sequence of the common minerals, Beaverlodge area, Canada (modified from Sassano et al, 1972b).

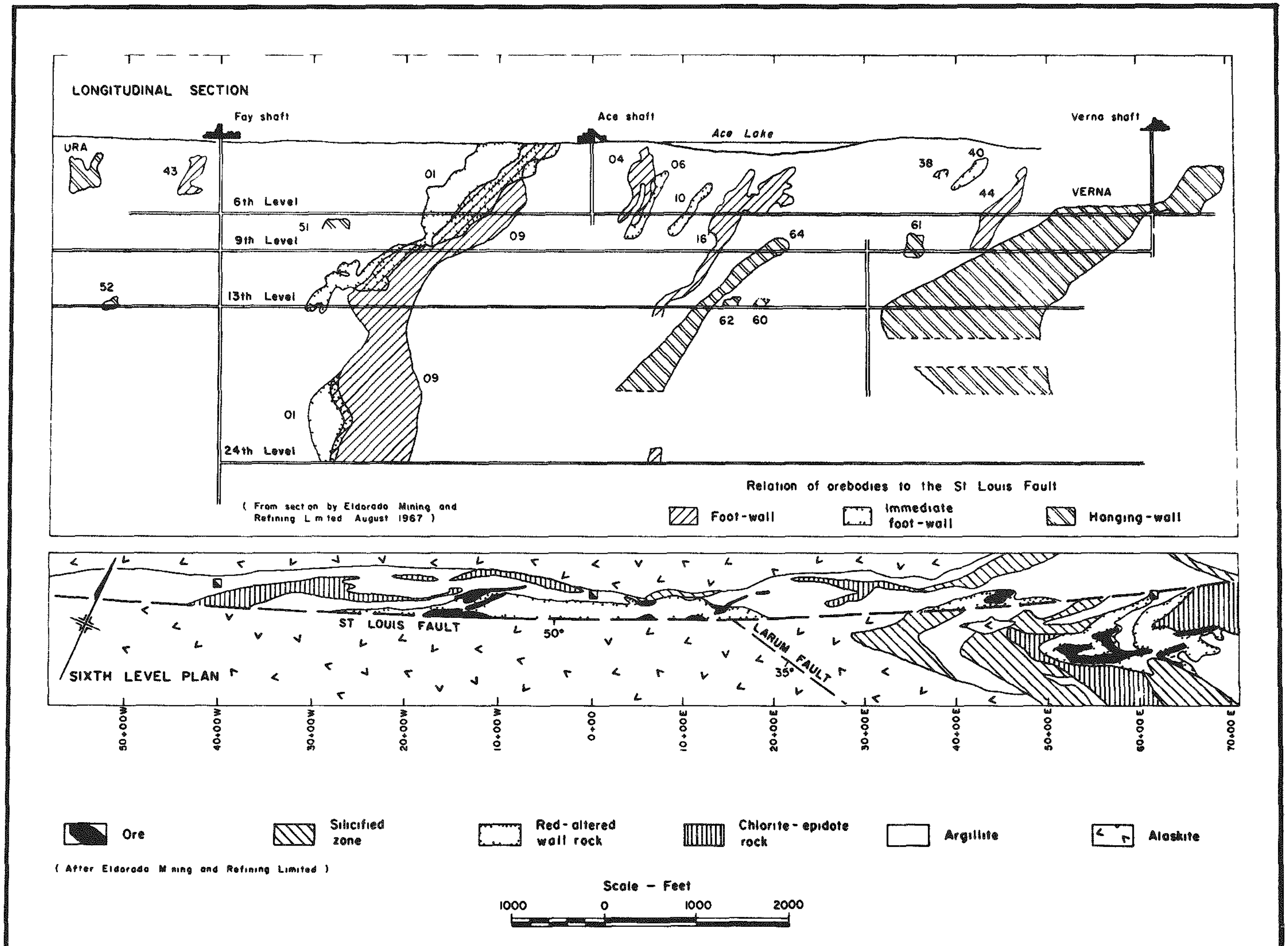


Figure 8. Longitudinal section and geologic plan for the sixth level of the Ace-Fay and Verna Mines of the Eldorado Nuclear deposit, Beaverlodge, Canada (from Beck, 1969).

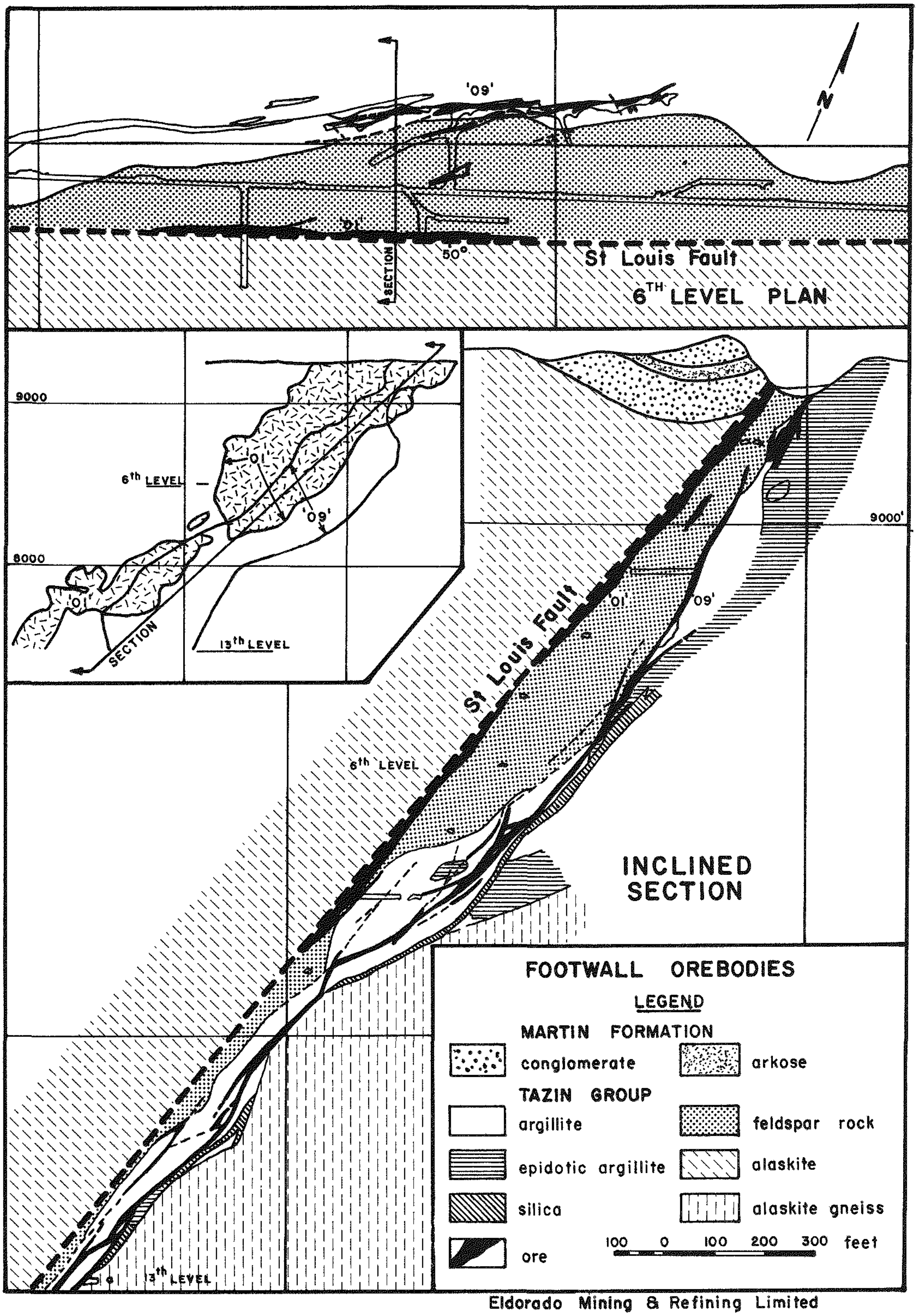


Figure 9. Footwall orebodies of the Beaverlodge Operations, Canada (from Griffith, 1967).

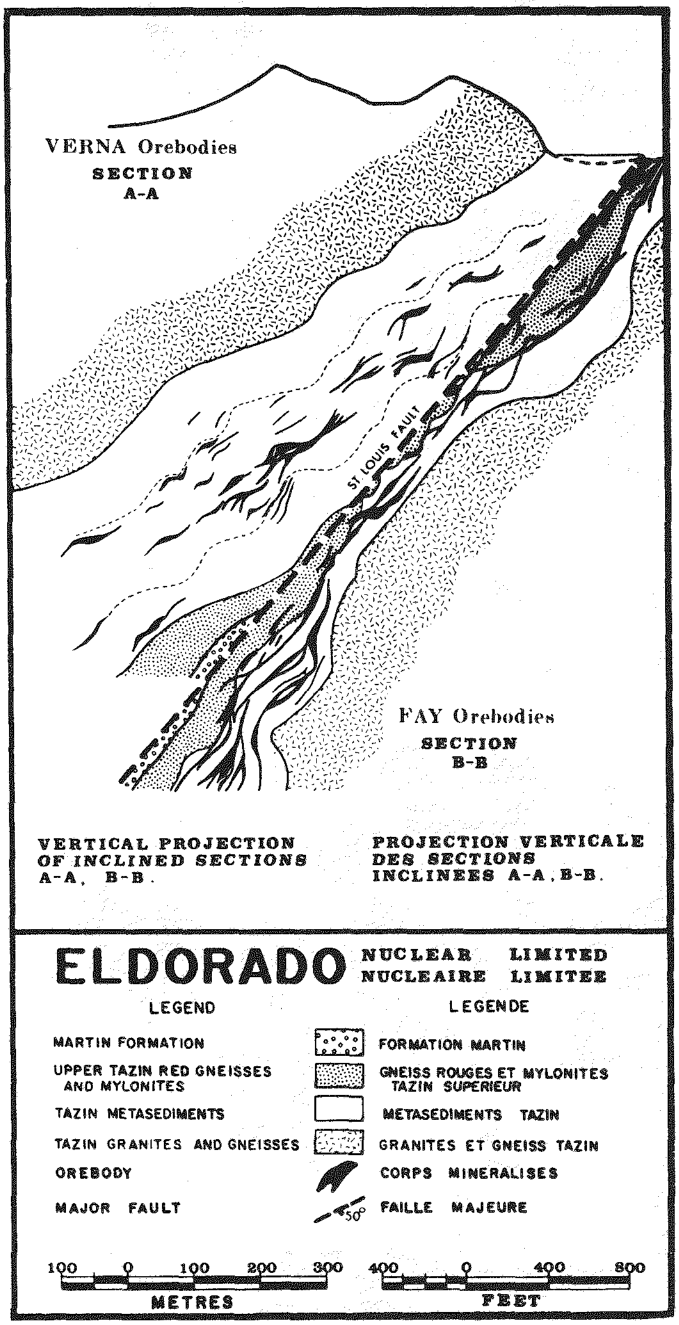


Figure 10. Projection of footwall and hanging wall mineralization onto a cross section, Beaverlodge Operation, Eldorado Nuclear, Canada (from Little et al, 1972).

At the Gunnar deposit, uranium mineralization consists of pitchblende and minor uranophane with chalcopyrite, pyrite, galena, quartz, kaolinite, and chlorite. Hematite is present with and without associated uranium. Uranophane persists to the deepest levels of the mine. The grade of the ore (0.175 percent U_3O_8) was fairly consistent throughout the mine. The deposit occurs within an altered granite (Fig. 11) close to its contact with the underlying gneiss and near the junction of the northeast-striking Zeemel and east-striking Iso (Fraser) Fault, a short distance north of the west-northwest-striking St. Mary's Channel Fault. The mineralization occupied fine fractures of a mylonite zone within the pipelike bodies of albitized, quartz-deficient, gneissic granite, locally referred to as "syenite".

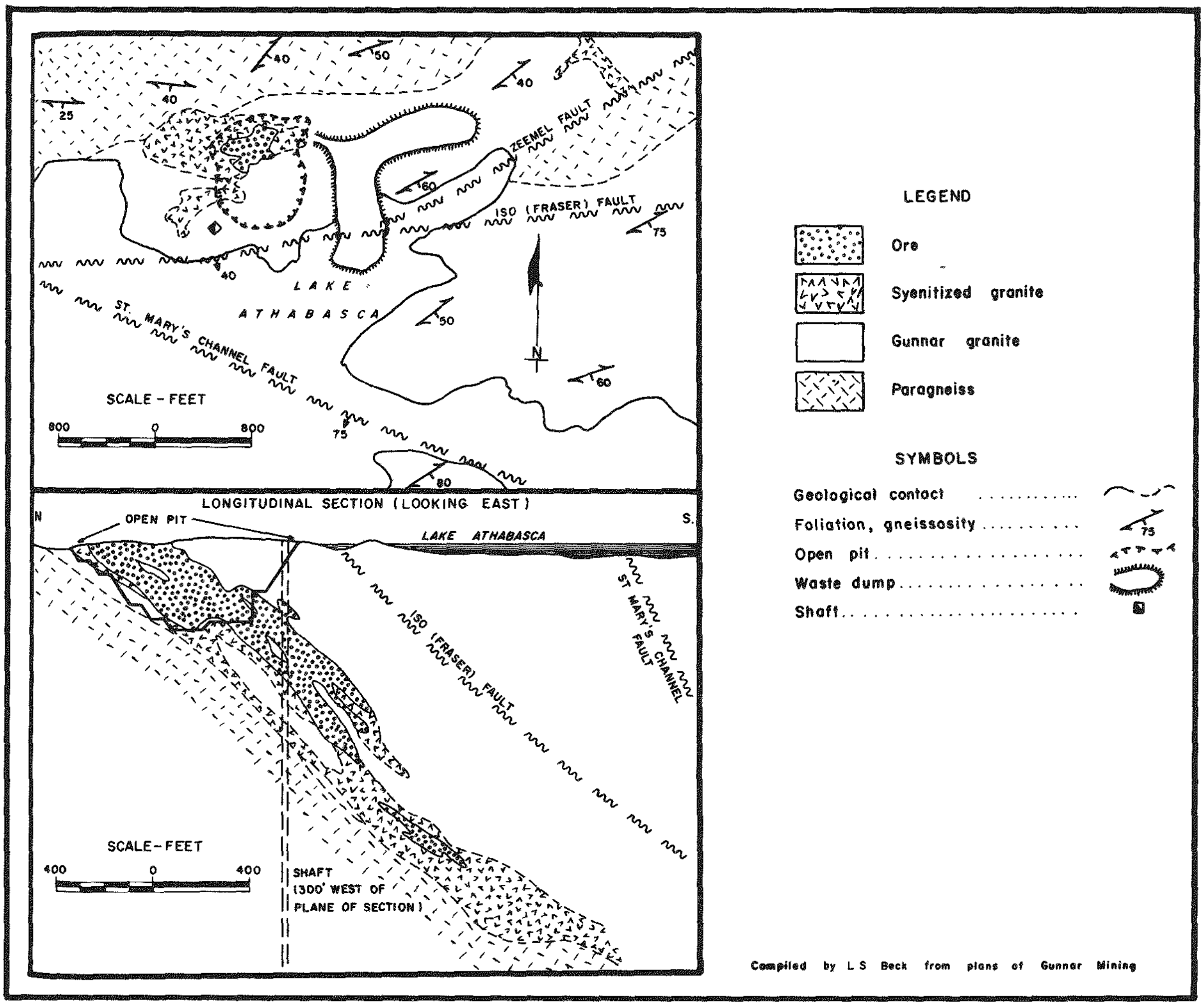


Figure 11. Geologic sketch map and cross section for the Gunnar Mine area, Canada (from Beck, 1969).

Only the major deposits have been considered in the foregoing discussion. Descriptions of mines and deposits of the Beaverlodge district have been published by Beck (1969, 1970), Lang et al (1962), and Tremblay (1972). Kalliokoski et al (1978) presented a summary of these deposits, and the reader is referred to those basic references.

Geochronology and Postulated Sequence of Geologic Events. Age dates and geologic observations lead to the following tentative sequence of geologic events in the Beaverlodge area (Beck, 1969, 1970; Burwash et al, 1962; Koeppel, 1968; Robinson, 1955a; Sassano et al, 1972a; Tremblay, 1972; Wanless et al, 1966):

(1) Kenoran orogeny and older events

2100 to 2500 m.y.	Formation of "old" granites and "greenstones" including Foot Bay Gneiss and Donaldson Lake Gneiss.
2100 to 2200 m.y.	Uraninite and monazite in pegmatites and associated with mafic minerals in metasediments.

(2) Deposition of Aphebian sediments

pre-1940 m.y.	Deposition of Middle and Upper Tazin sediments and associated volcanics including Fay Complex and Murmac Bay Formations.

(3) Hudsonian orogeny (1940 to 1780 m.y.)

1975 ± 20 m.y.	Age date from a pegmatite.
1940 to 1920 m.y.	Uraninite and monazite in pegmatites and "young" granites, and in mafic portions of metasediments; regional metamorphism, followed by faulting, mylonitization, and brecciation.
1840 to 1815 m.y.	Retrograde metamorphism; emplacement of late and post-tectonic granites (muscovite age date from Gunnar deposit), pegmatites (1815 m.y.), and gabbro dikes (biotite yielded 1835 ± 50 m.y., whole rock 1735 ± 51 m.y.).
1795 to 1740 m.y.	Retrograde metamorphism with "hydrothermal" alterations, formation of euhedral uraninite (?) and massive and colloform pitchblende.

(4) Deposition of Martin Formation (1740 to 1490 m.y.)

1640 m.y.	Age date from basalt sill.

1490 to 1410 m.y.	Gabbro and diabase dikes cutting Martin Formation.

(5) Redistribution of uranium mineralization

1125 to 1110 m.y.	First reworking of epigenetic pitchblende with formation of hematite (emplacement of diabase dikes in the Athabasca Formation).

(6) Redistribution of uranium mineralization

270 m.y.	Redistribution of pitchblende with formation of hematite, possibly with rejuvenation of faults and introduction of sooty pitchblende into Martin Formation; erosion.

(7) Redistribution of uranium mineralization

post 100 m.y.	Redistribution of pitchblende and reactivation of faults; erosion, glaciation, supergene alteration and partial destruction of deposits.

Tremblay (1978c) has summarized these data and interpretations graphically, and his illustration is reproduced in Figure 12. These geologic events are also shown in Figure 13, which emphasizes those events that were reactivated several times during the evolution of the deposits.

Concepts of Ore Controls and Ore Formation

Factors related to the control and formation of the uranium deposits have been discussed by numerous authors (Beck, 1969, 1970; Koeppel, 1968; Robinson, 1955a; Sassano et al, 1972b; Tremblay, 1972, 1978c) and are summarized below.

(1) The major deposits in the Uranium City area (Fay-Ace-Verna) occur in the Fay Complex of the Tazin Group. These rocks were originally deposited as carbonaceous, pelitic to psammitic sediments of Middle to Upper Aphebian age over a basement of "old granites" (Beck, 1969, 1970) of Archean age. During the Hudsonian orogeny the sediments were metamorphosed to an interbedded sequence of graphite-bearing quartzo-feldspathic gneisses, feldspathic quartzites, meta-argillites, amphibolites, and hornblende schists. The metamorphic facies ranges from granulite to amphibolite, with local anatexis and granitization. These metasediments were intruded by granites ("young granite") and subsequently altered to various degrees including retrogressive metamorphism to upper greenschist facies. At Gunnar the host rock is a metasomatic granite derived from Tazin sediments (?) and altered to a quartz-deficient albitized rock (episyenite).

(2) The Lower Proterozoic crystalline rocks are unconformably overlain by the early Middle Proterozoic Martin Formation which consists of red, oxidized continental, clastic sediments and locally interbedded volcanic flows which were deposited in basins or fault-bounded grabens. These sediments were deposited with essentially no regolith development as is found on the surface of the

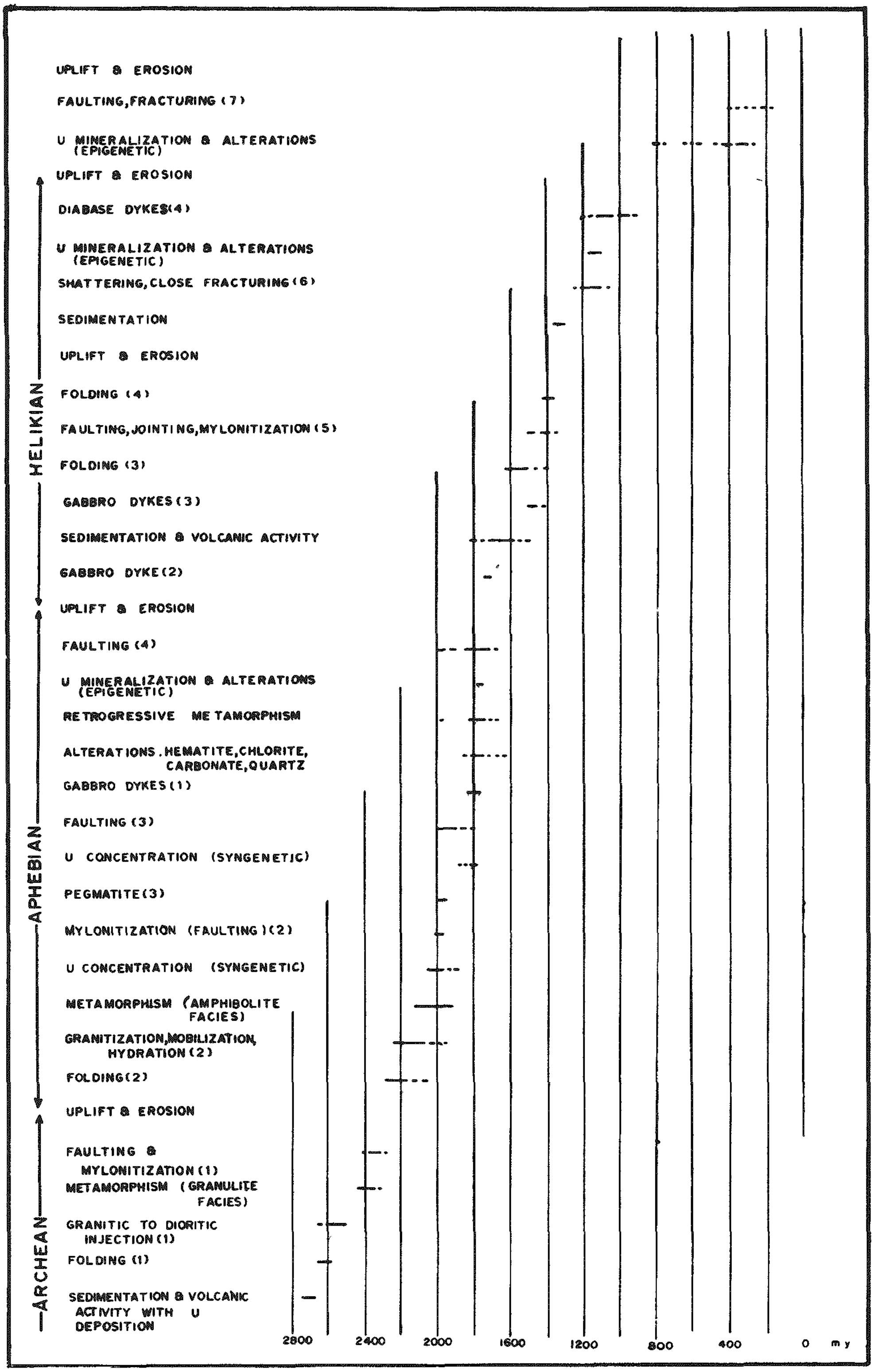


Figure 12. Sequence of geologic events in the Beaverlodge area, Canada (modified from Tremblay, 1978c).

metasediments in the southern Athabasca region. The Martin sediments were cut by diabase dikes and sills and were slightly deformed, by the latest Hudsonian movements, into broad northeast-trending folds.

(3) Economic ore deposits in the Lower Proterozoic Tazin Group have been found only where overlain by Martin sediments. Low-grade, disseminated "syngenetic" strata-bound deposits and epigenetic strata-structure-bound deposits have been discovered, but only the latter are of economic interest. The epigenetic deposits occur in the vicinity of major structures, but in detail they appear to be controlled by both subsidiary structures and certain metasedimentary horizons. The vertical extent of the deposits is variable but may extend to as much as 2,000 m, as in the Fay Mine. Individual mineralized zones may extend to the unconformity or may occur only at depth. Various types of alteration are associated with the deposits. All major orebodies are essentially mono-metallic, whereas small deposits can have variable multi-metallic mineral assemblages.

These geologic features have been variously interpreted by geologists familiar with the deposits. Most of the early investigators of the Beaverlodge uranium deposits postulate a hydrothermal origin, although some considered uraniferous Aphebian sediments as the uranium source (Sullivan, 1957). In recent years Smith (1974) has presented a supergene origin.

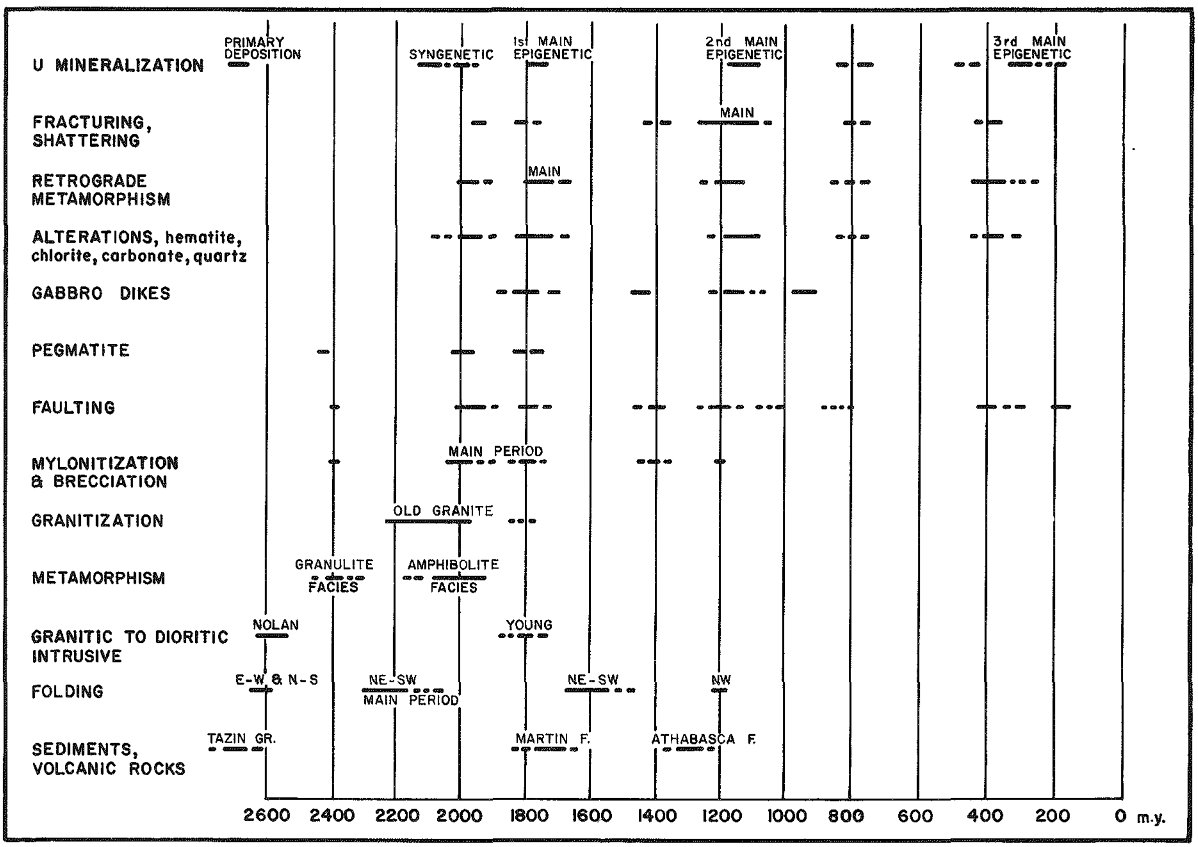


Figure 13. Diagrammatic illustration of recurrent activity of some important geologic events in the Beaverlodge area, Canada (modified from Tremblay, 1978c).

Sassano et al (1972b) conclude that the deposits were generated by metamorphic hydrothermal fluids with some possible contribution of surface waters during the final stages of mineralization to an otherwise "closed" system. This hypothesis was suggested by studies of fluid inclusions and stable isotopes ($\alpha\ ^{13}C$, $\alpha\ ^{18}O$) in dolomite, calcite and quartz from ore of the Fay and Bolger Mines. These studies identified five generations of carbonates and a cooling history from the initial phase of mineralization at 440°C $\pm$ 30°C down to the final stages at around 80 $\pm$ 10°C.

Tremblay (1978c) presented the most recent and comprehensive model for the formation of the Beaverlodge uranium deposits. His concept is presented in Figure 14 and summarized below.

ARCHEAN LATE	APHEBIAN EARLY			LATE	HELIKIAN & younger
> 2600 m.y.	2550-2450 m.y.	2300-1950 m.y.	2050-1900 m.y.	1830-1760 m.y.	1240-100 m.y.
SEDIMENTATION	METAMORPHISM	GRANITIZATION	GRANITE MELTS	SOLUTIONS	REMOBILIZATION
	WITH SEVERAL URANIUM MOBILIZATION CONCENTRATIONS				
TAZIN ROCKS	LAYERED GNEISS	GRANITE	PEGMATITE	VEINS & DISSEMINATIONS	VEINS
Average Uranium Content (ppm)					
(1) 3.2 (2) 3.1	? 3.7	5.8 3.85	430	2000	2000
Average Thorium Content (ppm)					
15	17(?)	22	90		

(1) Analyses for area north of St. Louis Fault
(2) Analyses for area north of Black Bay Fault

Figure 14. Proposed model for the formation of the principal uranium deposits of the Beaverlodge area, Canada (from Tremblay, 1978c).

(1) The accumulation of sediments and volcanics of the Tazin rocks in the Beaverlodge area started in Late Archean time, around 2600 m.y. "The Fay Complex, regarded as the possible source for the uranium in the various uranium deposits of the Beaverlodge area, is near the base of the known Tazin succession," and is composed of interbedded metasediments and metavolcanics (see Fig. 4), some of which display relatively high background uranium concentrations (Table 9). The locally higher concentrations of uranium in the rocks of the Fay Complex are regarded as being syngenetic accumulations.

(2) The Tazin sediments and volcanics were folded, metamorphosed to the amphibolite facies, and locally granitized between 2300 and 2000 m.y., leading to the formation of granite and granite gneiss, pegmatite dikes (approximately 2000 m.y.), and gabbro dikes (approximately 1835 to 1735 m.y.). This orogenic activity, and accompanying metamorphism and granitization, mobilized the uranium in the Tazin rocks into some granites and pegmatites. Syngenetic uranium accumulations in the metasediments were metamorphosed and are now preserved in xenoliths in granite and gneiss. Some epigenetic (vein) deposits may have formed during these events, but no vein deposits of that age have been identified.

(3) Toward the end of orogenic activity (about 1800 m.y.), the "Tazin rocks were cataclastically deformed, with the development of wide mylonite and breccia zones, accompanied by low-temperature retrograde effects and the circulation of metamorphic-hydrothermal solutions, as late effects of the regional metamorphism and granitization." Tremblay considers that uranium became mobilized during this tectonic event, and that most of the vein deposits of the Beaverlodge area were formed at this time. He considers them to be metamorphic-hydrothermal in origin, the mineralizing event occurring as one of the last stages in the granitization that had affected the Tazin rocks.

(4) Following the main period of mineralization, continued faulting affected the distribution of mineralization. According to Tremblay, it can be assumed that "the second main period of formation of the epigenetic (vein) deposits took place during this period, about 1140 ± 50 m.y. This second generation of vein development corresponds to a very important period of uranium mobilization and concentration in the Beaverlodge area and in all of northern Saskatchewan." Faulting and uranium redistribution continued after this event, as evidenced by younger pitchblende ages. However, Tremblay (1978c) notes, "it is possible that there was only one period of uranium mineralization at 1780 ± 20 m.y., and that all the other vein dates represent merely periods of uranium remobilization and not new mineralization periods."

(5) At a much later time, due to weathering and ground-water transport, uranium may have moved again with precipitation in breccias, along fractures, and at the unconformity to form supergene deposits. The Bolger deposit may be of this type.

Shape and Grade Characteristics of the Ore Deposit. Important factors, such as size, shape, continuity, and grade of the major deposits, have been presented by Beck (1969) and McMillan (1977b) and are briefly summarized below.

In the Ace and Fay deposits, two types of orebodies occur in the footwall meta-argillites of the St. Louis Fault. The first consists of breccia zones within 15 m of the fault in which the width of individual ore shoots ranges from 0.3 m to 15 m. The second ore type is vein-type bodies associated with fractures striking roughly parallel to and within 100 m of the St. Louis Fault and plunging moderately to the southwest. The orebodies consist either of one well-defined mineralized vein with branches (e.g., "16" and "20" orebodies), or an interconnected network of sub-parallel veins (e.g., "09" orebody). The ore shoots are known to a depth of more than 1,600 m. Strike lengths extend up to 150 m. The average thickness of ore shoots is around 0.4 to 0.9 m and the maximum 3.5 m.

In the hanging wall of the St. Louis Fault, the "Ura" orebodies occur in flat-lying shears in and adjacent to the unconformity between basement rocks and conglomerate of the Martin Formation. The "5" , "61", and "64" orebodies are in breccia and shear zones in alaskite and paragneiss.

In the Verna Mine, the orebodies occur in the hanging wall of the St. Louis Fault and about 120 m from this major structure. The mine is in a sequence of meta-argillites that are folded into an anticline that plunges gently southwest and is overturned to the north. The axial trace of the fold lies roughly parallel to the St. Louis Fault. The ore shoots, described as veins and stringers, lie in the north and south limb of the fold mostly parallel to the fold structure. The ore shoots range from 1 to 12 m in width, reach a maximum of 240 m in length, and extend to at least 400 m in depth. They contain pitchblende in fractures that range in width from microscopic to 10 cm.

In the Bolger Mine, the deposit is in the hanging wall of the St. Louis Fault about 300 m east of the Verna orebody. It consists of several, sub-parallel fractures striking north 70° east, and dipping 40 to 50 degrees south, parallel to the St. Louis Fault. Individual fractures are generally less than 6 m in length and are filled with carbonate and chlorite accompanied by stringers and blebs of pitchblende. Finely disseminated, sub-microscopic, radioactive grains, associated with patches of intense red alteration, occur in wall rock fragments. The radioactive veins are cut by stringers of pyrite and quartz. The overburden above the deposit for several meters was extremely rich in secondary uranium minerals (about 1,300 t of ore graded 0.73 percent U_3O_8).

At the Gunnar Mine, the ore zone lies in a brecciated portion of the Gunnar "syenite", a pipelike body with a maximum diameter of 135 m near the surface, plunging 45 degrees in a south-southeast direction for a length of at least 660 m. Between a depth of 75 and 105 m, in horizontal plane, the orebody changed from a circular shape to that of a figure eight. The northern zone became smaller and disappeared with depth; the southern zone became enlarged and continued to depth.

Production and Reserves. The approximate size of the Beaverlodge district, and its individual deposits, is indicated by the production data in Table 2, and the production and reserve information is compiled in Table 3.

Athabasca Basin District

The district is defined by the distribution of the Athabasca Sandstone, now preserved in the axis of the depositional basin, and the surrounding region particularly to the south of Lake Athabasca. The regional geology was discussed in an earlier section. The main deposits include Cluff Lake in the western part of the basin and Collins Bay, Key Lake, Midwest Lake, and Rabbit

Table 3. Composite production and reserve data for the principal deposits of the Beaverlodge area.

	Ore Metric Tons	Grade % U_3O_8	U_3O_8 Metric Tons
1. Eldorado Mines in Beaverlodge District			
(Canadian Mines Handbook, 1978-79)			
Proven Reserves (12/13/1977)	3,770,000	0.2	7,540
Production (1953-12/31/1977)	8,780,000	0.2	17,560
Total	12,550,000		25,100
2. Cenex-Cinch Mine (former Cinch Lake Mine)			
(Canadian Mines Handbook, 1978-79; Beck, 1969)			
Reserves	270,000	~0.2	540
Production (1957 to 1960)	113,000	~0.26	300
Total	383,000		840
3. Gunnar (Beck, 1969)			
Production	~5,000,000	0.175	8,700

Lake in the eastern part (Fig. 15). Additional deposits have been discovered near Rabbit Lake (Raven, Horseshoe, West Bear, and Eagle Point), at Maurice Bay, at McClean Lake, and at Dawn Lake. Rabbit Lake and Cluff Lake were discovered in 1968, Key Lake in 1975-76, and Midwest Lake in 1977-78. In 1980 only Rabbit Lake is in production, but Cluff Lake and Key Lake are under development.

Key Lake. Dahlkamp and Tan, 1977; Dahlkamp, 1978; Gatzweiler et al, 1979, 1980; Kirchner et al, 1979; von Pechmann and Voultsidis, 1979; Strnad, 1979; Tan, 1976, 1980; Voultsidis and Clasen, 1978; Voultsidis et al, 1980; Wendt et al, 1978.

The Key Lake orebodies are located at the southeastern rim of the Athabasca Basin about 200 km to the north of La Ronge in northern Saskatchewan. The deposits were discovered in 1975 and 1976 by a combination of exploration methods including radiometric tracing of mineralized boulders, surficial glacial geology, geochemistry, geophysics, and finally core drilling. Key Lake contains two major orebodies, the Gaertner orebody to the southwest and the Deilmann orebody adjacent to the northeast.

Geologic Setting of Mineralization. The Key Lake area is underlain by rocks of the Wollaston Belt comprising Lower Proterozoic (Aphebian) metasediments that mantle Archean dome-like complexes. The Aphebian sediments were metamorphosed during the Hudsonian orogeny and later affected by intense paleoweathering prior to the deposition of the Athabasca Formation. In Middle Proterozoic time (Helikian) continental clastic sediments of the Athabasca Formation were deposited unconformably over the crystalline basement.

The Archean rocks consist of granite gneisses and granulites. The Aphebian metasediments are comprised predominantly of (a) biotite-cordierite-feldspar gneisses, (b) graphite gneisses and schists, and (c) coarse-grained anatexites (pegmatoids). Minor amounts of amphibolites, biotite-rich gneisses, and biotite-cordierite-feldspar-garnet gneisses are present. The metamorphic grade is upper amphibolite facies. Contrary to the observations of many other authors, both in Saskatchewan and the Athabasca Basin Region, Voultsidis et al (1980) have not found evidence for retrograde metamorphism at Key Lake. Several authors report retrograde metamorphism in Australian deposits based on chloritized garnets. In the Key Lake area, fresh gneisses contain unaltered garnets except within the weathering zone where they are chloritized.

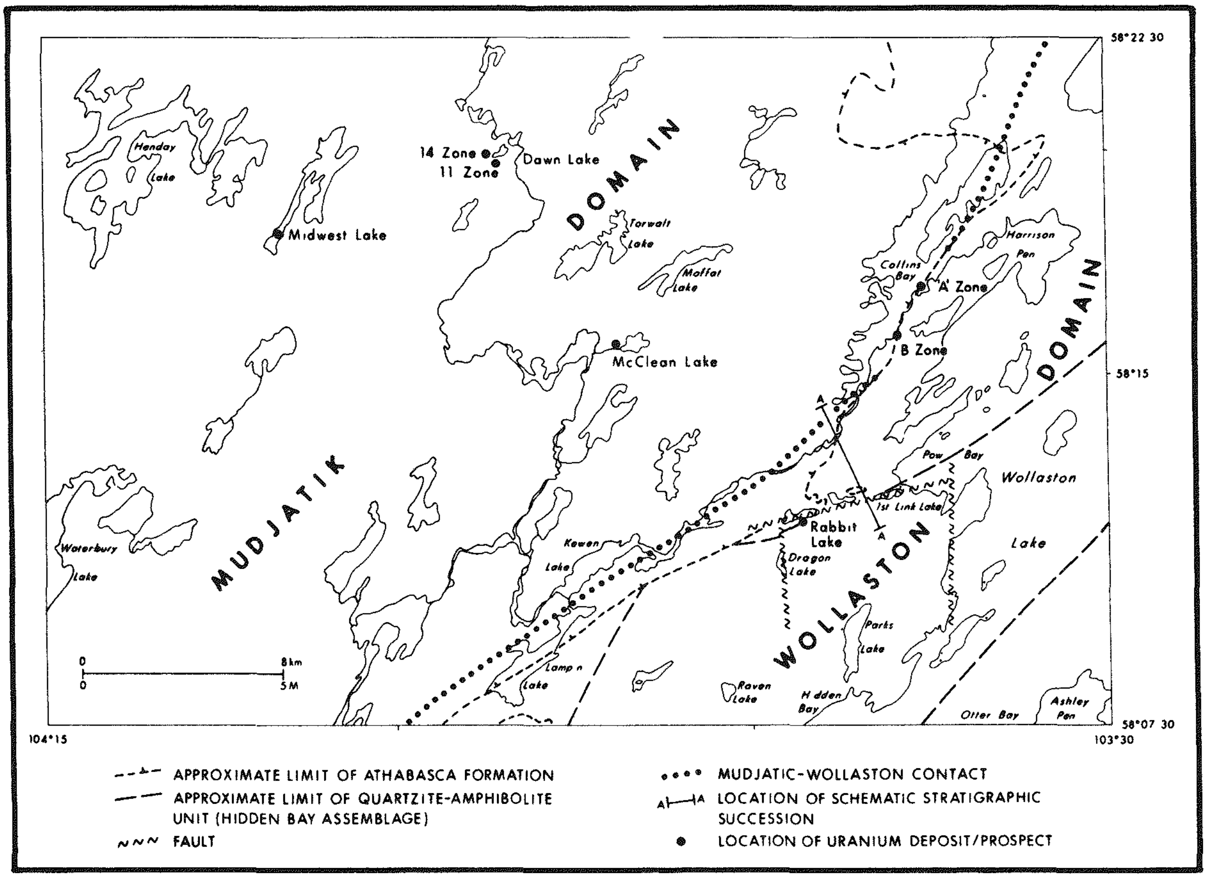


Figure 15. Location map for uranium deposits and prospects and major geologic domains in the eastern Athabasca Basin District (from Sibbald, 1979).

The gneisses are characterized by near-surface weathering that is strongest adjacent to the unconformity, but which extends to depths of 300 m. All minerals are altered except quartz and graphite so that ultimately sericite-chlorite dominate the mineralogy. The mineral stability decreases from K-feldspar to biotite, plagioclase, cordierite, garnet, and finally amphibole. The hydration of biotite is believed to be of special importance for the later formation of the uranium deposits.

The chemical changes in the rocks during increased weathering are shown in Table 4. Leaching removes K, Si, Ca, and some Fe whereas Al, Ti, and Mg remain; hence become relatively enriched. This type of weathering or regolith formation suggests a warm-humid climate (Voultsidis et al, 1980).

The Middle Proterozoic Athabasca Formation consists of basal conglomerates and fanglomerates grading upward into sandstones (90 to 95 volume percent quartz) which are cemented by younger quartz. Within the basal layers are fragments of basement rocks, some of them strongly weathered, suggesting that the alteration (weathering) of the basement took place prior to the deposition of the Athabasca sandstones rather than after as suggested by some authors.

The main structural features in the Key Lake area consist of Archean granitic cores draped with folded Aphebian metasedimentary rocks (Fig. 16). The regional strike of schistosity and bedding is generally northeast-southwest. The major faults also strike northeast-southwest and dip, within the ore zone, 50° to 70° to the northwest. These features are crossed by northwest-striking faults. Both fault systems have vertical displacements.

Table 4. Chemical analyses (in percent) of core samples (DDH H2) illustrating the decrease in weathering and leaching with greater depth below the unconformity, Key Lake area (from Voultsidis et al, 1980).

Sample No. CN-	1810	1811	1812-19	1820-31
Depth (ft.)	204-11	211-18	212-271	271-349
SiO_2	57.35	71.90	75.75	74.25
TiO_2	0.74	0.32	0.31	0.30
Al_2O_3	21.35	15.12	13.04	12.47
Fe_2O_3tot	1.25	1.04	1.88	2.20
CaO	0.08	0.16	0.15	0.18
MgO	9.46	6.14	2.17	4.16
K_2O	0.66	0.75	2.85	3.34
Na_2O	0.40	0.25	0.62	0.20

←——Increasing Decomposition——|

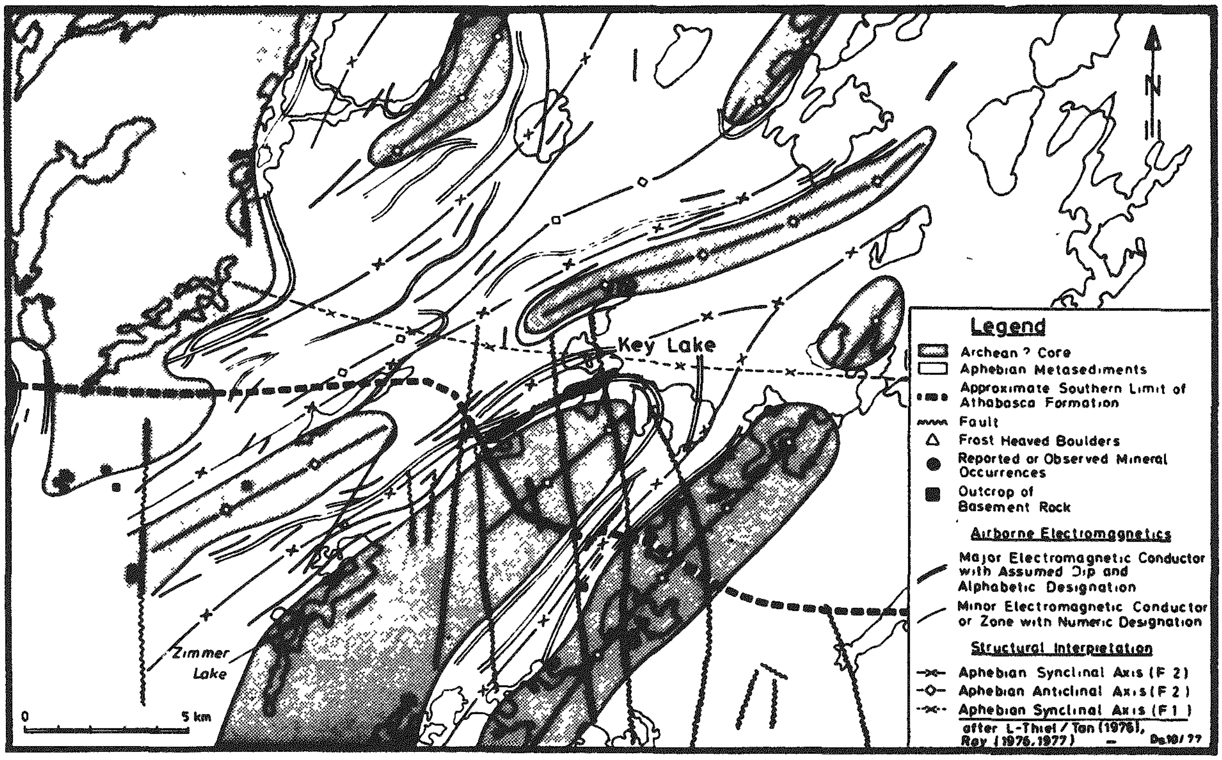


Figure 16. Interpretation of basement geology of the Zimmer Lake-Key Lake area, Canada (from Dahlkamp, 1978).

In the Gaertner orebody the southeast block downdropped 40 m (Fig. 17). In the northeastern section (Deilmann orebody) the fault zone is more complex than in the southwestern extension (Gaertner orebody). Figure 18 is a schematic longitudinal section of the Key Lake deposits showing the relation between the Deilmann and Gaertner orebodies.

Alteration. Two types of alteration, the first associated with mineralization and the second caused by weathering, are distinguishable in the cataclastic and mylonitic ore zones at Key Lake. Alteration associated with mineralization is itself of two types - Fe-chloritization and kaolinitization. The first, iron-rich chlorite, occurs in mylonites consisting predominantly of dark green iron-rich (Mg-free) chlorites with minor amounts of kaolinite and other constituents. The second type, kaolinitization, occurs as whitish-gray mylonite with kaolinite as the main and, in some cases, the only constituent. The kaolinitic mylonite is the principal ore host. Other types of alteration, particularly along shears, consist of Fe-hydroxides and minor hematite which color the host rocks brown to red. Narrow veinlets of calcite and siderite, locally abundant, cut the ore.

Alteration caused by weathering is composed of sericite, Fe-Mg-chlorite, and quartz. This type of alteration is also present in mylonites, but grades out into only slightly sheared gneisses and is generally unmineralized (see previous paragraph).

According to Voultsidis et al (1980), the formation of the ore-related iron chlorite and kaolinite is accompanied by nearly total removal of the primary cations of the immediately adjacent host rock, whereas the barren sericite-Fe-Mg-chlorite-quartz mylonites have a chemical and mineralogic composition identical to that of non-cataclastic weathered gneisses away from the ore zone. The kaolinite and Fe-chlorite are regarded as having been formed in zones of intense tectonic deformation through subsequent hydrous alteration causing recrystallization of kaolinite and Fe-chlorite. The kaolinitization and iron chloritization clearly postdate the regional paleoweathering processes and are associated with the ore emplacement.

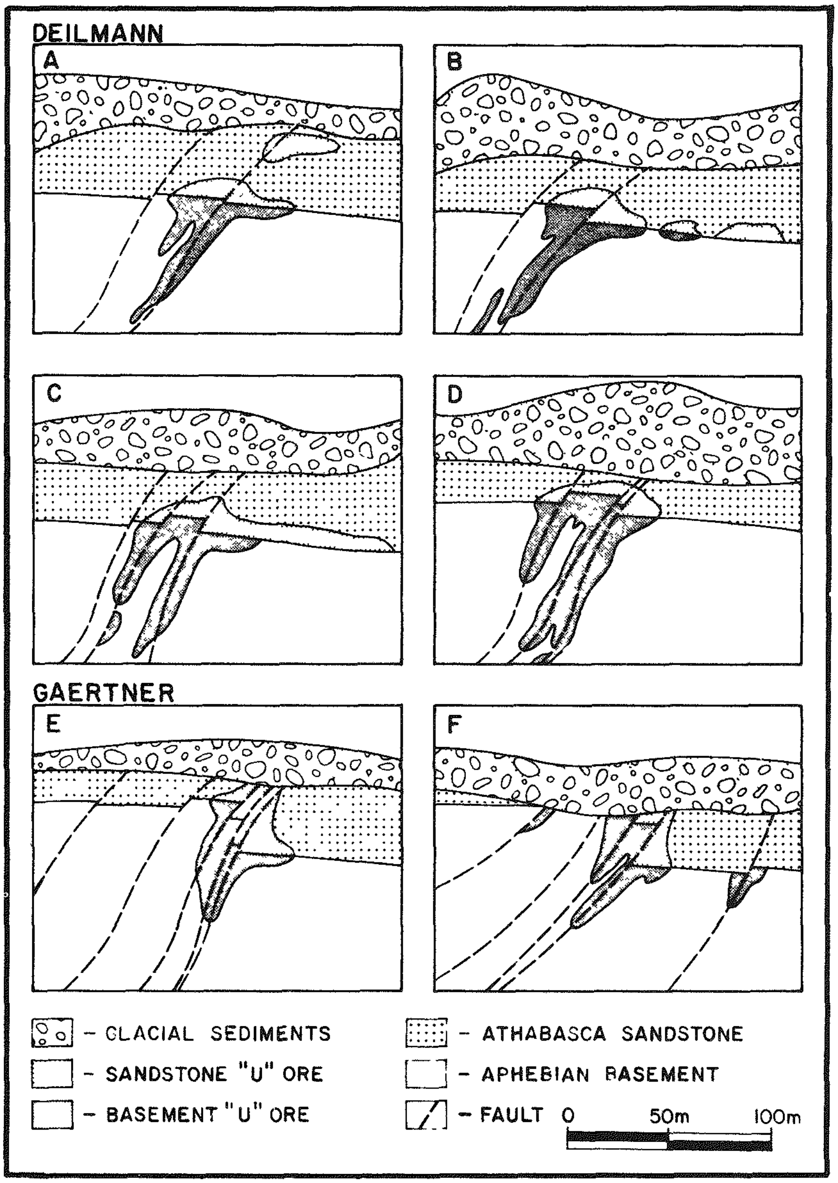


Figure 17. Schematic cross sections of the Deilmann and Gaertner orebodies, Key Lake (from Kirchner et al, 1980).

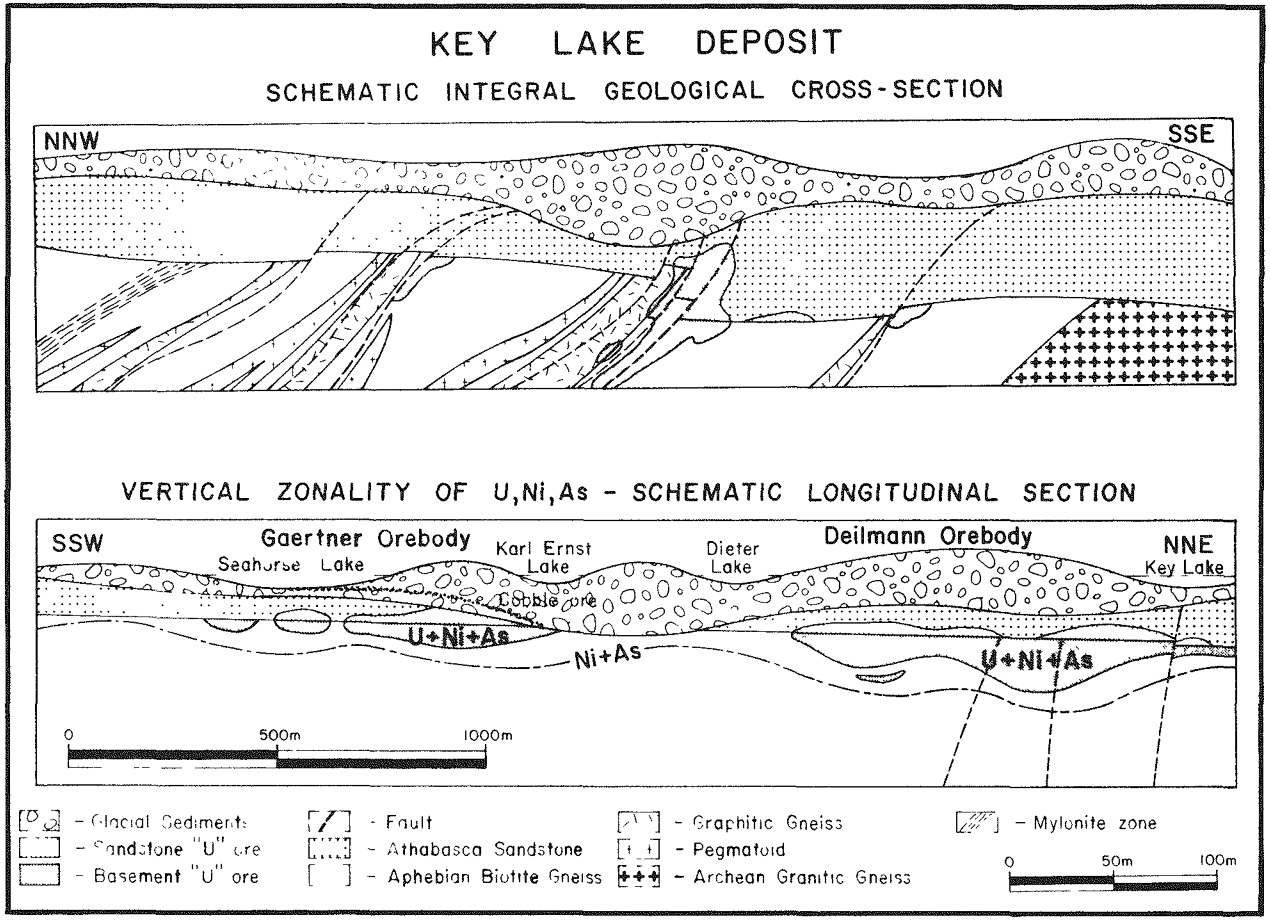


Figure 18. Schematic longitudinal geologic cross section of the Key Lake deposits, Canada (from Kirchner et al, 1980).

With respect to the structural relations of the alteration products, Voultsidis et al (1980) state: "The change from tectonized to undisturbed rocks is gradational, whereas the change of the mineralization and its typical Fe-chlorite and kaolinite matrix towards the barren sections within the tectonized parts is abrupt (cm to dm range)."

Mineralization. The principal ore elements of the deposit are U and Ni. Nickel occurs as sulfide and as sulf-arsenide, and uranium as oxide and silicate minerals. Pb, Zn, and Cu are present in accessory minerals. Minor amounts of Mo were detected. The mineral paragenesis as interpreted by Dahlkamp (1978) is presented in Figure 19. Voultsidis et al (1980), in a recent discussion of the mineralization in the Key Lake deposit, suggested that the ore mineralogy can be divided into an older assemblage in the mylonitized basement rocks and a younger one in the overlying Athabasca Formation:

> The ore minerals in the basement mylonites consist of $\alpha - U_3O_7$ (named 'tetra-uraninite' by Clasen and Voultsidis, 1980, in press), coffinite and sooty pitchblende, gersdorffite, niccolite, millerite, maucherite, rammelsbergite, galena, bravoite, pyrite and marcasite and minor chalcopyrite, covellite and sphalerite. $\alpha - U_3O_7$ as well as the nickel arsenides niccolite, maucherite and rammelsbergite do not occur in the sandstone domains.
>
> The adjacent graphite schists do not contain uranium minerals but, to a minor extent, may locally contain gersdorffite, niccolite or millerite. This mineralization might be of (primary) metamorphic formation (cf. Tilsley, 1979).
>
> The ore minerals in the Athabasca Formation are predominantly found in the grain interstices of the sandstone and locally between the originally rather well-rounded quartz grains and the secondary (younger) quartz rims. In places late mineralization (above all millerite) is located on fracture planes.

The most important uranium mineral in the basement rocks is $\alpha - U_3O_7$ ('tetra-uraninite') which occurs as massive fracture fillings, as films along the cleavage planes of sheet silicates, as colloidal masses and as well-developed idiomorphic grains. The $\alpha - U_3O_7$ has been subsequently oxidized to sooty pitchblende on its surfaces and along shrinkage cracks. The vertical distribution of minerals from core hole DDH-47 in the Gaertner deposit is shown in Figure 20.

Gersdorffite (NiAsS) formed contemporaneously with $\alpha - U_3O_7$. It occurs as idiomorphic grains, sometimes zoned, and as banded intergrowths with uranium, other nickel minerals, and gangue minerals. A later gersdorffite stage replaces other nickel minerals except millerite.

Bravoite [$(Fe, Ni)S_2$] also formed during the first period of ore formation and occurs with $\alpha - U_3O_7$ as inclusions in idiomorphic gersdorffite. Rammelsbergite ($NiAs_2$) also probably formed in the early mineral stage and is replaced by niccolite along cracks.

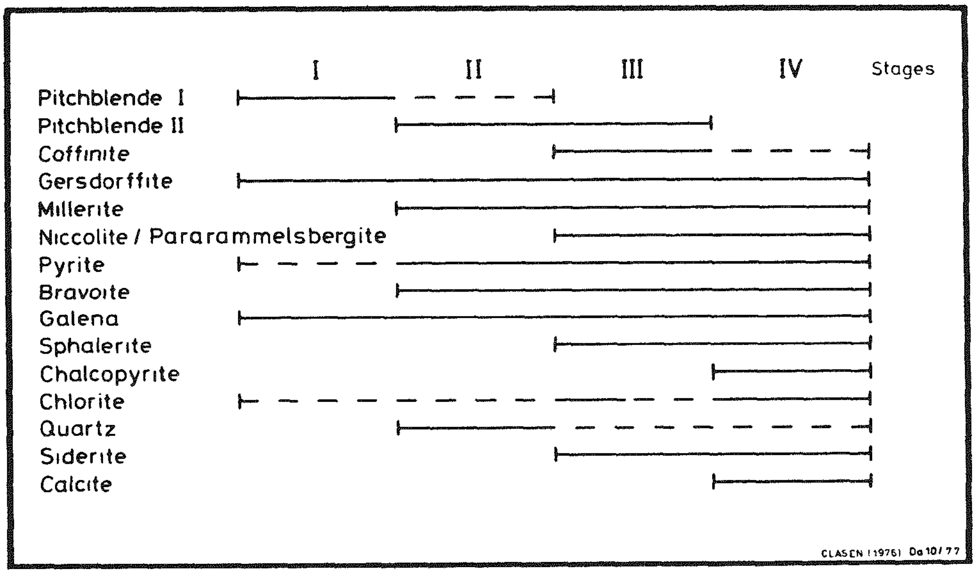


Figure 19. Generalized paragenesis of the Key Lake uranium-nickel deposits (Dahlkamp, 1978).

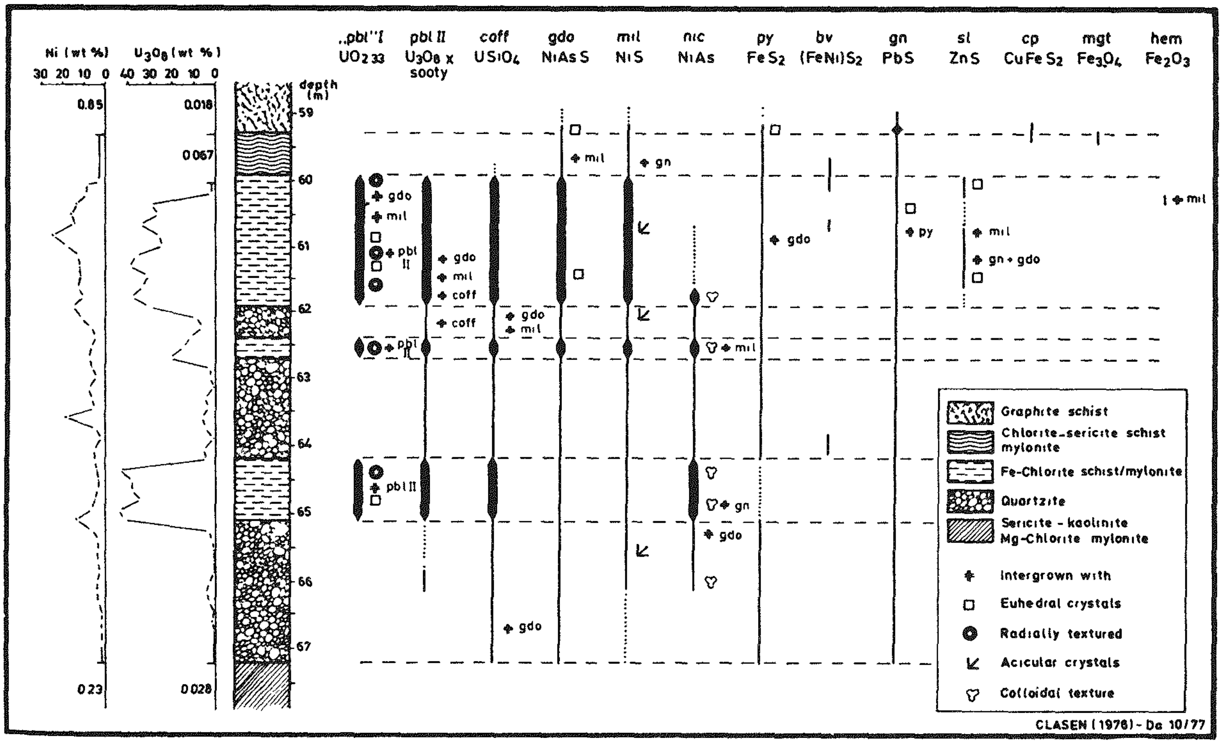


Figure 20. Vertical distribution, mineralogical habit, and relations between ore minerals in core hole DDH47 from the Gaertner deposit, Canada (Dahlkamp, 1978).

Niccolite (NiAs) occurs in rounded grains and is probably replaced by maucherite (Ni_3As_2). Niccolite is found intimately intergrown with sooty pitchblende and replaces all other nickel minerals mentioned above.

Coffinite ($USiO_4$) and sooty pitchblende are of a younger genetic stage and are found in the Aphebian metasediments as concentric intergrowths or in the interstices between other minerals.

Minor, though locally abundant, ore constituents include pyrite, marcasite, chalcopyrite and galena, and sphalerite. The ores in the metasediments are cut by locally numerous veinlets of calcite and siderite. The massive ore, apart from the minerals mentioned above, is essentially free of other introduced phases, particularly gangue minerals.

Geochronology. Preliminary uranium-lead age determinations (Wendt et al, 1978) of basement ore indicate an "old" pitchblende age of about 1270 m.y. ($\alpha - U_3O_7$) and younger ages of around 918 m.y. (mainly coffinite) and 270 m.y. Uranium ores within the overlying Athabasca Formation have yielded ages no older than 300 m.y. The basement gneiss has been dated at around 1700 m.y., presumably a metamorphic age. The "oldest" uranium age is comparable to an age of 1230 m.y. for a diabase dike cutting the Athabasca Formation at Cree Lake (Burwash et al, 1962).

Ore Controls and Ore Formation. The Key Lake orebodies exhibit the following ore-controlling features:

(1) The orebodies occur in a northeast-southwest-trending reverse fault zone which is cut in its northeastern section by northwest-southeast-trending cross faults.

(2) The mineralization occurs in direct contact with the Middle Proterozoic unconformity between the Athabasca Formation and the underlying crystalline basement.

(3) Mineralization extends only to a depth of about 150 m below the unconformity.

(4) Alteration of host rocks consists of (a) pre-mineralization, sericitization, and chloritization which is restricted to the paleosurface and was produced by paleoweathering; and (b) kaolinitization and iron chloritization which is associated with the uranium mineralization and was apparently formed by the ore-bearing fluids.

(5) Two distinct types of mineralization occur within the deposits: (a) an old (1270 m.y.) uranium oxide and nickel sulf-arsenide assemblage that is restricted to the crystalline basement; and (b) a younger (< 300 m.y.) U-Ni-bearing assemblage of different minerals which occurs in the overlying Athabasca Formation. Although likely, it has yet to be demonstrated that the U-Ni mineralization in the Athabasca Formation was formed by remobilization of mineralization in the underlying basement.

An early conceptual genetic model for the Key Lake deposits was presented by Dahlkamp (1978) and is shown in Figure 21. Other authors, e.g., Kirchner et

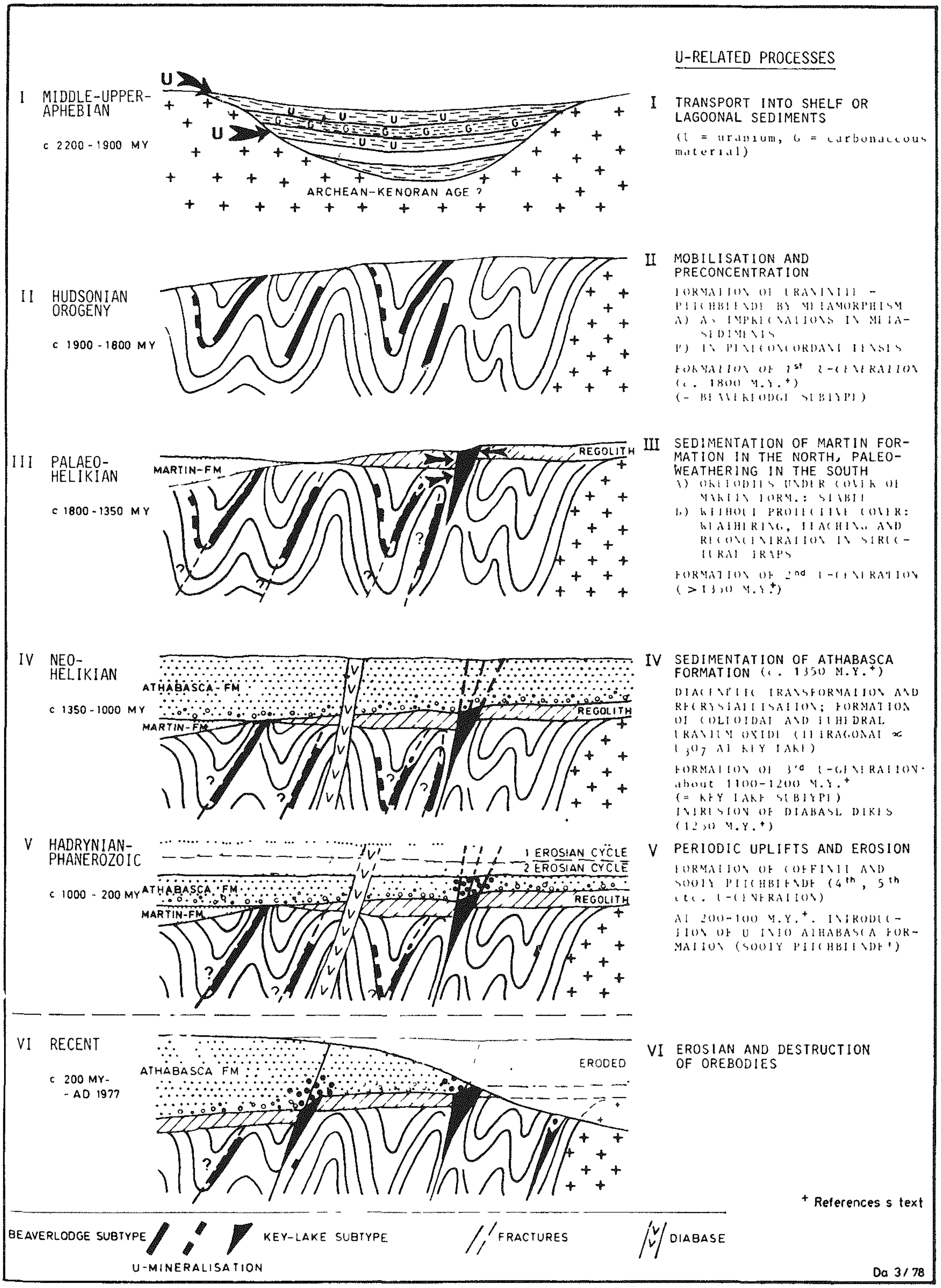


Figure 21. Schematic cross sections depicting the geologic stages in the evolution of veinlike uranium deposits (from Dahlkamp, 1978).

al (1979) and Strnad (1979), have come to somewhat different genetic conclusions. Voultsidis et al (1980) present more recent data and discuss in length the various genetic models. Their views are summarized later in this report.

Shape and Dimension of Deposits. Two major orebodies, Gaertner and Deilmann, occur within a northeast-southwest-trending structure which has been traced over a length of at least 6,000 m. Mineralization was found over a total length of about 5,000 m, having been removed locally by glaciation (see Figs. 17 and 18).

The Gaertner orebody exceeds 1,400 m in length and can be subdivided into two parts. The northern part, which is 800 m long, has a width of 10 to 50 m and an average depth of 10 m. The mineralization occurs normally between 50 and 80 m below the surface and grades up to 45 percent U_3O_8 and 45 percent Ni over a core length of at least 0.3 m. The southern section has a length of 600 m, an average width of 15 m, an average depth of 4 m, and is of lower grade.

The Deilmann orebody exceeds 1,400 m in length and has a projected width varying from 10 to more than 200 m. It occurs about 65 to 140 m below the surface with extensions of up to 160 m downdip. The highest grade intersection was 59 percent U_3O_8 and 30 percent Ni over a core length of 0.3 m. The orebodies are blanketed by 30 to 80 m of glacial overburden.

Grade and Reserves. Reserves are in excess of 155 million pounds of contained U_3O_8 (Northern Miner, July 17, 1980). The grade is reported to average 2.5 percent U_3O_8, 2.5 percent Ni, and 1.5 percent As.

Rabbit Lake. Cumming and Rimsaite, 1979; Dunning and Parslow, 1978; Hoeve, 1977; Hoeve and Sibbald, 1977, 1978a, 1978b, 1978c; Jones, 1980; Knipping, 1971, 1974; Pagel, 1976; Pagel et al, 1979; Rimsaite, 1977b; Sibbald et al, 1976.

Rabbit Lake is situated at the eastern edge of the Athabasca Basin, about 350 km north of La Ronge. An all-weather road connects La Ronge with Rabbit Lake. The deposit was discovered by an airborne spectrometric survey in 1968, which detected a uraniferous boulder field within a glacial ground moraine.

Geologic Setting of Mineralization. The mineralized area occurs within a steeply east-dipping sequence of metasediments which strike north-northeast (Fig. 22). The grade of metamorphism is amphibolite and locally granulite facies (Pagel et al, 1979). Rock types of the Aphebian metasediments in the vicinity of the deposit are shown schematically in Figure 23 and include (from east to west):

(1) Alternating calc-silicate rocks and gneisses (meta-arkoses). The gneisses are medium grained and consist of feldspar, quartz, biotite and amphibole, and minor amounts of pyrite. The calc-silicate rocks contain coarse-grained diopside, feldspar, and biotite. According to Hoeve and Sibbald (1977), dikes and concordant sills of granitic segregations and pink pegmatites (thicknesses up to several tens of meters) and masses of more irregular-shaped anatectic (?) quartz-feldspar rocks occur within the sequence.

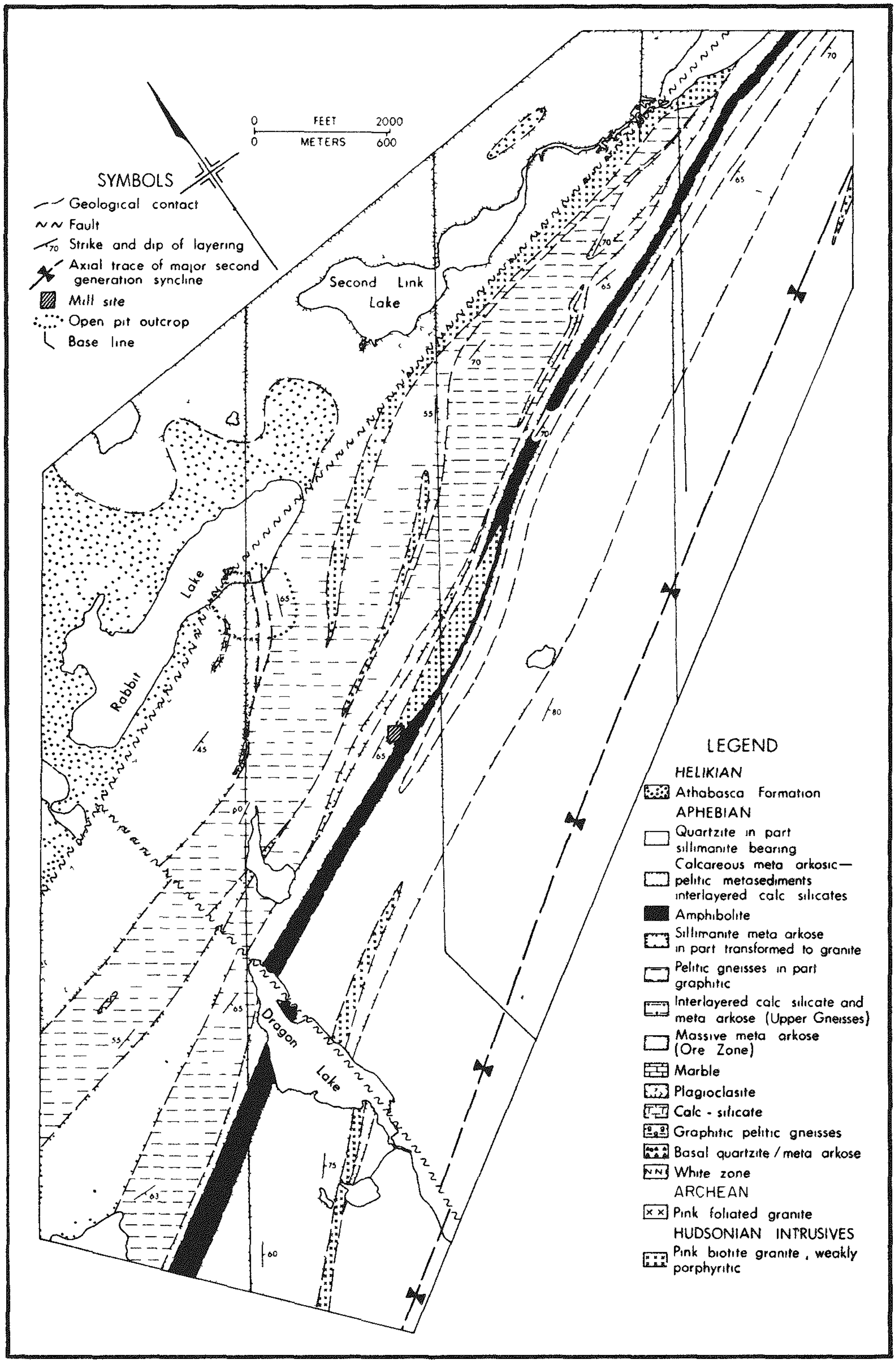


Figure 22. Geologic map of the Rabbit Lake area based on outcrop and drill-hole data, Canada (from Hoeve and Sibbald, 1978c).

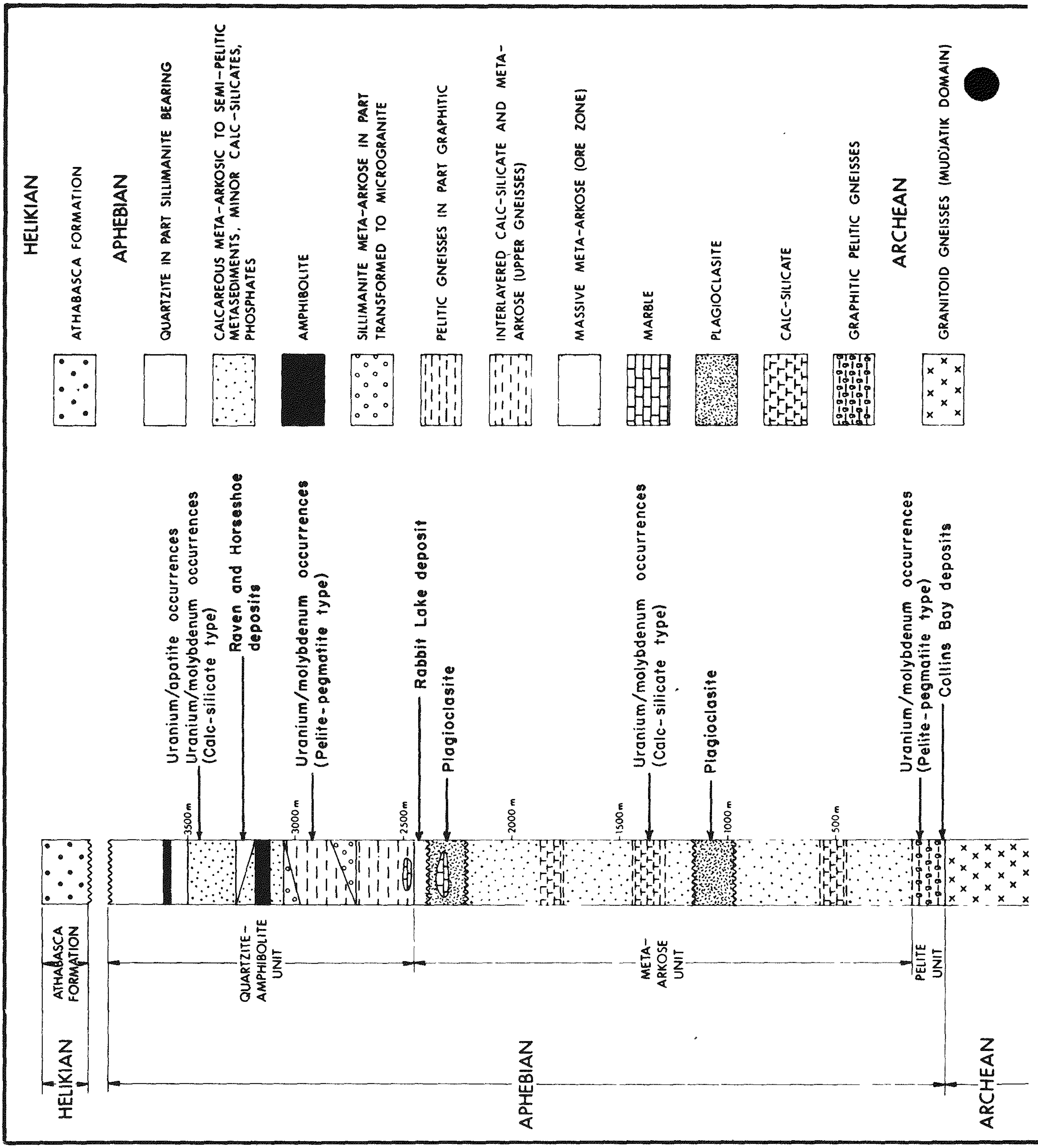


Figure 23. Schematic stratigraphic sequence for the Rabbit Lake area and the positions of the various types of uranium mineralization, Canada (modified from Hoeve and Sibbald, 1978c; and Sibbald, 1979).

(2) Massive quartz-feldspar rock (meta-arkose), strongly fractured and veined with massive quartz. Subconcordant layers of pegmatite and coarse- to medium-grained granite are present.

(3) Massive plagioclase-rich calc-silicate rock (plagioclasite) consisting predominantly of plagioclase with a few percent of pale-green amphibole which appears as porphyroblasts. Sulfides and biotite are locally present.

(4) Graphitic metasedimentary rocks were intersected under the orebody by drilling (in Hoeve and Sibbald, 1978c).

To the north and northwest, the basement metasediments are covered by flat-lying Athabasca sandstone which, particularly at its base, is locally rich in hematite cement. The upper part of the crystalline basement rocks immediately below the Athabasca Sandstone is weathered to a regolith. The depth of weathering ranges from several meters to almost a hundred meters (Knipping, 1974).

A prominent cataclastic zone with mylonites and breccias strikes north-northeast, i.e., almost parallel to the strike of the metasediments, and dips steeply to the east. Along the structure all rocks are strongly altered, particularly meta-arkoses and plagioclasite. The structure hosts the orebody and was interpreted (Knipping, 1974) to be related to an overturned synclinal structure. Hoeve and Sibbald (1977) consider it a simple shear structure. A zone of alteration, which includes the orebody, is associated with the structure and is terminated to the northwest by the Rabbit Lake Fault, a reverse fault that strikes east-northeast and dips 30° to the south. The crystalline basement of the southern block has been thrust over Athabasca sandstone with an estimated vertical displacement of about 60 m. The deposit is shown in cross section in Figure 24.

Alteration. Hoeve and Sibbald (1977) subdivide the zone of alteration into a "median subzone" which grades laterally into "marginal subzones". The core zone is characterized by strong chloritization, irregularly distributed silicification, and by replacement of chlorite by dolomite. Complex relations between these three alteration types have produced a variety of assemblages and rock types with gradational boundaries. Towards the margins dolomitization disappears, the grain size of chlorites diminishes, and alteration becomes less pervasive and more irregularly restricted to the margin of quartz veins.

The chloritization appears in three varieties: an older dark-green type, and both red and pale-green types of a younger age. In the green chlorites sulfides are present, whereas hematite is widespread in the red chlorite and accounts for its color. Mapping has demonstrated that the pale-green chlorite extends from the margins of fissures into wall rocks containing red chlorite.

With respect to alteration, Jones (1980) states: "Rocks of all characters in the region have been subjected to a pervasive phase of post-Athabasca 'clay' alteration. At Rabbit Lake the alteration process was essentially magnesium-boron metasomatism that was characterized by the formation of silver, white, pale green, or red chlorite. In addition, considerable clay, muscovite, quartz, dolomite, and dravite was formed."

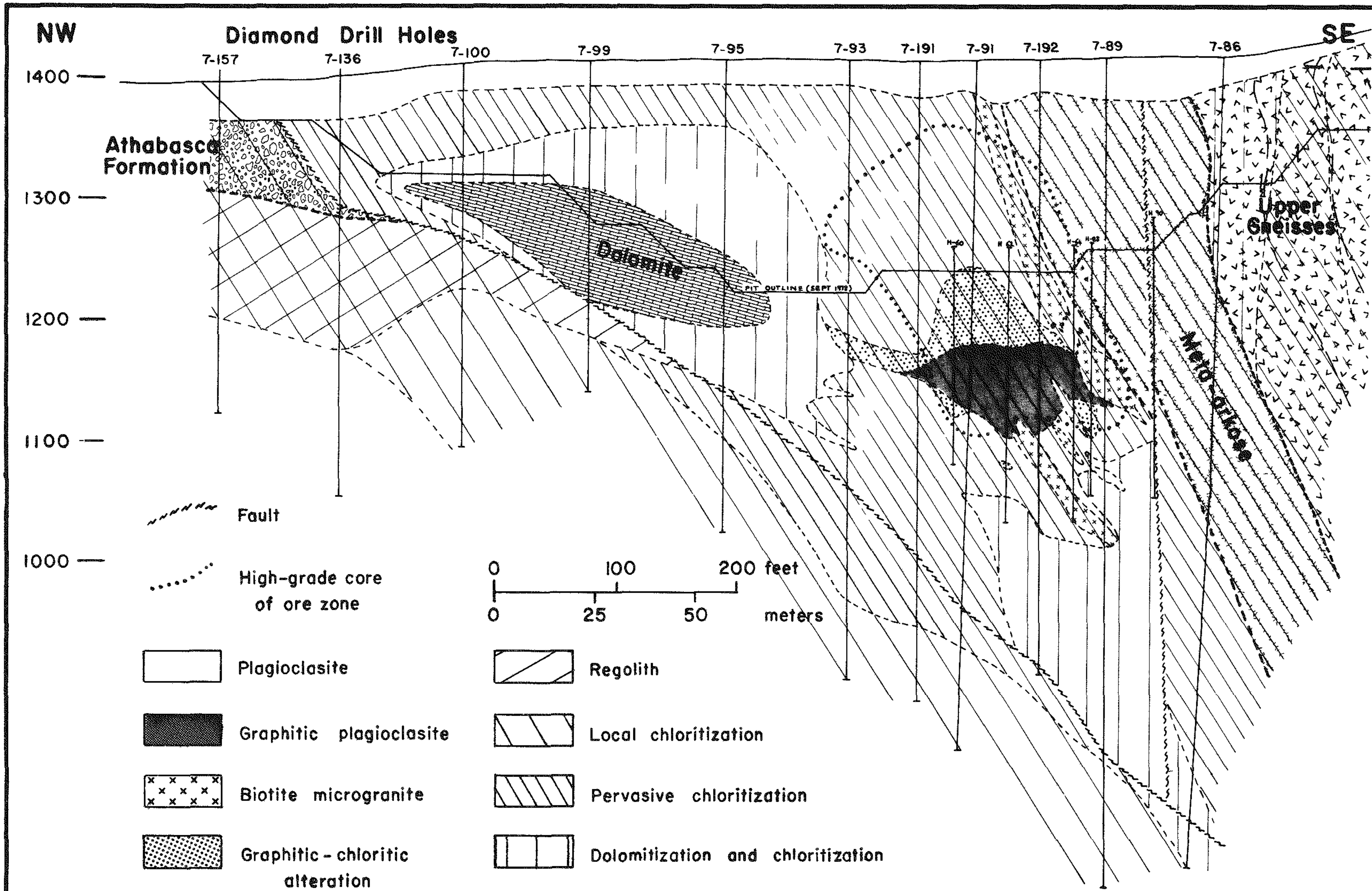


Figure 24. Geologic cross section of Rabbit Lake Deposit, Saskatchewan (from Sibbald, 1978).

Mineralization. The uranium ore mineralogy is simple, consisting essentially of pitchblende and its alteration products. Hematite is an important gangue mineral (up to 10 percent) and quartz and carbonate are present in lesser amounts. The deposit occurs as a relatively small core of high-grade ore surrounded by a halo of lower grade ore, all within a zone of chloritic alteration.

Hoeve and Sibbald (1977) recognize two stages of mineralization: a primary ore accompanied by little alteration and a secondary or younger ore associated with chloritization. The "primary" ore consists of massive colloidal pitchblende, accompanied by calcite and quartz. It is characteristic of the high-grade zone where it fills veins and breccias between xenoliths not significantly affected by chloritization. This mineralization appears to have formed prior to chloritization, and it has also been found in the generally unmineralized, overthrusted block on the north side of the Rabbit Lake fault.

"Secondary" mineralization occurs only in altered rocks, generally in zones of "green" chloritic alteration. It consists of sooty pitchblende and coffinite impregnating the host rocks and/or coatings on quartz crystals in vugs and fissures. The sooty pitchblende is considered to be syngenetic with chloritization.

Rimsaite (1977b) identified five varieties of pitchblende, one of them crystalline. The oldest generation is colloidal and occurs in veinlets, stringers and within breccia fragments within a matrix of tightly intergrown green chlorite-mica (sericite?)-montmorillonite with some fragments of quartz, yellow tourmaline, apatite, anatase, and occasionally K-feldspar. The oldest mineralization is cut by numerous joints and fissures which have been filled with secondary uranium minerals, calcite, and serpentine. In polished section, pitchblende shows variable reflections and indications of incipient alteration. Partly resorbed pitchblende is surrounded by fine-grained "crystals of pitchblende" which formed in a matrix of phyllosilicates.

The main period of uranium remobilization was accompanied by the removal of radiogenic lead, and the formation of galena and emplacement of other sulfides, arsenides, and selenides. Subsequently, fine-grained aggregates of sooty pitchblende, calcite, and coffinite-coated chalcopyrite, pyrite, quartz, calcite, titanium minerals, and "thucholite". Coffinite is poorly crystallized and is easily mistaken for sooty pitchblende. A number of secondary uranium minerals such as uranium oxide-hydrates, silicates, sulfates, and "thucholite" are also found in the orebody.

The principal gangue minerals comprise several generations of quartz in massive and crystallized habits, calcite, dolomite, minor ankerite, siderite, malachite, and widespread hematite. Accessory sulfides, selenides, and arsenides include galena (Pbs), clausthalite (PbSe), sphalerite (Zns), pyrite (FeS_2), chalcopyrite ($CuFeS_2$), bornite (Cu_5FeS_4), chalcocite (Cu_2S), covellite (CuS), niccolite (NiAs), carrolite ($CuCo_2S_4$), minerals of the linnaeite-siegenite group (Co_3S_4 with Ni), and cobaltiferous pyrite.

Paragenetic relations (Fig. 25) based on detailed fieldwork have been developed by Hoeve and Sibbald (1978c). They distinguish three stages of mineralization:

Stage 1. The earliest mineralization occurs as fracture- and breccia-fillings in comparatively unaltered rocks affected by dark-green chloritization. The mineralized veins are often surrounded by a hematitic, cream-colored alteration halo in which the dark-green chlorite and quartz of the wall rock are replaced by calcite. These relations suggest that stage 1 mineralization was introduced into an older, dark-green chlorite rock.

Mineralized veins consist of pitchblende, euhedral quartz, and calcite accompanied by adularia, chlorite, sulfides, coffinite, and hematite. Pitchblende of two different stages has been recognized. The first, pitchblende (1), is relatively hard, has a high reflectivity, and forms colloform encrustations on wall rocks and breccia fragments; the second, pitchblende (2), tends to be massive, has lower but variable reflectivity, replaces pitchblende (1) along fractures and growth surfaces, is commonly associated with coffinite, and occurs intergrown with sulfides and arsenides, e.g., galena, pyrite, arsenopyrite, chalcopyrite, bornite, chalcocite, and covellite. The proposed paragenetic sequence is shown in Figure 26.

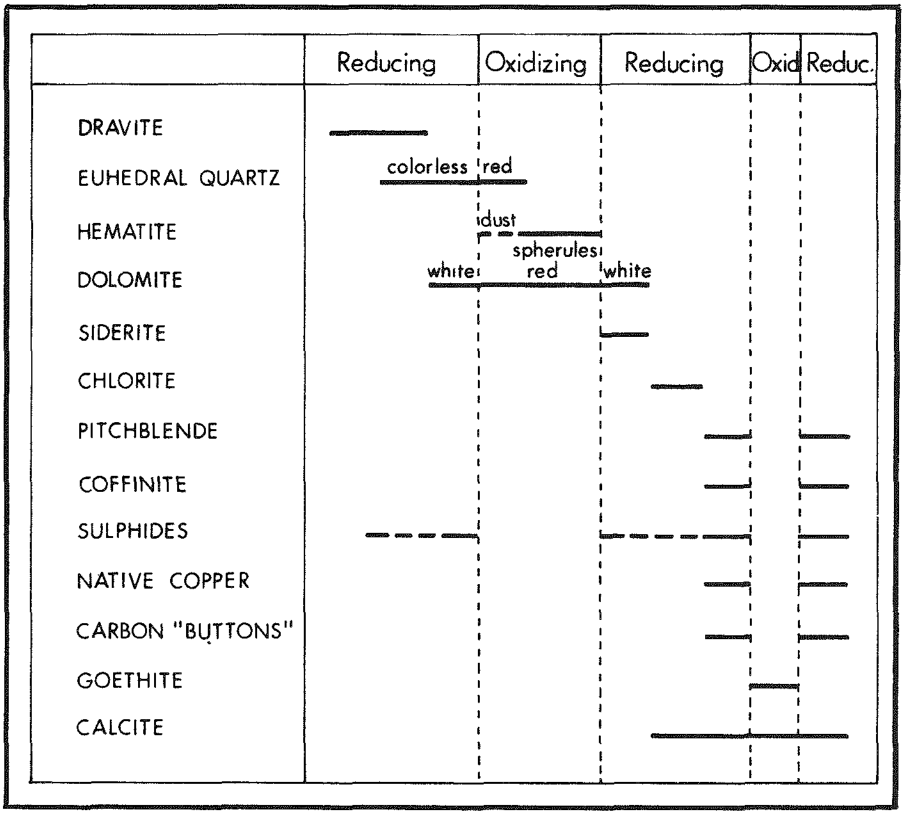


Figure 25. Idealized paragenetic sequence for the stages of mineralization at Rabbit Lake (from Hoeve, 1977; and Hoeve and Sibbald, 1978b).

Stage 2. The second stage of mineralization is associated with the formation of euhedral quartz veins which formed between the episodes of red and pale-green alteration. The mineralogy of these veins is complex and includes dravite, euhedral quartz, dolomite, calcite, hematite, siderite, goethite, pitchblende, coffinite, chlorite, psilomelane, kaolinite, sulfides, arsenides, native copper, and glassy pitchlike "buttons" of amorphous carbon or hydrocarbon. These are rarely all present together, and most of the veins have a simple mineralogy with dravite, euhedral quartz, hematite, and a few other minerals. Dolomite is only important in veins which intersect dolomitic portions of red alteration zones.

Although veins of euhedral quartz are abundant throughout the alteration envelope, few are mineralized with uranium. Those which are occur within the higher grade portion of the orebody and display very complex mineralogy. The sequence of mineral formation reflects oscillation between reducing and oxidizing intervals, the latter characterized by the formation of hematite or goethite.

Stage 3. The third stage of mineralization is represented by impregnation of sooty pitchblende and coffinite along fractures and joints associated with pale-green alteration. This stage appears to be a reworking of earlier mineralization rather than an introduction of additional uranium.

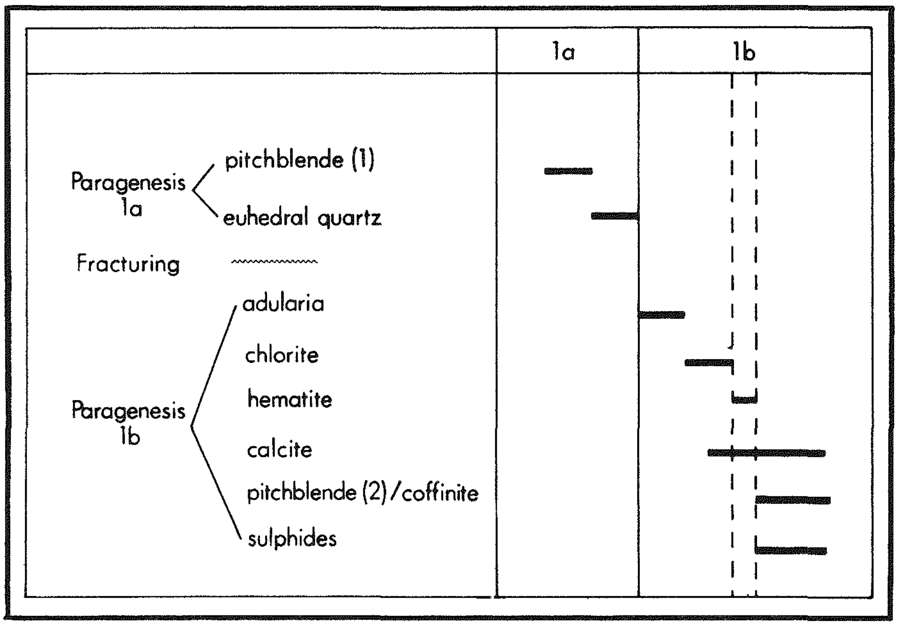


Figure 26. Idealized paragenetic sequence for stage 1 mineralization at Rabbit Lake (from Hoeve, 1977).

Cumming and Rimsaite (1979) present the following data with respect to mineralization:

> The mineralized zone coincides with a severely fractured, brecciated, and altered zone. The high grade ore (>0.5 wt.% U_3O_8) consists of broken fragments of pitchblende and iron oxide crusts, fracture fillings in quartz and in altered mica flakes, and amorphous uranium-carbon compounds that impregnate impure altered metaquartzite. Principal ore minerals composing the high grade ore are five types of pitchblende, coffinite, Pb-rich uranyl-bearing minerals, such as kasolite, masuyite, tri-uranium-lead heptaoxides, and their hydrated equivalents, all transected by carbonate and uranophane veinlets. The five types of pitchblende have been distinguished on the basis of apparent sequence of crystallization, morphological features, and their original radiogenic lead content. Pitchblende of type P-1 is the least altered and has retained the largest proportion of its radiogenic lead. It grades to pitchblende of type P-2 along fractures by losing radiogenic lead. In many specimens studies, pitchblende of type P-2 is fractured and replaced by secondary silicates and carbonates of the groundmass. Locally, minute remnants of pitchblende of type P-2 recrystallize to "euhedral cubic pitchblende" of type P-3. Pitchblende of type P-4 was observed in areas affected by sulphide, selenide, and arsenide mineralization. Uranium liberated from pitchblende of types P-1 and P-2, that are partly replaced by copper sulphides and niccolite, has recrystallized to a fine-grained mixture of Pb-poor pitchblende of type P-4, coffinite, and sulphides (Rimsaite 1978). Pitchblende of type P-5 consists of relatively pure uranium oxide. It precipitates as thin rims and crusts on, and in fractures of, various silicates, carbonates, hydrocarbons, and sulphides.
>
> The low grade ore forms a halo surrounding the high grade ore zones. It contains an erratic distribution of resorbed and silicified pitchblende, coffinite, and hydrous Pb-poor secondary uranyl-bearing minerals (uranophane, sklodowskite, boltwoodite, zippeite, becquerelite, liebigite, bayleyite, and uraniferous mixed-layer phyllosilicates have been identified). These form coatings and crusts on quartz and in fractures of hydrated metasediments and pseudomorphous replacements of pitchblende in oxidation zones. In the lower grade halo the U_3O_8 grades range from 0.5 wt.% to 0.1 wt.% (the cutoff value).

Pagel et al (1979) describe fluid inclusions in gangue minerals from the Rabbit Lake deposit as follows:

> In automorphic quartz crystals, there are many types of fluid inclusions. These can be divided into two principal groups: (1) Group I is characterized by two fluid phase inclusions with several solid phases, notably a cube of halite and acicular birefringent solids. Depending on the quartz crystal, the temperature at which the bubble disappears is either constant around 110°C or very variable between 127°C and 191°C. The cubes of halite have exactly the opposite behavior to the vapor bubbles in the same inclusions: in inclusions with highly variable temperatures of homogenization of the two fluid phases, the temperature of dissolution of the halite cube is relatively constant at 145 ± 15°C,

whereas in inclusions having constant fluid-phase homogenization temperatures, the temperature of dissolution of the halite cube is highly variable between 161 and 237°C. In one sample, a hydrate which melts between +2.7°C and +27.6°C has been observed. When there is no cube of halite in the inclusions, the melting temperatures of ice are very low at -23.7°C and -29.5°C. (2) Group II is characterized by inclusions having one or two fluid phases and which show two kinds of fluid phase transformations between -18°C and +3.3°C.

In dolomite crystals two or three fluid-phase inclusions are observed with solid phases, a cube of halite and an hexagonal flake of hematite. The melting temperatures of solid CO_2 are 56.6 $\pm$ .2°C and of the hydrates between -6.3°C to +7.1°C. Homogenization temperatures of the two CO_2 phases lie between +13.8°C and +30.7°C. When there is no cube of halite, the melting temperatures of ice are between -25.8°C and -26.9°C. When there is a cube of halite, the average dissolution temperature is +105°C. The H_2O-CO_2 inclusions decrepitate at temperatures above +130°C, before total homogenization. The homogenization temperatures, when the CO_2 content is very low, vary from +119.5°C to +144.7°C.

Both the $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios of these analyzed dolomites are very uniform, with values of $\delta^{13}C = 6.3 \pm 0.3\%$ (PDB) and $\delta^{18}O = + 15 \pm 0.7\%$ (SMOW). Assuming isotopic equilibrium between fluid and dolomite the approximate isotopic composition of the coexisting fluid is calculated using the carbonate-water and-CO_2 fractionation factors, the fluid inclusion temperatures and the isotopic data for the carbonates. The calculated isotopic composition of the water is $\delta^{18}O \sim 2\%$, and for the CO_2 is $\delta^{13}C \sim -10\%$.

Calcite contains two fluid phase inclusions with an aqueous phase of low salinity (1% weight eq. NaCl). Homogenization temperatures vary between +105°C and +127°C. The isotopic composition of a calcite is $\delta^{13}C = 7.6\%$ and $\delta^{18}O = +16.7\%$. The calculated isotopic composition of water (in equilibrium) is $\delta^{18}O \sim +1.5\%$ and of the CO_2 is $\delta^{13}C \sim 10.6\%$.

Neutron activation analysis of leachates (Pagel and Jaffrezic, 1977) have shown that the Cl/Br ratio is very low for both the brine in quartz (55) and the brine in dolomite (65). The values are similar to those obtained for formation waters in some sandstone basins.

The descriptions and comparisons of the ore and gangue minerals of the Rabbit Lake deposit as described by Hoeve and Sibbald (1978c), Rimsaite (1977b), and Cumming and Rimsaite (1979) lead to some confusion regarding the minerals and their relative times of formation. It would be of value if the researchers studying this deposit could correlate the reported parageneses into a single, consistent paragenetic sequence.

Geochronology. Knipping (1974) has provided the following isotopic ages: (a) metasediments, 1600 to 1800 m.y. (Hudsonian metamorphism); (b) foliated granite, 2000 to 2100 m.y. [possibly rejuvenated from Kenoran age (2500 m.y.)]; (c) diabase that cuts Athabasca Formation, 1113 m.y.; (d) pitchblende apparent ages that range from 190 to 1320 m.y. He regards a formation age for the primary pitchblende generation at about 1000 m.y. as the most reliable age. This corresponds well with an age of 1075 m.y. given by Little (1974).

Cumming and Rimsaite (1979) report (a) a minimum age for initial ore formation of 1281 ± 11 m.y.; (b) formation of a younger galena generation with high radiogenic lead concentration during the period 850-700 m.y.; (c) formation of uraniferous phyllosilicates at about 440 m.y.; and (d) coffinite overgrowths on pitchblende at about 200 m.y. (see Table 5).

Table 5. Selected isotopic data from the Beaverlodge area and Rabbit Lake deposit, Saskatchewan (from Cumming and Rimsaite, 1979).

	Beaverlodge-Goldfields area		Rabbit Lake deposit	
Selected characteristic data	Robinson (1955)	Koeppel (1968)	Knipping (1974)	This study
Selected isotopic ratios of galena and sulphides Pb^{206}/Pb^{204};Pb^{207}/Pb^{204};Pb^{208}/Pb^{204}		124.4; 36.7; 36.7 234.4; 44.1; 37.0 547.1; 70.0; 44.1		125.8; 23.8; 48.4 285.2; 35.1; 51.4 1576.6; 126.1; 53.9
Losses of radiogenic Pb from pitchblendes Origin and age of galena and clausthalite	Evidence of reworking	Multistage lead Episodic Pb losses from pitch-blende 1100 m.y. ago 270 m.y. ago 0-100 m.y. ago	820 m.y. "age of galena"	Evidences of Pb diffusion and episodic Pb losses from radioactive minerals 850 m.y. "recrystallization of galena in pitchblende"
Pb/U ratios in concentrates		1/3.5; 1/6; 1/66		1/2.9; 1/9; 1/665
Selected examples of differences between Pb^{206}/U^{238};Pb^{207}/U^{235};Pb^{207}/Pb^{206} apparent ages	1270; 1440; 1785 1280; 1385; 1590 210; 235; 535	1690; 1730; 1795 1050; 1225; 1580 221; 273; 310	1320; 1248; 1124 508; 662; 1240 190; 220; 564	1975; 1621; 1163 729; 795; 984 26; 31; 417
Suggested periods of mineralization (in m.y.) reworking pitchblende crystallization of secondary radioactive minerals	1400-1600 850-950 350-230	1780 1125 270 0-100	(1320) 1000-1100 (860) (390) (110)	1285 1081 (911) (850) (726) 440 200

Ore Control and Metallogenesis. Knipping (1974) evaluated the ore controls based on drill-core investigations, and his observations may be summarized as follows:

(1) Uranium mineralization occurs in direct contact with the unconformity between the metasedimentary basement and the Athabasca Formation.

(2) Mineralization extends to depths of only about 100 m below the unconformity.

(3) Alteration of the host rocks of the orebody postdates (Hudsonian) metamorphism and predates the oldest ore generation. The alteration is restricted to proximity to the paleosurface and does not extend more than 100 m in the metasediments.

(4) Alteration and mineralization are directly associated with a permeable brecciated and fractured zone. The structural deformation shows no time relationship to the Hudsonian orogeny.

(5) Ore mineralization is found only in the overthrown block of the Rabbit Lake reverse fault.

(6) Initial uranium deposition occurred at about 1000 to 1100 m.y., i.e., 500 to 600 m.y. after the Hudsonian orogeny and after the peneplanation of the Hudsonian terrane.

(7) Ore composition is simple, dominated by uranium and iron with subordinate amounts of other elements.

(8) Ore formation occurred in open structures with pitchblende precipitating as simple coatings of vugs, fissures, etc.

Based on these parameters, Knipping (1974) deduced that the initial ore formation was due to supergene processes.

Hoeve and Sibbald (1977, 1978c), based on investigations after the mine had been developed as an open pit, note the following important relations:

(1) Primary mineralization occurs in strongly brecciated rocks that were deformed prior to mineralization.

(2) Isotopic age date yielded 1100 m.y. for the oldest pitchblende, indicating that it is distinctly younger than the Athabasca Formation (1350 m.y.).

(3) Dark-green chloritization predates the earliest pitchblende whereas younger red and pale-green, chloritic alteration are superimposed upon the primary ore. Furthermore, the younger alterations are not entirely restricted to the unconformity (zone of paleoweathering) as they have been noted to transect the Rabbit Lake Fault, regolith, and reddish clay horizons within the Athabasca Formation.

(4) Sooty (second stage) pitchblende appears to have formed immediately after the oxidizing event indicated by the red chloritic alterations. The second stage mineralization, therefore, appears to have developed from the primary mineralization during the formation of the red and pale-green chloritic alteration.

(5) Slickensides with red chlorite alteration are overgrown by pale-green chlorite, suggesting that deformation occurred between the formation of the two types of chlorite. Other observations, such as veinlets of dolomite and replacement zones of red alteration cut by euhedral quartz veins and associated green alteration, support this interpretation.

(6) The formation of the Rabbit Lake Fault can be correlated to the phase of deformation that occurred between primary mineralization and the hematitic alteration. This is indicated by the observation that minor amounts of unaltered primary mineralization occur beneath the fault, whereas green chloritic alteration and dolomite crystals typical of the red chlorite alteration exist on the fault planes.

(7) Homogenization temperatures of fluid inclusions in quartz and dolomite, as determined by Little (1974) and Pagel (1975b), indicate formation temperatures between 180° and 225°C and 160° $\pm$ 10°C, respectively, and pressures of 100 bars.

Based on the above criteria, Hoeve and Sibbald (1978c) developed concepts of ore formation for the Rabbit Lake deposit (Table 6). They favor diagenetic hydrothermal processes which may be summarized as follows:

(1) After deposition of the Athabasca Formation above the unconformity, diagenetic fluids moved down through the sandstones and became heated due to the geothermal gradient.

(2) Access of the fluids to the impermeable crystalline basement was negligible except along structures.

(3) These solutions would have been oxidizing, as indicated by the pervasive distribution of hematite within Athabasca sandstone, thus capable of transporting uranium and of leaching uranium from the sandstones.

(4) The formation of pitchblende from oxidizing solutions requires reduction which could be accomplished by ferrous iron (Fe^{++}) in silicates of the host rocks. Hoeve and Sibbald (1980) suggest methane, derived from alteration of graphite, provided the reductant for the uranium.

Table 6. Geologic history of the Rabbit Lake deposit (from Hoeve and Sibbald, 1978c).

1350 ± 50 m.y.	-	Weathering of basement rocks, i.e., formation of pre-Athabasca regolith.
1350 ± 50 m.y.	-	Sedimentation of Athabasca Formation.
	-	Brecciation.
	-	Dark-green chloritization (?).
1100 m.y.	-	Stage 1 of mineralization; lustrous colloform pitchblende.
	-	Brecciation - Rabbit Lake Fault (?).
	-	Red alteration; chloritization; tourmalinization; silicification; dolomitization.
	-	Brecciation.
	-	Stage 2 of mineralization; massive pitchblende and coffinite and veins of euhedral quartz.
	-	Pale-green alteration; some silicification.
	-	Stage 3 of mineralization, sooty pitchblende and coffinite.
	-	Subsequent reworking of deposit.

(5) During the red chloritic alteration phase, which was contemporaneous with the activation of the Rabbit Lake Fault, oxidizing ground waters redistributed the uranium.

(6) A subsequent reducing event, supported by the pale-green chlorite, reprecipitated uranium as pitchblende and coffinite in the altered host rock.

(7) Renewed oxidation remobilized uranium again and it was finally precipitated as coatings of sooty pitchblende on quartz crystals.

According to the foregoing interpretation, chloritization was not related to the formation of the primary uranium mineralization but was formed during the destruction of the primary ore and with the formation of the secondary mineralization. As a source for the uranium, Hoeve and Sibbald (1978c) point to uranium previously contained in the Athabasca sandstone.

Cumming and Rimsaite (1979), based largely on their studies of uranium and lead isotopes (Table 5), made the following observations:

(1) The pitchblende and host rocks in the Rabbit Lake deposit are fractured and altered so that only small areas (a few microns in size) of unaltered pitchblende, having original, high Pb/U ratios, have been preserved.

(2) As a result of the recurrent fracturing and superimposed alteration, the original pitchblende was replaced by sulfides, selenides, and arsenides, and was preserved only in the core of brecciated ore fragments. The leaching of uranium and radiogenic lead from pitchblende during this alteration led to the formation of secondary minerals with extremely high lead content.

(3) An age date of 1081 m.y. for Pb-rich secondary oxidation products is similar to the age of pitchblende partly replaced and associated with hematite and uranium oxides reported by Koeppel (1968) and Rimsaite (1978). It is also compatible with dates reported by Little (1974) and Knipping (1974). Based on their work, the minimum age for initial ore formation is 1281 $\pm$ 11 m.y. compared with 1000-1100 m.y. suggested by Knipping (1974) and Little (1974). Elsewhere Cumming and Rimsaite (1979) state that this "does not necessarily represent the original time of formation but at least is a lower limit to that time."

(4) The diffusion and episodic removal of radiogenic lead from pitchblende after the initial alteration and replacement of pitchblende by sulfides and arsenides led to the formation of galena with high radiogenic lead concentration during the period 850-700 m.y.

(5) Mineral formation stages involving uranium and silica are represented by the formation of uraniferous phyllosilicates at about 440 m.y. and coffinite overgrowths on pitchblende formed at about 200 m.y. A comparable age of coffinite formation at Beaverlodge (100 m.y.) was reported by Koeppel (1968).

(6) The hydration and final resorption of Pb-depleted pitchblende, replacement by halloysite and montmorillonite clay minerals, and crystallization of hydrous uranyl-bearing mineral aggregates in fractures of the clays, are occurring at the present time.

Shape and Dimension of the Deposit. The Rabbit Lake deposit consists of a high-grade core with a low-grade halo. The high-grade core is an elongated northeast-southwest trending body with a length of about 270 m, a width up to 90 m, and a depth down to 80 m. Mineralization occurs in the form of almost massive fissure and breccia fillings with grades of several percent to tens of percent of uranium. The principal ore mineral is massive colloform pitchblende. A low-grade zone occurs around the high-grade core and consists predominantly of remobilized uranium in the form of sooty pitchblende and coffinite filling joints and fissures and also impregnating altered country rock.

The low-grade zone is triangular in plan with a length in the northeast-southwest direction of about 550 m, a maximum width of 250 m and an average width of 90 m. On a vertical section oriented approximately northwest-southeast, the orebody is also approximately triangular, the Rabbit Lake Fault being the footwall edge. The maximum depth below the surface is about 150 m.

Grade and Reserves at Rabbit Lake. The proven reserves are about 20,000 st U_3O_8 and the average grade of ore is 0.4 percent U_3O_8 (Northern Miner, September 22, 1977).

Collins Bay A & B. The deposit is situated on the west shore of Wollaston Lake approximately 700 km to the northeast of Saskatoon and about 10 km to the north of the Rabbit Lake Mine. Rabbit Lake is serviced by an all-weather road from La Ronge, 350 km to the south.

The first mineralization of Collins Bay was found by drilling in 1971-72. It led to the discovery of the A-Zone at the north end of the deposit. Another ore zone (B) was discovered by follow-up drilling in subsequent years.

Geologic Setting of Mineralization. The area of Collins Bay lies regionally on the eastern edge of a broad transitional zone between the predominantly linear Wollaston lithostructural domain to the east, and the predominantly non-linear Mudjatic domain to the west. The Wollaston belt is composed primarily of amphibolite to granulite facies supracrustal gneisses of the Aphebian Wollaston Group overlying granitoid gneisses of probable Archean age. The Archean (?) gneisses form elongate domes mantled by graphitic pelitic gneisses, quartzo-feldspathic gneisses, and pegmatoids. The Helikian Athabasca Formation overlies the crystalline rocks in the western part of the area. The Athabasca Formation consists of mature quartz sandstones, grits, lesser conglomerates, siltstones, and shales. The crystalline rocks under the basal conglomerates of the Athabasca Formation exhibit a weathered zone of lateritic character.

All rocks located along the Athabasca unconformity in the Collins Bay area have been subjected to pervasive post-Athabasca alteration which produced muscovite and clay, but apparently without the addition of magnesium or boron as found at Rabbit Lake. The alteration may extend upwards or downwards from the unconformity for over 300 m where permeable zones permit.

Several episodes of post-metamorphic faulting have produced three principal fault trends, two of which are normal faults that (a) strike northeast-southwest and dip steeply southeast, (b) strike north to northwest and dip steeply, and the third of which comprises (c) reverse faults that strike between north and east-northeast and dip moderately to the east. The reverse faults include the Collins Bay Fault that trends generally northeast, but locally north-south and east-west, and dips to the southeast or east at generally less than 60 degrees. The thrust faults occur at the Athabasca sandstone-crystalline basement unconformity as complex zones of close-spaced shears several tens of meters and more wide.

Mineralization. Mineralization occurs along the Collins Bay thrust fault as a mineralized zone approximately 3,000 m long. Two economic orebodies have been discovered to date. The A-Zone deposit occurs about 1,800 m to the north of the B-Zone, and additional uranium concentrations are known at two places between A and B deposits.

A-Zone Mineralization. The ore mineralogy comprises two varieties of pitchblende, rammelsbergite and pararammelsbergite, and traces of galena and sphalerite. Significant concentrations of silver and gold accompany the uranium mineralization, and niccolite has been tentatively identified. The nickel mineralization forms a halo around the uranium mineralization. Secondary uranium minerals occur in the overburden.

The orebody is located (a) at the crystalline basement-Athabasca sandstone unconformity, and (b) immediately above the contact of the Lower Proterozoic Aphebian metasediments and underlying Archean rocks (Figs. 27 and 28).

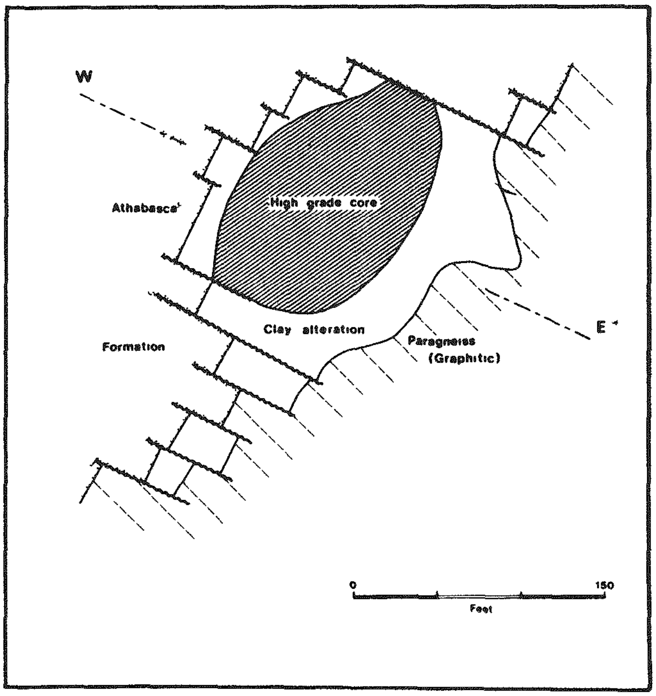


Figure 27. Schematic plan of the A-Zone, Collins Bay deposit, Canada (from Jones, 1980).

The mineralization occurs in, and is restricted to, a thick lens of "clay" alteration. The highest grade uranium mineralization is restricted to the center of this zone, occurring in fine, dark "clay", interlayered "clay", massive black pitchblende-rich seams, and hard, black lenses of solid pitchblende. Mineralization decreases gradually with depth below the high-grade core and extends into the altered basement rock. The western, northern, and possibly southern edges of the orebody are developed along fault-controlled contacts with the Athabasca sandstone. The western boundary consists of at least two series of northeast to southwest-trending, east-dipping thrust faults which belong to the Collins Bay fault system. The northern and southern boundaries are controlled by northwest to southeast-trending faults.

B-Zone Mineralization. Jones (1980) reports that uraninite, coffinite, gersdorffite, niccolite, skutterudite, galena, chalcopyrite, millerite, pyrite, ankerite, graphite, and carbonaceous material occur in this deposit. Pitchblende is present locally.

Ore-grade drill cores contained a gas mixture of methane, hydrogen, and carbon dioxide. Hard, glassy hydrocarbon buttons are found in the orebody. They form cores to globular, colloform nickel arsenide aggregates, and radially textured spherules of ankerite.

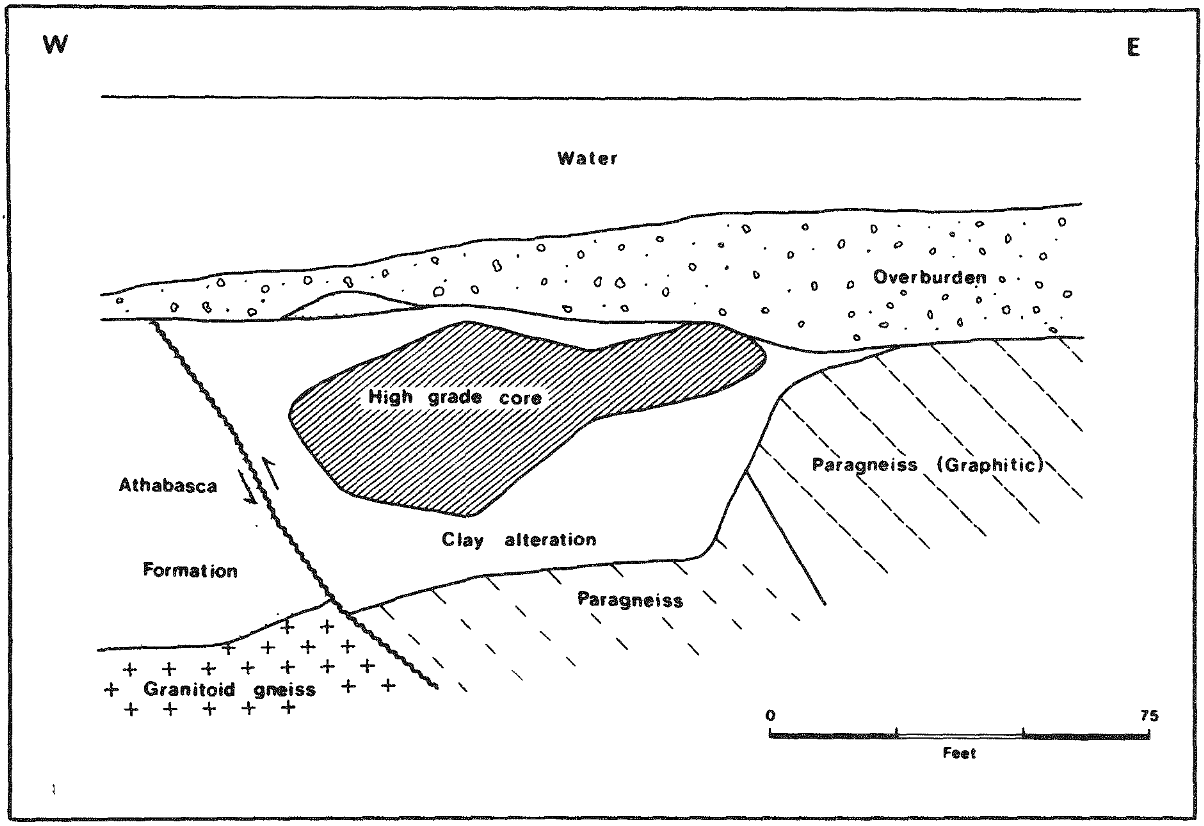


Figure 28. Schematic cross section of the A-Zone, Collins Bay deposit, Canada (from Jones, 1980).

The mineralization follows the Collins Bay thrust fault which strikes about north-south in the southern part and turns northeast in the northern section (Fig. 29). All but a small portion of the mineralization occurs within the Athabasca Formation, within and near a zone of intense imbricate thrust faults and clay alteration. The sole of the imbricate thrust zone lies along the Archean-Aphebian contact or in graphitic rocks just above this contact. The zone of imbrication occurs where the thrust sole entered the Athabasca sandstone and splayed into a rather flat-lying wedge of shear zones.

Mineralization in the sandstone consists of pitchblende and mixed pitchblende and nickel arsenides emplaced as intergranular fillings, fine dusting on grain boundaries, massive pods, and as veins. Mineralization in the clays generally occurs as powdery disseminations that produce a gray to black colored clay with occasional lumps of massive pitchblende and nickel arsenides, resembling the main clay host of the A-Zone. Most of the mineralized sandstone directly overlies granitoid gneisses of probable Archean age, but is, nonetheless, adjacent to graphitic horizons. Occasionally uranium is present in graphitic rocks, but only where they contain less graphite, where they are more intensely fractured, and where they are more altered than is customary.

The limits of the mineralization on the eastern side of the deposit coincide with overthrusted graphitic paragneisses that are locally the basal Aphebian metasediments. On its western side, the limit of mineralization corresponds with reduced imbrication and clay concentration.

In the northern part of the orebody, the mineralized zone rises somewhat within the Athabasca Formation. This is particularly apparent northeast of the bend in the deposit, where the base of the mineralization terminates against the erosion limit of the clay zone. In addition, the graphitic rocks at the north end of the deposit are replaced by pegmatoid masses which may also have controlled the distribution of mineralization.

A-Zone Alteration. The alteration consists of well-developed "clay" which changes gradationally into strongly altered quartzo-feldspathic gneisses, pegmatoids, and graphitic pelitic gneisses that overlie granitoid gneisses of probably Archean age. Some of the alteration "clay" is multicolored, but the majority is a gray to black graphitic "clay".

B-Zone Alteration. The zone of mineralization and the surrounding rocks are characterized by well-developed clay alteration as intergranular matrix filling along discrete fault slip planes, and as massive units several centimeters to one meter thick. The clay and the host sandstone show a wide range of vivid colors including red, purple, brown, and green. The amount of clay decreases from east to west across the deposit and appears to be related to the intensity of thrust faulting.

Clay alteration and fracturing are most strongly developed in the vicinity of the sharp bend in the thrust fault near the north end of the deposit. Here also are found the highest uranium and nickel grades.

Geochronology. Jones (1980) reports U/Pb ages for three samples from the B-Zone. Two samples collected from seemingly similar high-grade pitchblende zones give ages in the range of 440 and 1300 m.y. The third sample gave strongly discordant ages.

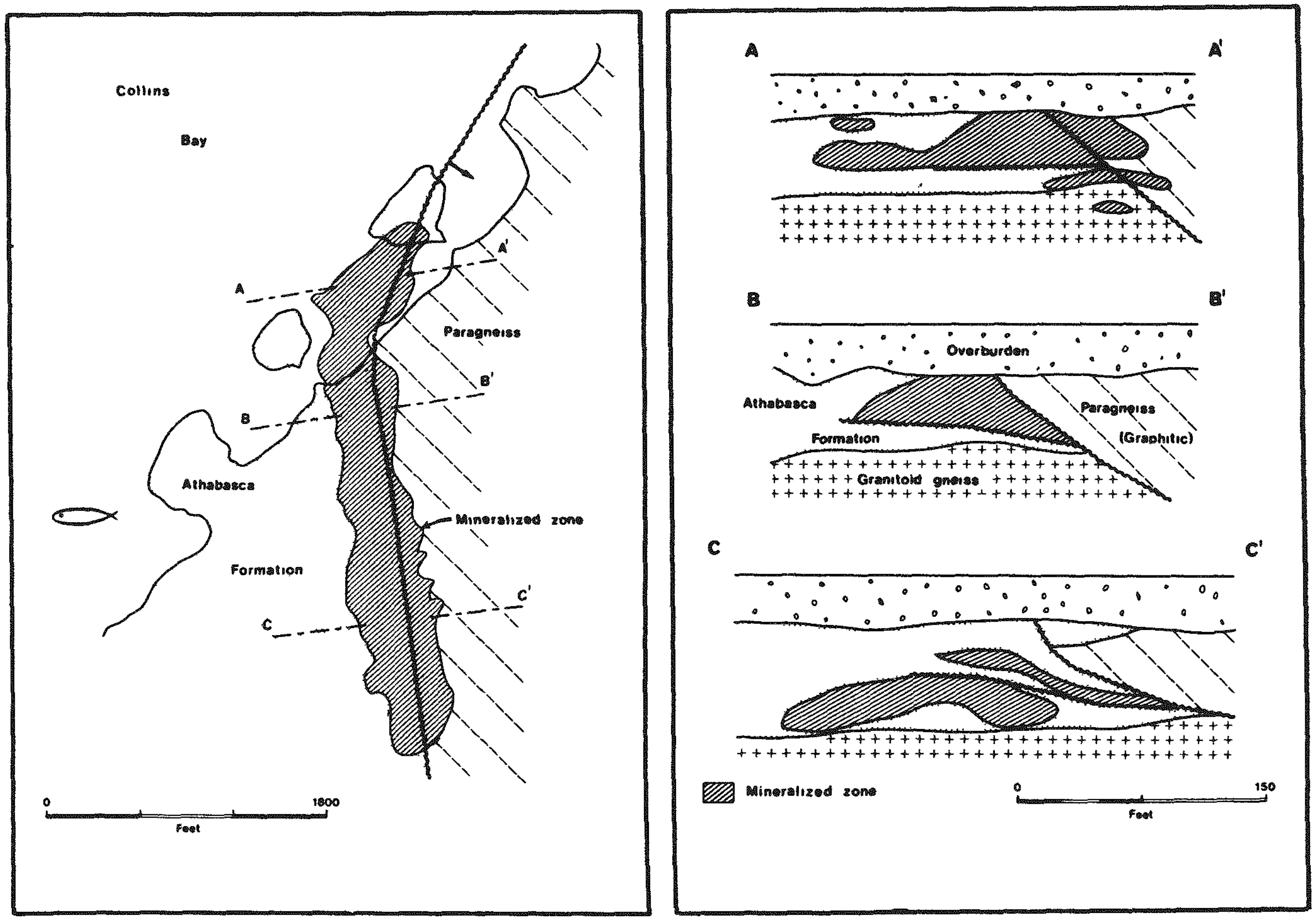


Figure 29. Schematic plan and cross sections of the B-Zone, Collins Bay deposit, Canada. Faults indicate the limits of the zone of imbrication (from Jones, 1980).

Ore Control and Metallogenesis. The Collins Bay deposits display mineralogic, lithologic, and structural controls (Jones, 1980). The structural control is provided by the regional Collins Bay thrust system, particularly by local zones of intense, imbricate faulting. In the B-Zone, the change in strike of the Collins Bay Fault in the northern part of this orebody may have provided an additional structural control.

The mineralogic control is indicated by the association of uranium and "clay" alteration and carbonaceous material in the basal part of the Athabasca sandstone. The "clay" was most likely derived from pulverized and altered slivers of crystalline basement. A lithologic control on the distribution of uranium mineralization appears to have been the proximity of graphite-bearing rocks, although mineralization seldom occurs within the graphitic rocks themselves. The uranium grade decreases markedly where adjacent graphitic rocks are replaced by pegmatoid masses.

With respect to ore formation, Jones (1980) favors the diagenetic-hydrothermal model of Hoeve and Sibbald (1978c), and he summarized the essential features of the model as follows:

(1) After the deposition of the Athabasca sandstone, oxidizing, diagenetic ground waters produced weathering and oxidation of the sandstones.

(2) Fracture zones within the metasedimentary basement provided access for the oxidizing diagenetic solutions which altered graphite to form methane.

(3) The methane migrated upwards into the overlying sandstones where it reduced and precipitated the ore components from the oxidized formation waters.

Permeability within the graphitic rocks of the Wollaston Group and perhaps the Athabasca Formation was probably provided by the Collins Bay thrust system, particularly in zones of imbricate faulting. Ore grades seem to correlate with more intense imbrication and zones of well-developed "clay".

Ore-grade drill cores from both Collins Bay and Rabbit Lake have a characteristic odor that has been determined to result from a gas mixture that contains methane, hydrogen, carbon dioxide, and probably other components. This association suggests that hydrocarbons may have been present during ore formation. Additional evidence is found in the hard, glassy hydrocarbon buttons that form the cores of globular, colloform nickel arsenide aggregates, and radially textured spherules of ankerite. Furthermore, the mineralization at Collins Bay is strongly related to the presence of adjacent graphite-bearing rocks.

The mottled color patterns of the "clays" and altered rocks in and around the deposit reflect the distribution and oxidation state of iron. Oxidized and reduced zones are complexly distributed, suggesting numerous and erratic changes in the oxidation state of ground waters. In terms of the "diagenetic-hydrothermal" model, Jones (1980) explains this by either (1) variation in the rate of reductant produced by the graphite as a result of changes in pressure or temperature, or (2) poor mixing of the reduced methane-bearing solutions and the oxidized metal-bearing solutions.

Shape and Dimension of Deposits. The A-Zone orebody is elliptical in plan with a northeast-southwest axis 45 m long and a northwest-southeast width of about 37 m. It has a maximum thickness of 15 m. The orebody is covered by up to 7 m of overburden and is below a lake.

The B-Zone is situated approximately 1,800 m to the southwest of the A-Zone. It consists of a north-south elongated orebody which turns to the northeast at its northern portion. It is approximately 900 m long, 90 m wide, and an average of 30 m thick. It is covered by up to 10 m of overburden, and its northern end is below Collins Bay.

Production and Reserves. No figures for reserves and grades have yet been published. It is speculated that the size of Collins Bay is on the order of Rabbit Lake, i.e., about 20,000 short tons U_3O_8.

Cluff Lake. Amok Ltd., 1974; Harper, 1977, 1978, 1979, 1980; Herring, 1975; Pagel, 1975a, 1975b; Pagel et al, 1979; Ruzicka, 1975; Tapaninen, 1976.

Cluff Lake is in the western part of the Athabasca Basin, about 300 km north-northwest from La Ronge, and about 150 km southwest from Uranium City. The deposit was discovered by airborne radiometric survey in 1968. There are three principal orebodies, the "D", "N", and "Claude", and a few smaller deposits.

Geologic Setting of Mineralization. The deposit occurs within the Carswell structure, a circular upheaval of crystalline basement rocks (diameter about 40 km) within the Athabasca Sandstone Basin. The impact of a meteor about 470 to 480 m.y. ago is considered the most likely cause of the structure. In the region around the structure, the Athabasca sandstone is flat-lying, whereas within the interior the sediments are strongly fractured and disturbed. The formations and lithologies in the vicinity of the structure are given in Table 7.

The Carswell structure itself is defined by three concentric lithologic zones (Fig. 30): (a) an outer zone of stromatolitic dolomite, (b) a zone, 5 to 6 km wide, of strongly faulted, fractured, and overturned Athabasca sandstone that is interthrusted with and overturned by (c) the central core of crystalline basement. The central zone is occupied by Aphebian and Hudsonian metasediments which include (Fig. 31):

(1) pelitic gneisses, including garnet-sillimanite and garnet-cordierite gneisses;

(2) quartz-feldspar gneisses, including fine-grained quartz-plagioclase-biotite gneiss and porphyroblastic granitoid gneiss (leptynite);

(3) mafic gneisses, including pyroxene-bearing granulites and amphibolites;

(4) pegmatoid and pegmatitic rocks.

Cataclastic derivatives of all these rock types are present. Numerous radial and tangential faults are present within the structure.

Table 7. Formations and rock types present in the vicinity of the Carswell structure (from Harper, 1977).

AGE	FORMATION/LITHOLOGY
Pleistocene to Recent	Glacial, aeolian, fluvial and lacustrine deposits; peat
Unconformity	
Ordovician	Cluff breccia
Intrusive Contacts	
Precambrian	
Helikian	Carswell Formation
	Douglas Formation
	Athabasca Formation
Unconformity	
Archean and/or Aphebian	Pegmatoid rocks
	Mafic gneiss
	Lean iron formation
	Pelitic gneiss
	Quartzofeldspathic gneiss
	Red granitoid gneiss

The peak metamorphic grade in the Aphebian metasediments is been granulite facies. The rocks were subsequently altered to upper-amphibolite facies by retrograde metamorphism. Post-metamorphic, low-temperature, "hydrothermal" alteration is indicated by the alteration of, for example, cordierite in cordierite gneiss to kaolinite, chlorite, and sericite.

The surface of the Aphebian metasedimentary basement was affected by paleoweathering which formed a deep regolith. The conglomerates and sandstones of the Athabasca Formation were deposited with angular unconformity over this surface and are flat-lying except where disrupted by later structures.

Alteration. Mineralized zones are characterized by alteration that includes chloritization, kaolinitization, sericitization, and magnesium and boron metasomatism. Pagel et al (1979), in describing the "hydrothermal" alteration that occurs at the unconformity, state that:

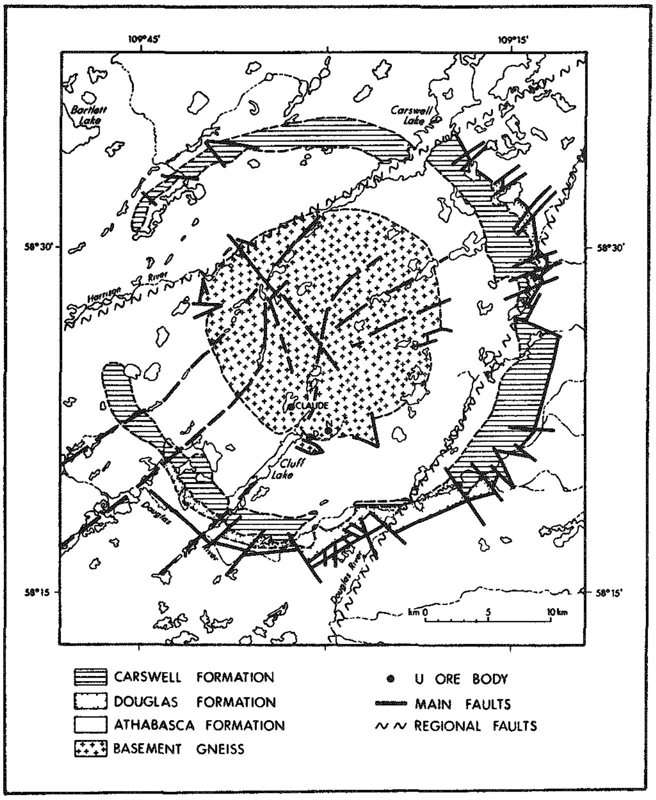


Figure 30. Generalized geology of the Carswell circular structure, Canada (from Harper, 1978, modified from Amok Ltd., 1974).

Alteration is restricted to the rocks along the unconformity. In the basement rocks, it involves the crystallization of chlorite and white mica and is posterior to a red alteration which has been attributed to pedogenetic processes. Fluid inclusions have shown that the alteration took place at around 200°C. In the sandstones, hydrothermal alteration is also marked by a strong dissolution of detrital quartz grains and a subsequent authigenic silicification. Such alteration has only been observed in the Carswell area; it is not known whether this is a regional process.

Mineralization. The three main orebodies, D, N, and Claude, are situated at the southern edge of the central crystalline core within the Carswell structure (Fig. 32). They occur as lenses or pods immediately adjacent to the unconformity between the Athabasca sandstone and the crystalline basement. Two types of mineralization have been recognized, one with complex polymetallic ore mineralogy and a second with simple, almost monometallic mineralogy.

(1) The D orebody (Fig. 33) shows a complex mineralogy consisting of uraninite and pitchblende with accessory native Au, Au-tellurides, native Se, Pb, Bi, Ni, Co-selenides and Co-sulfides, and minor amounts of other components.

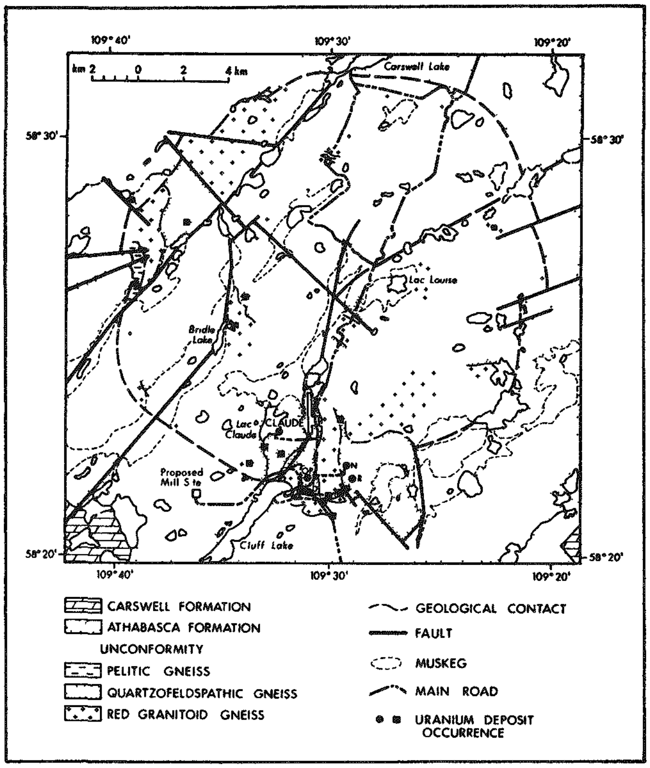


Figure 31. Generalized geology of the basement core showing the location of various uranium deposits and occurrences (from Harper, 1977).

(2) The N and Claude deposits (Figs. 34 and 35) are of simple mineralogy, and both occur in crystalline basement close to the unconformity with the Athabasca sandstone. The mineralization of the Claude deposit contains uraninite and coffinite as the principal uranium minerals, with minor amounts of molybdenite, galena, pyrite, graphite, and organic substance. The main host rock is mylonitized quartzitic gneiss.

The N orebody is comprised of colloidal pitchblende and coffinite as the principal uranium ore minerals, with associated pyrite, marcasite, a molybdenum-bearing phase (Harper, 1980), and minor chalcopyrite and galena. The ore minerals are embedded in a graphitic argillaceous matrix. The western boundary of the deposit consists of granitoid rocks and an alternating sequence of granitoid, quartz-feldspar gneiss, amphibolite gneiss, and garnet pelite gneisses that dip 50 degrees to the west and strike north-south.

Data on fluid inclusions in the Cluff Lake D orebody provide additional information on the mineralogy. According to Pagel et al (1979),

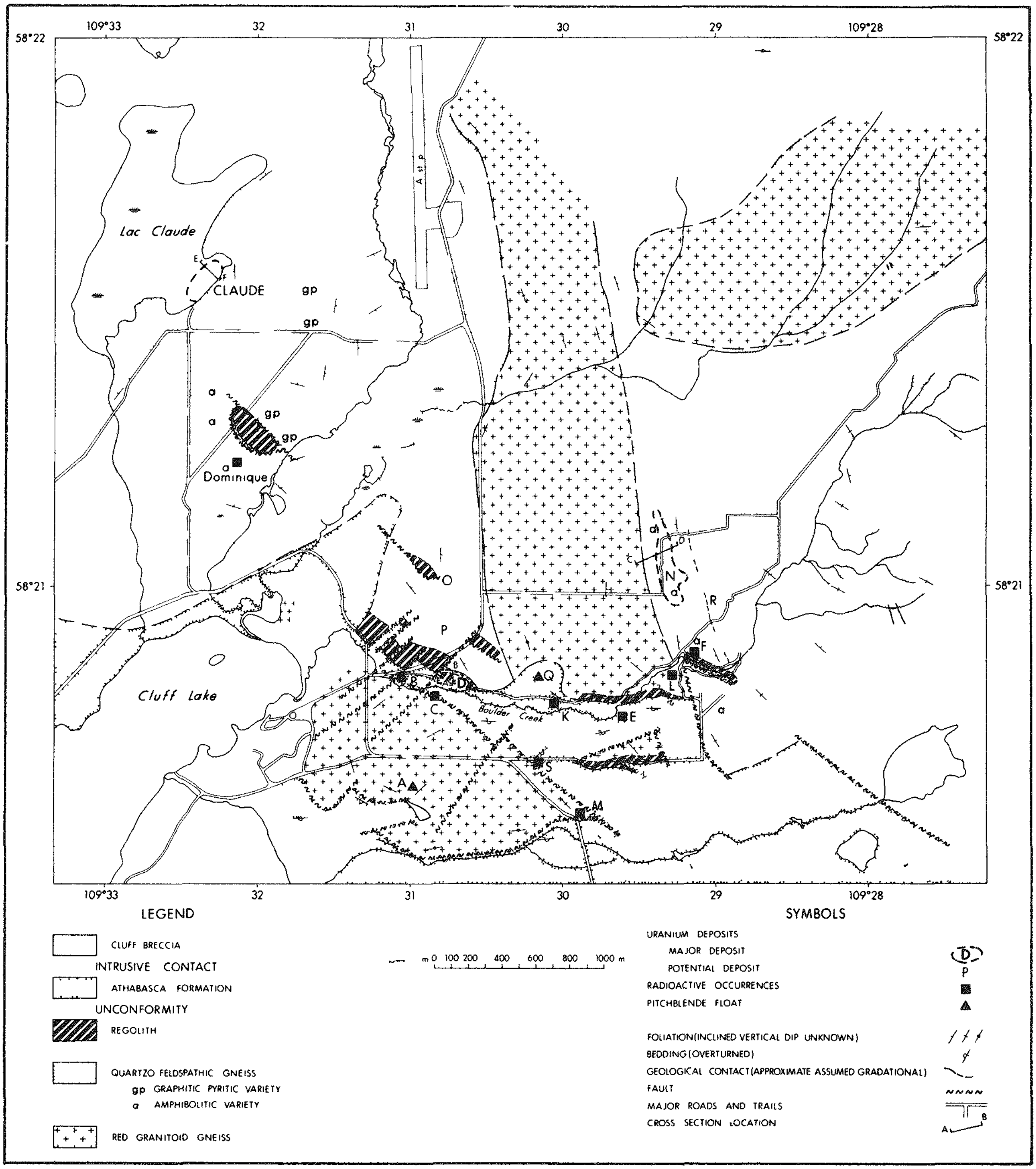


Figure 32. Geology of the area encompassing the major Cluff Lake uranium deposits and associated occurrences. The locations of the geologic cross sections shown in Figures 33 to 35 are indicated (from Harper, 1978).

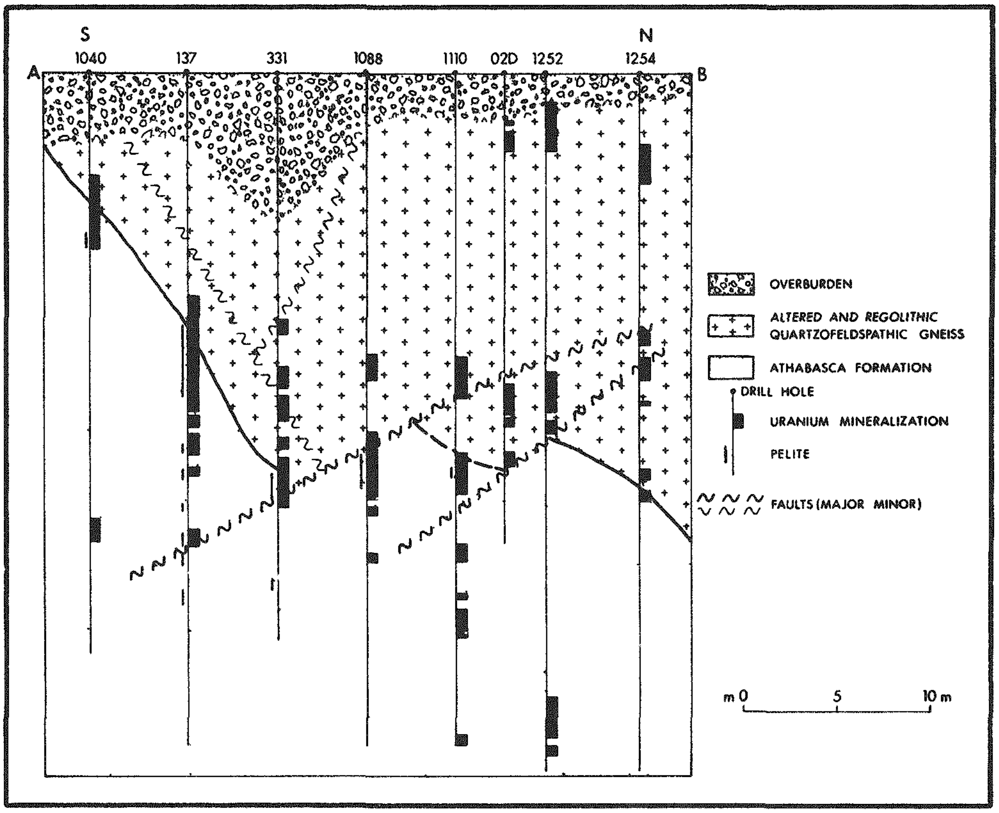


Figure 33. Geologic cross section of the D-Zone orebody, Cluff Lake (from Harper, 1978, after Tapaninen, 1976).

Microthermometry data were obtained on specimens taken close to the Cluff D deposit where a complex mineralogy has been described which includes the coexistence of uraninite and pitchblende and the existence of clausthalite, gold, gold tellurides, Co-Ni sulfo-arsenides and uraniferous bitumens. In the sandstones, there are quartz veins associated with a green alteration containing two-phase fluid inclusions. Melting temperatures range from -22.5°C to -28°C, hydrate melting temperatures are between -12°C and +5.6°C for variable homogenization temperatures between 250°C and 150°C. These veins are similar to those of Rabbit Lake.

At the contact of sandstones with the high grade zones a series of small planes of two fluid phase inclusions, generally having a highly variable Vb/Vt ratio, are observed around the borders of detrital grains or in the authigenic quartz overgrowths where such occur. The homogenization temperatures are up to 350°C and melting temperatures vary from -0.1°C to -14°C. Such inclusions were not observed at Rabbit Lake. Crystallization of uraninite is probably related to the high temperatures, such as has been suggested for the Oklo deposit where temperatures over 450°C were determined (Openshaw et al, 1978). There are three possibilities for

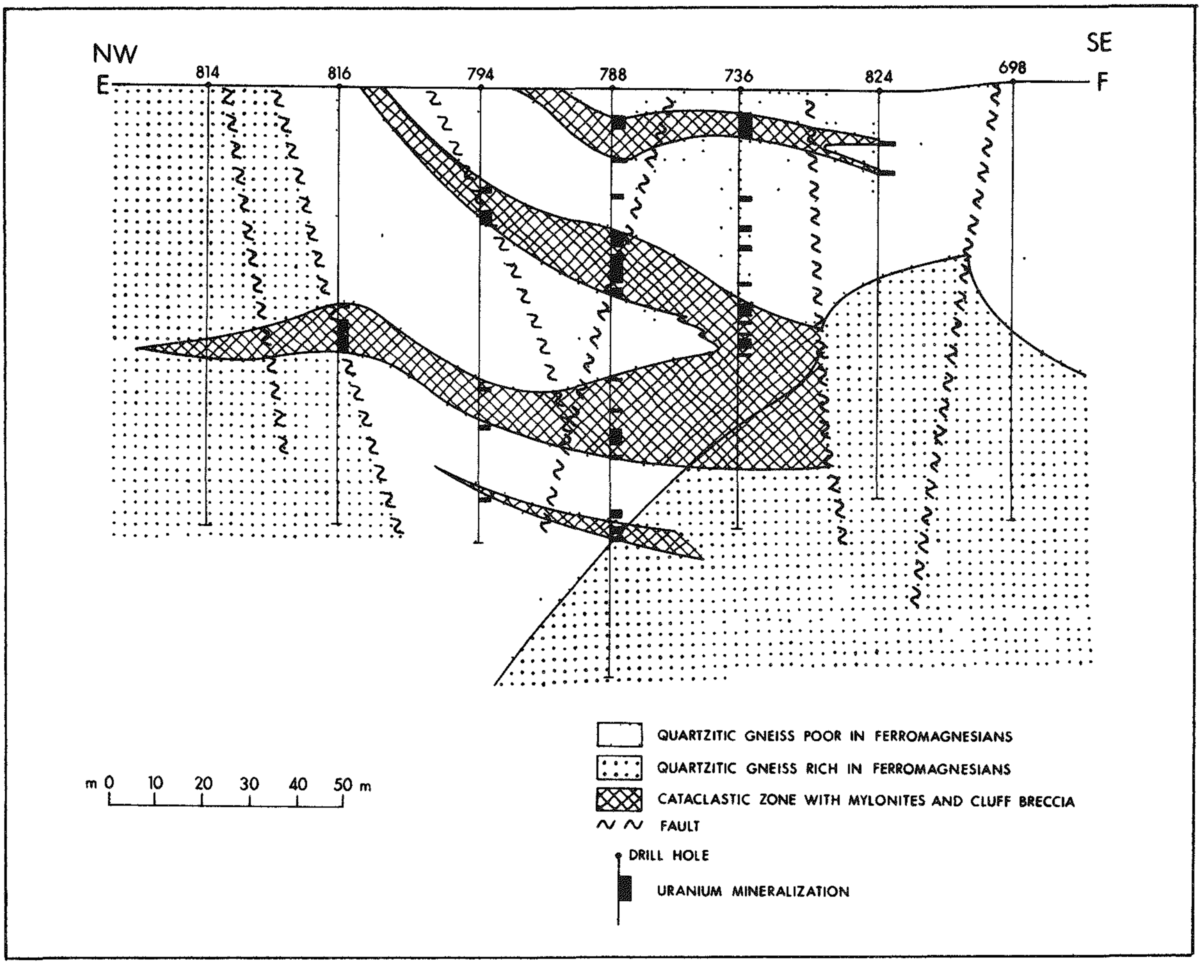


Figure 34. Geologic cross section through the N ore zone, Cluff Lake (from Harper, 1978, after Tapaninen, 1976).

producing these high temperatures (1) natural nuclear reactions (2) radioactive decay (3) formation of the Carswell structure. The third hypothesis is considered to be the most probable explanation because fluid inclusions studied in the impact breccias, melted rocks and in the planar features have the same characteristics as those occurring in the fractured sandstones (Pagel, 1975a, see also Pagel and Poty, 1975).

In the high grade U ore some calcite veinlets are formed which have two fluid phase inclusions with melting temperatures ranging from -1.4°C to -1.9°C and homogenization temperatures of about +120°C. These results are very similar to those of the Rabbit Lake calcite.

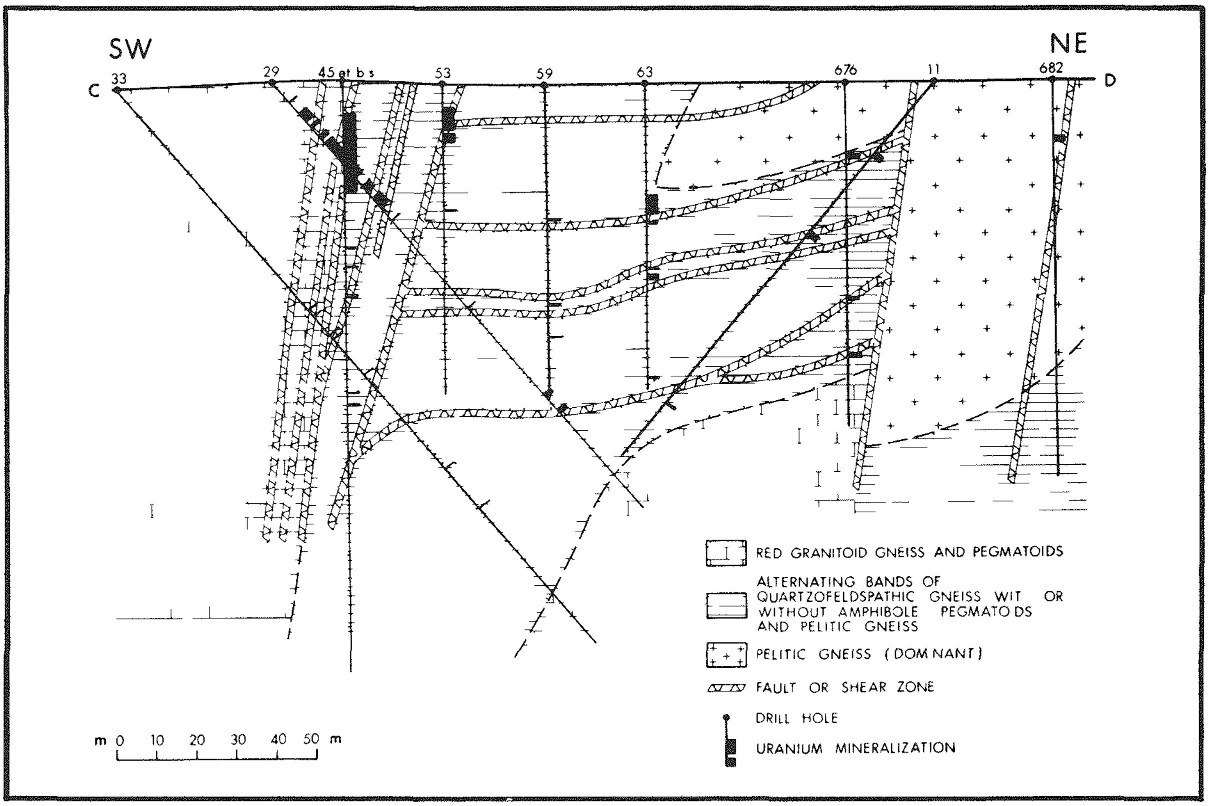


Figure 35. Geologic cross section of the Claude orebody (from Harper, 1978, after Tapaninen, 1976).

Geochronology. K/Ar determinations (Pagel, 1975b) on biotite of the garnet-cordierite basement gneiss yielded ages of about 1973 m.y. This age is regarded as the main phase of Hudsonian metamorphism. K/Ar age determinations on sericite in the altered rocks gave ages of about 988 m.y. This is definitely younger than the sedimentation of the Athabasca Formation (ca. 1350 m.y.). The age of the Carswell structure has been dated at 467 m.y. (Currie, 1969). U/Pb age determinations on uranium ore minerals have yielded an oldest age of about 1050 m.y. for the D orebody. Uranium of a younger generation and an unknown source (Gancarz, 1979) gave an age of 800 m.y.

Gancarz (1979) conducted U and Pb isotope studies and made several relevant observations. Summarizing earlier work he noted that U-Pb mineralization ages of 105 to 115 m.y. suggested the mineralization of the Cluff Lake deposits must have formed subsequent to the deposition of the Athabasca Formation for which Rb/Sr data yield ages of 135 to 143 m.y. Furthermore, the mineralization of the D orebody is cut by faults inferred to be associated with the formation of the Carswell structure for which K-Ar data on the breccia suggest an age of 475 m.y.

Gancarz worked on ore samples with a range of U concentrations from 0.5 percent to 62 percent U. All ore samples are discordant showing relative loss of Pb with respect to U and a general enrichment in common lead. By contrast, samples well away from the deposit show small relative lead enrichments.

There are no systematic relations among the U-Pb data that yield well-defined chronologic information. The youngest Pb^{206}/U^{238} model age is 234 m.y., hence U and/or Pb within the D orebody must have been redistributed more recently than formation of the Carswell structure (478 m.y.). The formation of the Carswell structure is not recorded in the U-Pb systematics for ore samples analyzed thus far.

In contrast to the U-Pb data, the Pb isotopic data are interpreted to yield useful chronologic information. Pb data for the three rocks from outside the D orebody gave ages in the range of 1.33 ± .03 b.y. This age is only slightly younger than the Rb/Sr deposition age of the Athabasca Formation. This suggests that within 50 to 100 m.y. after the deposition of the Athabasca Formation, U and Pb were redistributed, producing the uranium concentration in the rocks in the Cluff Lake region.

In addition to the high-grade ores, Gancarz (1979) also studied samples from low-grade mineralization. He states that these samples did not contain old radiogenic lead but formed at about 800 m.y. from uranium "transported in from outside the Cluff Lake region."

Ore Control and Metallogenesis. The D orebody occurs at the Middle Proterozoic unconformity in interbedded siltstones, sandstones, and conglomerates of the Athabasca Group and in altered Aphebian metasediments (Fig. 36). A post-Athabasca chloritic alteration affected both overlying and underlying rocks. Faults displace the unconformity and are the loci of uranium mineralization which extends into the basement.

The N and Claude orebodies occur in crystalline basement within or along fault and shear zones, adjacent to the unconformity. Chlorite and sericite-kaolinite alterations are characteristic of the mineralized areas.

According to Tapaninen (1976) and Pagel (personal communication, 1980), the following features are characteristic of the three deposits at Cluff Lake:

(1) Host rocks of N and Claude deposits are Aphebian phyllitic and graphitic metapelites which were metamorphosed to granulite facies and subsequently retrograded to upper-amphibolite facies. The metamorphic event is dated at 1973 m.y. and it is equivalent, therefore, to the early phases of the Hudsonian orogeny. The host rock of the D orebody is an organic-rich pelite apparently younger than the Aphebian metasediments. Harper (1980) identified pelitic sediments in recent open-pit mapping but does not refer to them as carbon bearing except where "hydrocarbon globules" occur in the ore.

(2) The metasedimentary basement was eroded and intensely weathered during pre-Athabasca time resulting in the formation of a well-developed regolith.

(3) Within the Carswell structure, the basement is overlain by strongly disrupted clastic sediments of the Athabasca Formation.

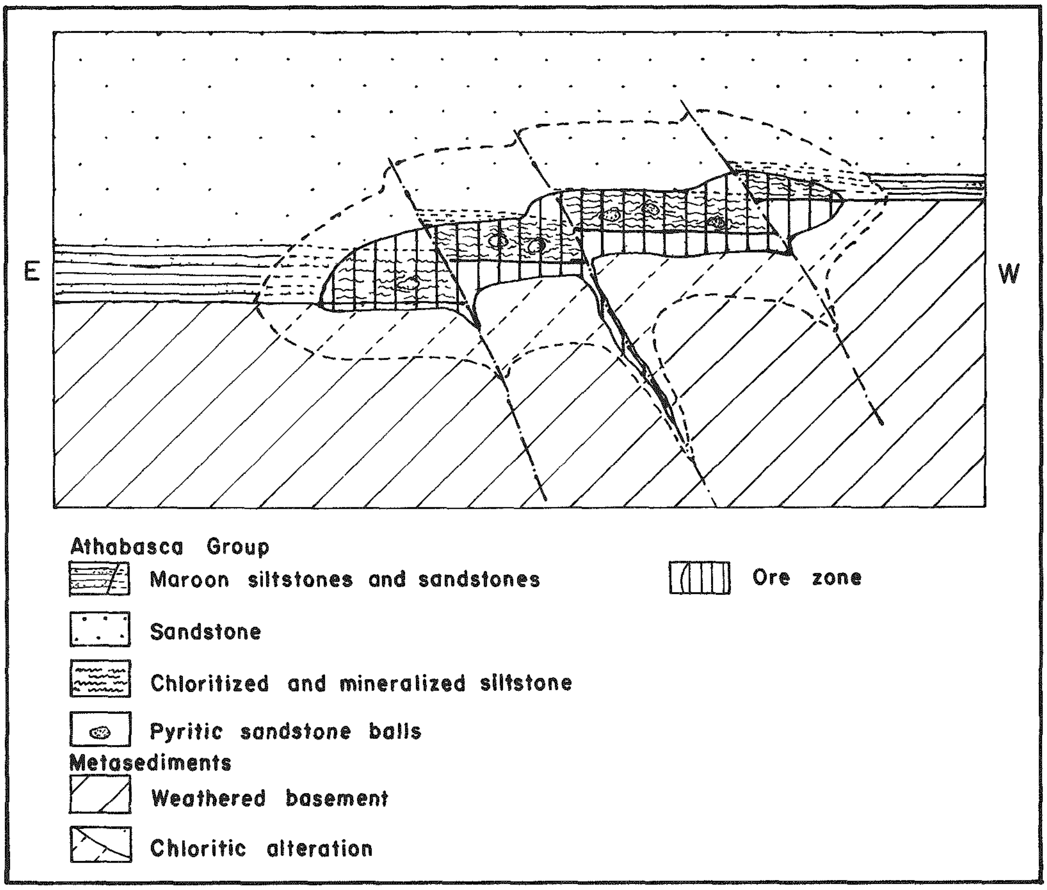


Figure 36. Open-pit mine map of the D orebody, Cluff Lake (modified from Harper, 1980).

(4) The N and Claude bodies are monometallic, the ore minerals consisting of uraninite (Claude) and pitchblende (N). In contrast, mineralization in the D deposit is complex and comprises uraninite, pitchblende, Au, and Se, with accessory Bi, Ni, Co, and Pb.

(5) Structural controls in the N and Claude deposits are reflected by north- and northeast-striking mineralized fracture and shear zones. All three deposits are restricted to the vicinity of the Middle Proterozoic unconformity and extend a maximum of 150 m into the basement metasediments.

(6) The N and Claude orebodies are characterized by alteration zones consisting of kaolinite, chlorite, and sericite within the pelites and quartzo-feldspathic gneisses. The highest uranium concentrations are located at the intersection of alteration zones and younger, steeply dipping faults.

The D orebody appears to be localized in interbedded siltstones and sandstones immediately above the unconformity. The sediments are oxidized outside the orebody, but the uraninite and pitchblende mineralization contain hydrocarbon globules. Mineralization extends into the underlying, altered metasediments and into the overlying sandstone. Harper (1980) suggests that (a) the decrease in the graphite content of the basement toward the orebody, (b) the hydrocarbons in the ore, and (c) the petroliferous odor of the ore support the hypothesis that graphite alteration produced hydrocarbon-bearing fluids that resulted in uranium precipitation.

Pagel et al (1979) have reported temperatures of mineral formation in the Cluff Lake area up to 350°C, higher than determined elsewhere in the Athabasca region. They explain the high temperature as resulting from the formation of the Carswell structure by meteor impact. Uraninite is likely to have formed at these high temperatures, and may be present as uraninite cubes.

According to Amok Ltd. (1974), the sequence of geologic events and the genesis of the ore deposits may be summarized as follows:

(1) surficial weathering of crystalline basement during pre-Athabasca time to form a deep regolith;

(2) sedimentation of Athabasca Formation, about 1350-1200 m.y.;

(3) deposition of the oldest uranium ore in D orebody, at about 1050 m.y.;

(4) tectonic and hydrologic events which produced chloritization, sericitization, and kaolinitization, and probably redistribution of ore, at about 988 m.y.;

(5) formation of Carswell structure, 480-470 m.y.

Regarding the genesis of the deposits, Amok Ltd. (1974) suggests that emplacement of mineralization took place during the pre-Athabasca weathering period in organic-rich pelites (D deposit) and shear zones (N and Claude deposits), the uranium source being gneisses and pegmatites in the exposed Archean basement. Subsequent to Athabasca sedimentation, alteration modified the initial mineralogy and locally redistributed mineralization.

Pagel (personal communication, 1980) considers that the uranium and other metals in the D orebody became concentrated in the organic-rich pelites (algae remains?) Rouzaud (1979) in an inland lake during the post-Hudsonian, pre-Athabasca weathering period. He notes that the host rocks for the deposits contain abnormally high concentrations of magnesium, boron, and lithium.

Based upon fluid inclusion studies, Pagel (1975a) presents evidence for post-depositional conditions that existed in the sediments above the unconformity after the deposition of the Athabasca sandstone. Increased salinity and temperature are reflected in fluid inclusions from sandstone silicified during late diagenesis. Conditions inferred from the fluid inclusions (T: 200°C, P: 1,500 bar, salinity: 33 Gew. % equiv. NaCl) would have required an overburden thickness of about 4,800 m during the time of silicification, assuming a normal geothermal gradient. With continued diagenesis, the quartz grains and their secondary overgrowths were strongly corroded, suggesting circulation of hot fluids along the unconformity. Pagel found that the fluid inclusions in a secondary quartz growth in the Athabasca sandstone and those in gangue minerals of the deposits suggest similar conditions of formation.

In other regions of the Athabasca Basin, e.g., at Rumple Lake approximately halfway between Cluff Lake and Rabbit Lake (Gulf Minerals drill hole, 1970), Pagel (1976) and Pagel et al (1979) detected effects of similar hot diagenetic fluids. They concluded that these fluids were of regional extent and importance, having affected most of the Athabasca Basin. They considered them responsible for the uranium mineralization and the widespread alteration of the crystalline basement immediately below the Middle Proterozoic unconformity.

Shape and Dimension of Deposits. The D deposit is ellipsoidal following the contact between crystalline basement and the Athabasca sandstone. The long axis of the deposit trends west-northwest for about 140m, and the deposit dips between 30 and 40 degrees to the north-northeast. The maximum width is 25 m, and thickness is 7 to 8 m.

The Claude deposit extends for about 600 m north to north-northeast parallel to and bounded by steeply dipping faults. The deposit is broken by steeply dipping east-west cross faults. The bulk of the ore is in fairly wide (average 200 m), horizontal to shallow dipping shear zones characterized by mylonite and breccia. The maximum thickness of the deposit is 90 m.

The N deposit extends for 1,200 m in a north-trending gneiss zone that dips 50 degrees to the west. The bulk of the ore is associated with numerous north-south shear zones that cut the gneiss. The width of the deposit is 120 to 200 m, and the thickness is 50 to 150 m.

The Claude and N deposits are best developed where alteration zones are cut by younger faults and fractures. These structures are often filled with Cluff breccias. In addition to the three main orebodies, two minor zones of mineralization, OP and R deposits, have been explored.

Production and Reserves. The Cluff Lake deposits have not yet produced uranium concentrate, but mining began in 1980. Published reserve estimates for the three deposits and the two additional occurrences are tabulated below (Tapaninen, 1976).

Deposit	Ore Class	Ore (mt)	Grade (% U_3O_8)	U_3O_8 (mt)
D	Measured	66,000	10.43	6,000
N	Measured	740,000	.56	4,300
Claude	Measured	700,000	.86	6,000
OP	Indicated	300,000	.65	1,900
R	Indicated	470,000	.56	2,600
		2,276,000		20,800

Maurice Bay. Lehnert-Thiel and Kretschmar, 1979; Lehnert-Thiel et al, 1979; Harper, 1979; Mellinger, 1979.

The deposit is situated on the northwestern edge of the Athabasca Basin, between Maurice Bay and Ness Bay on the northwest shore of Lake Athabasca, about 50 km southwest of Uranium City. The deposit was discovered in spring 1977 after geochemical surveying, radiometric boulder tracing, geophysical surveys, and finally, the drilling in a geologic target. The deposit contains three mineralized zones.

Geologic Setting of Mineralization. The Archean-Lower Proterozoic basement of the Maurice Bay area comprises two crystalline complexes, the Western Granodiorite Complex and the White Lake Complex (Koster, 1967). In the Maurice Bay area the White Lake Complex of Archean and/or Aphebian age contains a variety of gneissic to migmatitic rock types (Table 8) that include biotite-feldspar-cordierite gneiss, biotite and amphibole-rich gneisses, graphitic gneisses, amphibolites, and pegmatoidal anatexites of almandine amphibolite facies.

The Western Granodiorite Complex is of Hudsonian age according to Harper (1979) and is comprised of granodiorite, quartz-diorites, minor aplite, and pegmatite which intrude the White Lake Complex. In addition to the rock types discussed above, Harper (1979) mapped a late Aphebian sequence of meta-arkose, meta-argillite and meta-conglomerate that occurs on Lobstick Island and under Lake Athabasca about 20 km to the northwest of the deposit. It overlies with an unconformity the two older complexes. He correlates this sequence with the Thluicho Lake Group.

All the above-mentioned rocks were affected by strong weathering and regolith development that extends to a depth of about 80 m below the Middle Proterozoic unconformity. The Athabasca Formation was deposited over this weathered crystalline basement and covers almost all of the Maurice Bay area. As is typical for this formation, the brown to reddish, ferruginous continental sediments are comprised of basal conglomerates or fanglomerates, sandstones, and intercalated subordinate siltstones and mudstones.

Structurally, the Maurice Bay area is dominated by a regional horseshoe-shaped magnetic high that is probably related to a northwest-trending basement feature (Fig. 37). Faults with vertical displacements of at least 20 m along the south side of the deposit strike east to west, and faults along the northeast side of the deposit (Harper, 1979) strike northwest to southeast and have vertical displacements of 100 m. The mineralization is associated with an east- to west-striking basement horst. The deposit is covered by 15 m of glacial and recent overburden.

Alteration. Tentatively, two types of alteration in the basement rocks can be described. The first comprises alteration formed by paleoweathering, whereas the second is an alteration associated with mineralization. Paleoweathering affected the crystalline basement down to a depth of between 15 and 80 m, altering the rocks to assemblages of clay minerals, chlorite, sericite, and locally hematite/limonite that yield a greenish or reddish color. Near the unconformity strong bleaching is superimposed on the paleosol. The intensity of basement weathering seems to have depended on the pre-Athabasca topography.

Table 8. Stratigraphy and lithology of the rocks at Maurice Bay, Saskatchewan (from Harper, 1979).

AGE	UNITS
Pleistocene to Recent	Peat, modern fluvial and lacustrine sediments; post-glacial lacustrine and aeolian deposits; glacial deposits
	Unconformity
Rocks of uncertain age	Sedimentary breccias and minor igneous rocks
	Fault contact?
Paleo-Helikian	Athabasca Formation; conglomerate, sandstone, siltstone, and fanglomerate
	Unconformity
Late Aphebian to Paleo-Helikian	Sub-Athabasca weathered basement
	Gradational Contact
Late Aphebian	Thluicho Lake Group; meta-arkose, meta-argillite, meta-conglomerate
	Unconformity
Hudsonian	Granodiorite Complex; granodiorite, megacrystic granodiorite, and quartz-diorites I & II, minor aplite and pegmatite
	Intrusive Contacts
Archean and/or Aphebian	White Lake Complex; metaquartzitic, metapelitic and amphibolitic gneisses, and granitized equivalents. Mylonite and brecciated resilicified mylonites

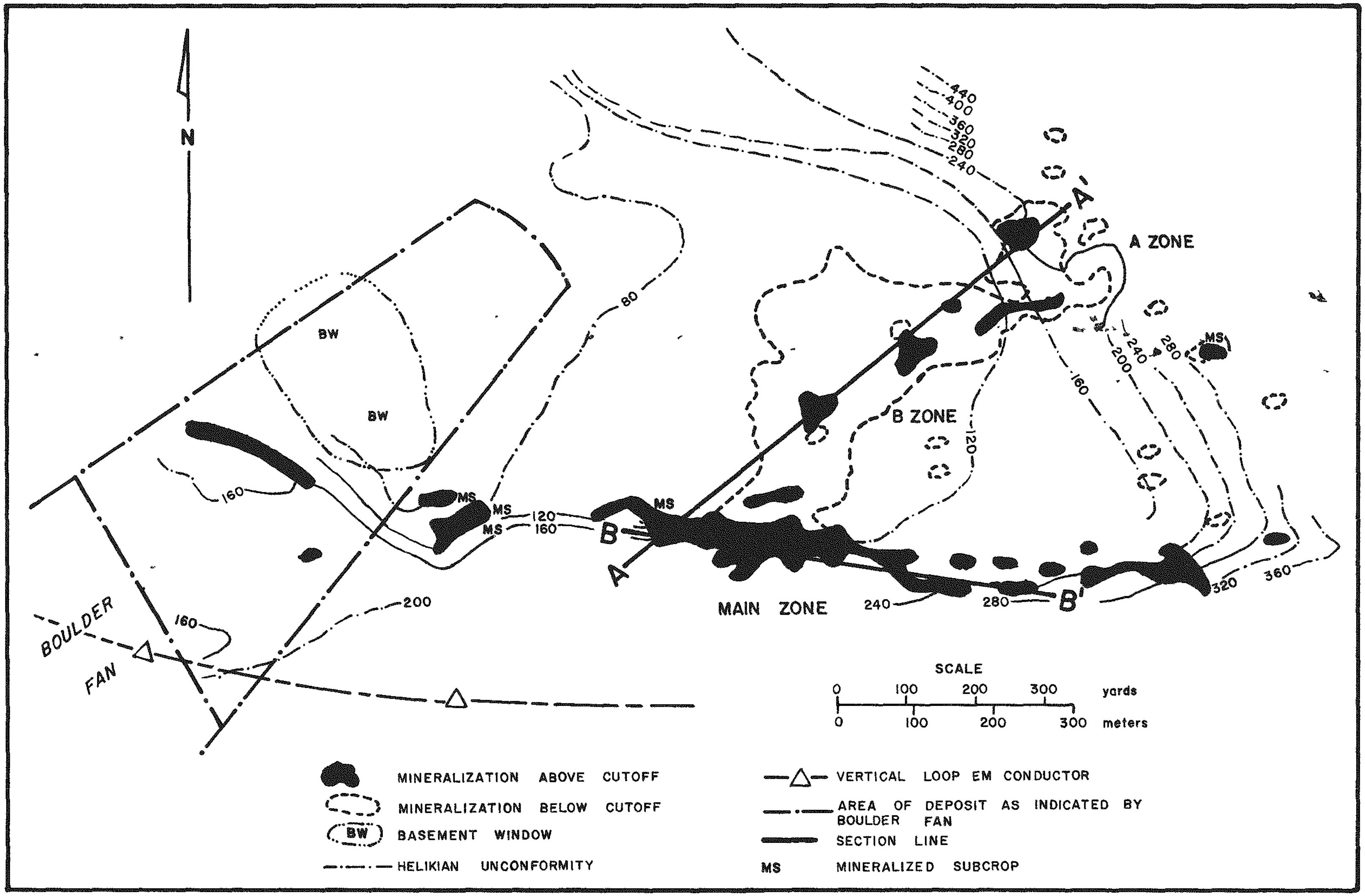


Figure 37. Structure contour map and uranium deposits and occurrences, Maurice Bay deposit, Canada (from Lehnert-Thiel et al, 1979). Locations of cross sections in Figures 38 and 39 are indicated.

Ore-associated alteration consists of chloritization, sericitization, and hematitization, and pitchblende occurs associated with specular hematite and quartz veins (Harper, 1979). In the A zone, for example, high-grade pitchblende mineralization (up to 3 percent U_3O_8 over 13 m) is associated with dark-green chloritized shears within a zone of brecciated and silicified (quartz-hematite breccias) mylonitic basement rocks.

Mineralization within the Athabasca Formation is accompanied by strong red hematitic/limonitic alteration and shows some relationship to a greenish-gray coloration. At some places ore near the unconformity is surrounded by strong bleaching. The Athabasca sediments were further affected by carbonate alteration and silicification that postdate the uranium mineralization and probably protect the ore against leaching and remobilization.

Mineralization. The ore is simple and consists essentially of pitchblende. Traces of molybdenum and cobalt are present, and Harper (1979) mentions the presence of traces of native Au, Cu, Fe, Zn, Pb sulfides, and black lustrous hydrocarbon material.

Mellinger (1979) divided the mineralization into three types:

(1) mineralization near the unconformity that extends into the basement rocks [South zone (Main zone), B zone];

(2) mineralization within the Athabasca Formation as lenses and fracture-fillings [South zone (Main zone), B zone, A zone]; and

(3) mineralization within basement rock (A zone).

Geochronology. Harper (1979) mentions a preliminary age date of less than 400 m.y. for pitchblende, but no further details on age determinations for the Maurice Bay deposit are yet published.

Ore Control and Metallogenesis. Lehnert-Thiel et al (1979) suggest that the Main zone (South zone) and the A and B zones (Figs. 38 and 39) are related to a domal basement uplift and spatially to the Athabasca unconformity. The Main zone and the A zone occur on the flanks of the east-west striking basement uplift, while zone B is confined within the sandstone of the uplift.

The Main zone is controlled by an east-west normal fault, dipping to the south and displacing the unconformity by about 20 m. In the central part of the A zone, northeast-trending faults seem to be an additional ore-controlling parameter.

The A zone is a stack-type deposit possibly controlled by the intersection of two faults, a major one striking west-northwest, and a crosscutting northeast-trending structure.

The B zone occurs within Athabasca sediments on top of the basement horst between the Main and A zones. The flat-lying B zone ore is obviously lithologically controlled, occurring at the base of the Athabasca Formation. No structural control is apparent, unless a postulated northeast-trending structure is considered to be an ore control. With respect to the formation of the deposits, no concepts have been published to date.

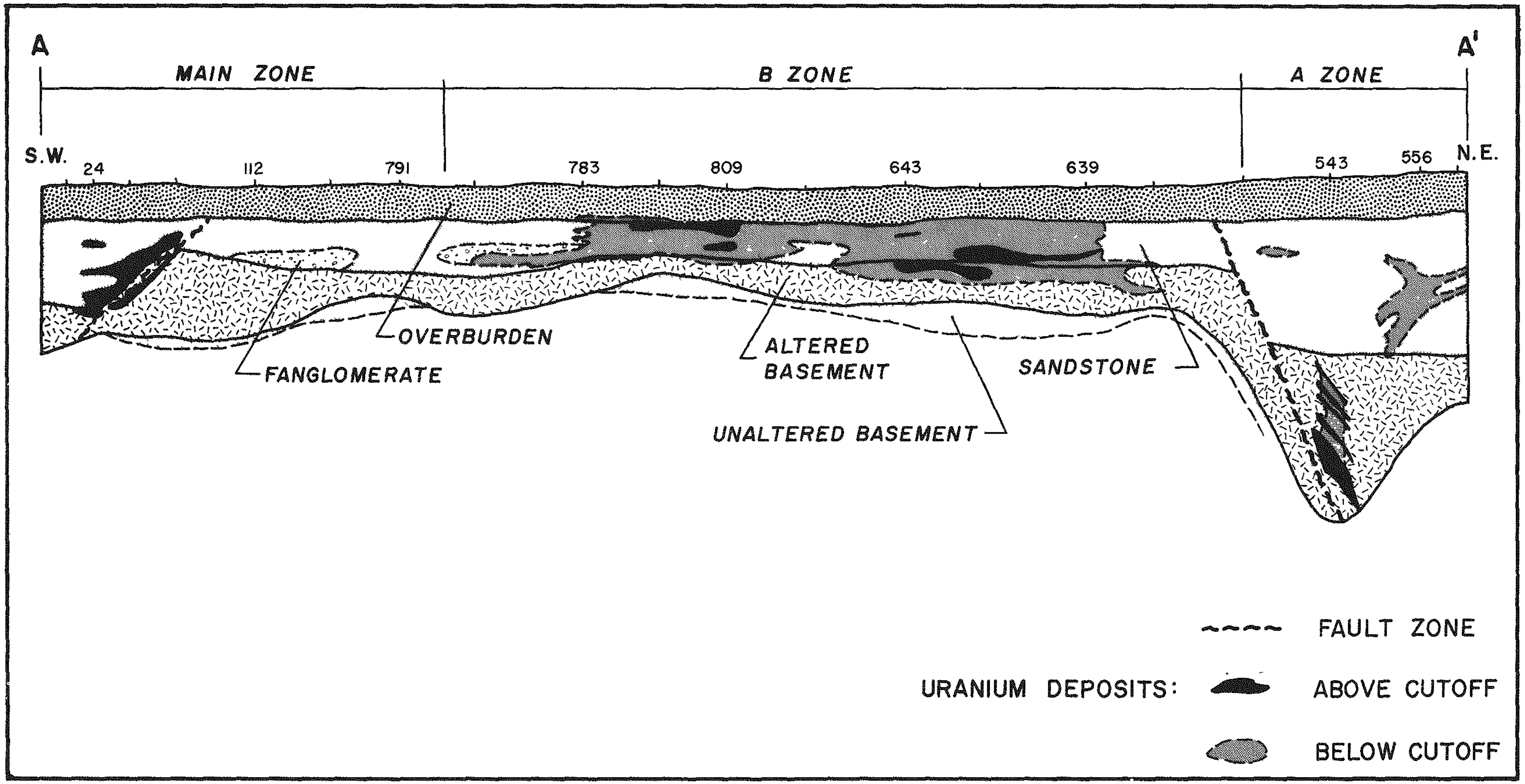


Figure 38. Generalized geologic cross section (A-A') for the Maurice Bay deposit, Canada (modified from Lehnert-Thiel et al, 1979).

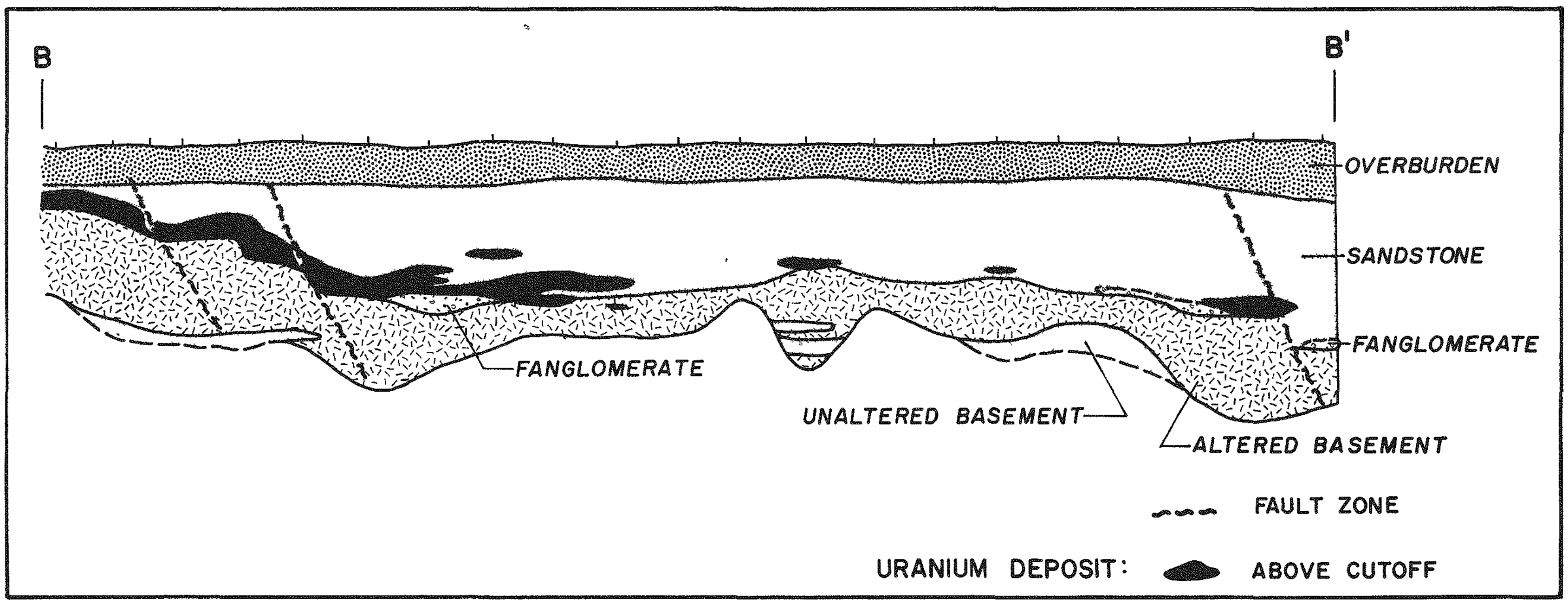


Figure 39. Longitudinal geologic cross section (B-B') for the Maurice Bay deposit, Canada (modified from Lehnert-Thiel et al, 1979).

Shape and Dimension of Deposits. The Main zone, occurring in an east-west structure, exhibits a tabular shape dipping 45 degrees to the south and plunging 10 degrees to the east. Uranium was traced over a strike length of 1,500 m, but ore grade is confined to a length of about 825 m in the central section. The orebody is 20 m thick and up to 60 m wide. The average grade is less than 0.5 percent U_3O_8. The best ore intersection was 2.147 percent U_3O_8 over a drill length of 13 m. More than 90 percent of the ore occurs in the basal strata of the Athabasca Formation.

The A zone has been intersected with only one drill hole to date. The core yielded 3 percent U_3O_8 over a length of 13 m. Adjacent holes showed only weak mineralization.

The B zone appears as an irregular, roughly northeast to southwest-trending lens. The ore is concentrated mainly in the Athabasca sandstone unit, but extends down to the Middle Proterozoic unconformity. Low-grade mineralization (ppm range) is found over a northeast-southwest length of almost 500 m and a maximum northwest-southeast width of more than 200 m. Within this broad zone, discontinuous zones of ore-grade mineralization have been found. The best intersection yielded 0.5 percent U_3O_8 over 7 m. Harper (1979) notes the presence of four additional radioactive occurrences in the Maurice Bay area.

Production and Reserves. The deposits have produced no uranium. The proven reserves are in the range of 1.5 million pounds U_3O_8, with a grade of less than 0.5 percent U_3O_8 (Lehnert-Thiel and Kretschmar, 1979).

Additional Occurrences in the Athabasca Region. Numerous additional occurrences of uranium mineralizations have been discovered in the Athabasca region. Of these, the following probably will be of economic size.

West Bear. This occurrence is approximately 45 km to the south-southwest of Rabbit Lake, close to the rim of the Athabasca Basin. Pitchblende is concentrated in the basal Athabasca Formation and in the underlying metasediments of the Wollaston Group, presumably close to graphitic pelites. Grades locally reach 7 percent U_3O_8. The Athabasca sandstone is only a few meters thick and is covered by glacial overburden. The mineralization has no surface expression.

Raven and Horseshoe. These two occurrences are situated close together and approximately 7 km south-southwest of Rabbit Lake. They are reported to occur in structures in quartzites of the Wollaston Group, 150 to 300 m beneath the surface. Mining would have to be conducted by underground methods.

Eagle Point. In May 1980, Gulf Minerals Canada Ltd. announced the discovery of an orebody about 3 km east-northeast from Collins Bay. A structurally controlled orebody occurs in an east to west-striking structure in basement metasediments. The structure appears to be a conjugate fault to the northeast to southwest-striking Collins Bay Fault. In one drill hole 34 feet of about 2 percent U_3O_8 was interpreted at a depth of about 270 m. No Athabasca sandstone is present over the ore-bearing structure (Northern Miner, May 1980).

Midwest Lake. The deposit lies about 25 km to the west-northwest of Rabbit Lake, along and under the Mink Arm of the Midwest Lake. The first indications of mineralization were uranium-bearing sandstone boulders in glacial debris that were found in 1969. Early drilling results were negative, but exploration was resumed after the discovery of Key Lake in 1975, and in 1978, an orebody was finally intersected by drilling.

The deposit is located along the Middle Proterozoic unconformity and contains uranium and nickel-cobalt mineralization. The overlying Athabasca Formation consists of approximately 200 m of quartz-sandstone and conglomerate, whereas the underlying basement consists of a subvertically dipping sequence of altered pelitic gneisses of the Aphebian Wollaston fold belt. Based on host rock, three types of ore exist:

(1) In the Athabasca sandstone, pitchblende is disseminated within the matrix and as coatings on fractures. This mineralization is commonly spatially associated with zones of sericitization. It extends from the unconformity to the sandstone surface, i.e., over 200 m of thickness.

(2) In the basement, pitchblende and nickel-cobalt arsenides occur on shear planes and in breccia zones with strong clay alteration; such basement mineralization is known to extend down to 100 m below the unconformity.

(3) Nodular to massive pitchblende and nickel-cobalt arsenides occur at the unconformity associated with extensively altered rock.

Galena, sphalerite, chalcopyrite, and marcasite occur in minor quantities, and silver is locally present. Mineralization was found discontinuously over a length of 3,330 m in a north-northeast direction. The bulk of the resources occur over a 900 m length, a maximum width of 110 m, and a maximum thickness of 36 m. The orebody is at a depth of 200 m. Indicated reserves are 26,000 t of U_3O_8 in 2 million tons of ore with an average grade of 1.2 percent U_3O_8 (Northern Miner, July 17, 1980).

James (1978) presents the following additional data for the orebody. The width of the deposit ranges from less than 30 m to more than 90 m. The depth to mineralization is between 30 m and 225 m with the main ore zone at 180 m to 195 m.

<u>Dawn Lake</u>. Dawn Lake is situated about 5 km to the northeast of Midwest Lake. The concession contains at least three mineralized locations. At Dawn Lake, uranium has been intersected within a well-mineralized zone of Athabasca Formation and underlying Wollaston Group gneisses. It has been encountered with some discontinuity and irregularity over a strike length of 550 m, a width of up to 70 m, and a thickness of up to 22 m. The main zone was encountered at a depth of 90 m to 100 m. Assays have ranged up to 5 percent U_3O_8. In the hole No. 11 zone, some 700 m south of Dawn Lake, a somewhat irregular and discontinuous zone of radioactivity was drilled over a strike length of 450 m, a width up to 60 m, and a thickness of 53 m. Approximately 800 m southeast from the hole No. 11 zone, a new zone (22 B) with a potential strike length of 1,000 m has been discovered.

About 8 km to the north-northeast of Dawn Lake, ore-grade mineralization has been encountered over a 3.9 m drill hole interval (Northern Miner, July 19, 1979, and July 17, 1980).

McClean Lake. The prospect lies 10 km to the northwest of Rabbit Lake and 15 km to the east of Midwest Lake. Uranium mineralization indicated by drilling extends with some possible discontinuities over a length of 660 m with a variable width locally exceeding 60 m. It occurs at depths from 150 m to 175 m. The ore thickness in the drill holes ranges from 3 m to 19 m with grades ranging between 0.25 percent and 27.8 percent U_3O_8.

McArthur River. The prospect is situated about 65 km to the northeast of Key Lake. In one drill hole, four separate zones were intersected. Each was 2 to 4 m thick and contained 0.25 percent to 0.30 percent U_3O_8 (Northern Miner, July 17, 1980).

Background Values of Uranium and Other Metals in Potential Source Rocks in Northern Saskatchewan

Systematic regional studies of the uranium content of basement rocks in northern Saskatchewan have not yet been completed. Although results from some local investigations are available, the data are still insufficient to present a comprehensive picture of uranium distributions and concentrations, hence to identify with any certainty the source rocks for the deposits. These data suggest, nonetheless, some important relations between uranium occurrences and their associated host rocks.

(1) The deposits are located in regions with seemingly more abundant anomalous uranium concentrations and locally high uranium background concentrations in certain rock types, i.e., within a uranium province.

(2) High uranium backgrounds occur preferentially in certain rock types and certain lithologic-stratigraphic horizons.

(3) Uranium and other metals are progressively depleted across weathering profiles as the intensity of weathering increases.

Several authors have published analytical data for various areas, some of which are presented below.

Beck (1969) studied the Beaverlodge region and provided information on the uranium content of pegmatites and metasediments. He distinguished three types of pegmatites:

(1) Lit-par-lit pegmatite lenses with uraninite and associated molybdenite grading up to about 0.05 percent U_3O_8 (Charlebois and Black Lake areas).

(2) Dike-like pegmatites with uraninite and uranothorite, grading less than 0.08 percent U_3O_8 (Gwillim Lake Gold Mines).

(3) Pegmatites in migmatite zones with uraninite and thorite and radioactive biotite-bearing pegmatites and biotite segregations in paragneiss (Camsell Portage).

Within the metasediments, he noted gneissic bands within zones of metamorphic and migmatitic rocks which contained uraninite, most commonly associated with biotite, but also with feldspar and hornblende. Some uraninite-bearing granites and gneisses contain local concentrations up to 0.07 percent U_3O_8 (Goldfields Uranium Showing No. 49-TT-1). Additional uranium analyses for the main rock types in the Beaverlodge area are given by Tremblay (1978c) and summarized in Table 9.

Table 9. Uranium concentrations in the main rock types, Beaverlodge area (from Tremblay, 1978c).

Rock Types	Number of Specimens Analyzed	Uranium (ppm) Average	Uranium (ppm) Range
Amphibolite	15	0.8	0.3-2.7
Argillite	6	4.6	3.0-8.8
Chlorite schist	3	4.4	3.6-5.5
Impure quartzite	5	4.3	3.4-6.8
White quartzite	7	3.0	1.6-4.7
Layered gneiss (white quartzite and chlorite schist)	6	3.7	1.2-5.3
Granite	15	5.4	1.0-13.0

Clark and Burrill (1979) have analyzed various rock types in northern Saskatchewan and have made some general observations about the distribution of uranium. Granitoid and metasedimentary basement rocks commonly contain 0.5 to 8 ppm uranium, with 10 to 15 ppm uranium in some granites. Athabasca sandstones and conglomerates from the region around Cluff Lake contain an average of 0.8 ppm uranium, and analyses for samples from three other areas in the region average 1.5 ppm (Table 10). The uranium content of some graphitic metapelites may be as low as that of other rocks, but concentrations average about 6 ppm and range up to 100 ppm in some samples unrelated to deposits.

Table 10. Summary of trace element analyses (in ppm) for three areas in the Athabasca sandstone and four areas in the metasedimentary basement, northern Saskatchewan (from Clark and Burrill, 1978).

	Number	U	Ni	As	Cu	Pb	Zn
Athabasca sandstone	210	1.5	7.4	1.5	4.0	7.1	5.2
Meta-arkose	190	2.9	48	2.5	7.9	14	17
Metapelite (graphitic in part)	261	5.6	57	2.3	7.5	12	24

Referring to the Key Lake area, Dahlkamp (1978) noted that certain types of Aphebian metasediments contained average concentrations of up to 50 ppm uranium and high concentrations of Ni as well. Locally, where unweathered, these unaltered metamorphic rocks contained U and/or Ni concentrations of several tenths to one percent. In such occurrences, the uranium is present as cubic uraninite, suggesting high-temperature formation, probably during the Hudsonian metamorphism. In these rocks, uranium shows an affinity for mafic mineral concentrations such as biotite, hornblende, and pyroxene, particularly in proximity to graphitic horizons. Referring also to the Key Lake area, Kirchner et al (1979) noted:

> These protore concentrations have been intersected in numerous exploration drill holes within a 40 km radius of Key Lake, where concentrations of 50 to 300 ppm U_3O_8 and 50 to 600 ppm Ni occur in biotite gneisses immediately adjacent to graphitic gneisses.

Additional analyses for the Key Lake area have been compiled by Voultsidis et al (1980) and are presented in Table 11. They analyzed for background values of uranium and nickel in fresh and weathered biotite-cordierite-plagioclase gneisses and established average values of 13 ppm U_3O_8 and 37 ppm Ni for the fresh rock and 14.2 ppm U_3O_8 and 38.2 ppm Ni for the weathered rock. These analyses do not indicate leaching of metals during weathering. The average uranium content of the Athabasca Formation is given as 1.5 ppm U.

Thomas (1979) analyzed uraniferous rocks of the Karin Lake area in the central Wollaston Domain, about 40 km to the southeast of the southeastern edge of the Athabasca Basin. The sample locations and rock types are shown in Figure 40 and the uranium concentrations tabulated in Table 12 (see Plate III).

Lewry and Sibbald (1978) describe uranium occurrences in the basement rocks of the "Cree Lake Zone" (see Fig. 41). Whereas limited subeconomic uranium mineralization occurs in granite, pegmatites, and migmatites of early Hudsonian or possibly later Kenoran age, most mineralization is within the Aphebian metasediments. According to their terminology, the three principal types of occurrences are in (a) arkose, (b) pelite-pegmatite rocks, and (c) calc-silicate rock. The first two types occur near the base of the Aphebian metasediments, whereas the calc-silicate occurrences are found at several stratigraphic levels.

According to Lewry and Sibbald (1978), the only known occurrence in arkosic rocks is west of Duddridge Lake (Fig. 42) in rocks of the lowest unit of the Wollaston Group, where drilling identified disseminated mineralization within discontinuous lenses in arkosic and graphitic semi-pelitic rocks. Ore minerals have been described as uraninite, tyuyamunite, and secondary uranium oxides with associated minerals such as chalcopyrite, bornite, chalcocite, galena, sphalerite, molybdenite, erythrite, and skutterudite (Munday, 1979; Coombe, 1978). Approximately 350,000 t of ore, at a grade around 0.1 percent U_3O_8, have been identified along a strike length of 1,460 m. The best intersection contained 0.14 percent U_3O_8 over 8.8 m.

With reference to the origin of this occurrence, they note that "the uranium mineralization, though locally concentrated along fractures, shows little evidence of being structurally controlled and was probably introduced prior to Hudsonian metamorphism." The mineralization is associated with a semi-pelitic carbonaceous horizon within the meta-arkoses and has associated Cu, Co, Ni, As, Se, Pb, Ag, Au, Mo, and V.

Table 11. Analyses of weathered and unweathered biotite-cordierite-plagioclase gneiss for U_3O_8 and Ni, Key Lake area. All samples are 50 meters or more from ore zones (modified from Voultsidis et al, 1980).

Sample Number	Rock Type	U_3O_8 (ppm)	Ni (ppm)	Sample Number	Rock Type	U_3O_8 (ppm)	Ni (ppm)
CN-1370	W	21	49	CN-9872	U	7	51
CN-1371	W	21	48	CN-9888	U	18	105
CN-1372	W	19	23	CN-9895	W	8	23
CN-1373	W	19	42	CN-9896	U	12	49
CN-1374	W	17	30	CN-9898	U	9	-
CN-1375	U	19	46	CN-9900	U	10	54
CN-2911	U	44	-	CN-9903	U	23	62
CN-2917	U	24	-	CN-9905	U	14	25
CN-2918	U	50	-	CN-9912	U	9	71
CN-2918	(*)	97	-	CN-9913	U	5	8
CN-2919	U	12	-	CN-9916	U	9	41
CN-2929	U	18	-	CN-9920	U	9	39
CN-9766	U	7	19	CN-9927	W	9	39
CN-9768	U	10	20	CN-9932	W	12	28
CN-9773	U	6	18	CN-9935	U	10	52
CN-9777	U	11	18	CN-9938	U	12	54
CN-9782	U	4	17	CN-9945	U	8	20
CN-9786	U	8	37	CN-9950	U	12	51
CN-9807	U	12	115	CN-9956	W	22	120
CN-9828	W	10	43	CN-9959	W	10	44
CN-9833	W	10	47	CN-9962	W	10	42
CN-9841	U	4	-	CN-9964	W	9	62
CN-9842	U	9	30	CN-9968	W	4	9
CN-9849	U	8	22	CN-9971	W	9	11
CN-9854	U	6	15	CN-9974	W	29	9
CN-9854	U	5	16	CN-9976	W	16	19
CN-9865	U	17	12	CN-9977	U	8	15

U = unweathered biotite-cordierite-plagioclase gneiss; W = weathered biotite-cordierite-plagioclase gneiss; (*) = biotite concentrate.

Describing the more general uranium occurrences in pelitic-pegmatitic rocks, Lewry and Sibbald (1978) noted that uraninite is disseminated throughout quartzo-feldspathic zones in pelitic gneisses which are commonly graphitic. These zones have commonly been referred to as pegmatites; however, this is seldom strictly the case, as the grain size ranges from medium to pegmatitic, typically medium to coarse. Molybdenite is commonly associated with the uraninite, and values in lead, copper, and zinc have been reported. Variations in the concentrations of smoky quartz, feldspars, biotite, garnet, and radioactive minerals are present within and between individual "pegmatite" bodies.

> The most heterogeneous bodies are concordant, less than 1 metre thick and laterally discontinuous over a few metres. Others display a more igneous aspect and are of 'granitic' composition occurring as subconcordant intrusive sheets, which include rafts of host gneisses, commonly several metres thick and tens of metres long (Lewry and Sibbald, 1978).

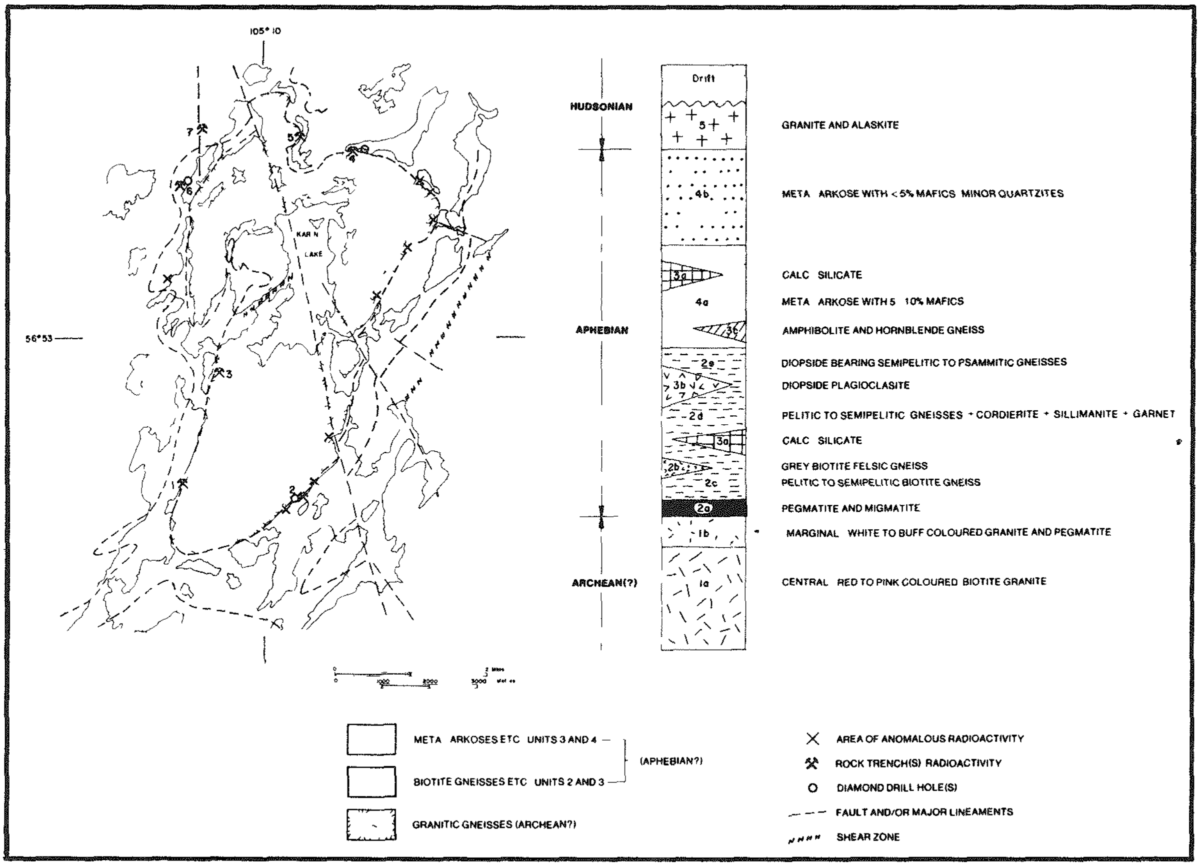


Figure 40. Geologic sketch map and schematic stratigraphic section for the Karin Lake area. Sample locations are numbered and stratigraphic units identified to correspond with analyses compiled in Table 12 (from Thomas, 1979).

Table 12. Uranium analyses for occurrences of uranium mineralization, Karin Lake area (modified from Thomas, 1979). Sample locations are shown on the map and schematic stratigraphic section in Figure 40.

Location Number	Mineralized Rock Type and Host Rock Unit	Accessory Minerals	U_3O_8 Assays (percentage)
1. 1 trench	White granodiorite pegmatites with large biotite books (Unit 2a)	Mo, Py	.006
2. 1 trench	Buff-colored granodiorite to quartz monzonite pegmatites (Unit 2a)	Ap	.017
3. 2 trenches	Red to pink biotite granite and pegmatite (Unit 1a)	Py, Mag	.017-.241
4. 4 trenches Diamond drill holes	Siliceous pegmatites, buff quartz monzonite pegmatites, and mineralized biotite selvages (Unit 2a)	Mo, Py	.040-.306
5. 4 trenches	Siliceous pegmatites, granodiorite to monzonite pegmatites (Unit 2a)	Py, Mo, Gr	1.22-1.57
6. 2 trenches Diamond drill holes	Lit-par-lit migmatites (Unit 2c and 2d)	-	.065-.209
7. 2 trenches	Massive scapolite, amphibole pyroxenites (Unit 3a)	Py, Po, Th	1.16-8.00

Key to Accessory Minerals:

Molybdenite	Mo	Apatite	Ap	Thucholite	Th
Graphite	Gr	Magnetite	Mag		
Pyrite	Py	Pyrrhotite	Po		

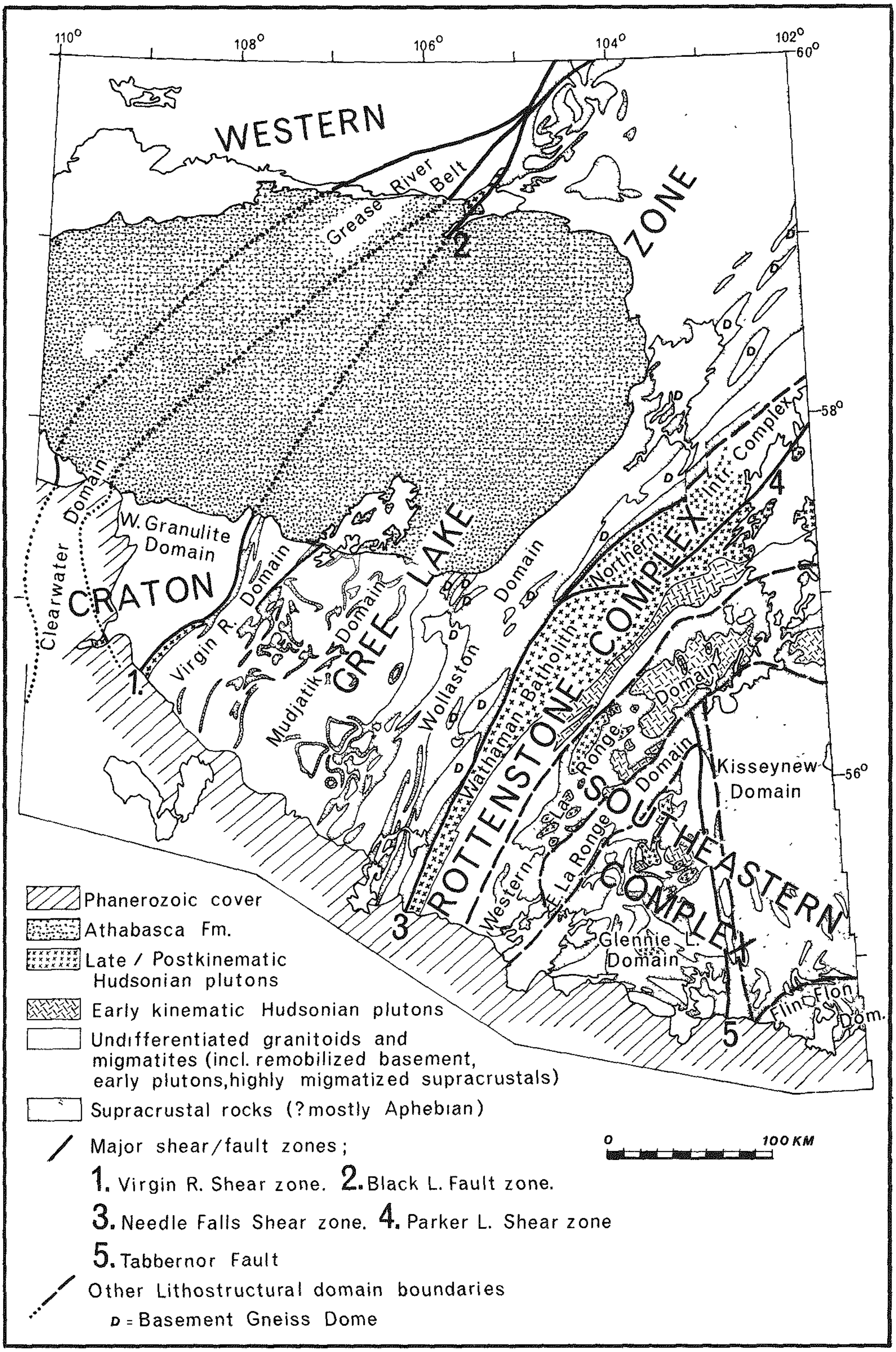


Figure 41. Major lithostructural subdivisions of the Canadian Shield, Saskatchewan (from Lewry et al, 1978).

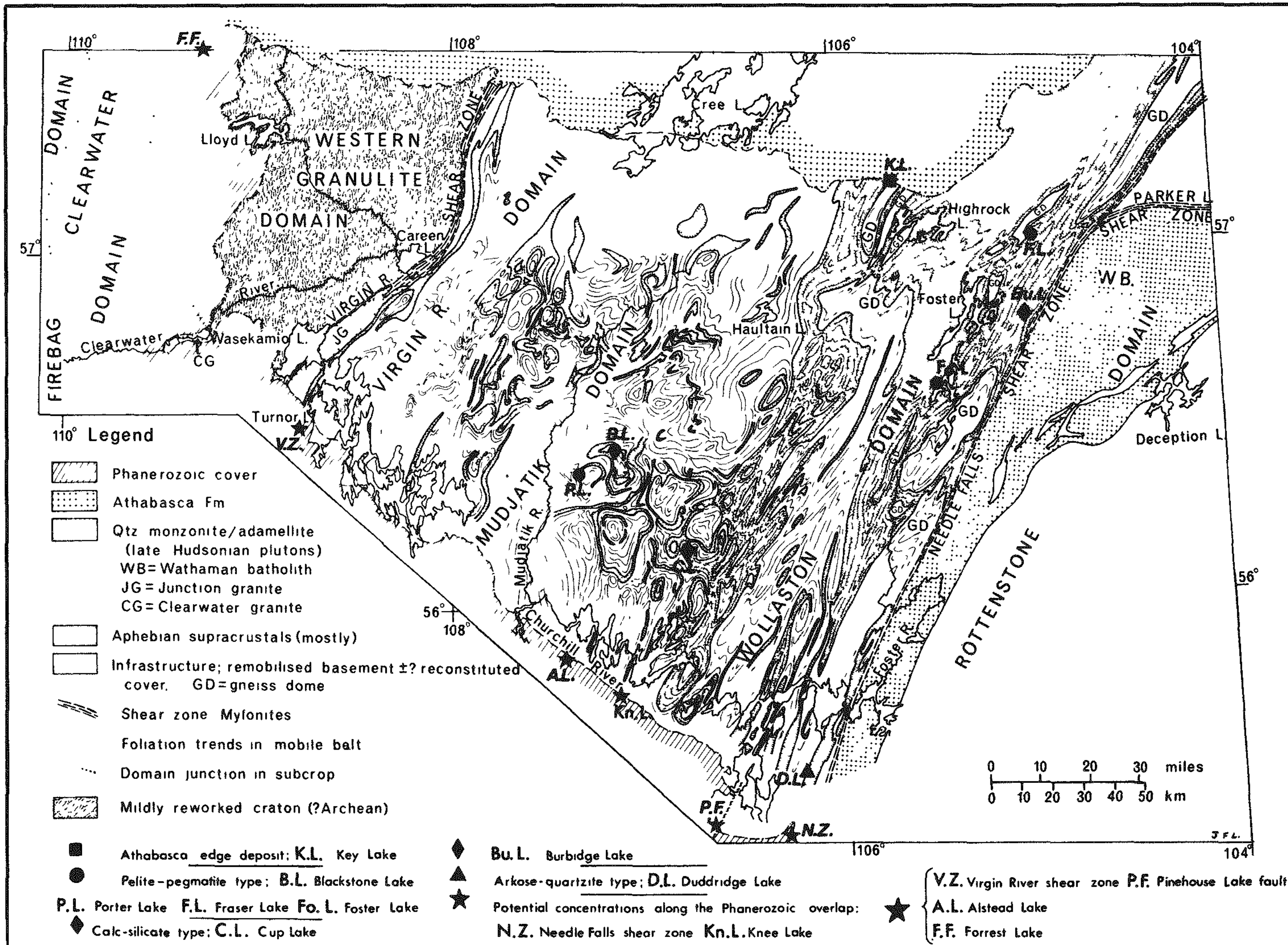


Figure 42. General geology of the southwestern part of the Precambrian basement of Saskatchewan showing uranium occurrences (from Sibbald et al, 1976).

Examples of the pelitic-pegmatitic hosted uranium occurrences are compiled in Figure 43. The occurrences at Charlebois Lake have been studied in some detail. Uraniferous pegmatites are strata-bound within migmatized, pelitic amphibolite facies metasediments that wrap around dome-shaped cores of granitic gneiss (Thomas, 1978). Lewry and Sibbald suggest that the granite gneiss is Archean basement upon which were deposited Aphebian black shales, now represented by graphite pelites and uraniferous pegmatites produced during Hudsonian metamorphism. Uranium analyses for a similar uranium occurrence in the Mudjatik domain (Table 13) provide an indication of the background concentrations and are instructive comparisons between the results of grab and grid sampling.

In describing the calc-silicate type of uranium occurrences, Lewry and Sibbald (1978) note that uranium concentrations have been recorded at various stratigraphic levels of the Wollaston Group succession in both the Wollaston and Mudjatik domains. At Cup Lake, for example, uraniferous calc-silicate pods are present in graphitic pelites with radioactive quartzo-feldspathic "pegmatite" segregations. These occurrences are adjacent to granitic gneisses of presumed Archean basement (Thomas, 1978). At Burbidge Lake, a mineralized calcareous unit occurs somewhat higher in the succession within a sequence of the meta-arkoses. At Spurjack Island in Wollaston Lake, mineralized calc-silicate rocks occur in a quartzite-amphibolite unit near the top of the exposed succession.

Table 13. Average uranium concentrations in pelitic rocks of the Mudjatik SW (74B) area based on grab and grid sampling (from Lewry and Sibbald, 1978).

	Grab Samples			Grid Samples		
Occurrence	No. of Samples	U (av. ppm)	Mo (av. ppm)	No. of Samples	U (av. ppm)	Mo (av. ppm)
Blackstone Lake	56	158	58	35	14	21
Porter Lake	26	128	27	37	17	11
Double Lake	13	99	34	26	19	6

The calc-silicate occurrences at Burbidge Lake contain approximately 35,000 tonnes of ore at about 0.18 percent U_3O_8. The mineralized sequence contains amphibolite, diopside-scapolite-phlogopite marble, spotted mica schist, and calc-silicate layers in part retrogressed to talc schists. It is flanked by calcareous meta-arkoses. Primary disseminated uraninite is present within medium-grained calc-silicate layers composed essentially of plagioclase feldspar and diopside, the latter replaced to varying degrees by pale-green clino-amphibole. Sphene, apatite, calcite, and opaques occur as minor constituents. A similar occurrence at Cup Lake is composed of diopside, clino-amphibole, plagioclase feldspar, and scapolite, with minor accessory quartz, sphene, and apatite. Uraninite occurs as euhedral crystals up to a few cm across; molybdenite and fluorite comprise the associated mineralization.

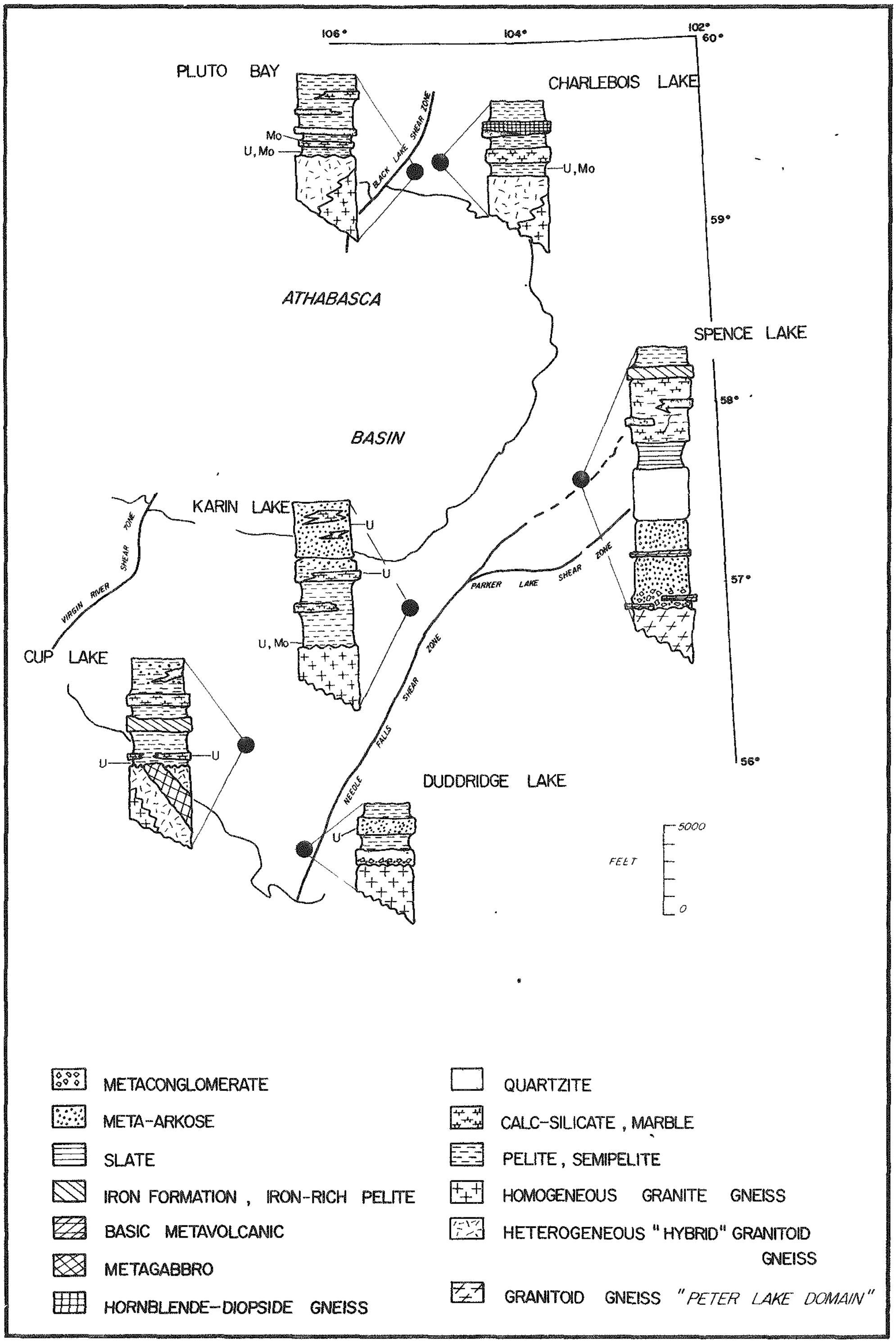


Figure 43. Schematic stratigraphic columns showing the position of uranium mineralization with respect to the Aphebian metasediments and the basement for six locations in the Athabasca Basin region (modified from Thomas, 1980).

The occurrence on Spurjack Island is similar to that of Cup Lake, with euhedral uraninite crystals and molybdenite flakes up to 1.5 cm across developed in a sub-concordant zone of mineralization a few cm thick. The calc-silicate host consists of varying proportions of diopside, clino-amphibole, scapolite, quartz, feldspar, and biotite, and minor amounts of apatite, sphene and carbonate. Apatite and dark-green clino-amphibole are commonly prominent in the mineralized zone.

Numerous other uranium occurrences in calc-silicate rocks are known in Saskatchewan. An important variation of this association occurs southeast of Rabbit Lake in rocks of the quartzite-amphibolite unit of the Wollaston Group, where low concentrations of uranium are found in calcareous metasediments as layers rich in diopside and apatite. Some analyses of these rocks are presented in Table 14.

Table 14. Analyses for uranium and other elements in calcareous metasediments of the quartzite-amphibolite unit southeast of Rabbit Lake. Samples 356A and 357A are from mineralized apatite-rich diopsidic layers; 356B and 357B are from intervening meta-arkose layers (from Lewry and Sibbald, 1978).

	ppm									%
Sample No.	Cu	Ni	Zn	Co	As	Mo	V	Pb	U	P_2O_5
76-17-356A	18	11	10	5	2	1	9	58	149	7.44
76-17-356B	3	7	4	1	1	1	4	13	9	0.16
76-17-357A	175	12	15	4	1	1	9	79	190	7.06
76-17-357B	4	7	3	1	1	1	1	26	3	0.18

Previous Concepts on the Metallogenesis of Uranium Deposits in the Beaverlodge-Athabasca Uranium Province

In addition to hypotheses for the formation of individual deposits discussed in preceding paragraphs, some authors have developed more comprehensive regional models for the formation of uranium deposits of northern Saskatchewan. In the following paragraphs, some concepts of Voultsidis et al (1980), Tan (1980), Tremblay (1978c), Rimsaite (1978), Hoeve et al (1979), Dahlkamp (1979), Beck (1970), and others are presented. These authors have devoted considerable time to the study of veinlike deposits, and their views deserve careful consideration. We do not attempt to synthesize these concepts or resolve their differences; in most cases the available data are still inadequate to do so. The working model which best seems to fit the data from all the veinlike districts is presented in a later part of this report.

Voultsidis et al (1980) reviewed the various genetic models for the unconformity-related Proterozoic uranium deposits, based on their extensive studies of the Key Lake deposit, and presented their concepts for ore formation. As they noted, published concepts of genesis for the unconformity-related deposits can be grouped into papers favoring hypogene, supergene, or diagenetic ore-forming processes. The points of greatest controversy are (a) source of the ore elements, (b) pre-enrichment and enrichment of ore minerals, (c) mechanism, age, and temperature of ore deposition, and (d) remobilization and redistribution of the mineralization. In the following paragraphs some of their important observations are briefly summarized.

With respect to the primary source of ore elements, some authors have proposed that the uranium was derived from the Athabasca Formation. Johns (1970) even postulated that a roll front had previously existed in the sandstone, but intensive exploration has found no support for this theory. More recently, Hoeve and Sibbald (1978b) suggested that uranium was leached from the detrital minerals of the sandstone, such as feldspars and mafic and heavy minerals. Studies of the basement gneisses in the Key Lake area, on the other hand, have identified uncommonly high uranium and nickel concentrations that average 13 ppm U_3O_8 and 37 ppm Ni, whereas the Athabasca sandstone contains only 1.5 ppm uranium (Hoeve and Sibbald, 1978b; Strnad, personal communication, 1979). Both uranium and nickel occur preferentially in biotite-rich horizons, and Voultsidis et al (1980) consider these rocks more likely sources for the elements than the Athabasca sandstone.

A hypogene origin for the deposits has been suggested by several authors. Voultsidis et al (1980) give several factors which they feel argue against a hypogene origin for the Key Lake deposit including: (a) geologic thermometers that include maximum temperatures of 135°C and 137°C, (b) a limited vertical extent of the orebodies, (c) the ore parageneses, (d) the lack of lateral mineral zoning, and (e) the absence of typical magmatic-hydrothermal gangue minerals such as euhedral quartz, carbonates, barite, or crystalline chlorite. Finally, the distribution of alteration within the mineralized structures suggests that hypogene solution did not move up structures. At the base of the uranium mineralization, there is an abrupt mineralogical change within the fault where the predominant Fe-chlorite and kaolinite of the zone give way to Mg-Fe-chlorite, sericite, and quartz in the underlying mylonite. The latter assemblage is typical of the paleosol, and had hypogene solutions moved up structure, conversion to ore-related alteration should have occurred.

Diagenetic ore-forming processes, originally suggested by Hoeve and Sibbald (1977, 1978a), of one type or another are preferred by several authors including Morton and Beck (1978), Clark and Burrill (1979), and Pagel et al (1979). Hoeve and Sibbald developed a theory whereby hot diagenetic solutions altered graphite of the basement metamorphosis to produce methane that reduced and precipitated the uranium. Voultsidis et al (1980) contend that thermodynamic considerations indicate that graphite would not release methane or carbon dioxide under the 200°C ore-forming conditions assumed by Hoeve and Sibbald (1978b), a temperature they believe to be too low. Furthermore, their investigations show that graphitic schists in the Key Lake area have only local and low concentrations of uranium (Ni is locally more concentrated) which are probably synmetamorphic. The graphitic schists are not, therefore, sites of anomalous concentrations of uranium in spite of publications to the contrary (Kirchner et al, 1979).

Referring to the work of Pagel et al (1979), Voultsidis et al (1980) note that CH_4 and CO_2 were observed in fluid inclusions but that the authors preferred a source for the gases in the Athabasca Formation rather than from graphite.

Furthermore, fluid inclusions studied thus far are mainly from secondary quartz rims in the sandstone and, unfortunately, no fluid inclusions have been found in gangue minerals contemporaneous with pitchblende. The most serious weakness of the diagenetic theory is the apparent absence of leachable uranium minerals in the Athabasca Formation.

Supergene or sandstone-contemporaneous theories suggest ore formation prior to, or syngenetic with, the deposition of the sandstone that overlies the unconformity. Knipping (1974) first proposed such a model for the Rabbit Lake deposit. Voultsidis and Clasen (1978) presented detailed investigations from the Key Lake deposits that support this theory. Strong support to this hypothesis was provided by Dahlkamp (1978) for the Athabasca region and by Ferguson et al (1979) for the East Alligator district. According to Voultsidis et al (1980), the concentrations of uranium and nickel, for example within biotites in the basement rocks, were leached during weathering, when all rocks were strongly altered (see Table 15), and subsequently reconcentrated in favorable sites.

Table 15. Chemical analyses for samples from drill hole (DDH H2) illustrating the increase in weathering and leaching in the basement up towards the unconformity (from Voultsidis et al, 1980).

Sample No.	CN-1810	CN-1811	CN-1812-19	CN-1820-31
Depth (ft)	204-11	211-18	212-271	271-349
SiO_2	57.35	71.90	75.75	74.25
TiO_2	0.74	0.32	0.31	0.30
Al_2O_3	21.35	15.12	13.04	12.47
Fe_2O_3 (total)	1.25	1.04	1.88	2.20
CaO	0.08	0.16	0.15	0.18
MgO	9.46	6.14	2.17	4.16
K_2O	0.66	0.75	2.85	3.34
Na_2O	0.40	0.25	0.62	0.20

← Increasing Weathering

Increasing Depth →

With respect to mechanisms for precipitating and concentrating the mobilized uranium, they refer to the following published suggestions. The fault zone at Key Lake resembles a "gley" or soil-like horizon (Isrusch, 1979), characterized by restricted water flow and reducing conditions. Uranium may have been precipitated on the clays under conditions of restricted ground water flow. Robertson et al (1978) and Tilsley (1978) presented a model analogous to electrolytic plating which may have operated at and below the unconformity in response to high Eh conditions of the oxygenated weathering environment and the low Eh conditions at greater depths. Such an electrolytic cell might form, they argue, in a conductive structure such as a fault zone with dissolved salts or a graphitic layer. Uranium was presumably precipitated through reduction as ground waters moved past the "electrode".

Published data on fluid inclusions suggest temperatures in the range of 200°C which would have required deep diagenetic conditions. Voultsidis et al (1980) also argue, however, that two mineralogical thermometers ($\alpha - U_3O_7$ and bravoite) indicate a maximum temperature of ore formation of around 135°C. Voultsidis and Clasen (1978) identified the tetragonal phase, $\alpha - U_3O_7$, which is stable in air up to a temperature of 135°C. The occurrence of primary bravoite with low cobalt content indicates a similar low maximum temperature of 137 ± 6°C (Clark and Kullerud, 1963; Springer et al, 1964). Although these observations were noted by Dahlkamp (1978) and Gatzweiler et al (1979), they are rarely referenced in later papers on these types of deposits. Low temperatures of formation have also been reported for ore assemblages (bravoite with pitchblende in basement mylonite) at Maurice Bay (Lehnert-Thiel et al, 1979) and from the gold-bearing assemblage in the Jabiluka deposit (Hegge, 1977). Furthermore, they state that published data on higher temperature fluid inclusions in most cases represent diagenetic temperatures principally in the Athabasca Formation, and not the primary temperatures of ore formation. The presence of $\alpha - U_3O_7$ in the oldest dated mineralization at Key Lake suggests that this mineralization has not exceeded 135°C since 1270 m.y. (Dahlkamp, 1978).

As an argument against pre-Athabasca formation of the unconformity-related mineralization, Kirchner et al (1979) suggested that mineralization in fault structures would have been mechanically washed out during the high-energy sedimentation of the basal Athabasca sediments; hence, the mineralization must be post-Athabasca. In reply, Voultsidis et al (1980) report that experiments with the mylonitized Key Lake core suggest that open spaces would have tended to be closed rather than opened by water movement. Since the basal conglomerates and sands of the Athabasca exist essentially everywhere over regolith, it seems this altered basement material survived the high-energy depositional environment.

Uranium-lead age determinations suggest that ores that have been dated were formed well after the deposition of the Athabasca, not prior to or syngenetically with the early Athabasca sediments. The oldest date for Key Lake was performed on $\alpha - U_3O_7$ and is 1270 m.y. (Wendt et al, 1978). The oldest pitchblende age for Rabbit Lake is 1281 m.y. (Cumming and Rimsaite, 1979), and for Cluff Lake 1330 ± 30 m.y. (Gancarz, 1979). Both are approximately coincident with the end of sedimentation for the Athabasca Formation, which was 1350 ± 50 m.y. according to Koeppel (1968) and Ramaekers and Dunn (1977), and 1428 ± 30 m.y. according to Ramaekers (1979). By contrast, the oldest pitchblende ages in the East Alligator Rivers district are between 1700 to 1600 m.y. (Ferguson and Rowntree, 1979). One may assume, as do Voultsidis et al (1980), that because of the general geologic similarities between the Canadian and the Australian deposits, the ages of around 1270 to 1330 m.y. are not primary ages but were produced at the end of the Athabasca sedimentation. At Key Lake, evidence for strong remobilization of uranium and lead and the abundance of radiogenic lead supports such an hypothesis.

Voultsidis et al (1980) conclude that the evidence for redistribution of "primary" basement ore is compelling and includes (a) age dating (Wendt et al, 1978), (b) mineralogical differences between the older basement mylonite ore and the younger sandstone ore, and (c) the evidence of redistribution indicated by radiogenic galena and millerite coating joints. They feel these features indicate that after the formation of primary ore in the basement, it was in part redistributed up into the sandstone, so that mineralization in the latter may be viewed as a secondary halo over the basement ore. They (Voultsidis et al, 1980) favor a

> supergene pre- to syn-Athabasca formation with strong subsequent redistribution of parts of the ore resulting in a secondary halo in the overlying Athabasca sandstone. Adjacent graphite horizons played no chemical role as producer of reducing gases, but they may have facilitated ore deposition due to their physical properties, possibly in places representing a gliding plane for the tectonic fault or as a conductor in an electrolytic cell; they may also have formed part of a synmetamorphic protore in the area.

Tremblay (1972, 1978a, 1978b, 1978c) has conducted extensive field studies in the Beaverlodge area, and his observations are important to any discussion of these types of deposits. In a recent publication (Tremblay, 1978c), he compared the deposits of the unconformity and Beaverlodge types (Table 16). Some important comments are expanded below.

(1) It appears that the unconformity-type deposits have formed when the unconformity was being formed and were enriched later when the unconformity was structurally a trap.

(2) The Beaverlodge-type deposits are related to major faults such as the St. Louis, the Black Bay and the Boom Lake faults, but the mineralization generally is within the brecciated and fractured rocks adjoining the fault plane itself. These subsidiary features are the main mineralization control. However, since many of the subsidiary fractures are late, much of this mineralization must be late. Similarly, the unconformity-type deposits are related to major faults, but in this instance the mineralization is maximum at the fault-unconformity intersection and extends along the fault zone and the adjoining brecciated and fractured rocks for a few hundred meters above and below the unconformity, suggesting that the unconformity and the fault, and particularly their intersection, are the main mineralization control.

(3) The unconformity-type deposits can be high-to-low grade whereas those of the Beaverlodge type are generally low-grade. The high-grade unconformity-type deposits are generally in basement rocks whereas the low-grade ones occur in both basement and cover rocks. Where the mineralization has been identified only in the cover rocks, it probably indicates that the possibly-rich basement mineralization has not been located yet.

    In both Beaverlodge-type and unconformity-type deposits, the uranium mineralization locally occurs as fracture-fillings and as disseminations in the adjoining rocks. Elsewhere, there are fairly large massive accumulations of pitchblende. These accumulations also have been observed in both types of deposits, but are more common in the unconformity-type where they occur both in the Archean basement and in the Proterozoic cover rocks.

(4) Most Beaverlodge-type deposits occur at a specific stratigraphic level within the Tazin Group. In this sense they are stratabound . . . . By contrast, unconformity-type deposits do not appear to be related to any particular stratigraphic horizon but they are commonly associated with graphitic rocks and/or carbonate rocks. Carbonaceous and calcareous matter may have controlled precipitation. Amphibolite also has been considered to be a preferential ore host. However, it is possible that local alteration to white clay minerals has been the main control on unconformity-type mineralization.

The wall rocks in the Beaverlodge deposits are hematitized and contain mafic minerals and garnet that are altered to chlorite. These rocks are cut by veins of hematite, chlorite, carbonate, quartz and albite. The unconformity-type deposits are characterized by ubiquitous white claylike alteration. In basement rocks this alteration is concentrated at the unconformity and has been interpreted as regolith. It extends to some depth in basement rock along fault and fracture zones below the unconformity and is commonly seen superimposed by another light greenish-white magnesium-rich alteration composed of chlorite and micas . . . . The two alterations associated with the unconformity-type deposits appear to have formed in Helikian time while those related to the Beaverlodge-type deposit are late Aphebian to middle Helikian.

(5) The mineralogy of both types of deposits is locally either simple or complex. The largest Beaverlodge-type deposits have a simple mineralogy, consisting mainly of pitchblende, hematite, and pyrite with minor amounts of chalcopyrite, galena and sphalerite. Secondary uranium minerals are uncommon and occur mainly near the surface. However, the Gunnar Mine had secondary minerals to a depth of 300 meters (980 ft.). Some minor deposits in the Beaverlodge area have a complex mineralogy. In addition to pitchblende, they have several arsenides and selenides of copper, cobalt, and nickel. The main uranium minerals of the unconformity-type deposits are pitchblende and coffinite. Much of the pitchblende is sooty and dusty. Secondary uranium minerals are fairly common and locally are abundant. Some deposits have a relatively simple mineralogy, displaying only sulphides and carbonaceous matter in addition to pitchblende and coffinite. Other deposits of this group are characterized by a complex assemblage of sulphides, arsenides, tellurides and selenides of Ni, Co, Bi, and Pb. These may also contain substantial amounts of gold and silver. In both the Beaverlodge and unconformity-type deposits, a rough chemical zonation may be present, but this has not yet been demonstrated regionally. In some deposits, there is obvious variation in the contents of uranium, vanadium, titanium, selenium, nickel, etc. among the mineralized zones.

(6) The Beaverlodge-type deposits seem to have formed about 1780 ± 20 m.y. (Koeppel, 1968; Tremblay, 1972) with important remobilization of uranium about 1140 ± 50 m.y. and possibly at several other, later times. The time of mineralization for the unconformity-type deposits appears to be around 1200 m.y., as indicated by the available dates from Rabbit Lake,

Table 16. Comparison of Beaverlodge and unconformity-related deposits, Saskatchewan (modified from Tremblay, 1978c).

Unconformity-Type

1. Stratigraphically confined to Athabasca unconformity.
2. Related to faults in both basement and Athabasca sandstones. Faults are old with late movements.
3. Mineralization is along faults and disseminated in wall rocks; it is entirely either in basement or in Athabasca sandstone; locally it is in both.
4. Not restricted stratigraphically but associated in basement with graphite, calcsilicate and amphibole-bearing rocks.
5. Not related to granitization.
6. Associated with clay-white altered regolithic areas in basement and with late green chloritic and sericitic areas in basement and sandstone.
7. Maximum development of regolith at unconformity; widespread chemical alteration.
8. Large horizontal but little vertical extent of ore zones.
9. Pitchblende, coffinite and locally abundant secondary uranium minerals; sooty.
10. Simple and complex mineralogy.
11. Cu, Ni, Se, As, Au, Ag and/or Te: in variable amounts and of erratic distribution; crude zoning locally.
12. Age of mineralization: 1200 m.y., with remobilization periods.
13. Temperature of formation: 260°C to 60°C.
14. Age of host rocks: mainly Aphebian and Helikian; locally Archean.

Table 16 (continued)

Beaverlodge-type

1. Not stratigraphically confined to Martin unconformity.
2. Related to major faults or wide mylonite zones and to zones of closely spaced fractures superimposed on mylonite zones.
3. Mineralization is along fractures and disseminated in wall rocks.
4. Related to a specific lithologic succession at a definite stratigraphic level in Tazin rocks.
5. Related to areas intensely granitized and widely retrograded to greenschist facies.
6. Associated with areas intensely altered with red hematite, dark-green chlorite and white carbonate; some silicification; rare argillization.
7. Mechanical detritus along unconformity is thin near ore and distribution is erratic.
8. Large horizontal and vertical extent of ore zones.
9. Pitchblende, minor secondary uranium minerals, rare brannerite.
10. Generally simple mineralogy, locally complex.
11. Cu, V, Se, and Ti: in variable amounts and of erratic distribution; crude zoning locally.
12. Age of mineralization: 1780 ± 20 m.y., 1140 ± 50 m.y. and several remobilization periods.
13. Temperature of formation: 440°C to 80°C.
14. Age of host rocks: mainly Archean; locally Aphebian and Helikian.

Key Lake and Cluff Lake, with several later periods of ore mobilization (Tapaninen, 1975; Little, 1974; Knipping, 1974; and Gatzweiler et al, 1978). However, older pitchblende of similar age as that found in Beaverlodge-type deposits is probably present in basement deposits.

(7) Fluid-inclusion studies indicate that the Beaverlodge-type deposits were formed under conditions of decreasing temperature from 440° ± 30°C to 80° ± 10°C accompanied by decreasing salinity (Sassano et al, 1972b). Those of the unconformity-type probably formed at somewhat lower temperatures, that is between 260°C and 60°C, as indicated by fluid-inclusion studies and the presence of minerals such as bravoite and tetragonal pitchblende (Dahlkamp and Tan, 1977).

Based on mineralogical investigations of the unconformity-bound deposits of the southern Athabasca Basin area, particularly the Rabbit Lake deposit, Rimsaite (1978b) proposed the following sequence of events in the formation of the deposits:

(1) Tectonic activity produced recurrent movements on fractures and breccia zones that both preceded and followed uranium mineralization.

(2) Primary uranium mineralization was formed in these structural zones but evidence was destroyed by subsequent alterations and uranium remobilizations. Uranium was remobilized and radiogenic lead removed from most pitchblende during the emplacement of sulfides, selenides, tellurides, and gold, at about 1120 m.y.

(3) After formation of pitchblende mineralization a thermal event recrystallized some minerals.

(4) Following the thermal event, poorly crystalline uraniferous mixed-layer phyllosilicates were formed at temperatures below 200°C from liberated uranium and groundmass silicates.

(5) Subsequently, uranium ore minerals and host rocks were hydrated, argillized, bleached, and replaced by clays, with the removal of iron, alkali, magnesium, and uranium.

(6) The variability among uranium deposits in northern Saskatchewan is due in part to different post-mineralization alteration histories, more than one generation of pitchblende, and several secondary uranyl-bearing minerals in even small samples of ore.

Hoeve et al (1979) noted that metallogenetic concepts for the Athabasca Basin deposits could be "grouped into models advocating near-surface supergene, magmatic/metamorphic-hydrothermal and diagenetic-hydrothermal origins," the latter of which they prefer.

The model proposes that saline, oxidizing diagenetic solutions of the Athabasca Formation, at elevated temperatures of around 200°C and at a depth of 4-5 km (as inferred from fluid inclusion studies, Pagel, 1975a), penetrated the metamorphic basement along fault and breccia zones and reacted with graphitic rocks to yield reducing solutions containing carbon dioxide and methane. Mineralization resulted from interaction of flows of the newly generated methane-bearing reducing solutions and of the oxidizing diagenetic solutions carrying ore constituents and, hence was subjected to hydrological control. The geometry of several orebodies suggests that a flow of reducing solution, discharging into the Athabasca aquifer, was laterally deflected by a flow of oxidizing solution directed along the unconformity. Exceptionally high grades as encountered in many unconformity-type deposits, may develop in a situation of prolonged stationary hydrodynamic equilibrium, as the system is marked by continuous replenishment of ore constituents and methane reductant. Repeated oscillations between oxidizing and reducing conditions as documented by the authors at Rabbit Lake, may have arisen from changes in the hydrological regime in response to modification of the plumbing system by intermittent brecciation.

The source of the ore constituents was in detrital minerals of the Athabasca Formation, from which they were released by intrastratal weathering, which also resulted in widespread hematitization of the formation. Oxidation and destruction of feldspars, mafic and heavy minerals, must have liberated a broad suite of trace elements including U, Ni, Co, As, and other ore constituents in addition to iron. Whether such constituents were taken directly into solution or remained initially adsorbed to iron hydroxides and were released later when these recrystallized to hematite, is unknown for the moment.

They consider significant the correspondence of ages between "primary mineralization" (1000-1250 m.y.) and the Grenville age magmatic and tectonic activity (900-1250 m.y.), suggesting that the latter produced the large-scale convection of diagenetic solutions required for extraction and reconstitution of the ore constituents.

The Athabasca Formation has red-bed characteristics, and although its initial oxidation state and diagenetic history are little known, there is increasing evidence to suggest that, like many more recent red beds (Walker, 1967), the formation was subjected to prolonged and intensive post-depositional oxidation and leaching. Such processes, which might have started shortly after deposition, continued for millions of years after deposition of the Formation.

The ore-forming process (Hoeve et al, 1979) may have been similar to the formation of epigenetic sandstone-type deposits, which involves (see, for example, Adler, 1974) either movement of oxidizing ground waters into reduced sediments, or migration of mobile reductants (H_2S, volatile hydrocarbons, etc.) into red beds containing uraniferous pore waters.

Although the original oxidation state of the Athabasca Formation is unknown, it can be speculated that roll-fronts might once have been present and that conditions as observed in the Wyoming basins might represent a transient stage in a process of intrastratal oxidation that has gone to completion in the Athabasca Basin. In contrast to Phanerozoic sediments, post-depositional oxidation of the Proterozoic Athabasca Formation may have been facilitated by the absence of organic trash.

Continuing, they note that:

further similarities between Athabasca Basin unconformity-type and sandstône-type deposits relate to geochemistry and host rock alteration; mineralization is marked by a similar broad suite of elements accompanying uranium, including Ni, Co, Cu, Zn, Pb, Ag, Fe, As, Se, S and others and ore zones are often enriched in magnesium and characterized by chloritization.

In summary, although general conditions of formation have been somewhat different, reflecting deep burial rather than a more surficial environment, processes and mechanisms involved in the formation of Athabasca Basin unconformity-type and epigenetic sandstone-type deposits may be closely related.

Beck (1969) conducted extensive studies on the uranium deposits of the Athabasca region, particularly those of the Beaverlodge district. He favors an hypothesis involving epigenetic pitchblende mineralization transitionally following syngenetic uraninite crystallization, without a marked break in time, because of the following criteria:

(1) The apparent age of the initial pitchblende deposition (1780 $\pm$ 20 m.y.) is so close to the K-Ar ages of micas from the basement gneisses (1740-1795 m.y.) that pitchblende was probably emplaced during the latter part of the Hudsonian orogeny.

(2) Although the radiometric ages of the Hudsonian granites and related radioactive pegmatites (1820-1920 m.y.) established by whole-rock Rb-Sr dating and U-Pb ages (1930 $\pm$ 40 m.y.) of the syngenetic uranium minerals are slightly older than the pitchblende ages, field evidence indicates that some of the granites were emplaced toward the end of Hudsonian tectonism and, therefore, granitization was probably followed closely in time by the deposition of pitchblende. In fact, granitization and pitchblende mineralization may have overlapped chronologically, as a pegmatite at the Gunnar Mine, dated at 1815 m.y., is intrusive into, and therefore younger than, the pitchblende-bearing ore zone.

(3) The two types of deposit overlap in spatial distribution, and the hybrid deposits suggest a syngenetic-epigenetic transition.

Since their initial emplacement, the pitchblende deposits have had a long and varied history of reworking and rejuvenation. The concept of a single period of pitchblende mineralization about 1780 m.y. ago, followed by rejuvenation of existing deposits, is preferred by Beck (1969) to a concept involving successive and separate epochs of mineralization because of the following criteria:

(1) The existence of several generations of pitchblende in a single polished section is more easily explained by rejuvenation of existing pitchblende than by successive and separate periods of mineralization.

(2) In polished section, remnant veins of pitchblende rimmed by galena suggest a process involving migration of initial pitchblende with concomitant precipitation of lead.

(3) The abnormally high content of radiogenic lead in lead minerals associated with the ores is attributed to dissolution of early pitchblende and chemical separation of the accumulated radiogenic lead.

(4) The apparent U-Pb ages of pitchblendes are best explained on the basis of a single period of mineralization followed by successive periods of rejuvenation (Koeppel, 1968).

Rejuvenation of pitchblende is believed to have been caused by localized tectonic-thermal events, including downwarping of the basement prior to deposition of the cover rocks, subsequent uplift and folding of the cover rocks, intrusion of diabase dikes and gabbro sills, and intermittent movements along the major faults related to epeirogenic movements in the Shield. The history of mineralization, listing the main events and the evidence for them, is summarized in Figure 44.

Beck (1969) has also considered the composition and changes in the composition of the ore-forming solutions.

> Paragenetic sequences indicate that the chemical nature of solutions, particularly the concentration of metal ions, has varied considerably throughout a long and complex, but apparently continuous, history of mineralization. A general increase in the amount and variety of sulphide minerals is correlated with decreasing age of the deposits. This suggests that early uranium-bearing solutions were relatively free of other metal ions and that later solutions became enriched in these constituents, but there are many local changes and reversals of this sequence.
>
> Despite the changes in the concentration of various metal ions, ore-bearing solutions must have been similarly charged with both calcium and CO_2 ions, because calcite is ubiquitous in all stages of pitchblende mineralization and it seems likely, therefore, that most of the vein-forming minerals were transported as carbonate complexes.
>
> Much of the early pitchblende shows textural features, including colloidal forms with synaeresis cracks, which are indicative of colloidal deposition. . . . It is therefore likely that early pitchblende formed by coagulation of colloidal dispersions or sols which probably consisted of very fine particles of uranium oxide (the dispersed phase) held in hydrothermal solution (the dispersing medium). . . . Later pitchblende is mainly massive and lacks colloform textures and may, therefore, have been precipitated from true solutions perhaps derived, in part, from the dispersing medium of the sol after coagulation of colloidal pitchblende. It is probable, however, that much of the massive pitchblende was deposited long after the colloidal variety was formed, and therefore may have been precipitated from solutions in which the uranium content was derived from the dissolution of earlier colloform pitchblende. Moreover, it is probable that these later solutions carried the ions which formed metallic accessory minerals.

With respect to the mechanisms of ore deposition, Beck (1969) states that it is apparent that loss of pressure and catalytic reaction with iron have been critical factors in causing precipitation and that the structural environment has determined which of the two factors was dominant in the formation of a specific ore zone.

> Most of the large botryoidal masses and veins of massive pitchblende are restricted to breccia zones and other open-space structures where tensional, and therefore relatively low-pressure, conditions were operative.

PROBABLE DURATION OF EVENTS

EVENT	ISOTOPIC EVIDENCE M.Y.	Method	Regional Meta-morphism. Syn-tectonic Granites	Syngenetic Uranium Emplacement	Late- and Post-Tectonic Granites	Early Faulting and Mylonitization	Normal or Block Faulting	Pitchblende Mineralization	Diabase Intrusion
12. Further fault movements and erosion. Glaciation and subsequent isostatic response. Supergene alteration of deposits by ground water.	0-100	U-Pb data							
11. Uplift. Fault movements. Erosion of Phanerozoic sediments. Rejuvenation of pitchblende.	270	U-Pb data							
10. Peneplanation. Subsidence and partial covering by Phanerozoic sediments.									
9. Tectono-thermal events in shield. Rejuvenation of pitchblende.	1110	U-Pb data Episodic lead loss							
8. Deposition of cover rocks and intrusion of diabase	1410-1490 1610	K-Ar on gabbro and diabase K-Ar on basalt							
7. Erosion of Hudsonian orogen and formation of basins of deposition									
6. End stages of orogeny. Retrograde metamorphism, hydrothermal alteration, emplacement of pitchblende	1780 1740-1795	U-Pb concordia on pitchblende K-Ar on gneisses							
5. Emplacement of late- and post-tectonic granites. Crystallization of uraninite	1815 1820	K-Ar on muscovite, Gunnar mine Rb-Sr isochron, Athabasca							
4. Widespread mylonitization and formation of thrust and tear faults									
3. Regional metamorphism, formation of gneisses and syntectonic granites. Crystallization of uraninite	1900 1930	U-Pb concordia, and Rb-Sr isochron, Alberta U-Pb concordia. Athabasca							
2. One or more orogenic periods	2200 2250 2350 2440	Rb-Sr isochron, Athabasca Rb-Sr isochron and U-Pb concordia, Alberta K-Ar on hornblende K-Ar on hornblende							
1. Sedimentation and volcanic activity		Probably >2500 m.y. ago							

Note: Events 3-6 would be probably transitional and overlapping and would not necessarily be of equal duration or extent in all parts of the orogen.

Figure 44. Proposed sequence of geologic events in the Athabasca region (from Beck, 1969).

Although hematite is commonly associated with such veins, it is not ubiquitous and, therefore, it is concluded that loss of pressure has been the most important factor in promoting the precipitation of pitchblende. In contrast, fine-grained and sub-microscopic pitchblende is virtually restricted to heavily hematized wall rocks in mylonite and breccia zones where confining pressures were presumably relatively high. Consequently, catalytic reaction of the hydrothermal solution with iron in the wall rock was probably the dominant factor in this type of environment.

In summary, Beck (1969) concluded that

> pitchblende deposition is related genetically to the syngenetic uraninite mineralization. Deposits of uraninite in country rock appear to have been formed by recrystallization of paragneiss accompanied by the concentration of uranium. As this type of deposit shows no clear-cut distinction from the type 'pegmatites in migmatite zones', it is possible that the known types of uraninite-bearing deposits -- 'uraninite in country rock'; and 'dyke-like pegmatites'-- merely represent stages of recrystallization in the transformation (granitization) of country rock to granite. Because there also appears to be a transition between uranium-bearing pegmatites and hydrothermal pitchblende deposits, it is logical to postulate that a late stage in the granitization process would be the release of uranium-bearing solutions.

Pagel et al (1979) investigated fluid inclusions in the gangue minerals of the Cluff Lake D and Rabbit Lake deposits. They concluded that the genetic model which is most consistent with their results, previously suggested by Pagel and Jaffrezic (1977) and Hoeve and Sibbald (1976, 1978c), places great importance on deep diagenetic processes and may be summarized as follows (see Fig. 45):

(1) Uranium was preconcentrated either by sedimentary metamorphic processes (Dahlkamp, 1978) or by anatectic mobilization (Sibbald et al, 1976).

(2) Weathering of the basement rocks mobilized uranium which became concentrated in organic-bearing argillaceous sediments and along faults.

(3) The Athabasca Formation was deposited.

(4) Diagenesis and silicification of the Athabasca sandstones occurred under deep burial in association with uranium-bearing, oxidized brines. Adjacent to the unconformity with the underlying basement, uranium was precipitated, probably through mixing with a fluid derived from the basement, as indicated by the pervasive hydrothermal alteration.

(5) During a period corresponding to the Grenville orogeny, modification of P-T conditions and fluid flow paths led to the deposition of pitchblende. Isotopic data from fluid inclusions suggest the solutions were meteoric water.

(6) Within the Carswell structure temperatures higher than 300°C (Rimsaite, 1978), probably related to the formation of the structure itself, produced recrystallization of pitchblende to uraninite.

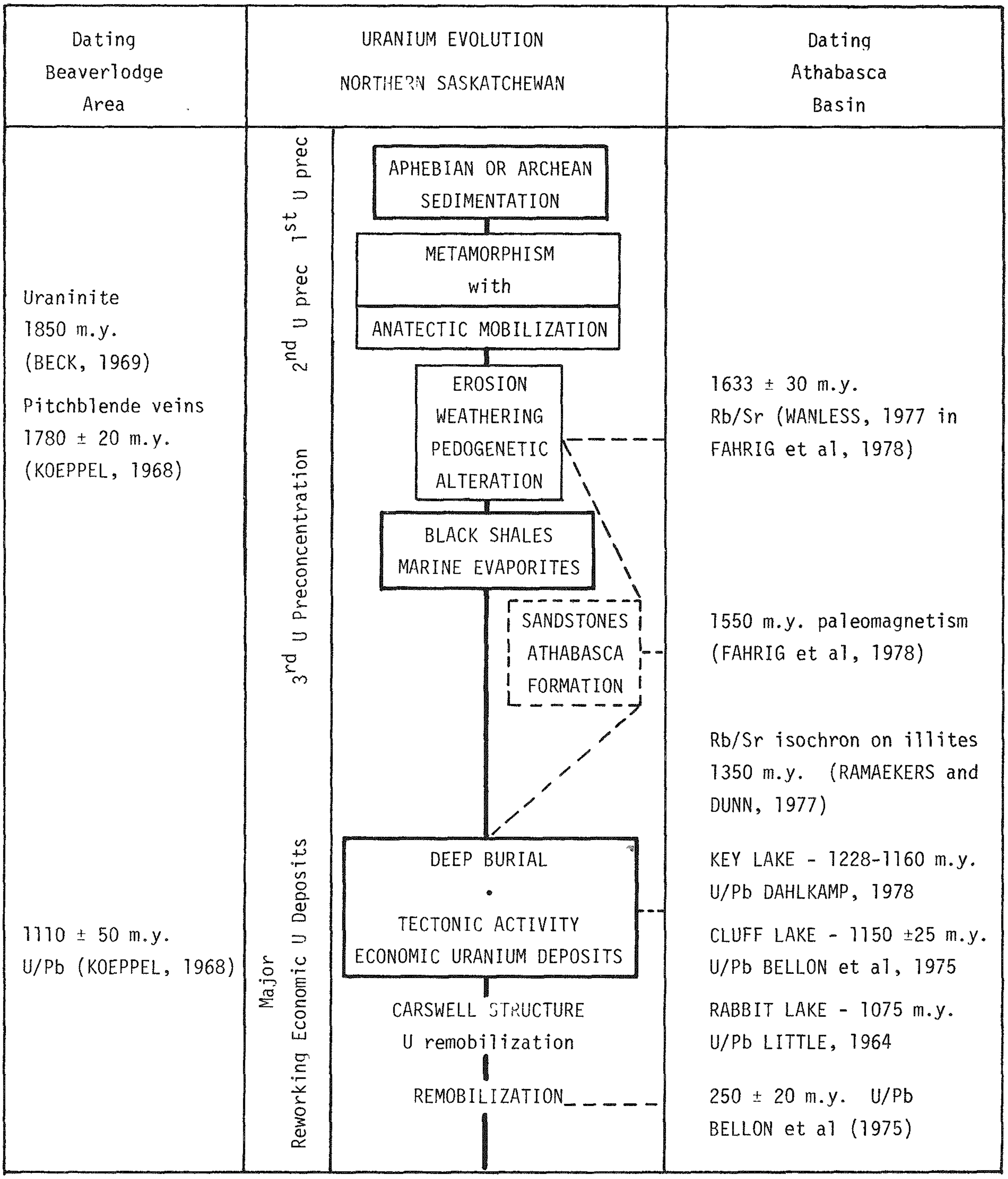


Figure 45. Model for the formation of the uranium deposits in northern Saskatchewan (Pagel et al, 1980).

Pagel et al (1980) subsequently amended the foregoing model as follows:

(1) Uranium preconcentration has been demonstrated in metamorphic rocks (Dahlkamp, 1978) and thus U was already present in Lower Proterozoic (Aphebian) or Archaean sediments, some of which are interpreted as black shales (Sibbald et al, 1976; Hoeve and Sibbald, 1978c). A further concentration step for uranium may have been the anatectic mobilization of these rocks.

(2) Pedogenetic alteration at the Lower Proterozoic (Hudsonian) unconformity must have released uranium. Part of this uranium was trapped in algal mats which are characteristic of the intertidal zone of lagoons where a Mg, B and Li rich sedimentation, of an evaporitic type, was occurring. Formation of the economic deposits at this time is negated by both fluid inclusion and isotopic data.

(3) Deposition of the Athabasca sandstones and later sediments.

(4) During burial the formation waters acquired their chemical and isotopic character (density, Cl/Br ratio, δD, $\delta\ ^{18}O$, $\delta\ ^{13}C$, etc. . .).

(5) Probably as a consequence of tectonic activity during the Grenville orogeny, there was major migration of the formation waters and redistribution of uranium. The economic uranium deposits date from this period. The source of uranium must be located in these argillaceous and organic rich sediments (fossil lagoons?) and not in the sandstones which are very mature, rather clean and apparently quite different from those of typical sandstone type uranium deposits.

Dahlkamp (1978) presents the results of detailed mineralized and geochemical studies for the Key Lake deposit. He interpreted the data as indicative of syngenetic accumulations of uranium in the Aphebian sediments followed by redistribution during late metamorphism, weathering, and diagenetic processes. Figure 21 is a schematic representation of the evolution of the deposits.

Northwest Territories

Although no discoveries of veinlike-type uranium deposits of economic magnitude have been announced in the Northwest Territories, with the possible exception of the former Eldorado Mine at Port Radium, many subeconomic uranium occurrences of this type have been discovered, particularly around the Baker Lake and Thelon Basins. It seems only a question of time until a viable discovery is announced.

The uranium province of the Baker Lake and Thelon Basins lies between latitudes 60° and 66°N and longitudes 94° and 105°W in the districts of Mackenzie and Keewatin (see Fig. 2). The region is known as Barren Lands and is within the Arctic climatic zone. The terrain is flat to slightly undulating tundra, and outcrops are rare.

The only established settlement is the Eskimo village of Baker Lake on the northwest shore of Baker Lake. Access is by boat from Churchill, Manitoba, during the summer, or by aircraft. The remoteness has been a handicap to exploration and would retard development should deposits be discovered.

Bell, 1970; Bundrock and Fuchs, 1980; Curtis and Miller, 1979, 1980; Fraser et al, 1970; Laporte et al, 1978; LeCheminant and Miller, 1978; Lord et al, 1979; Miller, 1979; Miller and LeCheminant, 1978; Ruzicka, 1978, 1979; B. Free, J. Blackwell, R. Netolitzky, and J. Davis (personal communication, 1980).

The oldest formations of the region consist of Archean volcanic and sedimentary rocks (Fig. 46) which are intruded by late Archean plutonic complexes, dominantly diorites and quartz monzonites older than about 2500 m.y. The grade of metamorphism is amphibolite to granulite facies. The Archean complex is cut by porphyritic diabase dikes, dated at approximately 2300 m.y. They are clearly older than the superjacent Hurwitz and equivalent groups.

The Archean is unconformably overlain by shelf-facies sediments of the Aphebian Hurwitz, Amer, and equivalent groups. Both geotectonic units have been involved to varying degrees in the Hudsonian orogeny (about 1700 to 1800 m.y.). The age range for the Hurwitz strata is 2300 to 1700 m.y. (Bell, 1970). During the Hudsonian orogeny, the Hurwitz and equivalent sediments underwent deformation and metamorphism up to greenschist facies.

The Hurwitz Group can be broadly differentiated into three litho-stratigraphic units: (a) a lower unit comprising graywacke, phyllite, carbonate, and conglomerate; (b) a middle unit largely composed of white quartzite; and (c) an upper unit composed of feldspathic quartzite, slate, graywacke, carbonate, siltstone, conglomerate, minor schist, and hornfels. The upper unit is in part equivalent to the Amer Lake Group.

Unconformably overlying the Hurwitz metasediments are unmetamorphosed volcanic and sedimentary rocks of the Dubawnt Group of early Middle Proterozoic to Paleo-Helikian age (Fraser et al, 1970). The Dubawnt sequences are cut by diabase dikes dated between 1500 and 1100 m.y. The age range for the Dubawnt rocks, therefore, is from about 1700 m.y. to 1100 m.y.

The Dubawnt Group consists of three stratigraphic sequences which are, in stratigraphically ascending order (Fig. 47):

(1) South Channel Formation, composed of discontinuous conglomerates, and the Kazan Formation, composed of arkosic sandstones and mudstones. These two formations of the lower Dubawnt sequence are a red-bed sequence with an aggregate thickness of probably 3,000 m. They are characterized by pink to maroon colors and typical fluvial sedimentary structures. Their distribution is essentially confined to an area south of Baker Lake and east of the Kazan River. This depositional site represents, as do most of the early Helikian basins, a fault-controlled intracratonic basin of molasse sediments. The South Channel Formation represents the near-source coarse clastic wedge of the basin fill. There appears to be no regolith developed on the crystalline basement, where early Middle Proterozoic sediments and volcanics are present.

(2) Christopher Island Formation, composed mainly of trachytes, andesites, minor rhyolitic lavas and some intercalated quartzites, arkoses, and conglomerates (up to about 2,000 m thick) and the Pitz Formation, composed mainly of rhyolitic lavas with hyaloclastites and volcaniclastic sedimentary rocks (up to about 100 to 200 m thick). Some intercalated quartzites, arkoses, and

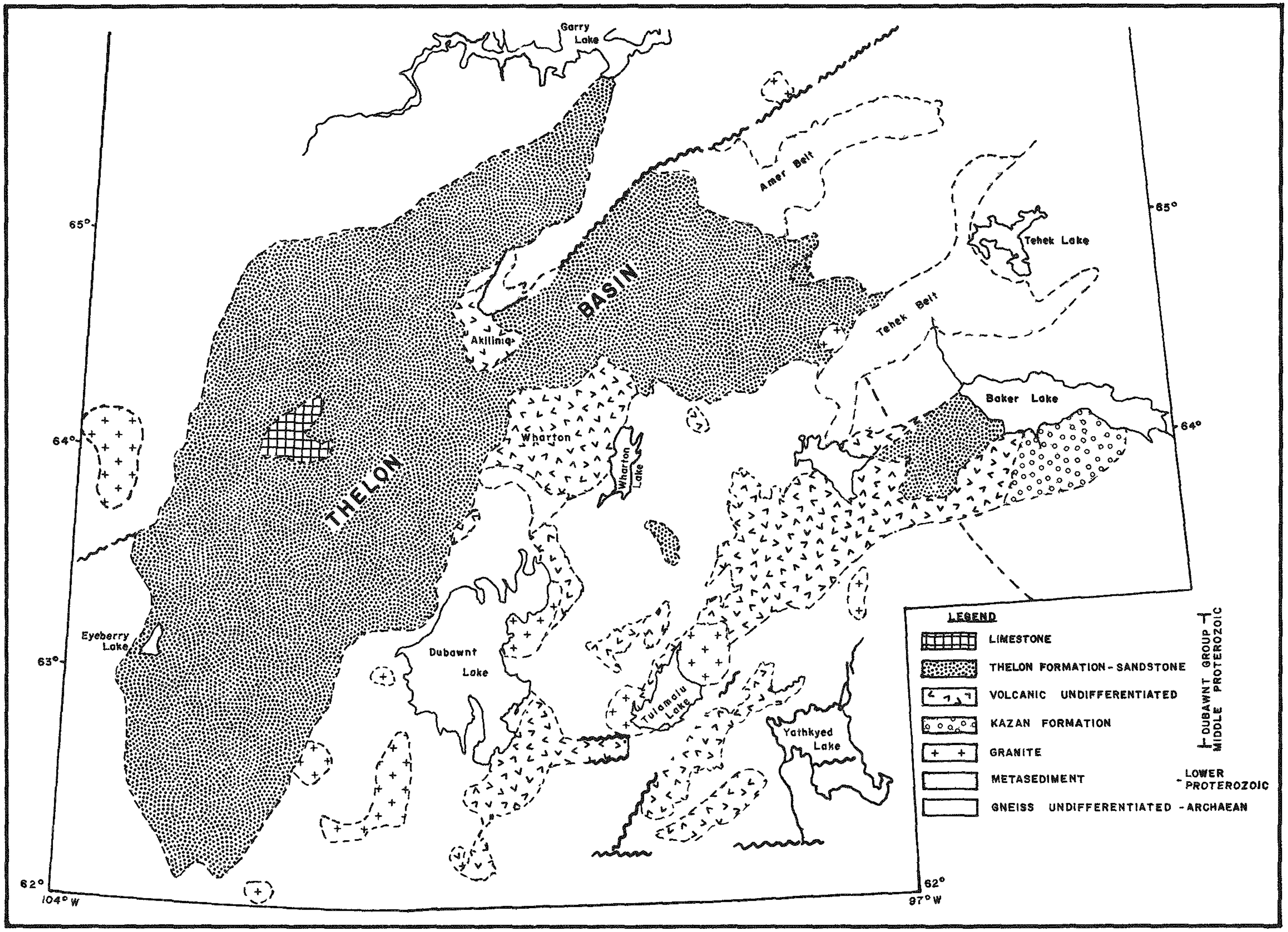


Figure 46. Geologic location map for the Baker Lake-Thelon Basins area, Northwest Territories, Canada (modified from Bundrock and Fuchs, 1980).

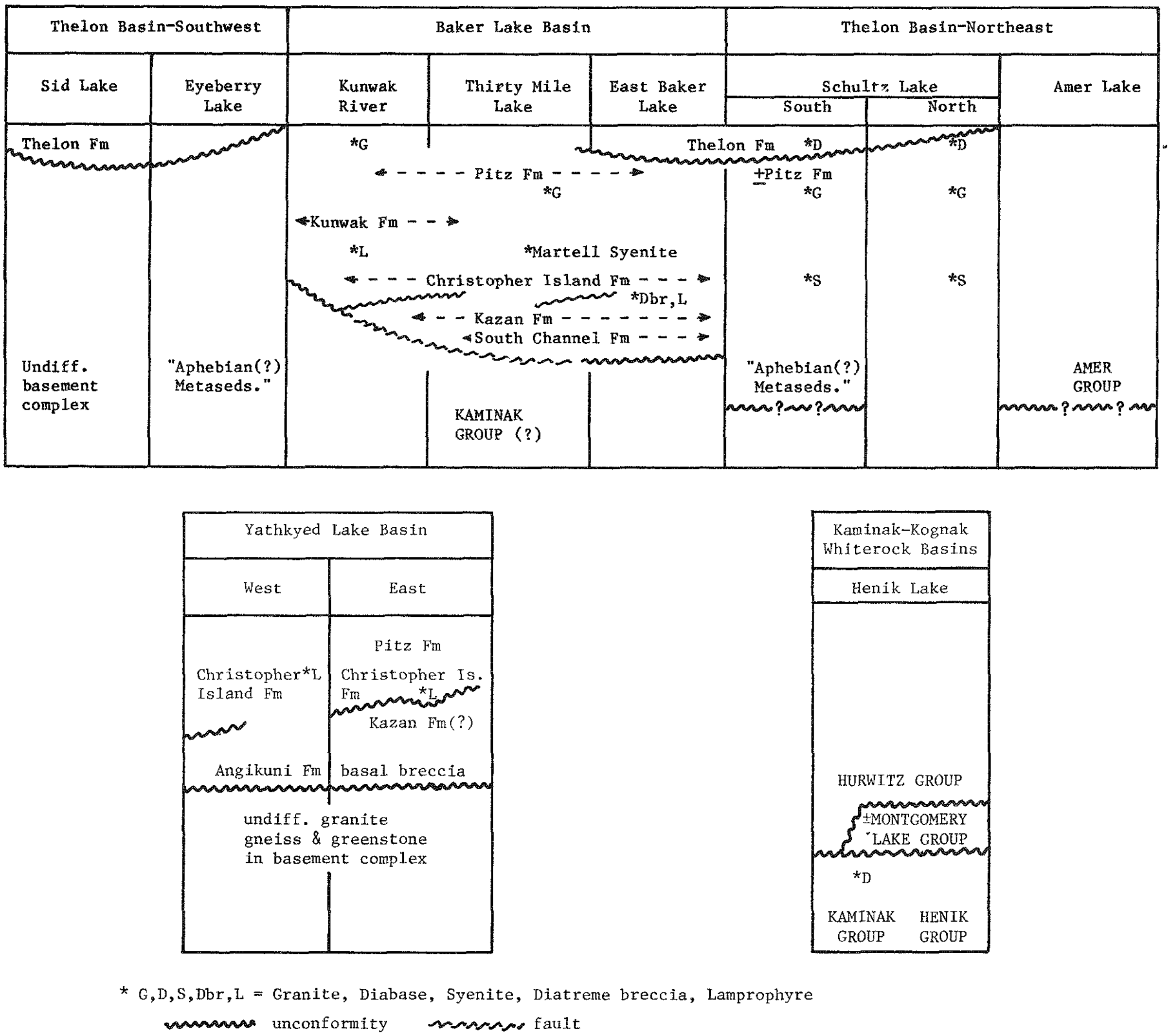


Figure 47. Simplified stratigraphic sections for the Keewatin and Mackenzie districts, Northwest Territories (Curtis and Miller, 1980).

conglomerates are present. K/A dating of Dubawnt volcanics yielded a mean age of about 1700 m.y. (Wanless and Loveridge, 1972). The Christopher Island volcanics are considered to be the extrusive equivalents of the intrusive Martell syenite, and both yield concordant ages. The syenite is noted for its high uranium background (> 30 ppm U). Toward the west (Thelon Basin), the volcanics overlap the basement granites and gneisses, whereas toward the east, in the vicinity of Baker Lake, they lie with slight unconformity upon the red beds of the basal Dubawnt sequence.

Stocks of miarolitic fluorite-bearing granite intrude the Christopher Island volcanics and overlying red clastics in the southwestern part of the Baker Lake Basin. A large intrusion of non-fluorite-bearing, porphyritic micrographic alkali-granite underlies almost 700 km^2 northeast of Tulemalou Lake. It intrudes Christopher Island and Pitz volcanics.

(3) The Thelon Formation, of middle Middle Proterozoic age, is composed of conglomerates and sandstones, which grade upwards from coarse conglomerates at the base to fine-grained sandstones and shales at the top. The sediments are flat-lying and at least several hundreds of meters thick. The Thelon Formation is the most extensive Dubawnt unit and is locally conformably overlain by dolomite and basalt. The Thelon sandstones are considered to be the time stratigraphic equivalent to the Athabasca Formation.

Prior to the deposition of the Thelon Formation, a period of weathering developed a thick regolith on the underlying rocks. The regolith ranges in thickness from several meters to perhaps 100 meters and is composed of silicified and hematitized rock debris which grades downward into weathered bedrock. The regolith is best developed where the Thelon Formation rests directly on granitic basement. Regolithic patches, however, are locally observed along the contact between the Thelon Formation and the underlying Pitz and Christopher Island Formations, demonstrating a post-volcanic age for the regolith.

The Dubawnt Group was mildly deformed and intruded by generally northwesterly trending diabase dikes that have been dated at between 1100 m.y. and 1500 m.y. The region is characterized by a predominant east-northeast trending series of faults and folds and a younger set of northwest-trending faults, with minor north-south and east-west striking faults. The northwest-trending fault system underwent tensional stress during the time of diabase emplacement. The Dubawnt basins tend to be bounded by structures.

The present distribution of the Dubawnt Group is confined to a series of basins and sub-basins preserved as erosional outliers of a much more widespread cratonic basin. The entire region has remained essentially stable; Paleozoic shelf sediments are locally present. Pleistocene glacial erosion and deposition have substantially modified the terrain.

Lithologic and Stratigraphic Distribution of Uranium Mineralizations

Curtis and Miller (1979), based in part on work by LeCheminant and Miller (1978), have described the uranium concentrations in the rocks of the Thelon-Baker Lake area. In Archean-Lower Proterozoic rocks, uranium occurs in primary disseminated mineral phases such as monazite, within heavy mineral concentrates such as apatite, and as U-Th concentrations in pegmatites in granitoid basement rocks of probably Archean-Lower Proterozoic age.

The Early Aphebian rocks in the Padlei area contain a radioactive pyritic quartz-pebble conglomerate, with uranothorite, brannerite (?), and zircon (Lord et al, 1979) directly overlying the Archean basement. This occurrence is probably similar to the Elliot Lake deposits. Uranium occurs in two different types of settings in the Aphebian rocks.

(1) First, as synsedimentary concentrations or fracture-related mineralization within slightly metamorphosed Lower Proterozoic shelf sediments. The majority of such occurrences appear to be associated with pelitic, quartzitic, and feldspathic metasediments of the upper clastic unit in the Amer Group. Very fine-grained pitchblende occurs in arkosic lenses and disseminated in magnetite-bearing, calcareous quartzite and meta-arkose. Pitchblende is often accompanied by magnetite, pyrite, and chalcopyrite. At some locations, uranium has been concentrated in fractures which are peneconcordant with the enclosing uraniferous horizons. Stratiform mineralization is also known to occur in Lower Proterozoic belts southeast of the Amer belt.

(2) As veins, fracture fillings, and disseminated mineralization in the vicinity of Lower-Middle Proterozoic unconformities. Uranium is associated with the unconformity between the Middle Proterozoic Thelon Formation and the Lower Proterozoic sediments on which a well-developed regolith was formed. This geologic setting is considered to have significant potential for ore deposits in the Thelon Basin area. The important Lone Gull-Sissons Lake uranium occurrence south of Schultz Lake is in this stratigraphic setting. Second, uranium occurs along local unconformities within the Dubawnt Group and at unconformities between the Dubawnt Group and underlying basement rocks.

Four types of uranium occurrences have been identified within Helikian rocks of the Dubawnt Group (Curtis and Miller, 1979):

(1) Fracture controlled mineralization occurs in the Lower-Middle Dubawnt Group, particularly at the eastern terminus of the Baker Lake basin. The mineralization consists of pitchblende, associated with copper and lead selenides and electrums of gold and silver. Hematite, chlorite, quartz and carbonate comprise the alteration assemblage. The mineralization is related to major post-Dubawnt northwest-trending fracture zones.

(2) Mineralization in the same area is also associated with alkaline diatreme breccias which intrude Archean granulites. Mineralization is confined to loosely packed breccia and includes pitchblende, chalcopyrite and sphalerite, with associated hematite, barite, quartz, chlorite and calcite gangue.

(3) Uranium mineralization occurs in metasomatized Christopher Island volcanics adjacent to a high level fluorite-bearing granite.

(4) Alkaline syenite stocks and dykes considered to be co-magmatic with the Christopher Island volcanics often have high U-Th backgrounds. Disseminated metamict uranium-thorium bearing phases are responsible for the high radioactivity.

A particular type of mineralization occurs adjacent to the Dubawnt Group and the immediately underlying basement rocks at Kazan Falls. Here, fractures in

Archean granites near the unconformity with the Kazan Formation contain mineralization consisting of pitchblende, pyrite, chalcopyrite, bornite, and galena with local sphalerite and accompanied by quartz, calcite, hematite, and barite gangue.

Uranium Occurrences

Only limited data on the results of exploration have been published. Therefore, the following brief descriptions are preliminary and incomplete. On the basis of present data, two types of potentially significant uranium occurrences have been recognized in the region. The first occurs within, or associated with, pre-Hudsonian crystalline basement rocks, predominantly Aphebian metasediments, that are directly overlain by Thelon Formation. The second type occurs within, or associated with, post-Hudsonian Christopher Island volcanics of the Dubawnt Group.

Pre-Hudsonian occurrences in crystalline rocks may prove to contain economic concentrations of ore, as is indicated by the Urangesellschaft discovery at Lone Gull Lake, north of Sissons Lake. The second type of occurrence, on the other hand, appears to locally contain high uranium grades but thus far only subeconomic ore tonnages.

Lone Gull Lake-Sissons Lake. This significant uranium occurrence is associated with pre-Hudsonian crystalline rocks and is the best example of the type of mineralization which is found in and around the Thelon Basin to the west of Baker Lake. The prospect is located approximately 70 km to the west of Baker Lake. The initial discovery of significant mineralization was associated with frost heaves in the glacially covered terrain. Subsequently, drilling discovered the deposit, which was announced in 1977-78.

Uranium occurs within an east-northeast trending fault zone in impure quartzite and phyllite of the Hurwitz Group which is conformably overlain by white orthoquartzite (Fig. 48). The sequence is intruded by fluorite-bearing granite, syenite, lamprophyre, and diabase (Lord et al, 1979). A well-developed regolith is present at the top of the metasediments. The basement rocks are overlain by the Thelon sandstone, which is exposed about 2 to 3 km to the north of the deposit (Fig. 49).

With respect to reserves, Bundrock (Northern Miner, July 19, 1979) stated they do ". . . not have any idea of reserves in the area, but on very limited data, we think we might be able to prove 1 million lb. of U_3O_8 per hole, or a total of 20 million lb. for the 20 (mineralized) holes." The uranium is believed to be similar to that found in the Athabasca Formation. The best hole of the first 40 drilled contained 33 m of 1 percent U_3O_8, but intersections with more than 50 percent U_3O_8 have been encountered. Pitchblende is the dominant uranium mineral and is associated with kaolin, limonite, hematite, and chlorite (Curtis and Miller, 1980).

Amer Lake. The prospect is situated approximately 200 km north-northwest of Baker Lake at the northeastern end of the Thelon Basin.

Uranium occurs in slightly metamorphosed carbonate-bearing (up to 10 percent) arkose lenses (up to 80 percent feldspar) that are some tens of meters long and wide, and several centimeters to a few meters thick. They are interbedded

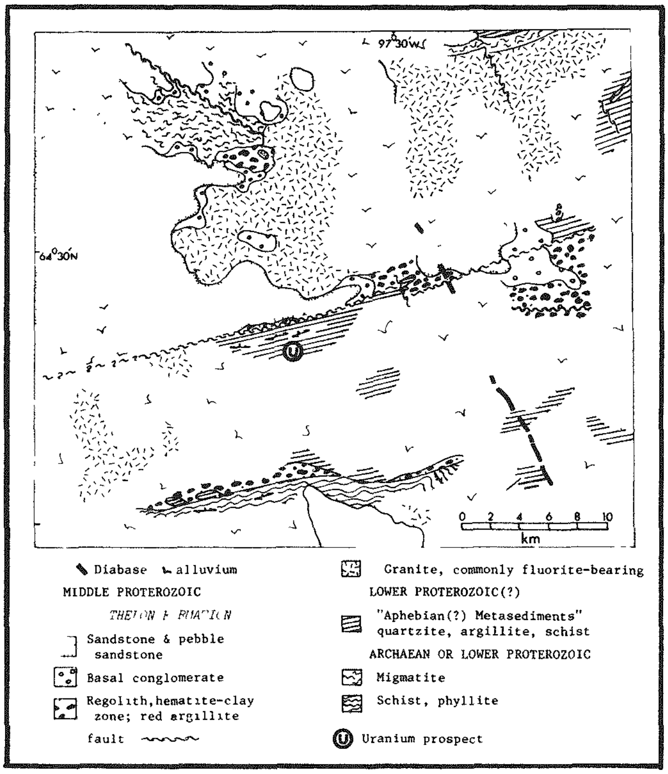


Figure 48. Geology in the vicinity of the Sissons Lake prospect, Keewatin district (from Curtis and Miller, 1980, modified from Donaldson, 1965).

in at least two metamorphosed siltstone sequences (chlorite and/or biotite phyllites) of the Amer Lake Group. The siltstone sequences are fifty to a hundred meters thick. They overlie a carbonate sequence (about 200 m thick) composed of former oolithic limestone, cross-bedded quartzites, biotite-bearing quartzites and sedimentary quartzite-carbonate breccias. This unit was deposited upon approximately 300 m of limestone and dolomite which rest on 1,000 to 2,000 m of white quartzites with an interbedded black shale horizon rich in base metals but void of uranium.

The uranium-bearing siltstone sequences are relatively continuous, but the mineralized arkose lenses are discontinuous. The uranium content is rather irregular, grading between several tens to several thousands of ppm (average about 0.1 percent U_3O_8).

The uranium is present in the form of euhedral crystals (uraninite?). In places, the uraninite appears to be concentrated with magnetite (up to 30 percent). Occasionally some chalcopyrite, galena, and barite are present (no Mo, Ni, Co, As).

At places where peneconcordant thrusts cut the strata, subsidiary "strata-bound" fractures and shears that follow the uraniferous strata are mineralized with pitchblende(?), quartz, calcite, and some chlorite. This type of

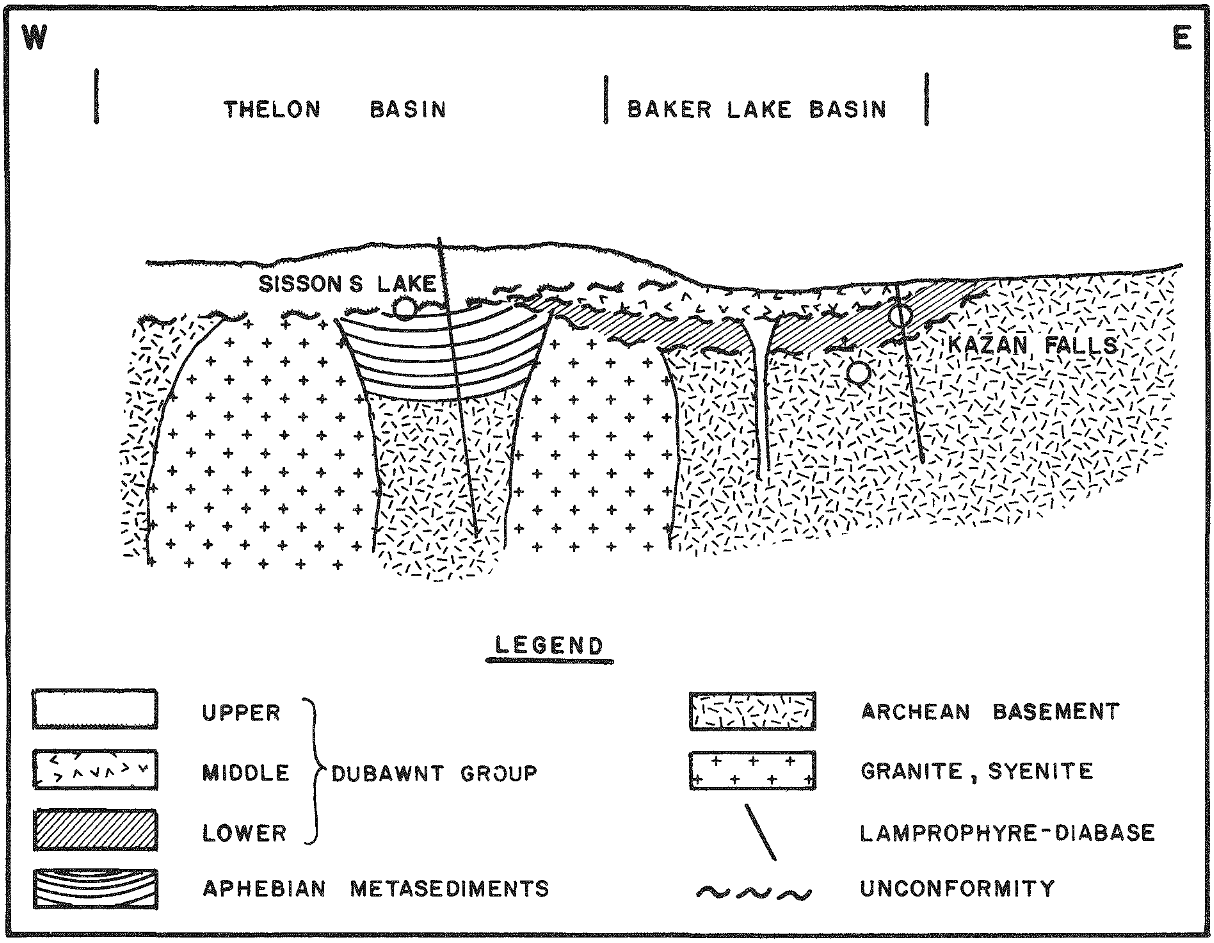


Figure 49. Schematic geologic cross sections for the Baker Lake area showing the positions of the Sissons Lake and Kazan Falls uranium occurrences (modified from Bundrock and Fuchs, 1980).

structure-strata-bound mineralization has uranium contents up to 10 percent and more. The mineralized structures are up to several tens of meters long and up to several decimeters (1 decimeter = 10 centimeters) thick. The host rocks immediately adjacent to the mineralized structures show almost no sign of alteration (J. Blackwell, personal communication, 1980). All discovered orebodies to date are limited in extension and do not achieve economic magnitudes. No Helikian cover sediments are found in the vicinity of the Amer Lake orebodies.

Post-Hudsonian occurrences are found within or associated with volcanics and sandstones of the post-Hudsonian Lower and Middle Dubawnt Group (Fig. 50). These occurrences are in (a) the Baker Lake Basin (bounded by the eastern end of Baker Lake to the northeast, Dubawnt Lake to the west and Tulemalu Lake to the southwest), and (b) smaller isolated basins of Dubawnt Group rocks between

Yathkyed and Angikuni Lakes to the southeast of the Baker Lake Basin. All occurrences discovered to date contain only subeconomic reserves in the range of several tens of tonnes uranium.

Christopher Island. At the Christopher Island occurrence, uranium and copper occur in northeast-trending fractures in the Christopher Island Formation.

Kazan Falls and Martell Lake. A narrow zone of pitchblende mineralization occurs in a northwest-trending fracture system in basement migmatites and augen gneiss near the overlying Dubawnt unconformity. The zone has a width of 5 m, a length of 200 m, and a drilled depth of 100 m. The best intersections averaged 0.46 percent U_3O_8 over 2 m (Laporte et al, 1978). One hole drilled in 1975 intersected 53 m of mineralization grading from 0.12 to 0.81 percent U_3O_8 (Northern Miner, July 19, 1979).

	Age m.y.	Stratigraphy	Mineralization
Upper Dubawnt	>1350 possibly ≈1600	Thelon Formation: dolostone (no formal name) sandstone & pebbly sandstone	(U)
		major unconformity	
Middle Dubawnt	minimum 1786 ± 25	Pitz Formation: calc-alkaline volcanics hyaloclastites	U
		*Granite	U-F(Cu)
		Kunwak Formation**: volcaniclastics	U-(Cu)
		disconformity	
		Martell Syenite	Th-U, REE
		*Diatreme breccia	U(Cu,Zn)
		Christopher Island Formation: Potassic alkaline volcanics, agglomerates	U(Cu,Pb,Zn)
		vent breccia, volcaniclastic sediments	U-F
		*Lamprophyre dikes	U(Se,Cu,Ag,Au)
		disconformity	
Lower Dubawnt		Kazan Formation: arkosic red bed.	U(Cu,Ag)
		South Channel Formation: conglomerate	
		major unconformity	
		Angikuni Formation**: sandstone, mudstone	

* The stratigraphic position of these units is not known.
** These units are only developed locally.

~ ~ ~ ~ ~ disconformity   ~~~~~~ major unconformity

Figure 50. Stratigraphic positions of uranium occurrences in the Dubawnt Group (from Curtis and Miller, 1980).

Yathkyed Lake. Fracture-bound uranium mineralization occurs adjacent to the basal Dubawnt unconformity in basement metasediments and metavolcanics, and in overlying Christopher Island volcanics. Assays up to 1.13 percent U_3O_8 are reported (Ruzicka, 1978; Lord et al, 1979). Some disseminated uranium was found in oxidized sediments of the South Channel-Kazan Formation.

Concepts of Ore Genesis

Due to the limited published information on these deposits, speculations on the origin and controls of these deposits are largely unsupported by data and based on little more than apparent similarities with other deposits, particularly those of the Athabasca region. With this caution, brief comments are made on four possible deposit types in the region.

(1) Strata-bound uranium occurs in Aphebian metasediments, the best example of which are the mineralized meta-arkose lenses near Amer Lake. This protore mineralization is reasonably widespread and offers potential for strata-structure-bound type deposits and possibly strata-bound types as well.

(2) Uranium occurrences of the unconformity-related type may be concentrated in structures within Aphebian metasediments, and where unconformably overlain by the Thelon Formation they may have been protected against later erosion. A regolith is present on the basement metasediments along the pre-Thelon unconformity. This geologic setting is similar to the Athabasca region, and unconformity-related deposits can be expected. The uranium source rocks might have been Aphebian metasediments similar to those at Amer Lake, and ore-forming processes could have been similar to those described for the Athabasca district. The Lone Gull Lake deposit may be an example of this type of uranium mineralization, or it may be an older mineralization, perhaps hydrothermal, that was affected by near-surface processes. This has not been established.

(3) Several occurrences of mineralization (e.g., on Christopher Island and at Yathkyed Lake) are associated with Middle Proterozoic uraniferous acid volcanics, in particular of the Christopher Island Formation. Weathering prior to the deposition of the Thelon Formation probably leached uranium from the uraniferous felsic volcanics and formed small deposits in structures. The source rocks apparently provided sufficient uranium for high-grade occurrences, but the ore-forming processes were apparently incapable of forming orebodies of economic size. In places with only a thin volcanic capping where the paleoweathering could penetrate through the volcanics into uraniferous Aphebian basement, and also where such basement is exposed in windows through the volcanics, somewhat larger occurrences or deposits may have formed. The geologic setting of this type of mineralization resembles to some extent that of the South Alligator River district, Northern Territory, Australia.

(4) A number of uranium occurrences are present in a somewhat different geologic setting in the South Channel and Kazan Formations. The uranium minerals pitchblende and coffinite are associated with finely disseminated native copper, chalcocite, silver, and molybdenite in undetermined forms. This mineralization is more prevalent in the Kazan sandstones than in the South Channel conglomerates, and it occurs always in close proximity to either syenitic dikes or the intrusive Martell syenite. Strong albitization and calcite development accompany the uranium mineralization. One drill hole

encountered 103 m with an average uranium grade of 0.15 percent U_3O_8 and about 300 t of uranium are roughly inferred. These deposits most likely represent hydrothermal concentrations formed in association with late-stage uranium-bearing granites and subvolcanic intrusives such as the Martell syenite.

Labrador

The uranium province of the Kaipokok Bay-Big River area, also known as the Makkovik area, is located on the central Labrador coast between latitudes 54°30' and 50°15'N and longitudes 59° and 60°W. The small harbor of Makkovik is the major town in the area. Uranium discoveries were first made in the early 1950s. Two deposits of interest have been discovered to date: Kitts in 1958 and Michelin in 1967. Besides these sizable deposits, numerous uranium showings were also found. The profitability of these two deposits was in question for a long time, but they are now expected to become uranium producers.

Regional Geology of Kaipokok Bay-Big River Area

Beavan, 1958; Gandhi, 1978; Gandhi et al, 1969; Smyth and Ryan, 1977; Smyth et al, 1975; Sutton et al, 1971.

The Kaipokok Bay-Big River district is situated on the eastern margin of the Canadian Shield, at the boundary of the Nain and Grenville structural provinces. Gandhi (1978) presents a comprehensive review of the geology of the district and its uranium occurrences.

The oldest rocks are Archean migmatized gneisses called the Hopedale gneisses (Fig. 51). To the west and south of the Archean basement is a large area underlain by Aphebian rocks. The rocks to the west are predominantly paragneiss, granulite, migmatite, and granite-gneiss, and those to the south predominantly metasediments and metavolcanics which were metamorphosed by the Hudsonian orogeny (about 1600 m.y.).

The uranium-bearing Aillik Group belongs to the Aphebian supracrustal sequence, which is comprised of five major units (Gandhi, 1978): (a) paragneiss, paraschist; (b) metabasaltic lava and mafic metatuff; (c) metasiltstone, metaconglomerate, with minor quartzite, chert, meta-argillite, laminated felsic to mafic metatuff; (d) metarhyolite, felsic metatuff, metavolcaniclastic breccia or fragmental rock; (e) meta-quartz-feldspar-porphyry, porphyritic gneiss.

The total thickness of the Aillik Group is estimated to be 2,300 m at the Kaipokok Bay and 7,600 m near Makkovik and at Walker Lake, southeast from Kaipokok Bay.

Abundant Hudsonian intrusions cut the Aphebian rocks. They include syntectonic granodiorite and granite gneisses, and post-tectonic granites, gabbro, diorite, and syenite.

Paleo-Helikian clastic sediments and intermediate to acidic volcanics occur farther to the west (1474 $\pm$ 42 m.y., Wanless and Loveridge, 1972). They contain several minor uranium occurrences and are intruded by Elsonian age plutons.

The Paleo-Helikian rocks are unconformably overlain by sandstones, shales, basaltic flows, and diabase sills of the Seal Lake Group (1278 ± 92 m.y., Baragar, 1977). The Seal Lake Group was folded during the Grenville orogeny (about 1000 m.y.). Gabbroic dikes and sills of Neo-Helikian and Hadrynian age and lamprophyric dikes of various ages intrude the older sequences.

Adjacent and to the south of the uranium province of the Kaipokok Bay-Big River district, Grenville age granites and gneisses (about 100 m.y.) occur over wide areas.

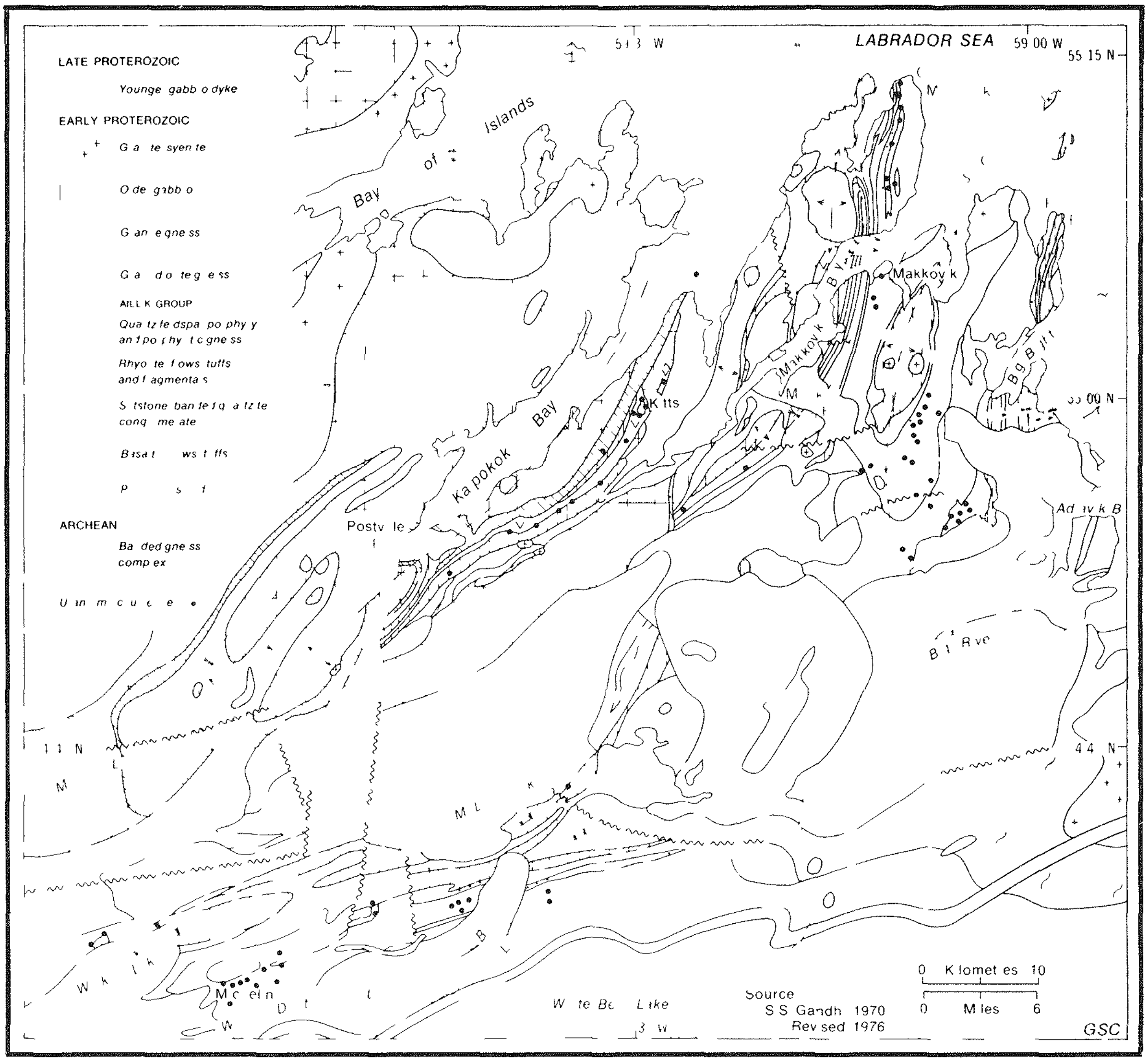


Figure 51. General geologic map and uranium occurrences of the Kaipokok Bay-Big River area, Labrador (modified from Gandhi, 1978).

These various units occur in an arcuate fold belt, with a northeasterly trend in the southwest to a northerly trend to the north. The prevalent dips of beds and regional foliation are moderate to steep in the east and southeast but are deflected by granitic domes. The major fault directions trend north-northwest, north-northeast, and east-northeast.

The predominant host for uranium occurrences in the Kaipokok Bay-Big River area is the Aphebian Aillik Group. The depositional environments for these sediments ranged from relatively deep, possibly marine water, as represented by the argillaceous beds and basaltic flows in the Kaipokok Bay area, to shallow waters where siltstones and conglomerates were deposited. Some rhyolitic volcanics may have been deposited subaerially. Acidic volcanism and sedimentation were to some extent contemporaneous. The Aillik sediments were folded and regionally metamorphosed in the greenschist-amphibolite facies and locally affected by contact metamorphism of upper hornblende-hornfels facies.

According to Gandhi (1978), the uranium occurrences are found along four fold belts associated with a particular stratigraphic unit or interval. The four belts are referred to as: (a) the Kitts-Post Hill belt near the south shore of Kaipokok Bay; (b) the White Bear Mountain-Walker Lake belt in the south; (c) the Cape Makkovik-Monkey Hill belt in the north; and (d) the Falls Lake-Shoal Lake-Bernard Lake belt east of Monkey Hill.

Uranium Occurrences and Deposits

Gandhi (1978) describes the uranium occurrences as tabular or lenticular bodies of disseminated mineralization, approximately conformable with the structure of the enclosing rocks. Massive to disseminated mineralization in veins, shear zones, and fractures that are both conformable with and cross-cut the rock structure, is less common. The uranium mineral is pitchblende, with only trace amounts of thorium, which Gandhi uses as a criterion to differentiate it from uraninite. Associated minerals occurring in minor amounts include some combination of calcite, hematite, pyrite, sphene, and fluorite.

Two deposits of significant size have been discovered: Kitts (1454 st U_3O_8) in the Kitts-Post Hill belt, and Michelin (4674 st U_3O_8) in the White Bear Mountain-Walker Lake belt. Michelin is about 150 km to the southeast of Kitts.

Kitts Deposit. The deposit is situated approximately 25 km to the southeast of Makkovik about 3 km west of the Kaipokok Bay. It contains three ore zones, designated A, B, C.

Geologic Setting of Mineralization. The Kitts deposit and other occurrences in the Kitts-Post Hill belt are located along a narrow stratigraphic zone of metamorphosed argillaceous and tuffaceous sediments (Fig. 52). The zone is less than 100 m thick and traceable over 20 km in a north-northeast direction. It exhibits a double-plunging anticlinal structure with an approximate north-south trend (Fig. 53).

The Kitts orebodies occur in a tightly folded meta-argillite unit which is interbedded with cherty quartzite and basaltic flows. Gandhi (1978) estimates the thicknesses of the meta-argillite and chert units as approximately 20 m and 15 m.

The meta-argillite consists of several beds with andalusite (chiastolite) and garnet (almandine) set in a fine-grained matrix of albite, quartz, amphibolite, biotite, and minor amounts of pyrrhotite and possibly microcline (Fig. 54). Thin but persistent beds of biotitic quartzite (presumably metamorphosed siltstone) are also present. The most important uranium host rocks are intercalated dark gray, graphitic, pyrrhotite-bearing beds and lenses.

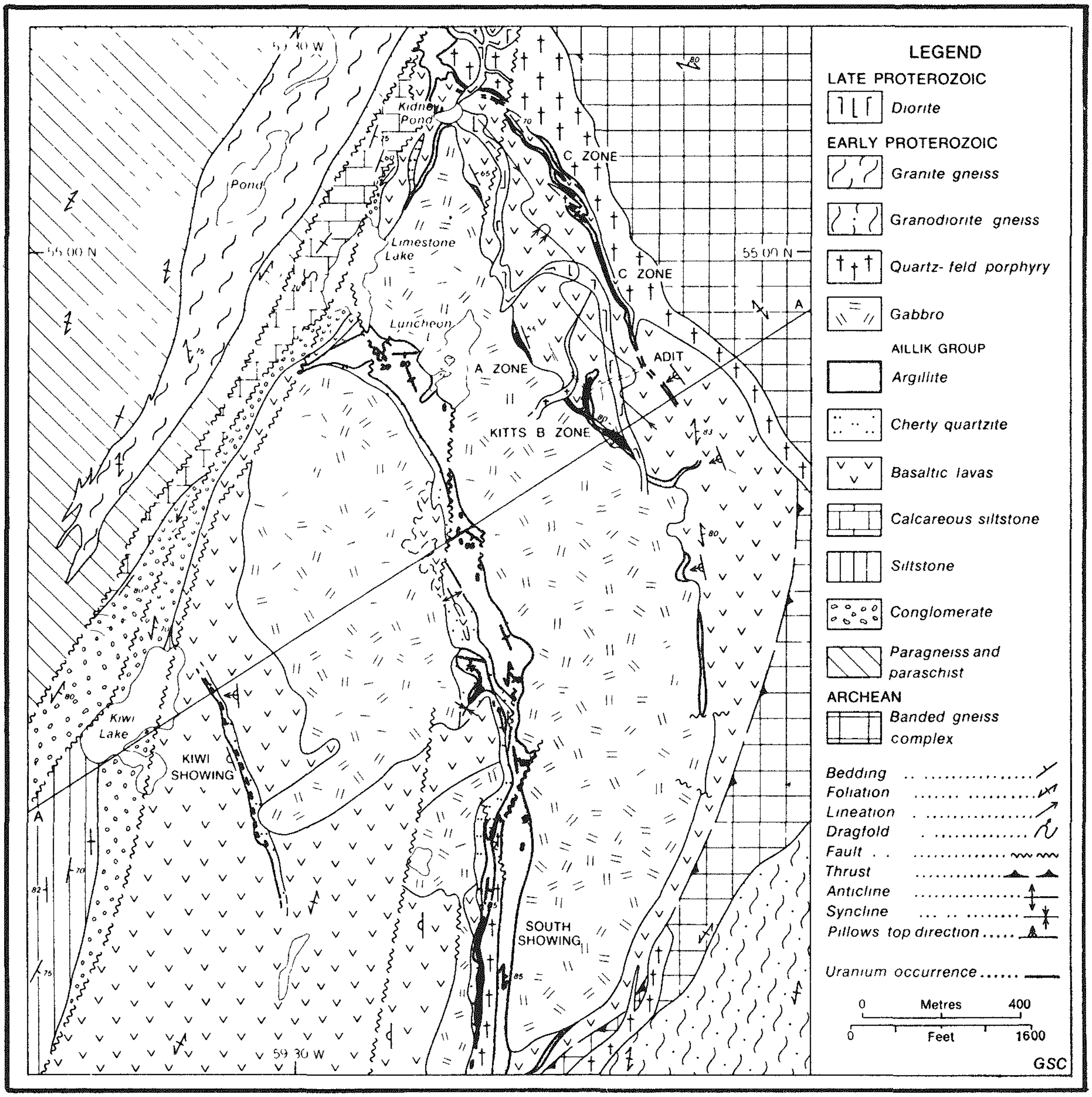


Figure 52. Geologic setting of the Kitts uranium occurrences, Labrador (from Gandhi, 1978).

The host rock is fine-grained and consists of varying amounts of albite, quartz, amphibole, pyroxene, biotite, chlorite, graphite, calcite, pyrrhotite, pyrite and chalcopyrite, and traces of arsenopyrite, molybdenite, ilmenite, and hematite. Numerous dikes and irregular bodies of quartz-feldspar porphyry intruded the older sequences.

Faults and shears with displacements up to a few tens of meters are present. The chert has undergone tectonic brecciation.

Alterations. Essentially no alteration is associated with the mineralization, excepting chlorite on shear planes.

Mineralization. The uranium ore mineral, as determined by Gandhi (1978) on samples from the Kitts A and B zones, is 'pitchblende' which has a lattice constant of 5.47 Å and contains only traces of thorium. This lattice constant is typical of uraninite rather than pitchblende, suggesting a higher temperature of formation. The low associated thorium content suggests thorium was not available during formation. It is distributed as disseminated grains along the beds and as small stringlike aggregates along bedding planes. Accumulations are more pronounced at the crests of minor folds. The pitchblende grains are commonly about 5 mm in diameter with a rounded to subhedral shape. Some pitchblende occurs as large, irregular lathlike grains scattered along the finely disseminated pitchblende horizons.

The host rock has a graphite content of 1 to 2.5 percent and contains amphibole as the main mafic silicate. The amphibole is normally green and clouded with inclusions of opaque minerals, including pitchblende, and appears to have grown later than the other minerals. It becomes brownish-red in highly radioactive zones. Chlorite is restricted to sheared surfaces. Pyrrhotite (amount up to 10 percent) occurs as disseminations and locally as thin lenses up to 5 mm thick. In tight folds, the sulfide occurs also as veinlets cutting the

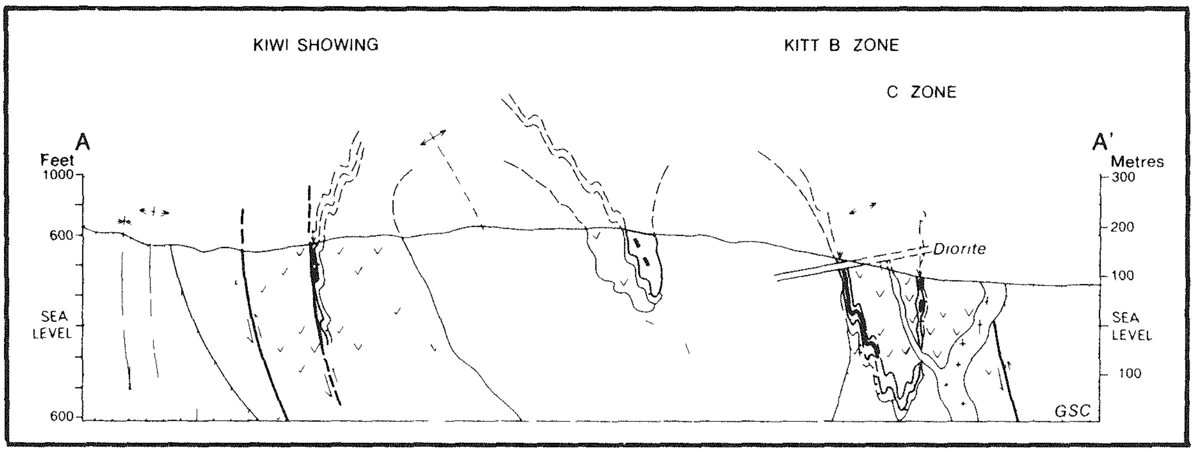


Figure 53. Geologic cross section A-A'(see Fig. 52 for location of sections) for the Kitts area, Labrador (from Gandhi, 1978).

surrounding rocks. Pinkish and white calcite (2 to 7 percent) is present in veinlets. The pinkish calcite is typical of mineralized zones. Veins of calcite and quartz with traces of pitchblende extend into adjacent country rock.

Geochronology. Pitchblende yielded an age of 1730 m.y. Additional age dates are discussed subsequently under the Michelin deposit.

Ore Control and Metallogenesis. Gandhi (1978) emphasized that the significant features related to the origin of the Kitts deposit are: (a) the dominantly stratigraphic control of uranium mineralization in the argillaceous host rocks, and (b) "the field relations and isotopic age data which indicate that the mineralization predates the Hudsonian intrusions and at least the later phases of deformation and regional metamorphism that affected the host rocks."

Based on these features, Gandhi (1978) postulates a syngenetic sedimentary origin for the Kitts deposit, with concentrations of pitchblende in or near layers and lenses rich in either pyrrhotite or graphite or both. Later events have produced local redistribution of uranium, which is present as concentrations of pitchblende along bedding planes, fold hinges, fractures, shears, and veins.

Minor uranium occurrences in the southern part of the Kitts-Post Hill belt occur conformably within marly beds and mafic tuffs (Inda Showing) and laminated tuffs and siltstones (Nash Showing), with an abundance of material apparently derived from acidic volcanics and tuffs.

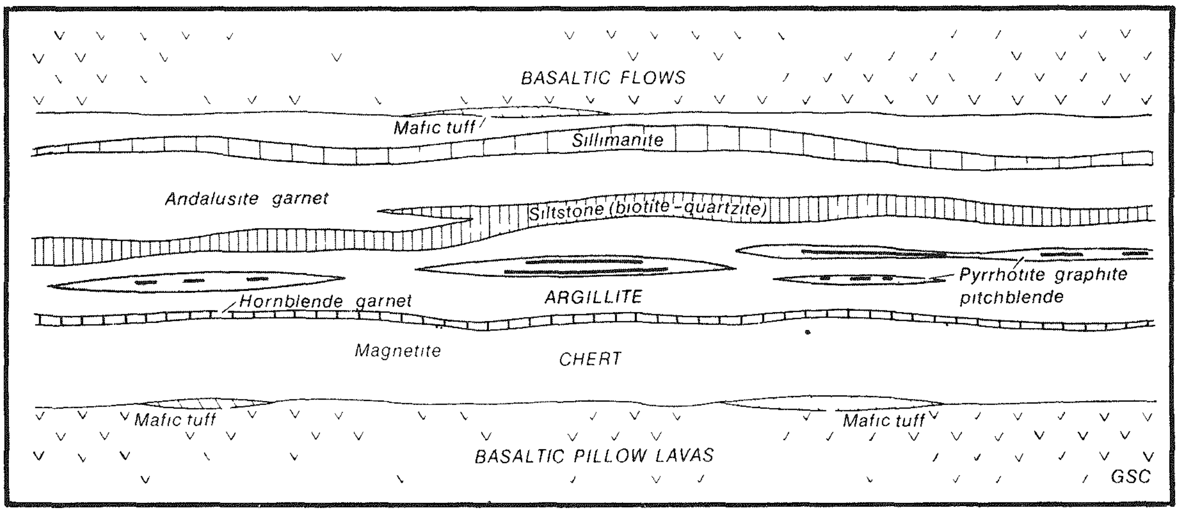


Figure 54. Schematic diagram of the stratigraphic sequence in the Kitts area, Labrador (from Gandhi, 1978).

Shape and Dimensions of Deposits. Uranium concentrations are along bedding in stratiform zones less than 10 m wide and 10 to 300 m long. The thickness is variable, on the order of centimeters to decimeters, with thicker sections in zones of tight folding. The proven mineralization extends discontinuously to a depth of almost 200 m in three ore zones, A, B, and C (Fig. 55). The A and B zones occur on the west flank of a local syncline, and the C zone on its east limb about 300 m to the east (Figs. 52 and 53). The A zone has a simple structure; the B zone is complexly folded. The C zone is locally complexly folded and intruded by numerous dikes and irregular bodies of quartz-feldspar porphyry.

Production and Reserves. There has been no production at the Kitts deposit. Gandhi (1978) has summarized the reserves which are:

Estimated Reserves (mt)	Grade % U_3O_8	U Content (mt)
188,693	0.70	1,120

Michelin Deposit. The deposit is situated about 80 km to the southwest of Makkovik.

Geologic Setting of Mineralization. The Michelin deposit is in the White Bear Mountain-Walker Lake belt, within an east-northeast trending uranium-bearing zone that is 1 km wide and 15 km long (Fig. 56). The host rock sequence comprises metamorphosed coarse feldspar porphyritic rhyolites alternating with subporphyritic and non-porphyritic rhyolites, and thin fine-grained tuffaceous lenses. The sequence is about 40 m thick. It follows the regional east to northeast-trending belt. Foliation or schistosity is crude to well developed in different parts of the rhyolitic rocks. The strike is approximately east-northeast and the dip 50° to 55° to the south. A number of pre- and post-metamorphic mafic to felsic dikes cut the rhyolites. The sediments and volcanics were metamorphosed during the Hudsonian orogeny.

The mineralized rocks are similar to their unmineralized, textural equivalents except for the presence of uranium, hematite, and albite to the exclusion of potash feldspar. The unmineralized rocks contain albite together with potash feldspar. The enrichment of Na_2O occurs in parts of all types of rhyolitic rocks and is considered by Gandhi (1978) to be the result of sodium metasomatism. The uranium mineralization occurs characteristically within the sodium-enriched rocks, and particularly in the coarse porphyritic feldspar rhyolite.

The rocks have been deformed to varying degrees, with some minor faults parallel to the regional folding.

Alteration. Except for some hematitization and perhaps sodium metasomatism, no alteration accompanies the mineralization.

Mineralization. The uranium ore mineral, Th-free uraninite or pitchblende, occurs as granules up to 10 mm in diameter within metamict sphene (Gandhi, 1978). A mineral resembling apatite is also found in the host sphene. Mineralization is accompanied by hematite, which is an indicator (red coloration) of the finely disseminated uranium in unweathered rocks. All mineralization is within albitized zones.

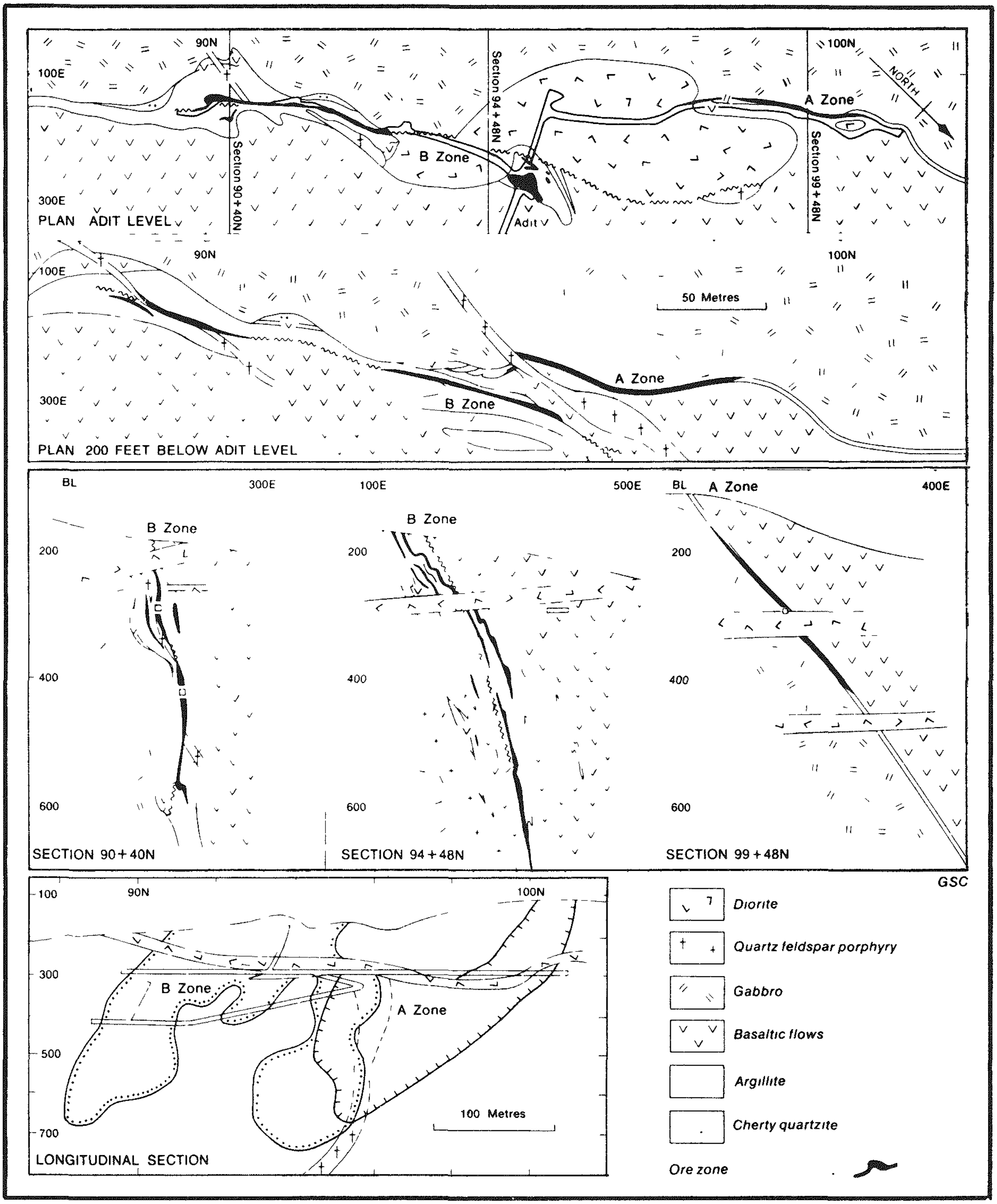


Figure 55. Geologic maps and cross sections of the Kitts A and B zones, Labrador (from Gandhi, 1978).

The uranium is disseminated in lenticular zones occurring predominantly in metamorphosed coarse feldspar porphyritic rhyolite, but it extends into sub- to non-porphyritic rhyolites and into tuffs, crossing the lithologic boundaries at a very low angle. The grade of mineralization tends to decrease sharply but is sometimes gradational over a meter or so at the footwall and hanging wall. Along the strike, the mineralization pinches or frays into long, narrow wedge-shaped zones with rather sharp terminations. Near the west end of the Michelin deposit, an exceptional high-grade vein-type concentration of pitchblende was found, with widths up to 2 cm wide and a length of about 30 m. The zone is subparallel to the regional foliation in strike and dip.

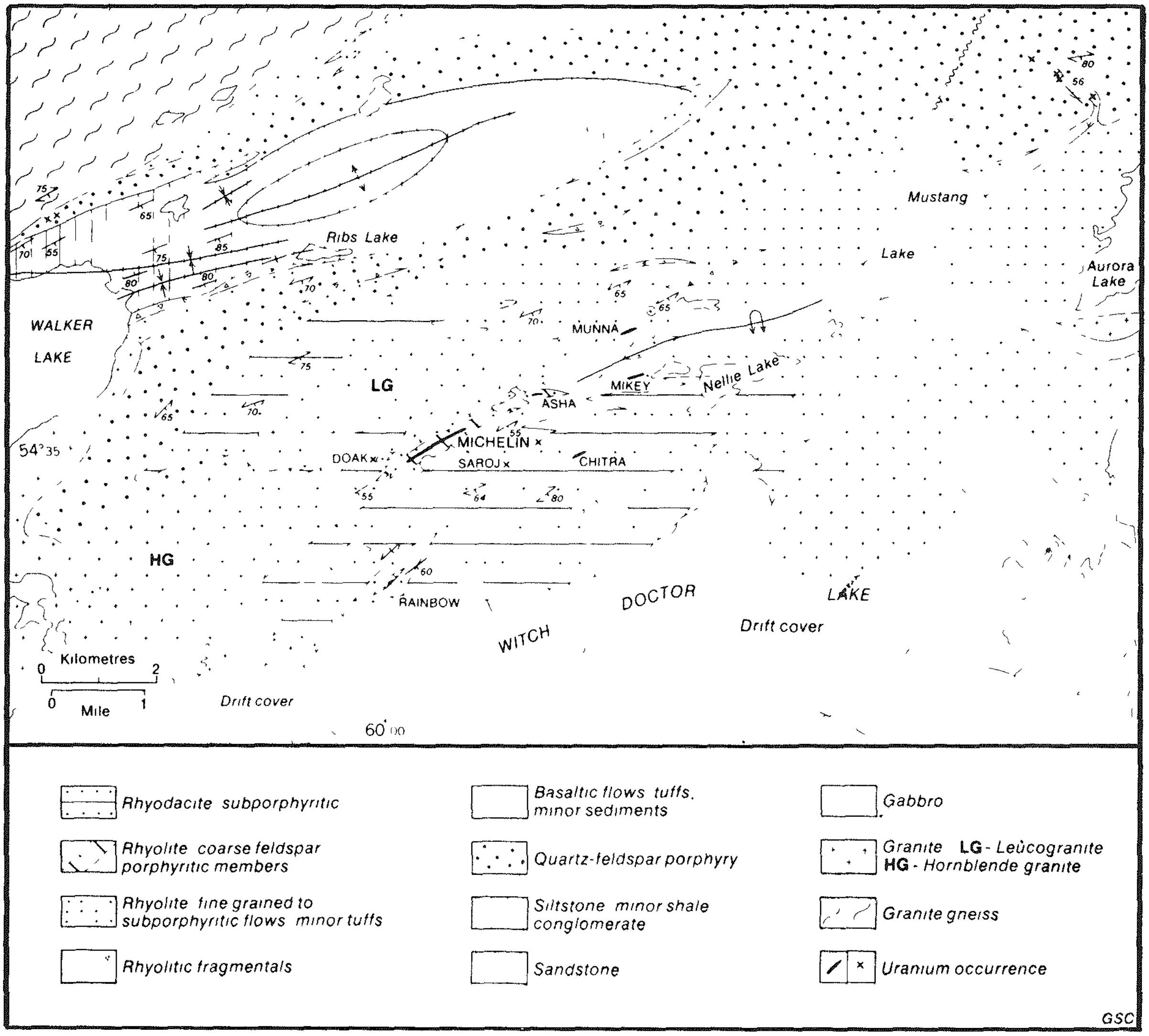


Figure 56. Geologic map and uranium occurrences of the Michelin area, Labrador (from Gandhi, 1978).

Geochronology. Gandhi (1978) reports age dates of 2400 m.y. (basement rocks) and 1728 m.y. (Hopedale gneiss) for the basement rocks affected by the Hudsonian orogeny. Dates for igneous rocks include: (a) 1645 m.y. for a granite extension of the Walker Lake granite, (b) 1659 and 1676 m.y. for the rhyolites of the Aillik Group, (c) 1832 m.y. for a syntectonic (granodiorite gneiss) intrusive into rhyolitic rocks correlatable with the Aillik Group, and (d) 1531 and 1570 m.y. for a syntectonic (granite gneiss) intrusion. Pitchblende samples from the Kitts and Michelin deposits have given age dates of, respectively, 1730 and 1244 m.y. The sample from the Michelin deposit was from vein-type mineralization within 100 m of granite and diorite dikes.

Ore Control and Metallogenesis. Geologic observations important to the formation of the Michelin deposit may be summarized as follows (Gandhi, 1978):

(1) The uranium occurs as pitchblende grains within sphene.

(2) The mineralized zones are subconcordant with the enclosing rhyolitic host rocks and show evidence of post-mineralization deformation and minor shearing (Fig. 54).

(3) The host rocks are enriched in Na_2O and depleted in K_2O in proximity to mineralization.

(4) The mineralized zones are cut by mafic dikes which are barren and metamorphosed to amphibolite.

These observations strongly suggest that mineralization predates at least the final phase of the deformation which is interpreted to be Hudsonian in age. The close association of sodium metasomatism and the uranium mineralization suggests that they are related genetically. Uranium occurrences similar to the Michelin deposit are widely distributed in the Kaipokok Bay-Big River area, indicating that the mineralizing process acted over a broad area.

Gandhi (1978) interprets the mineralization at the Michelin deposit as having formed after the intrusion of the oldest albite-amphibole-biotite-calcite dikes. These dikes may be related to basaltic flows of a bimodal volcanic sequence but apparently underwent alkali metasomatism and uranium mineralization. Amphibolitic dikes were introduced after mineralization because they are apparently unaltered. The concordant U-Pb age for the Michelin deposit, which is close to the age of the rhyolitic host rocks, is consistent with the model. Subsequent deformation, metamorphism, and intrusions provided local redistribution of uranium into vein-type occurrences, which yield younger U-Pb ages.

Gandhi (1978) considers the pitchblende veins, such as those at Pitch Lake, to be typical hydrothermal veins related to the post-tectonic granites. He concludes that the Michelin deposit is volcanogenic in origin, having formed during alkali metasomatism of the host rocks. The Kitts and Michelin deposits were then affected by the Hudsonian orogeny, which produced local redistribution of pitchblende into veins, shears, and fractures.

Shape and Dimension of Deposit. The uranium mineralization occurs in a stratigraphic sequence about 40 m thick. It is traceable, although discontinuously, for an east-northeast strike length of more than 1,000 m. The deposit extends to at least 300 m below the surface.

The uranium is concentrated in individual lenticular zones up to 5 m thick, and each is traceable for several hundred meters along strike. The edges of the mineralized zones are generally sharp at the footwall and hanging wall; they pinch out into long narrow wedges along strike.

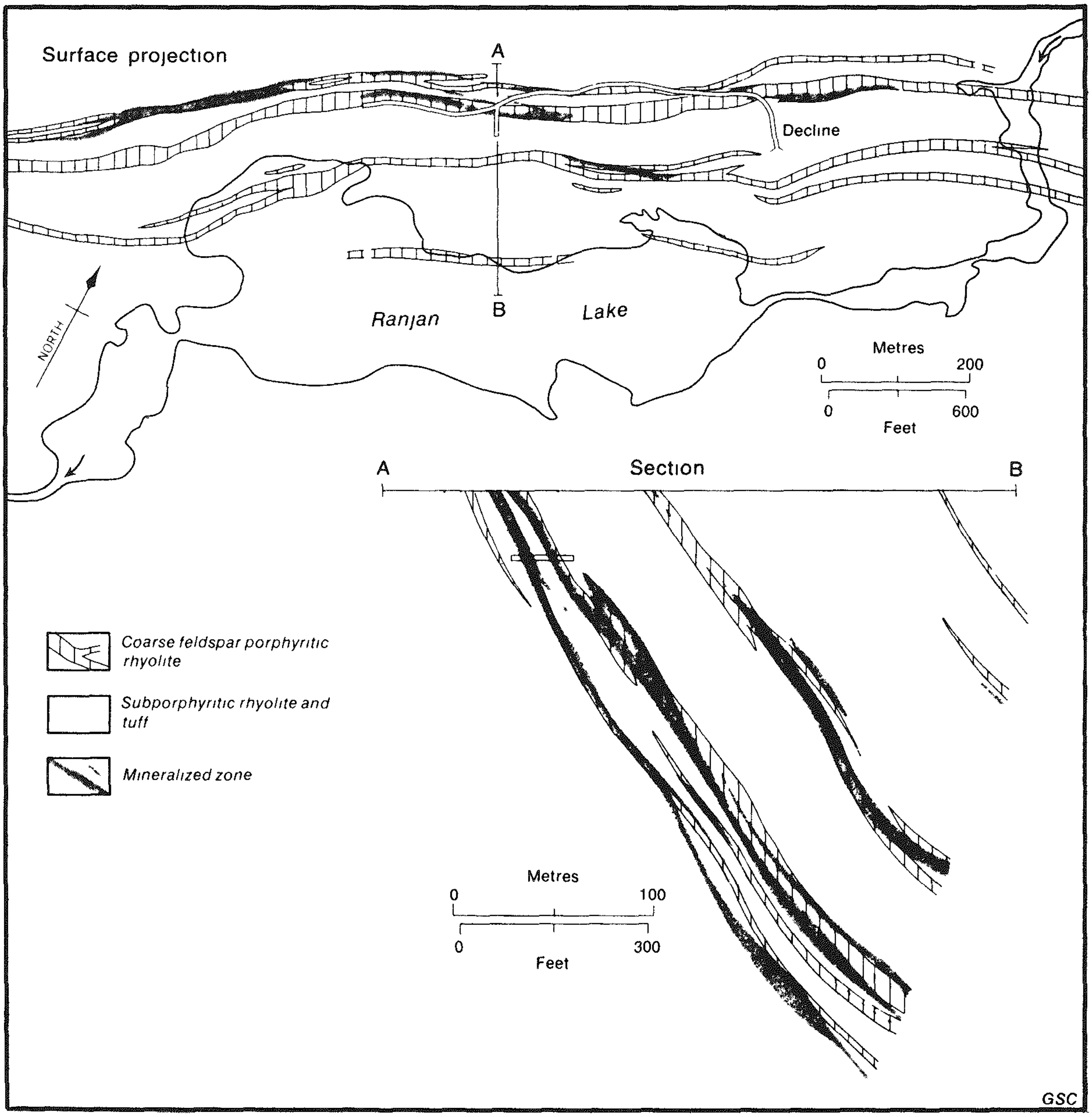


Figure 57. Surface projection and a cross section of the Michelin uranium deposit, Labrador (from Gandhi, 1978).

Production and Reserves. There has been no production at the Michelin deposit. Gandhi (1978) has summarized the reserves as follows:

Estimated Reserves (mt)	Grade % U_3O_8	U Content (mt)
2,826,773	0.15	3,596

Australia

Australia contains, together with Canada, the vast majority of large veinlike uranium deposits. The deposits are clustered in the northern part of the Northern Territory which is geologically referred to as the Pine Creek Geosyncline.

Pine Creek Geosyncline

Compston and Arriens, 1968; Condon and Walpole, 1955; Crick and Muir, 1979; Crick et al, 1978; Crohn, 1975; Dodson, 1972; Dodson et al, 1974; Dodson and Prichard, 1975; Donnelly and Ferguson, 1979; Donnelly and Roberts, 1979; Dunn, 1962; Eupene et al, 1976; Ferguson, 1979; Ferguson et al, 1979a; Goulevitch, 1979; Hegge and Rowntree, 1978; Hills and Richards, 1972, 1973, 1976; Hochman, 1979; Huntington et al, 1979; Hurley et al, 1961; Ingram, 1974; McLennan and Taylor, 1979; Mosher et al, 1979; Mumme et al, 1979; Needham, 1979; Needham et al, 1974, 1979a; Needham and Roarty, 1979; Needham and Stuart-Smith, 1976; Nicholson, 1979; Noakes, 1949; Page, 1976; Page et al, 1979; Plumb and Derrick, 1975; Riley, 1979; Riley and Korsch, 1979; Rossiter and Ferguson, 1979; Ryan, 1977; Smart et al, 1975; Stewart, 1965; Stuart-Smith et al, 1979; Tucker et al, 1979; Walpole and Crohn, 1965; Walpole et al, 1968.

General

The Pine Creek Geosyncline is situated in the belt of subtropical, monsoonal climate in northern Australia, between southern latitudes 12° and 14°, and longitudes 131° and 133° (Fig. 58). Geographically, three uranium districts can be distinguished: the East Alligator Rivers district in the east, South Alligator River district in the south, and Rum Jungle district in the west. All the important deposits are in the East Alligator Rivers district. The South Alligator River and Rum Jungle districts are former uranium producers, but their known deposits have been exhausted.

Infrastructure is not well developed in the East Alligator Rivers region. Only one all-weather road, the Arnhem Highway, connects Darwin with Jabiru, a distance of about 225 km. The Rum Jungle area is connected by rail and road with Darwin, a distance of about 60 km. The South Alligator River district can be reached on a gravel road from the town of Pine Creek on Stuart Highway, about 200 km to the southeast of Darwin.

Regional Geology of the Pine Creek Geosyncline

The Pine Creek Geosyncline is filled with metasediments and subordinate metavolcanics of Lower Proterozoic age, probably middle to upper Lower Proterozoic. The original sediments and volcanics were deposited in an extensive shallow marine(?) environment, as indicated by the presence of gypsum and anhydrite beds (Crick and Muir, 1979). They were altered by regional metamorphism, partially migmatitized, such as in Nimbuwah Complex, and intruded by granites at about 1800 m.y. The metamorphosed sequence throughout the whole of the geosyncline is intruded by dikes and sills of dolerites, and phonolites of various ages.

In the western part of the region, the supracrustal sequence overlies Archean-Lower Proterozoic basement, referred to as the Litchfield, Rum Jungle, and Waterhouse granitic complexes. In the Alligator Rivers region, the Nanambu Complex comprises the basement. Lower-Middle Proterozoic (1800 m.y.) metamorphism partly affected and rejuvenated these Archean complexes.

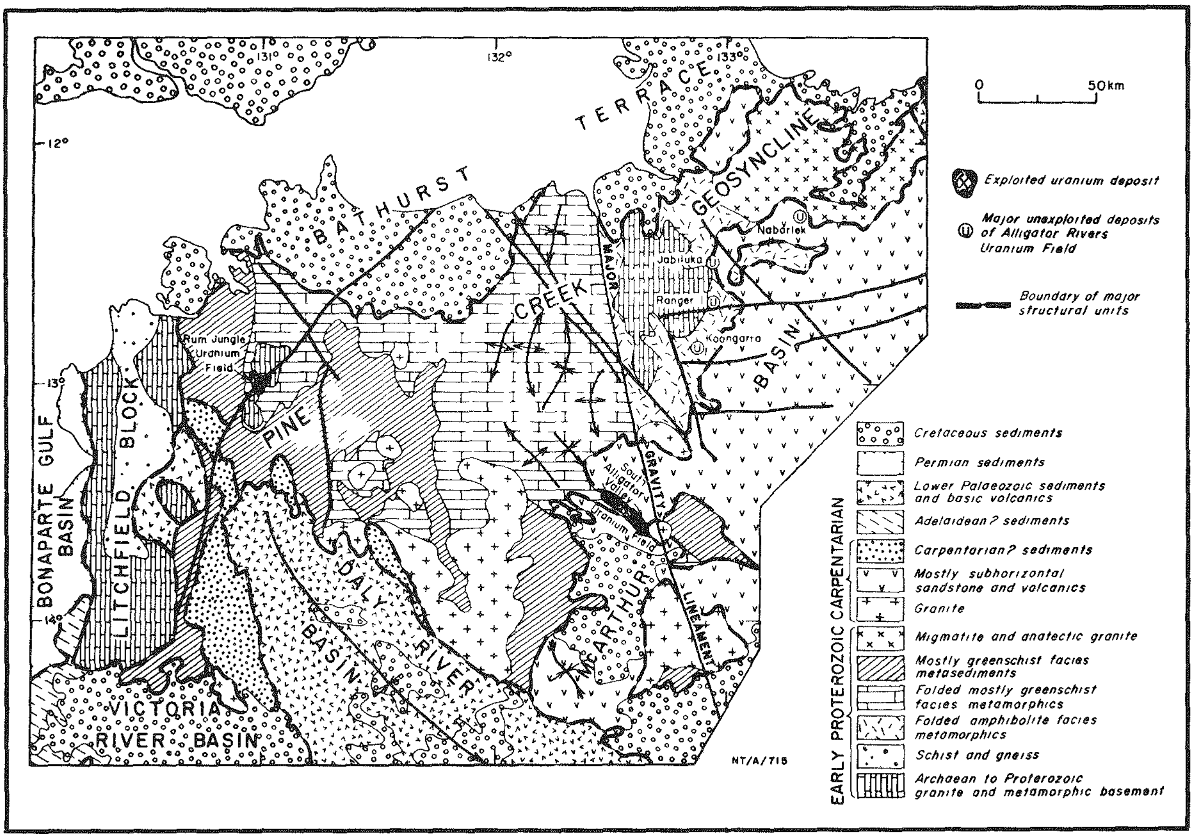


Figure 58. Simplified geology and major structural units, Pine Creek Geosyncline, Northern Territory, Australia (from Tucker et al, 1980).

The regional metamorphism of approximately 1800 m.y. did not affect the entire geosyncline with the same intensity. The sediments in the Alligator Rivers district and the Litchfield region to the west were exposed to amphibolite-to granulite-facies, whereas the central part of the geosyncline reached only greenschist facies. Excluding the Litchfield Complex, the region can be divided into two broad provinces. The boundary between them coincides, in part, with the north-south trending South Alligator Hinge Zone at approximately 132°30'E. The following summary of the two provinces is drawn from Ferguson (1979) and Needham et al (1979a).

The eastern province (province I) extends from the South Alligator Hinge Zone to the east where it disappears under the younger Kombolgie Formation. It contains the Alligator Rivers uranium field. In this province, the metapelitic assemblages contain the mineral assemblage: almandine + kyanite/ sillimanite + biotite + quartz ± staurolite ± plagioclase ± K-feldspar. Mafic rocks of the Zamu Dolerite suite contain hornblende + plagioclase + quartz ± clinopyroxene ± garnet ± biotite. Calc-silicate rocks are dominated by the assemblage hornblende ± diopside + dolomite + plagioclase + zoisite + scapolite. In the marble suites, the following are found: dolomite + magnesite + actinolite/tremolite + diopside; calcite + grossularite + diopside; calcite + K-feldspar + scapolite + epidote/zoisite + hornblende; calcite + quartz + zoisite + hornblende + scapolite + K-feldspar. Mafic granulites occur in the southern part of the Nimbuwah Complex, where orthopyroxene, clinopyroxene, and garnet can be found.

The western province (province II) covers the area between the Hinge Zone and the Litchfield Complex and Rum Jungle to the west. It contains the former uranium mines at Rum Jungle and South Alligator River. Away from the contact metamorphic aureoles, associated with later granitoid intrusions, the rocks have reached only low-grade metamorphism. The metapelitic assemblages contain Na-plagioclase + K-feldspar + quartz + biotite + muscovite + chlorite + epidote/ zoisite. The calcareous units contain dolomite + calcite + magnesite ± tremolite. Mafic intrusions of the Zamu Dolerite contain hornblende + quartz + albite/oligoclase.

Late orogenic high-level granitoid plutons have locally superimposed a contact metamorphism on the ~1800 m.y. regional metamorphic event in province II. Of the areas investigated, the highest grade of metamorphism was observed in rock units dominated by the South Alligator and Finniss River Groups in the areas surrounding the Burnside, Prices Springs, and Cullen Granites. In the pelitic/graywacke assemblages, contact metamorphism produces andalusite and cordierite, which in places coexist with K-feldspar + quartz + muscovite + biotite. In the calcareous units, the assemblages found include: calcite + diopside + wollastonite; calcite + dolomite + talc + tremolite; and tremolite + calcite + diopside. The mafic intrusives of the Zamu Dolerite are contact metamorphosed to amphibolite, commonly sheared, and contain hornblende + andesine/labradorite + quartz. These various assemblages place these contact-metamorphosed rocks in the zone of low-pressure medium-grade metamorphism.

Structurally, the geosyncline rocks show the following characteristics. Foliations trend west to northwest in the Rum Jungle Complex and northwest in the Waterhouse Complex, and generally strike about north in the Archean rocks of the Nanambu Complex. In the low-grade metamorphic terrane, the Lower Proterozoic rocks form tight folds with steep limbs, which trend about north in the northern part of the area, and northwest in the southern part. This change in direction of the fold axes occurs about the northeast-trending "Grove Hill Cross-flexure". Folding increases in intensity eastward to isoclinal folds with steep limbs near the boundary of the low- and medium-grade terranes, into polyphase-folding involving at least two isoclinal events in the medium-grade terrane. Fold axes are commonly concentrically disposed around the granitoid complexes and around some of the concordant late orogenic granitoids. Major fault directions are northwest and northeast (mainly strike slip), and also curvilinear east to northeast (mainly dip slip). The greatest proven displacement is 5.5 km lateral movement on the Giants Reef Fault.

After a period of intense erosion, the crystalline basement was covered to the east by the Carpentarian, i.e., Middle Proterozoic Edith River Volcanics of acid volcanic rocks, and by the Kombolgie Formation of generally flat-lying, non-metamorphosed, red-bed (?) sandstones and intermediate basalts. Platform clastic and carbonate sediments of Carpentarian (?) and Adelaidean, and younger Cambrian-Ordovician age were deposited in the southwest. In the north and locally in the south, Mesozoic sediments and Cenozoic alluvium were deposited over the Precambrian rocks.

Below the Kombolgie Formation, the top of the crystalline rocks is somewhat altered to regolith, which is 1 to 2 m thick in the Jabiluka area (Binns et al, 1979b).

Stratigraphy and lithology are presented in Table 17 and stratigraphic units in Table 18.

Major uranium deposits are hosted in the Masson Formation/Lower Cahill Formation/Mount Partridge Group (East Alligator Rivers and Rum Jungle), and in the Koolpin Formation/South Alligator Group. Occasionally uranium mineralization occurs in the Kombolgie Formation and the Edith River Volcanics.

Alligator Rivers District

The district lies along the central portion of the East Alligator River in northwestern Arnhem Land, N.T., about 75 km to the southeast of Van Diemen Gulf/Timor Sea, with a center of about 133°E and 13°30'S. The district covers an area of about 75 km northeast-southwest, i.e., from Nabarlek to Koongarra, and 25 km northwest-southeast. The only original settlements are Jabiru and Oenpelli Mission.

The topography is rather flat to the west where underlain by floodplain-covered crystalline basement. To the east the terrain is that of a high plateau (Arnhem Land Plateau) capped by the flat-lying Kombolgie Formation cliffs and cut by deep canyons. A prominent escarpment marks the margin of the Kombolgie Plateau.

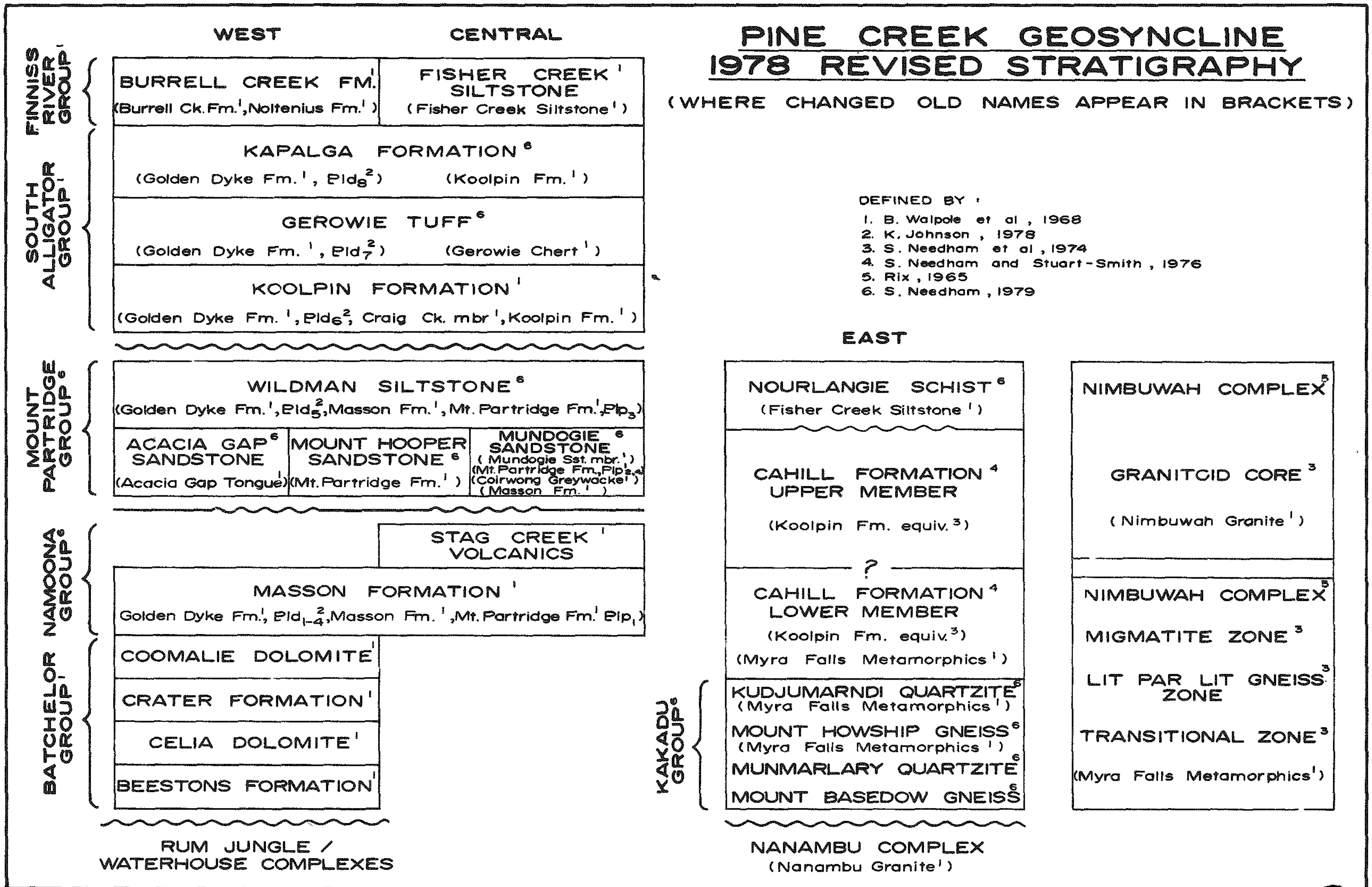
The major deposits in the district are Jabiluka, Koongarra, Nabarlek, and Ranger One. Jabiluka and Ranger are comprised of two or more orebodies. Other mineralized areas include Caramel, Hades Flat, 7 J, Ranger Four, Ranger 68, and Mamurri.

Regional Geology of the Alligator Rivers District. The East Alligator Rivers district is situated on the eastern limits of the Pine Creek Geosyncline.

Table 17. Summary of stratigraphy of the Pine Creek Geosyncline (from Needham et al, 1979b).

	Unit	Lithology	Thickness (m)	Age (m.y.) ref. Page and others (this volume)
PLATFORM COVER	BATHURST ISLAND FORMATION	sandstone, siltstone	< 65	EARLY CRETACEOUS
	PORT KEATS GROUP	siltstone, sandstone, limestone, minor conglomerate	2000	PERMIAN
	DALY RIVER AND WESSEL GROUPS	basalt, limestone, sandstone, siltstone	< 600	CAMBRIAN-EARLY ORDOVICIAN
	BULLITA, AUVERGNE AND FITZMAURICE GROUPS	sandstone, siltstone, minor dolomite	< 12000	ADELAIDEAN
	MINOR DOLERITE	quartz dolerite dykes and small plug-like bodies		1200 ± 35
	MUDGINBERRI PHONOLITE MUNMARLARY PHONOLITE	phonolite dykes	1	1316 ± 50
	TOLMER GROUP	sandstone, dolomite, siltstone	<1000	possible lateral
	KATHERINE RIVER GROUP	sandstone, conglomerate, minor greywacke, siltstone. Interbedded basalt-andesite volcanics and pyroclastics	1200	equivalents
TRANSITIONAL IGNEOUS ACTIVITY	OENPELLI DOLERITE	layered tholeiitic dolerite lopoliths	< 250	1688 ± 13
	EDITH RIVER VOLCANICS	rhyolite, dacite, tuff, ignimbrite, minor syenite, basalt, volcanic breccia; sandstone and conglomerate lenses	1200	1760
	GRANITE EMPLACEMENT	biotite granite, adamellite, syenite, granodiorite (numerous plutons)		1730 - 1780
	NIMBUWAH COMPLEX	granitoid migmatite, granite, gneiss, schist (anatexis of Lower Proterozoic sediments)		1803 - 1870
	ZAMU DOLERITE	layered tholeiitic dolerite sills and minor dykes	<2500	
LOWER PROTEROZOIC SEDIMENTATION	FINNISS RIVER GROUP (flysch)	siltstone, slate, shale, greywacke, arkose, quartzite, schist	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, jaspilite, tuff	5000	1870 - 2400
	MOUNT PARTRIDGE GROUP (fluviatile)	Sandstone, siltstone, arkose, shale, conglomerate, quartz schist, quartzite	5000	
	NAMOONA GROUP (shallow marine, chemical, detrital)	pyritic carbonaceous shale and siltstone, calcareous in places, calcareous sandstone, tuff, agglomerate, dolomite, schist	< 3500	
	KAKADU GROUP (fluviatile)	sandstone, arkose, siltstone, conglomerate, quartzite, schist, gneiss	<1000	lateral equivalent of Batchelor Group
	BATCHELOR GROUP (recurrent fluviatile, chemical)	conglomerate, arkose, siltstone, sandstone, algal dolomite and crystalline magnesite	1500	lateral equivalent of Kakadu Group
ARCHAEAN BASEMENT	RUM JUNGLE COMPLEX WATERHOUSE COMPLEX NANAMBU COMPLEX LITCHFIELD COMPLEX? HERMIT CREEK METAMORPHICS?	coarse, medium, and porphyritic adamellite, biotite-muscovite granite, migmatite, gneiss, schist, pegmatite, meta-diorite, banded iron formation		1800 - 2500

Table 18. Stratigraphy of various parts of the Pine Creek Geosyncline revised (from Needham et al, 1979b).



The major uranium deposits are in the Lower Cahill Formation, part of a sequence of Lower Proterozoic metasediments which occupy a folded, north-trending synclinorium lying between two prominent granitic migmatitic highs (Fig. 59). To the west is the Nanambu Complex of Archean/Lower Proterozoic age (about 2500 m.y.); to the east is the Nimbuwah Complex, which was dated about 1800 m.y. but is supposed to be rooted in the Archean. The basal Lower Cahill Formation is locally composed of recrystallized dolomite and magnesite up to 250 m in thickness. These sediments are overlain by approximately 700 m of biotite-muscovite-feldspar-quartz schists, with local intercalations of graphite schist. A further 2,000 m of monotonous metapsammitic rocks comprise the upper part of the sequence.

The Cahill rocks are supposed to have been formed from locally carbonaceous, pelitic, and psammitic sediments during sillimanite-grade amphibolite facies metamorphism (ca. 600°C, 5 kb, Binns et al, 1979b), toward the close of an intense episode of polyphase deformation. Synkinematic quartz veins occur in the schists. Relatively undeformed pegmatites, and more rarely aplites, intrude the sequence. Locally, particularly in the vicinity of uranium deposits, a pervasive retrogressive metamorphism to greenschist facies affected the metasediments. Dolerite (Oenpelli Dolerite) was intruded after the regional metamorphism. In close proximity to the deposits, the Kombolgie Formation uncomformably overlies the crystalline basement and dips about 5 degrees to the southeast. All major uranium deposits occur within 250 m (?) above the contact with the Archean granitic basement. The region is cut by major northwest-southeast and east-west structures, but north-northeast- and north-trending faults are also present.

<u>Jabiluka</u>. Binns et al, 1979a, 1979b; Deutscher et al, 1979; Dodson and Pritchard, 1975; Ewers and Ferguson, 1979; Gulson and Mizon, 1979; Hegge, 1977; Hegge and Rowntree, 1978; Riley et al, 1979; Rowntree and Mosher, 1975, 1976; Ryall and Binns, 1979; Ypma and Fuzikawa, 1979.

The deposit lies approximately 220 km to the east of Darwin, 40 km to the southwest of Narbalek, and 15 km to the north of Ranger One. It comprises two orebodies: Jabiluka I and, 300 m to the east, Jabiluka II. A third orebody is indicated by drilling south of Jabiluka I. Jabiluka I was discovered in late 1970 by ground radiometric surveys. An airborne radiometric survey failed to record any anomaly. The ground radiometric anomalies were only slightly more than twice background (50 cps against 20 cps background) over an area of 100 x 45 m. Jabiluka II was discovered in 1973 as the result of step-out drilling based on geologic interpretations east of Jabiluka I.

<u>Geologic Setting of Mineralization</u>. The two Jabiluka orebodies occur within deformed, metamorphosed, and finally retrogressively metamorphosed pelitic sediments of the Lower Cahill Formation along the eastern edge of the Nanambu Complex. They form an open asymmetric-folded flexure dipping south and striking east-southeast. Jabiluka I coincides with an erosional window through unconformably overlying sandstones of the Kombolgie Formation (Fig. 60). Jabiluka II is located about 300 m to the east of Jabiluka I and is covered by between 20 to 220 m of Kombolgie Sandstone which has been in part faulted over the deposit. Major basic intrusives are not known at Jabiluka II, but sporadic tourmaline-bearing granitic pegmatite dikes up to 1.5 m thick intrude the older rocks. The upper 1 to 2 m of the crystalline basement are altered to a regolith.

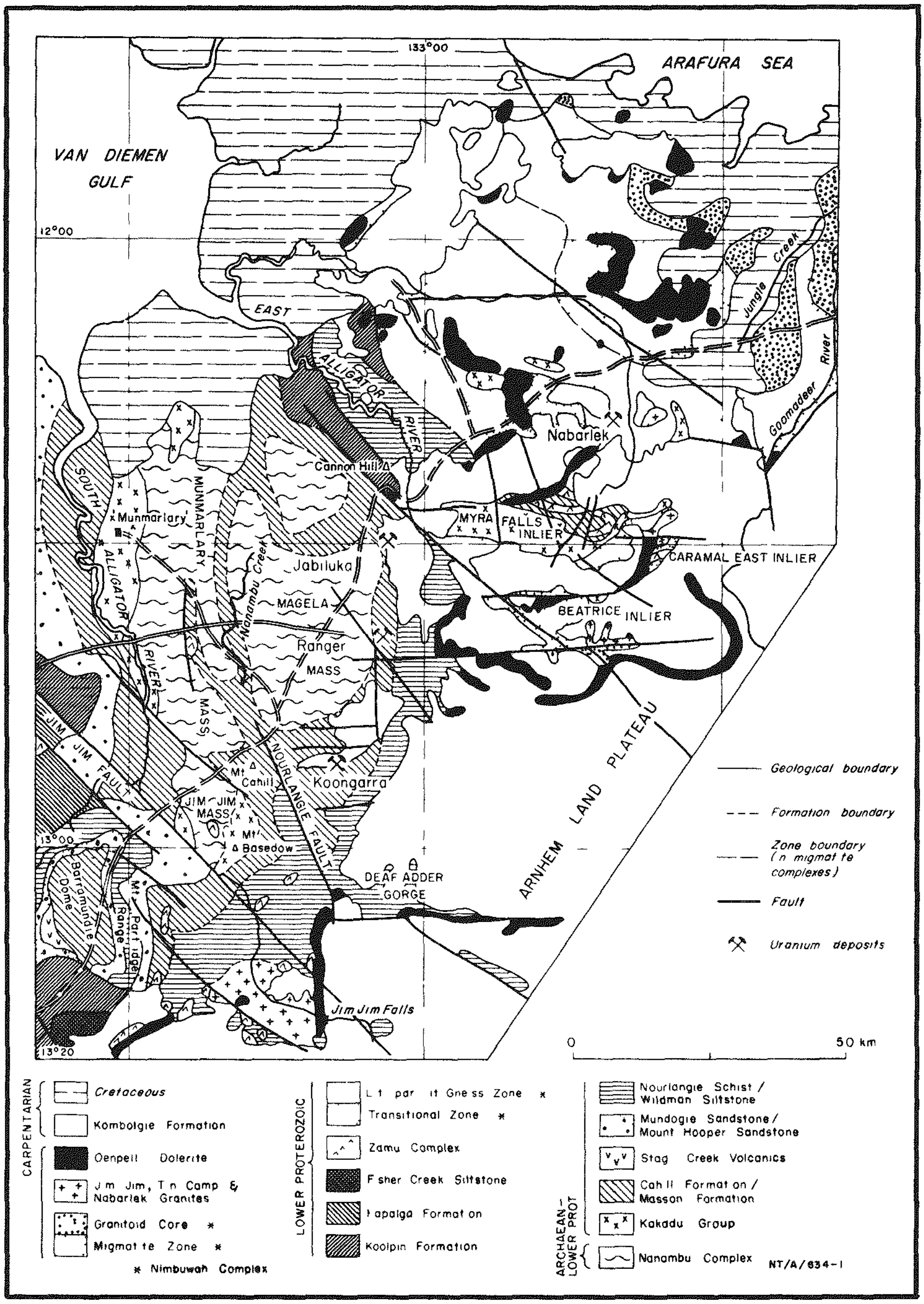


Figure 59. Generalized geology of the Alligator Rivers uranium area (from Needham and Stuart-Smith, 1979).

Lithologically, the host rocks consist of an alternating sequence, 140 m to 200 m thick, of locally graphitic quartz-muscovite-chlorite schists which occasionally contain cordierite, sillimanite, and garnet, and inclusions of dolomite and magnesite (Table 19). Detrital zircon, tourmaline, and rutile are present. This is the Main Mine Series, the most favorable host unit for uranium and gold. Hegge (1977) subdivides it as follows: The uppermost unit is a pyritic graphite schist, which is the most continuous and correlatable unit in the entire succession. The second unit is a series of chlorite-muscovite-feldspar schists up to 20 meters thick, and it is locally similar to those of the overlying Hanging-Wall Series. This is underlain by the third unit, a chlorite and chlorite-graphite schist of similar thickness, and at the base of the section a less consistent, brecciated chlorite schist and chlorite-graphite schist.

Chlorite schist of the Main Mine Series consists of quartz (25 to 30 percent), chlorite (predominantly penninite) (40 to 60 percent), feldspar (5 to 10 percent), minor biotite, pyrite and chalcopyrite, and occasionally leucoxene, apatite, and rutile. Brecciated varieties contain angular to sub-angular fragments in a matrix of normally fine-grained quartz and chlorite. Some of the fragments are "cherty" quartz, the angularity of which suggests they formed by collapse brecciation.

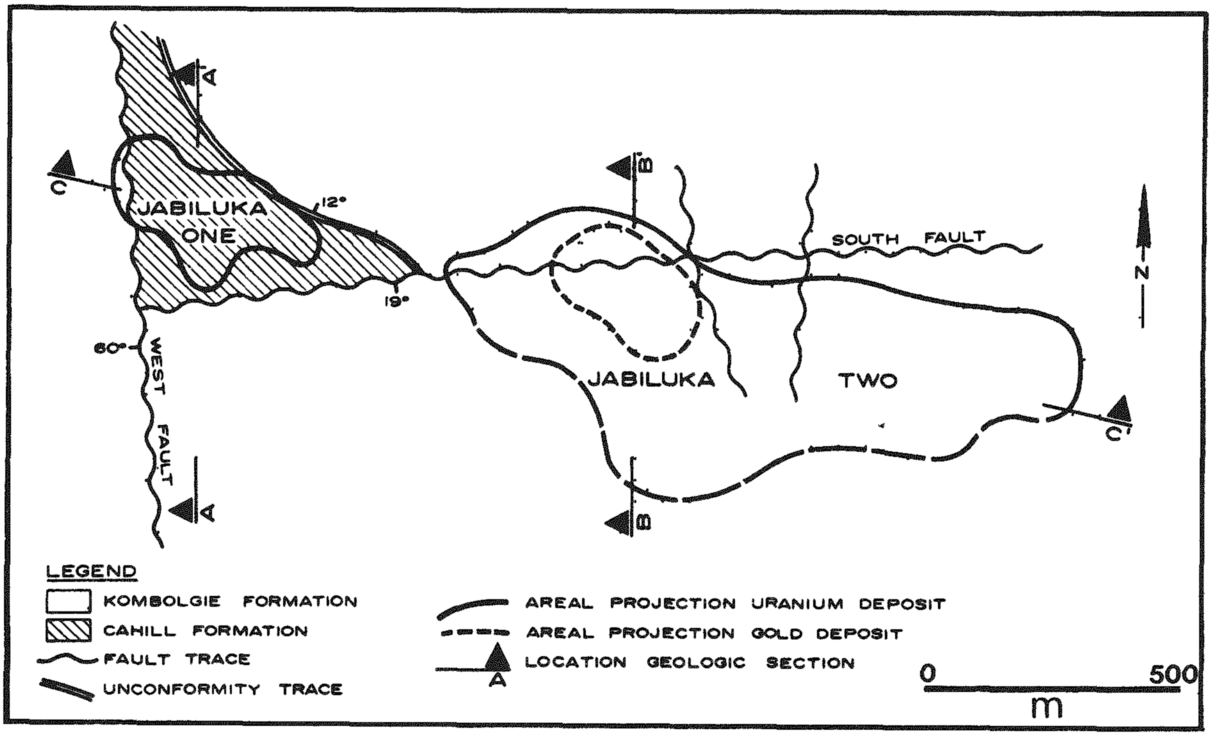


Figure 60. Geologic map for the area of the Jabiluka I and Jabiluka II deposits (from Needham et al, 1979b, modified from Hegge, 1977).

Table 19. Stratigraphy in the Jabiluka area (from Rowntree and Mosher, 1975).

Stratigraphy in the Jabiluka area

Era	Formation	Unit	Lithology	Mineralization
CAINOZOIC	Superficial Deposits		Silts, Sands 1–10 m; Laterite 0–1 m	
MIDDLE PROTEROZOIC	Kombolgie Formation		Sandstones, basalts Conglomerates 0–120 m	
CARPENTARIAN UNCONFORMITY				
LOWER PROTEROZOIC	Nanambu Complex	Intrusives	·granite pegmatites, 1–15 m; ·phonolite 1–2 m	
LOWER PROTEROZOIC	Fisher Creek—Koolpin Formation	Upper Schist Series +30 m	·quartz-muscovite-chlorite schist	
		Graphite Schist 13 m	·graphite schist	Units containing uranium mineralization
		Hanging Wall Schist Series 50 m	·quartz-muscovite-chlorite schist	Units containing uranium mineralization
		Mine Sequence 15 to 70 m	·chlorite-graphite and quartz-graphite schist; ·quartz-muscovite-chlorite schist; ·chlorite-graphite schist complex; [·quartz-chlorite breccia + chert; ·chlorite schist; ·dolomite magnesite (3:2); ·chlorite-graphite schist]	Units containing uranium mineralization
		Footwall Schist Series 45 m	·quartz-muscovite-chlorite schist	Units containing uranium mineralization
		Dolomite Magnesite Complex 15 m	·dolomite magnesite complex includes [·chlorite schist; ·chlorite graphite; ·dolomite magnesite]	Units containing uranium mineralization
		Lower Schist Series 50 m	·quartz-muscovite-chlorite schist; ·quartz-muscovite-feldspar schist; ·muscovite-magnetite augen schist	
		Amphibolite +25 m	·amphibolite, some chloritization	

Chert is found mainly in the Main Mine Series and occasionally updip in chloritic breccia units carrying chert fragments. It is composed mainly of cryptocrystalline silica and was probably formed by the silicification of dolomite, a process involving volume reduction and a possible mode of formation for the collapse breccias.

The graphite-chlorite and chlorite-graphite schists of the Main Mine Series vary only in the relative amounts of the two minerals. Brecciated units are usually healed by a chlorite-quartz-sulfide-carbonate assemblage, which may contain uranium mineralization.

Dolomite horizons (facies equivalents of the Main Mine Series) occurring between Jabiluka I and II are wedge-shaped bodies up to 20 m thick. They are medium to coarse grained, relatively free of inclusions, and locally exhibit up to 40 percent magnesite. Quartz is present in trace amounts; pyrite and/or chalcopyrite are commonly intimately associated with calcite crystals in vugs. Sepiolite, a white, fibrous, magnesian clay mineral, is also common near cavities and open-space fillings.

The second most favorable host sequence is the Lower Mine Series. Lower Mine Series I and II occur as a number of thin, unmineralized units at Jabiluka I. Lower Mine Series I is represented by thin, chloritic and/or graphite units, whereas Lower Mine Series II consists of a dolomite-magnesite unit, up to 10 m thick, with subordinate chlorite schist and chlorite-graphite schist. Biotite-feldspar schist also occurs in the Lower Mine Series II south of Jabiluka I.

In the eastern part of Jabiluka II, Lower Mine Series I and II become more chloritic and brecciated, with better developed uranium mineralization. Chlorite-feldspar schist, with lesser chlorite, and chlorite-graphite schist form the most common assemblages. The former sediment was fine- to medium-grained, but the rock is now a strongly chloritized biotite-feldspar schist with variation in the proportions of quartz and sericite. The rocks with low muscovite content are more competent than the Footwall Series and have been readily brecciated or fractured. In zones of strong shearing, mylonites are developed in association with increased chloritization; these are composed of fine-grained chlorite, quartz, muscovite, lesser graphite, sulfides, and clay minerals. Hematite is common in the uranium-bearing mylonite zones.

Alteration. Extensive retrograde metamorphism altered the former high-grade metamorphic schists for distances exceeding 500 m from mineralization. The following alterations of the primary minerals are described: chloritization of biotite, garnet, and possibly cordierite; replacement of sillimanite and cordierite by sericite and muscovite; alteration of feldspars to very fine-grained sericite-chlorite-septechlorite (minerals of serpentine family, e.g., amesite) aggregates; replacement of dolomite by magnesite. The alteration proceeded without significantly disturbing the earlier metamorphic fabric, i.e., the retrogression must have taken place under essentially static conditions.

The alteration transgressed from the basement through the regolith into the Kombolgie Formation, transforming matrix material into sericite, chlorite and, rarely, biotite, according to Binns et al (1979b). The authors also suggest that retrograde metamorphism of the Cahill Formation was coeval with (?)

burial metamorphism of the Kombolgie Formation; however, metamorphic fluids in the latter were evidently more oxidized, since prograde hematite is common.

The main structures strike around north-south and east-north. They offset mineralization and Kombolgie Formation for up to several tens of meters.

Mineralization. The primary ore consists predominantly of uranium oxides, lesser coffinite, and brannerite. According to Hegge (1977), pitchblende and subordinate uraninite are present. He defines pitchblende as cryptocrystalline or amorphous UO_2 in non-stochiometric proportion. In this context, it should be noted that the crystallographic structure (lattice, oxidation stage, etc.) of the various uranium oxides in the Alligator Rivers deposits have not yet been properly established; thus, the same specimen may be referred to as pitchblende and uraninite (Binns et al, 1979b; Ewers and Ferguson, 1979). Obviously, both varieties exist since euhedral shapes (uraninite in sensu stricto) and colloform habits (pitchblende in sensu stricto) are both described. The importance of correctly establishing the crystallographic parameters of the various uranium oxides, and hence their environments of formation, has been emphasized by several authors, including Clasen and Voultsidis (1980).

In Jabiluka, uranium oxides are accompanied at one location by native gold in economic amounts. Traces of Ni and Pb tellurides accompany the gold, together with minor amounts of pyrite, chalcopyrite, sphalerite and galena. Chalcocite and covellite are rarely present. Hematite is present, but it does not show a direct relationship with uranium. The principal gangue minerals are chlorite (30 percent), quartz (25 percent), and sericite (10 percent), with lesser amounts of calcite, kaolinite, montmorillonite, apatite, tourmaline, sphene, leucoxene and rutile (Hegge, 1977).

According to Binns et al (1979b) "uraninite" occurs in three principal settings, as veins, disseminations and replacements:

(1) Veins contain uraninite as selvedges and around rarer layers or disseminations within the vein structure. These are transgressive or conformable to schistosity, and occur in both graphitic and chlorite-mica schists. The vein gangue may be subhedral quartz, but more generally it is a distinctive microcrystalline chlorite-septechlorite-quartz (CSQ) intergrowth. This usually appears brownish in thin section and conspicuously waxy in polished section, and commonly replaces the coarser quartz gangue. The veins appear to be replacements of country rock rather than dilational in character. Uraninite has itself replaced CSQ, vein quartz, or retrograde phases in immediately adjacent wall rock. It is almost invariably bordered by a narrow zone of a different, possibly Fe-rich chlorite. The uraninite crystals are commonly zoned, usually with rims richer in oxygen. Fan-shaped clusters of acicular uraninite crystals may replace chlorite in a reniform manner, giving a false impression of open-space filling. Tiny radiogenic galena inclusions within uraninite imply later sulfurization. Sulfides, including pyrite, chalcopyrite, chalcocite, sphalerite and galena, are occasionally abundant within CSQ in these veins. Uraninite and sulfides are distinctly antipathetic, the two tending to occur separately within individual veins. Carbonates are lacking, but tiny rosettes of anhydrite may occur within CSQ.

(2) As disseminated grains within fragmented country rock, which varies from narrow microbreccia zones through gleitbretter to thicker breccia intervals (e.g. 10-20 cm) containing a mixture of angular, disoriented schist fragments. The matrix of these breccias and microbreccias includes fine rock and mineral fragments, especially quartz, extensively replaced by a brownish CSQ similar to that in the aforementioned veins. Localized growths of coarser, subhedral quartz also occur, and via accumulations of this and CSQ the breccia matrices may grade imperceptibly into veins, so that these two kinds of occurrence appear cogenetic. Uraninite occurs principally as isolated grains within CSQ, generally near quartz fragments, and again surrounded by a narrow rim of (Fe ?) chlorite. However, the margins of quartz clasts are locally replaced by botryoidal coffinite which in turn is replaced either by CSQ or by uraninite. The uraninite crystals again show variation in oxygen content. Pyrite, chalcopyrite and chalcocite occur in the CSQ, but the antipathy between sulfides and uraninite is maintained. Apatite is also a common phase.

(3) Within narrow, irregular replacement zones of CSQ extending outwards (1-2 cm) from either veins or breccias into adjacent schist. As well as early replacement of quartz relics by coffinite, these zones also exhibit alteration of sphene or anatase to brannerite. Uraninite once more appears a late-stage replacement within CSQ, its abundance decreasing markedly with distance from the 'source' vein or breccia. Several kinds of later vein occur at Jabiluka II, the most abundant being drusy-structured quartz-dolomite-magnesite-chlorite veins commonly carrying appreciable pyrite and chalcopyrite. These appear dilational, and cut across the uraninite-bearing veins and breccias. Except for isolated, incompletely dissolved relics, the drusy veins lack uraninite. Similar veins have been observed cutting the basal Kombolgie Sandstone. An even later, lower-temperature, but much rarer form of dolomitic vein within graphite schist may carry uraninite, presumably remobilized.

According to Hegge (1977), mineralization occurs as lenselike and layerlike zones in several successive horizons, with the bulk of the ore (67 percent) within the Main Mine Series of the Lower Cahill Formation associated in part with intensive brecciation (Fig. 61). He noted a predominance of mineralization in axial zones of broad flexures. The uranium exhibits a distinct affinity for chlorite-sericite rocks adjacent to graphitic schists, in which it is also present in lesser amounts. Ore stringers 20 to 30 cm thick extend from the footwall of orebodies into the subjacent schists of the "footwall series", similar to Ranger One. Mineralization was found locally also in Kombolgie Formation. Secondary uranium minerals were found only at Jabiluka I. They are confined to 15 m below surface and include autunite, saleeite and sklodowskite.

Geochronology. Hills and Richards (1976) report ages of 1700-1800 m.y. for uranium oxide (uraninite, pitchblende) and 800-900 m.y. for uranium oxide. Gulson and Mizon (1979) obtained ages of 1400 m.y. on pyrite and 1100 m.y. on uraninite, which they interpret to reflect the resetting of 1800 m.y. ages by an 800-900 m.y. event. The high-grade regional metamorphism, emplacement of pegmatite, and K-metasomatism or greisenization was dated by Riley et al (1979) at 1780 m.y. A younger metasomatic event involving local chloritization and sericitization was dated at 1600-1650 m.y. by Page et al (1979). Various rock ages are compiled in Table 20.

Ore Control and Metallogenesis. The primary mineralization seems to have been controlled predominantly by lithology-stratigraphy and to some extent by structures. It follows chloritized sequences adjacent to graphitic horizons, and thus appears to be strata-bound. To what extent the brecciation of the host rocks controlled localization and deposition of the primary ore has not been established, but it certainly influenced the redeposition of later mobilized uranium.

According to Hegge (1977), available data suggest the deposits formed by the initial accumulation of uranium in Lower Proterozoic sediments, followed by remobilization and reconcentration during subsequent orogenic events. The deposits only became economically viable through the "post-prograde metamorphic" remobilization of uranium into structurally favorable sites. The following is a postulated sequence of events which has resulted in their formation.

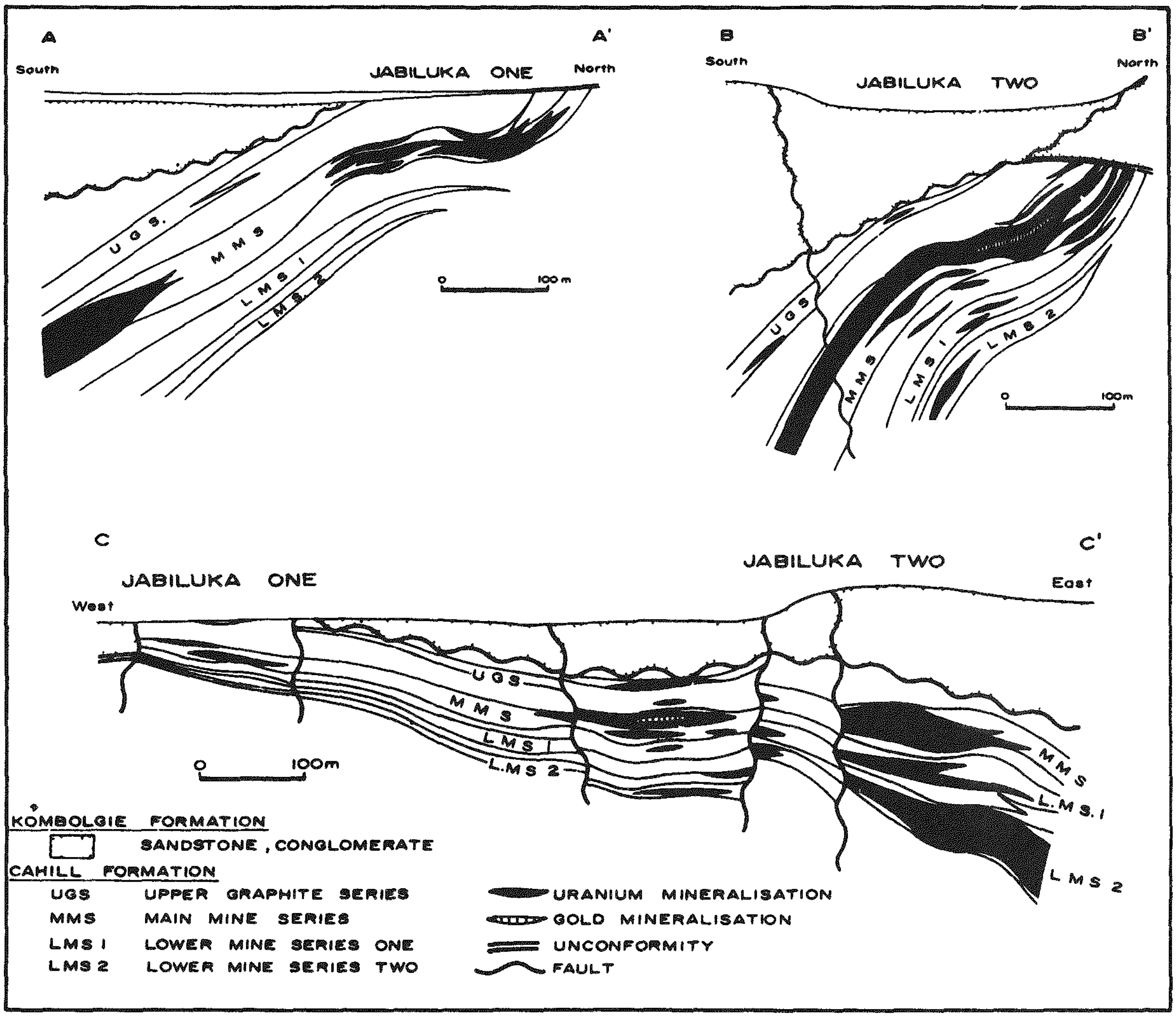


Figure 61. Generalized cross sections of the Jabiluka I and Jabiluka II orebodies (from Needham et al, 1979b, modified from Hegge, 1977).

Table 20. Summary of isotopic age dates for the Pine Creek Geosyncline, Australia (compiled from Page et al, 1979).

	Age	Method
(1) Basement rocks		
Rum Jungle and Waterhouse Complex	2400 m.y.	
Nanambu Complex	2470 $\pm$ 32 m.y.	
(2) Lower Proterozoic granitoid rocks of the Nimbuwah Complex	1870 $\pm$ 20 m.y.	U-Pb (zircons)
	1803 $\pm$ 20 min. to 1905 $\pm$ 32 max. m.y.	Rb-Sr
(3) Regional metamorphism		
Metasediments	approx. 1700 m.y.	
Granitoids	1750 to 1780 m.y.	Rb-Sr
(4) Oenpelli Dolerite	1683 $\pm$ 13 m.y.	Rb-Sr
(5) Metasomatic events		
Nabarlek (chloritization)	1610 m.y.	Rb-Sr
Jabiluka (chloritization)	1600 m.y.	Rb-Sr
Amphibolite dikes	1650 $\pm$ 20 m.y.	K-Ar
Oenpelli Dolerite (alteration)	1620 $\pm$ 20 m.y.	K-Ar
Carpentarian granite (alteration)	1630 m.y.	K-Ar
(6) Nabarlek mineralization ore zone alteration	850-1000 m.y.	Rb-Sr
(7) Late Carpentarian dikes		
Phonolite	1316 $\pm$ 50 m.y.	Rb-Sr
Dolerite (younger than Kombolgie Formation)	1370 m.y.	K-Ar

(1) Lower Proterozoic pelitic and chemical sediments derived from the erosion of uraniferous Archean granitic basement were deposited in a Lower Proterozoic marine environment. Uranium was transported as UO_2 or hydrated in solution and precipitated by reduction.

(2) An orogenic event at about 1800 m.y. produced extensive migmatization and local intrusion of dikes into the folded and faulted metasediments flanking Archean basement complexes. Toward the end of regional metamorphism, uranium was redistributed.

(3) Retrograde metamorphism of the metasediments, possibly accompanied by some uranium redistribution, followed regional metamorphism. The metasediments were eroded, peneplaned, and finally covered with the Kombolgie Formation at about 1500 m.y. ago.

(4) Following retrograde metamorphism, widespread chlorite development preceded or accompanied the main stage of uranium remobilization.

(5) After deposition of the Kombolgie Formation, tectonism at about 900 m.y. led to the main redistribution of uranium in the deposits. Temperature of ore formation appears to have been in the range of 260°C. Open-space vein and breccia fillings suggest pressures were low.

Shape and Dimension of Deposits. According to Hegge (1977), the mineralization in Jabiluka I occurs over a distance of about 450 m along a northwest direction parallel to the strike of metasediments, and 250 m in a north-south direction (Fig. 60). The orebody dips to the south at variable dips between 15 and 30 degrees (Fig. 61). The ore zone in the Main Mine Series reaches thicknesses of 35 m and more.

Jabiluka II. The deposit is about 300 m east of Jabiluka I, and the mineralization extends for at least 1,000 m in a west-northwest direction and for at least 400 m in a north-south direction. The northern end of the orebody is under the Middle Proterozoic unconformity, approximately 30 to 50 m below the surface. The deposit dips to the south in a series of flexures at between 30 and 60 degrees. Ore in the Main Mine Series is up to 135 m thick. Lower-grade ore up to 100 m thick occurred in the Lower Mine Series in the east. In the western part of this deposit, little ore occurs in the Upper Graphite Series, which is 4 to 20 m thick. Some erratic pitchblende-chlorite veinlets have been found in the Hanging and Footwall Series.

Gold mineralization occurs in the western part of Jabiluka II and covers an area approximately 300 by 150 m, elongated in northwest-southeast direction. The zone is limited to the north by the Middle Proterozoic unconformity, to the east by a fault. The thickness of the ore is up to 12 m, but the average is 2 m. Gold grades are erratic, and gold does not necessarily coincide with uranium.

Hegge (1977) presents the following distribution of uranium ore by stratigraphic units:

Upper Graphite Series	1%
Main Mine Series	67%
Lower Mine Series I	11%
Lower Mine Series II	16%
Hanging and Footwall Series	5%

Production and Reserves. There has been no uranium production at Jabiluka, but the large reserves make it one of the major deposits of its type. The reserves have been summarized as follows (Needham and Roarty, 1980):

	tonnage	grade	content
Jabiluka I	1,361,000 mt	0.256% U_3O_8	3,484 mt U_3O_8
Jabiluka II	51,900,000 mt	0.39% U_3O_8	203,800 mt U_3O_8
Jabiluka II	529,000 mt	10 dwt (15.3 g/t)	8,094 kg Au

Ranger One. Donnelly and Ferguson, 1979; Eupene et al, 1975; Ewers and Ferguson, 1979; Hills and Richards, 1976; Needham et al 1979a; Ryan, 1972, 1977.

Ranger One is situated approximately 225 km to the east of Darwin and about 20 km south of Jabiluka. The deposit contains two proven, economic orebodies (Fig. 62). Three more prospects exist but are not yet explored. The deposit was indicated by an airborne spectrometric survey in 1969 and finally discovered by drilling of the anomalies in 1970.

Geologic Setting of Mineralization. The host rocks for the uranium mineralization belong to the Lower Proterozoic Cahill Formation. They occur on the eastern flank of the Archean/Lower Proterozoic Nanambu Complex. Eupene et al (1975) subdivide the 350 to 400 m thick sequence of alternating metasediments into the 'Upper Mine Sequence' (UMS) and 'Lower Mine Sequence' (LMS), both being part of the Lower Cahill Formation. They are overlain by the Hanging Wall Sequence, which is part of the upper member of the Cahill Formation and underlain by the Footwall Sequence attributed to the Archean/Lower Proterozoic Nanambu Complex.

Host Rock Lithology and Alteration. The Upper Mine Sequence comprises biotite-quartz-feldspar schists with intercalated pyrite-bearing graphite layers and dolomitic marbles. The rocks were presumably derived from psammitic sediments. In the ore zone, the schists are strongly altered into sericite-quartz-chlorite schists. Chlorite replaces biotite and feldspar. The alteration is expressed chemically by removal of SiO_2, A_2O_3, CaO, Na_2O, K_2O, and by enrichment of Fe_2O_3, MgO and water of hydration. Relatively high TiO_2 and P_2O_5 concentrations are noteworthy.

The Lower Mine Sequence consists of dolomitic marbles, fine-grained dolomite with intercalated chlorite, chlorite-sericite schists with lenses and veins of chlorite, and variably grained, in part schistose, magnesite/dolomite with lenticles of talc and tremolite. The rocks are supposedly derived from carbonate-bearing, carbonaceous, pelitic sediments.

The metasediments strike approximately north-south and dip to the east (Fig. 63). Within the ore zone, carbonates become thin, and near the surface are completely replaced by chert.

The chlorite lenses and veins are up to 10 m thick. They consist mainly of pennine and contain disseminated hematite, TiO_2, apatite and pitchblende. The veins rarely show evidence of deformation and metamorphism, and they are considered by Eupene et al (1975) to be of hydrothermal origin.

Dikes of pegmatite and dolerite are intruded into the metasediments. The pegmatites appear to have been formed during metamorphism. Dolerites are present in the No. 1 orebody but are almost non-existent in the No. 3 orebody. They postdate the metamorphic events. Both types of dikes are strongly chloritized in the vicinity of the ore zones but are not significantly mineralized. The dikes show sharp contacts to the chlorite veins. The rocks are locally strongly deformed, fractured, and sheared. The prominent Footwall Shear Zone, with a thickness of up to 20 m, is present just below the No. 1 orebody along the contact between the Footwall schists/gneisses and the Lower

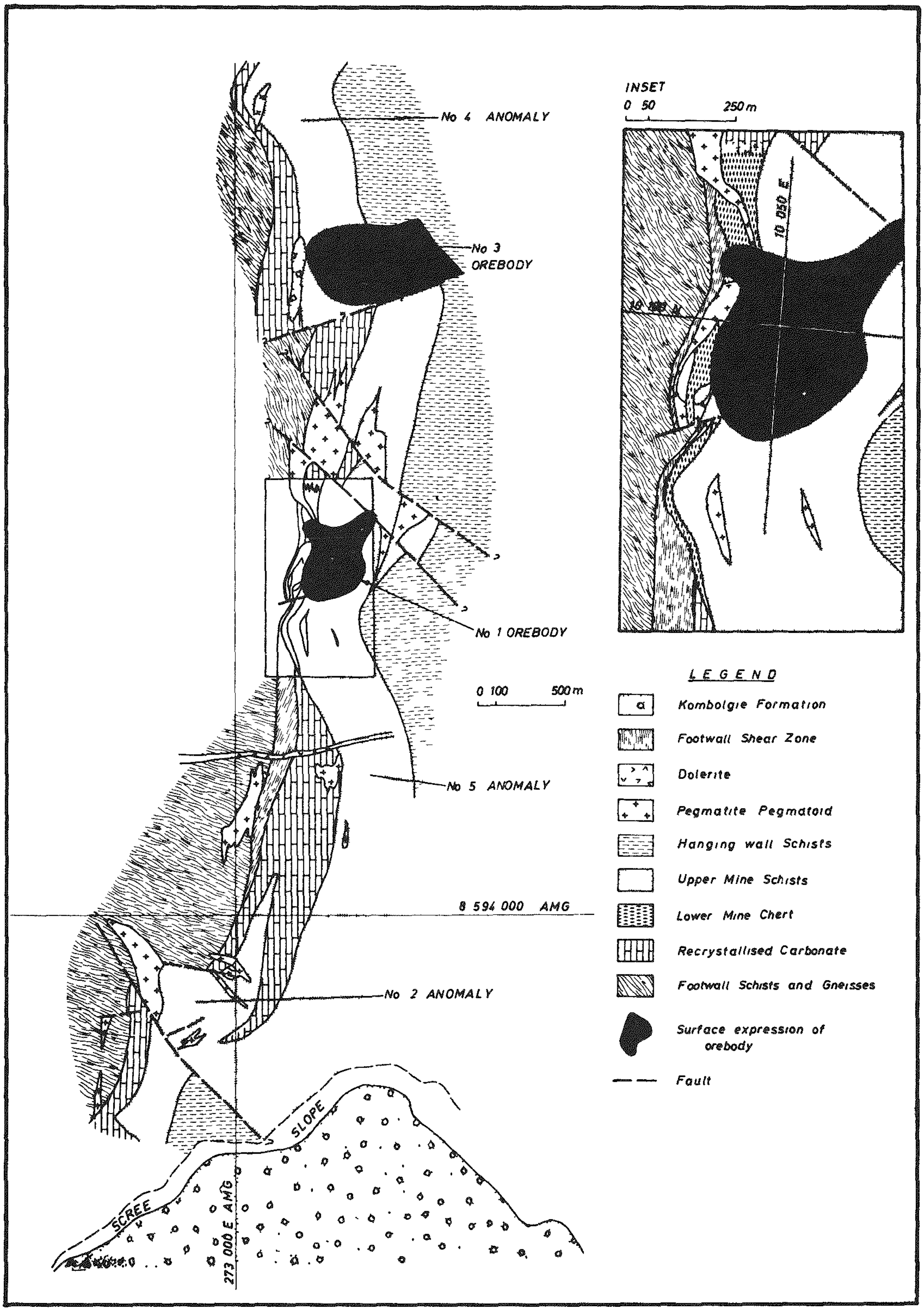


Figure 62. Ranger One surface geology projected from drill-hole data (from Needham et al, 1979b, modified from Eupene et al, 1975).

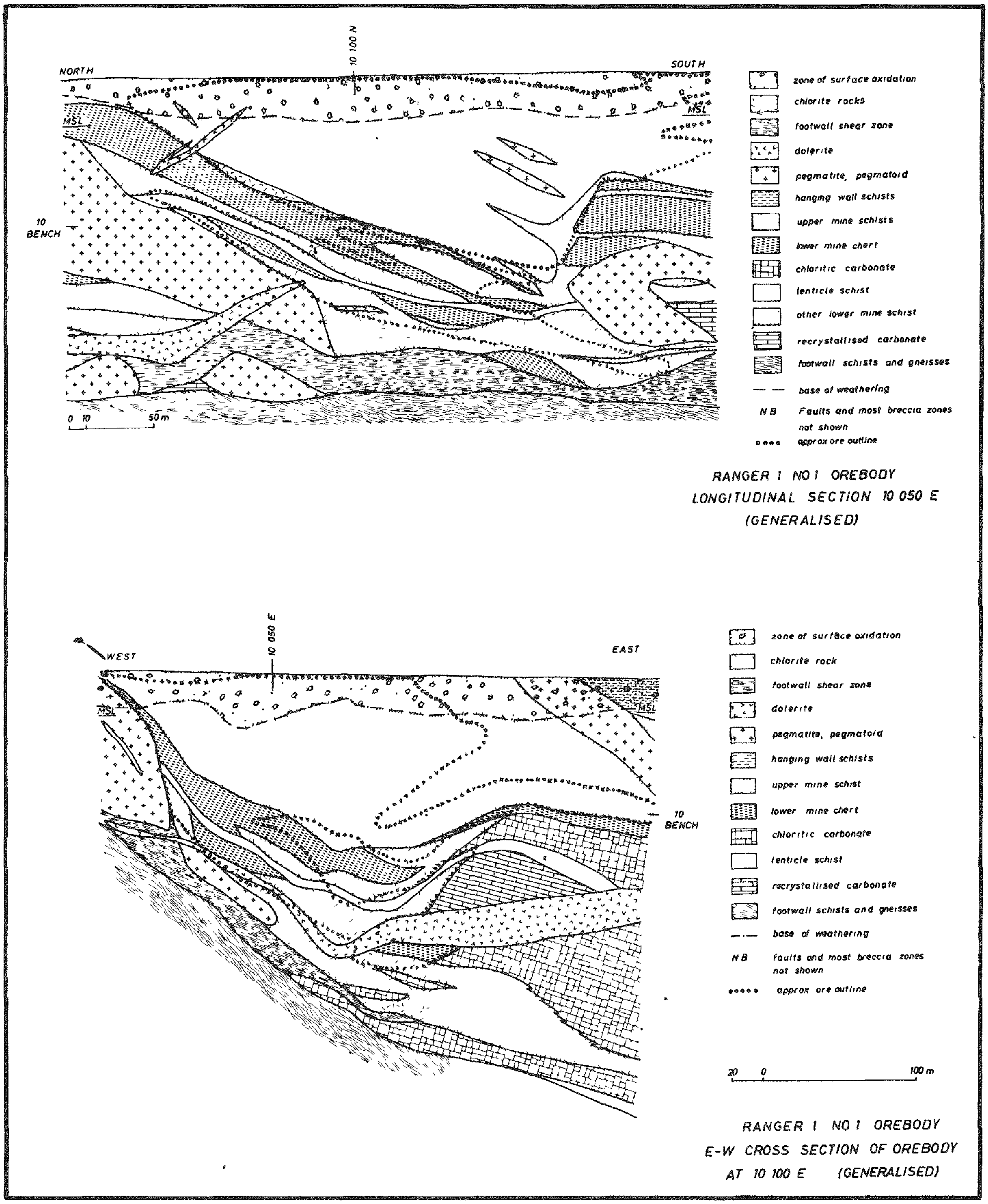


Figure 63. Generalized cross section of the Ranger One No. 1 orebody (from Needham et al, 1979b, modified from Eupene et al, 1975).

Mine Sequence. Other faults strike approximately northwest and east to east-northeast, and both sets caused offsets of up to several hundreds of meters.

The metasediments of the ore zone are locally overlain by small erosion remnants of Middle Proterozoic Kombolgie Formation; the main mass starts approximately 2.5 km to the south of the No. 1 orebody with the Mount Brockman Massif.

Cretaceous arenites of the Petrel Formation are present north of Ranger. The entire area was subjected to lateritization during the Tertiary. The depth of weathering generally extends to about 30 m below the surface but decreases towards the Kombolgie Formation escarpment south of the deposit at Mount Brockman.

Mineralization. Mineralization in the No. 1 orebody of the Ranger One deposit is almost monomineralic. The main ore mineral is pitchblende, with lesser amounts of brannerite and amorphous mixtures of U, TiO_2 and phosphates (Eupene et al, 1975). Ewers and Ferguson (1979) noted that "cubes of uraninite are found in progressive stages of replacement of chlorite". Pitchblende is accompanied by, in decreasing amounts, chlorite, quartz, Ti-oxides, hematite, apatite, Fe-sulfides (predominantly pyrite), Cu-sulfides (predominantly chalcopyrite), and galena. The lead of the galena is dominantly radiogenic. Gold is present in very minor amounts. Locally, relatively high concentrations of leucoxene, anatase, and apatite are found in the orebody.

The oxidation zone at the surface ranges in thickness from a few meters to as much as 35 m, with an average around 18 m. It contains secondary uranium hydrous-oxides and uranyl minerals such as gummite, saleeite, sklodowskite, metatorbernite, and others. The primary ore minerals occur as bands or veinlets and disseminated pitchblende. The bands or veinlets commonly consist of massive pitchblende concentrations within selvedges of chlorite or quartz-chlorite. These veinlets follow fine fractures and joints and are rarely thicker than 1 cm. The disseminated pitchblende occurs as minute particles (about 5 microns) within small bands of chlorite, whereas in thicker chlorite veins, pitchblende forms spherulites of up to 1 cm in diameter. Pitchblende also coats foliation planes and may occupy hairline fractures which are discordant to the foliation and in some cases appear to postdate the earliest mineralization. Narrow lenses of pitchblende are also found within and parallel to the cleavage of chlorite. According to Ewers and Ferguson (1979), "massive uraninite (?) with the characteristic concentric banding and radial fractures is apparently absent from the Ranger I ore zones". With respect to gangue minerals, they note that vugs are common in the Ranger I deposits, and are usually filled with euhedral quartz and chlorite but may also contain hematite, sulfides, and carbonate.

Stable isotope studies of bedded, vein and vug sulfides, bedded, vein and vug carbonates, and graphite were undertaken for the Ranger, Jabiluka, and Koongarra deposits by Donnelly and Ferguson (1979). The results of those studies are presented in the description of the Koongarra deposit.

The bulk of the ore in the No. 1 orebody, equivalent to about 70 percent, occurs in the unoxidized Upper Mine Sequence, predominantly in finely banded sericite-quartz-chlorite schist. About 20 percent of the ore is in the Lower Mine Sequence, particularly in chlorite veins underlying silicified carbonates, and about 10 percent is in the oxidation zone. The uranium grade is reasonably constant in all rocks at between 0.2 and 0.3 percent U_3O_8.

Mineralization and petrology in the No. 3 orebody of Ranger One are identical to those of the No. 1 orebody. The bulk of the ore is also in the Upper Mine Sequence, with the best mineralizations in the basal parts of this unit. A second ore zone was found 300 m beneath the main orebody in a chlorite-filled carbonate breccia.

At the western end of the orebody, non-metamorphosed but chlorite-bearing and silicified sandstone was discovered. Tentatively it is interpreted as Kombolgie Formation that is wedged into the Cahill metasediments.

In both orebodies, there is a direct association between uranium mineralization and Mg-metasomatism. The chloritic alteration zones within the orebodies, and the normally dolomitic carbonates of the Lower Mine Sequence as well, are magnesitized in and adjacent to uranium ores.

Geochronology. Hills and Richards (1976) obtained ages from U-Pb and Pb isotopic studies that suggest pitchblende formed at about 1700 m.y., indicating an old original mineralization at Ranger and a younger one at about 900 m.y. They do not feel, however, that any of the evidence from Ranger can be regarded as definitive.

The host rocks were metamorphosed at about 1800 m.y. Younger dolerite dikes, if related to the Oenpelli Dolerite, should be about 1688 m.y. old (Page et al, 1979). The dikes show sharp intrusive contacts with vein chlorite and are completely chloritized within the orebodies, indicating syn- to post-chlorite emplacement. The dikes are only mineralized where fractured. Eupene et al (1975) consider dolerite intrusion and ore formation as contemporaneous.

Ore Control and Metallogenesis. The ore shows the influence of structural, stratigraphic-lithologic and mineralogic-chemical controls. It occurs in a distinct unit of the Lower Cahill Formation and tends to occur adjacent to graphitic schists within the pervasive envelope of chloritic alteration.

The orebodies are situated at or close to the Middle Proterozoic unconformity, as indicated by the occurrence of Kombolgie Formation in the vicinity of the deposits.

The mineralization in the Upper Mine Sequence occurs in strongly deformed host rocks or immediately adjacent to shear and breccia zones. In the Lower Mine Sequence, pitchblende is associated with veins of chlorite which were emplaced in zones of structural weaknesses just above the major Footwall Shear Zone (Eupene et al, 1975). Fracturing in the Upper Mine Sequence, particularly in the No. 1 orebody, may have been formed in part by collapse due to leaching and/or silicification of carbonate units of the Lower Mine Sequence.

Eupene et al (1975) do not think that chemical controls, at least with respect to relations between mineralization and graphite-pyrite horizons, are very convincing. They note that, although the main graphitic horizon is present along the basis of the Upper Mine Sequence where the most continuous mineralization is found, considerable quantities of ore occur up to several tens of meters above and below the graphitic metasediments.

With respect to genesis, the source of the uranium and the relative importance of hypogene and supergene processes are the principal topics of continued discussion. Eupene et al (1975) have emphasized the association between uranium mineralization and magnesium metasomatism in the form of chlorite. In addition, the usually dolomitic carbonates of the Lower Mine Sequence are commonly magnesitic near mineralization. They feel the mineralogy of the deposits and the apparent lack of a chemical control for uranium deposition preclude a source either in the overlying Kombolgie Formation or through the weathering of the Lower Proterozoic schist and gneisses. They prefer a hypogene origin and point to uranium anomalies at depth within the Lower Mine Sequence carbonates as possible vestiges of the ore-forming process.

Shape and Dimensions of Deposits. The Ranger One, No. 1 orebody occurs in the general form of a bowl; however, the boundaries are quite irregular in detail (Fig. 60). The maximum north-south diameter is about 400 m, and the east-west diameter is more than 300 m. The deposit extends to 200 m below the surface, with ore stringers extending further in depth.

The No. 3 orebody is about 122 m to the north of the No. 1 orebody along strike. In an east-west cross section, it is a wedge-shaped body dipping gently to the east for a known distance of about 600 m. Mineralization has a maximum thickness of almost 100 m, a north-south width of almost 500 m, and extends to more than 400 m below the surface. The deposit is open to the east.

About 50 to 100 m below the No. 3 orebody, a carbonate breccia filled with chlorite and extremely high-grade uranium was discovered.

Production and Reserves. There has not yet been any production at Ranger One. The No. 1 and No. 3 orebodies have a combined total reserve of 41,000,000 ore tonnes at an average grade of 0.2007 percent U_3O_8, yielding 100,350 t U_3O_8 (Needham and Roarty, 1980).

About 50,000 t U_3O_8 are contained in the No. 1 orebody at an average grade of about 0.27 percent U_3O_8. The grade of the No. 3 orebody appears lower.

The limits of the No. 1 orebody are reasonably well known, but the No. 3 orebody is open to the east, providing potential for increased reserves.

Koongarra. Dickson and Snelling, 1979; Donnelly and Ferguson, 1979; Ewers and Ferguson, 1979; Foy and Pederson, 1975; Hills and Richards, 1976; Snelling, 1979.

Koongarra is situated about 225 km east-southeast of Darwin, about 10 km to the south-southwest of Ranger One. It consists of two adjacent orebodies. Discovery resulted from an airborne spectrometric anomaly in 1970.

Geologic Setting of Mineralization. According to Foy and Pederson (1975), the uranium host rocks belong to the Lower Proterozoic Koolpin Formation, now referred to as Lower Cahill Formation (Needham et al, 1979a). The host rocks were derived from a series of organic-bearing pelites which were metamorphosed and folded at about 1800 m.y. They form a sequence about 260 m thick in the area of mineralization. The sequence is cut by a prominent reverse fault on the northwest side of the deposit that thrusts metasediments over Kombolgie Formation (Fig. 64). The sequence at the mine, therefore, consists of (from the surface down):

Lower Proterozoic:	Thickness
quartz-mica schists with feldspars	> 100 m
quartz-chlorite schists with bands of mica, garnet, pyrite	± 100 m
graphitic, partly pyritic quartz-chlorite schists	1-10 m
quartz-chlorite schists with cherty silica bands (main uranium host rock)	50 m
footwall fault breccia	7 m
reverse fault	
Middle Proterozoic:	
coarse-grained Kombolgie Formation	

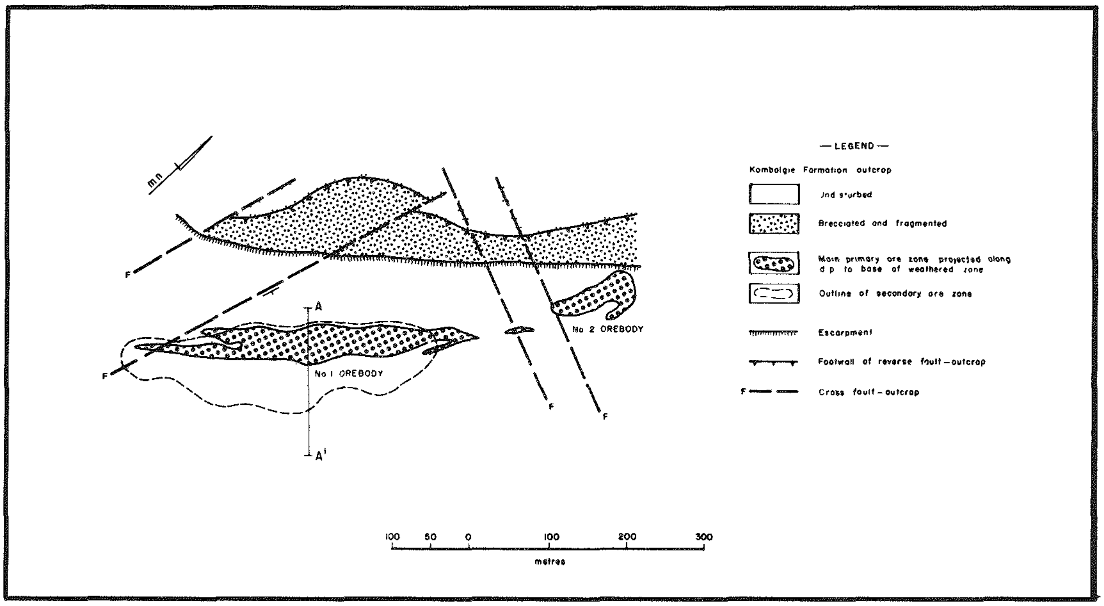
The fault strikes northeast parallel to the strike of metasediments and fold axes and dips at 60 degrees to the southeast. A vertical displacement of about 200 m has been estimated, but stratigraphic correlation requires a displacement of almost 600 m. The fault is accompanied by a major breccia zone with intensive silicification and hematitization and massive hematite in vugs.

Crosscutting faults with minor displacements cut metasediments and Kombolgie Formation but apparently do not affect mineralization.

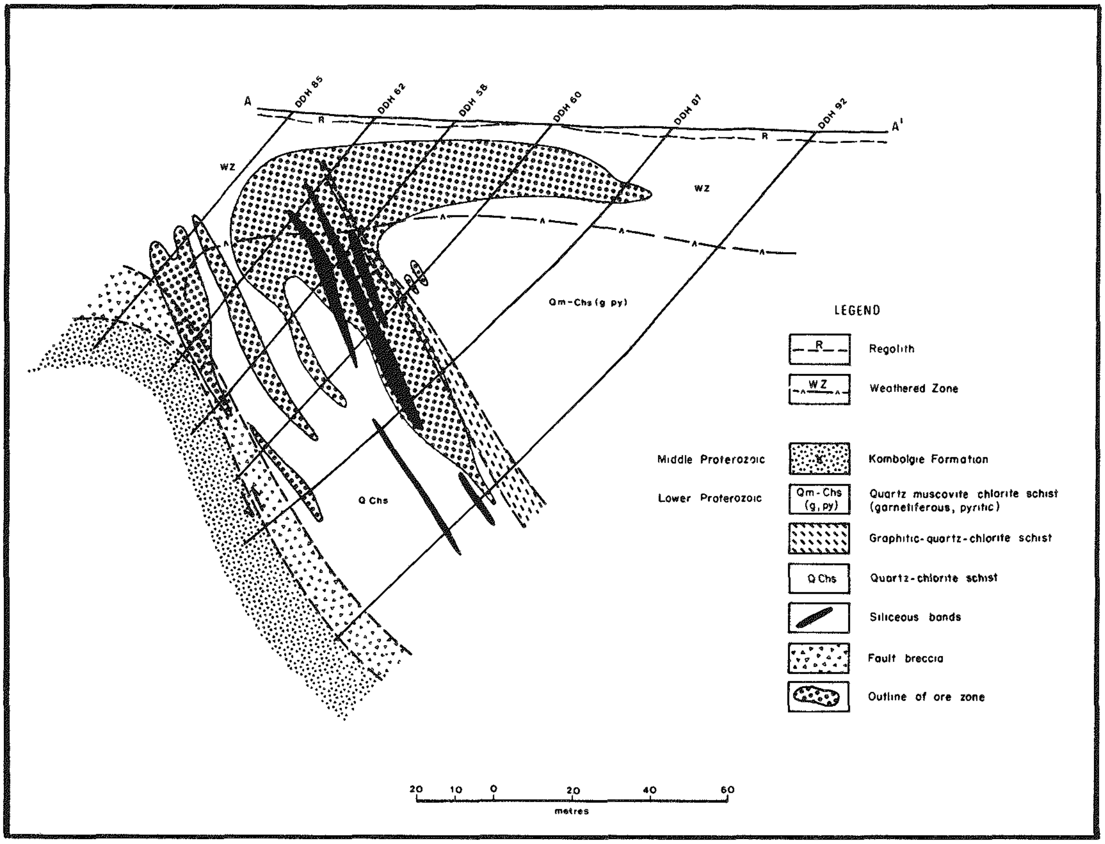
Host Rock Lithology and Alteration. The main uranium host rocks are quartz-chlorite schists. They are present above the Footwall Fault Breccia and beneath graphitic schists. Major rock-forming constituents are chlorite (35 percent) and quartz (50 percent). Some sericite is present. Chlorite is present, in part, in massive zones. Distinctly layered cherty lenses with lengths of up to 5 m are intercalated in the schists, and the rocks are strongly sheared and occasionally brecciated.

The Hanging Wall graphitic quartz-chlorite schists are pervasively sheared and intensively folded. Their mineral contents are as follows: graphite 3 to 7 percent; chlorite 20 to 70 percent; quartz 70 to 20 percent in reverse proportion to chlorite. Pyrite is locally present.

Deformation and alteration decrease from the graphitic chlorite schists upwards into the Hanging Wall Sequence. In these rocks, muscovite (up to 50 percent) and chloritized biotite (25 to 35 percent) are present. Muscovite appears in thin bands parallel to schistosity. A higher content of pyrite is often found in these bands. Garnets are chloritized and stretched along schistosity.



MAP



CROSS SECTION

Figure 64. Generalized plan and cross section of the Koongarra orebody (from Needham et al, 1979b, modified from Foy and Pederson, 1975).

Massive dolomites occur as intercalations within the metasediments to the southwest and northeast, outside of the zone of mineralization. Eluvial sands and lateritic crusts up to 5 m thick cover the ore zone.

Mineralization. Two separate orebodies are present at Koongarra, the No. 1 orebody and, 200 m to the north, the No. 2 orebody. Both contain primary zones of pitchblende veins conformable within the steeply dipping quartz-chlorite schists. They wedge out at a depth of about 100 m. The No. 1 orebody also contains a tonguelike, tabular dispersion fan of uranium in the 30 m thick weathered zone above the orebody. The deposit consists, therefore, of an unweathered deep zone and a weathered shallow zone.

The unweathered deep zone contains pitchblende or uraninite (?) and sooty pitchblende as the main ore minerals. Minor amounts of pyrite and traces of chalcopyrite and galena are present, particularly within high-grade ore sections. Au was found in some assays.

The primary ore mineral is described by Foy and Pederson (1975) as hard, crystalline uraninite in thin veinlets both parallel to and crosscutting schistosity planes. It is also present in grains and botryoidal masses within a chlorite matrix. Snelling (1979) described the pitchblende forming the primary ore veins as typical of 'vein type' and hydrothermal pitchblendes. Hills and Richards (1973) showed that the primary pitchblende has unit cell dimensions comparable to those of vein pitchblende. The low Th and rare earth contents, and CaO content in the range of 1 to 2 percent (Snelling, 1979), are is similar to pitchblende in both vein and sandstone-type deposits.

Ewers and Ferguson (1979) observed that in Koongarra, Jabiluka, and Ranger, the primary uranium mineral is uraninite, which tends to be restricted to the breccia zones and is always associated with chlorite. Where disseminated, the uraninite occurs as cubes 10 to 100 mm in diameter.

It is unclear from these differing descriptions of the primary uranium oxide whether there are (a) two different, but essentially contemporaneous, habits of uranium oxide (the high-temperature, euhedral form uraninite, or the somewhat lower temperature tetragonal $\alpha\ U_3O_7$, and the yet lower temperature colloidal pitchblende form); or (b) whether there are an old crystalline uraninite (formed during metamorphism at about 1800 m.y.) and a younger ore-related pitchblende (see following section on geochronology).

The best mineralization occurs over a thickness of several meters in quartz-chlorite schists just below the thin hanging wall graphitic schist. At the north end of the orebody, the ore also enters the overlying mica-garnet schists. The pitchblende is in thin bands and veinlets parallel to and oblique to the schistosity planes, but is also in botryoidal masses within chlorite. At least two remobilizations of primary pitchblendes have been recognized (Snelling, 1979). They formed sooty pitchblende occurring as botryoidal masses, fracture and cavity fillings, and spherules, often with colloform banding. The unit cell dimensions and textures indicate precipitation from low-temperature ground waters. The remobilized pitchblende generally has a higher CaO content of between 3 and 5 percent.

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Within the primary ore zones of both orebodies, some secondary uranium minerals are found. The uranyl silicates uranophane and sklodowskite, and lesser amounts of hydrous oxides, are also found as veins and filamentous aggregates within fractures, between grain boundaries, and even within cleavage planes of chloritized biotites, without accompanying pitchblende. These minerals, together with hematite, indicate oxidation and alteration, principally along fractures, to 100 m below the present land surface. According to isotope studies by Dickson and Snelling (1979), this alteration took place more or less in situ, with only small-scale uranium and/or daughter isotope migration. Disequilibrium in favor of daughter products was found mainly in low-grade (< 0.1 percent U_3O_8) zones. High-grade ores are closest to equilibrium.

The weathered zone is present just above the primary No. 1 orebody in weathered schists from where it extends as a tabular tonguelike dispersion zone for up to 100 m downslope to the southeast. The zone contains only secondary uranium minerals that are zoned along the transport direction. Above the primary orebody uranyl-phosphates, with some uranyl-silicates, are present. Further downslope only uranyl-phosphates are present, and at the southeastern nose the uranium is absorbed on clays.

Dickson and Snelling (1979) studied the distribution of uranium (U_3O_8) and its daughter products (eU_3O_8) in the dispersion zone. They found a significant and progressive variation in ratio U_3O_8/eU_3O_8 from less than 1.0 above the primary orebody, to greater than 1.0 at the southeast edge. The strongest development of secondary minerals is above the primary ore zone at the base of the weathering. Here disequilibrium is strongest in favor of daughter products ($U_3O_8/eU_3O_8 = 0.265$). There is no evidence in the underlying primary No. 1 orebody that uranium has been mobilized. Thus, the secondary dispersion zone was probably derived from an updip extension of the primary ore zone.

Donnelly and Ferguson (1979) studied stable isotopes of the Koongarra, Ranger, and Jabiluka orebodies and found that bedded pyrite, and to a lesser extent chalcopyrite and sphalerite, have $\delta^{34}S$ values in a narrow range near zero per mil. They concluded these data indicate that the sulfides formed from H_2S, of a deep-seated origin, probably through volcanism. The sulfides from the deposits are a mixture of two or more of the minerals, pyrite, chalcopyrite, galena, and sphalerite, are not dominated by pyrite, and are characterized by a much wider spread of $\delta^{34}S$ values (6 to 10 percent). Sulfur isotope values for coexisting sulfide pairs from the Jabiluka deposit yielded temperatures of formation ranging from 227°C to 315°C (average 266°C $\pm$ 40°C). They concluded (Donnelly and Ferguson, 1979) that the sulfide pairs examined represent original sediment sulfide and sulfide introduced with uranium mineralization.

Investigations of $\delta\ ^{13}C$ values for bedded carbonates indicate they are of a marine sedimentary origin (Donnelly and Ferguson, 1979). The vein and vug carbonates yielded values that indicate biological activity. The $\delta\ ^{13}C$ values of all carbonates suggest recrystallization from isotopically light ground water. At Koongarra (in contrast to Jabiluka I and II) all $\delta\ ^{13}C$ values of graphite are significantly $\delta\ ^{13}C$-enriched, suggesting that the organic matter at Koongarra has undergone reactions which changed the original $\delta\ ^{13}C$ values.

Geochronology. Koongarra ore samples dated by Hills and Richards (1976) do not yield a simple age interpretation. Two galena samples gave age pairs 1800, 964 m.y. and 1700, 1000 m.y. Another age pair for lead in pitchblende gave 860, 0 m.y. They conclude that the two discrete galena samples appear to reflect an earlier period of uranium mineralization comparable in age to the Ranger deposit and the regional metamorphism. The uranium originally associated with this lead may have been remobilized during Upper Precambrian to form pitchblende such as yielded the younger dates.

Ore Control and Metallogenesis. The uranium mineralization of the two Koongarra orebodies also shows distinct structural and chemical-lithologic controls. The structural control is expressed as (a) a northeast-striking breccia zone associated with the reverse fault which displaces the Lower Proterozoic metasediments over the Middle Proterozoic Kombolgie Formation, and (b) strong shearing and fracturing of the rocks of the ore zone.

The chemical-lithologic control is suggested by the occurrence of ore in strongly chloritized schists, in proximity to graphitic horizons. The mineralization is intimately associated with chlorite cement in the breccias. Two varieties of chlorite (Fe-rich and Mg-rich) were identified by Ewers and Ferguson (1979).

Although uranium mineralization has not been genetically tied to precise chlorites, it appears that the Fe^{2+}/Fe^{3+} ratio of the chlorite decreases with increasing uranium content, suggesting that redox reactions involving Fe may have led to uranium deposition. Which factors were most important for the formation of the primary ore is not yet known.

The secondary mineralization in the near-surface dispersion zone is predominantly controlled by the depth of weathering and ground water flow. An additional ore control is the nearby Middle Proterozoic unconformity. It is likely that the unconformity once extended just above the present land surface, hence the Kombolgie Formation capped the deposit. Formation of the primary ore at Koongarra is believed to have been the same as was discussed for Ranger and Jabiluka.

The formation of the secondary mineralization within the primary ore zone and within the dispersion zone of the weathering profile has been reviewed by Snelling (1979). He believes the occurrence of uranyl-silicates below the base of weathering and uranyl-phosphates above suggests different conditions of formation. He suggests that the formation of uranyl-silicates and hydrous oxides from the pitchblende of the No. 1 and No. 2 orebodies is related to chlorite formation in low-temperature ground waters. These conditions presumably existed prior to the removal of cover rocks and the commencement of surficial weathering of the top of the No. 1 orebody. Surficial weathering subsequently produced abundant uranyl-phosphates from the partly altered pitchblendes and uranyl-silicates.

Lateral ground water movement in the weathered zone dispersed uranium downslope to form the secondary dispersion fan above the No. 1 orebody.

Shape and Dimensions of Deposits. The Koongarra deposit consists of two separate orebodies, which are 200 m apart along the northeast strike direction. The No. 1 orebody is 200 m southwest of the No. 2 orebody and consists of primary and secondary zones of mineralization as discussed in preceding paragraphs.

The primary mineralization forms an elongated northeast-trending orebody about 350 m long. The width of the deposit is irregularly up to 60 m, but the average thickness of the major portion just under the weathering zone is 30 m. In the northwest-southeast cross section, the deposit resembles an irregular wedge that terminates about 100 m below the surface and dips at 55 degrees to the southeast parallel to the enclosing rocks. The mineralization in the heart of the deposit, beneath and adjacent to the graphitic quartz-chlorite schist, is persistent both along strike and downdip. Below this horizon, mineralization occurs irregularly distributed throughout the schist sequence down to the footwall breccia associated with the reverse fault.

The secondary dispersion zone extends up to 100 m beyond the primary mineralization to the southeast. Its maximum thickness is about 30 m.

The No. 2 orebody is deeper than the No. 1 orebody and is not intersected by the zone of weathering. It consists mostly of primary mineralization but of a generally lower grade. Its length along the northeast trend is about 100 m. The width ranges from 30 m near the southwest end to 70 m in the northeast part. The deposit extends to about 150 m below surface and dips 55 degrees to the southeast.

Production and Reserves. Uranium has not yet been produced at Koongarra. Reserves have been estimated at 12.301 mt U_3O_8 with an ore grade of 0.345 percent U_3O_8 (Needham and Roarty, 1980).

Nabarlek. Anthony, 1975; Ypma and Fuzikawa, 1979.

The Nabarlek deposit is the most northeasterly of the uranium deposits of the East Alligator Rivers district. It lies about 270 km to the east of Darwin. Discovery resulted from an airborne anomaly.

Geologic Setting of Mineralization. The host rock consists of actinolite schists, chlorite schists, quartz-mica schists and chlorite-muscovite schists of the Lower Proterozoic Cahill Formation (formerly called Myra Falls metamorphics) (Fig. 65). The rocks are folded, sheared, and in part metasomatized schists of amphibolite facies which were altered by retrograde metamorphism. Within the area of mineralization, the rocks are fragmented into vertically dipping breccia zones.

A dolerite sill cuts off the orebody at 85 m below the surface. Granite was intercepted by drilling at depth of 470 m. Erosion remnants of the Middle Proterozoic Kombolgie Formation occur a few hundred meters from the deposit.

Alteration. Within the mineralized area, the Cahill metasediments are strongly altered by chloritization, sericitization, and hematitization.

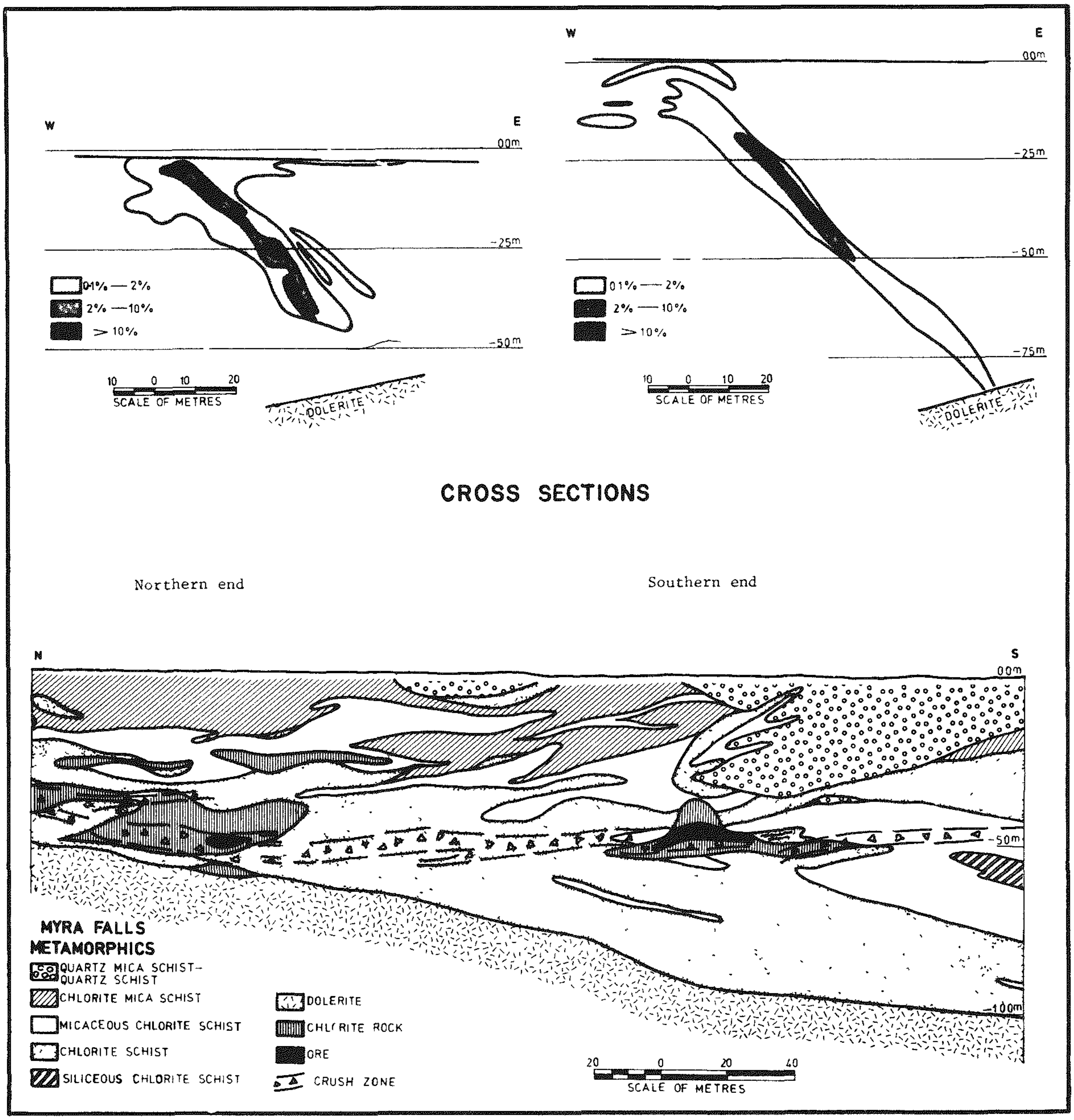

Figure 65. Generalized cross sections and plan of the Nabarlek orebody (from Needham et al, 1979b, modified from Foy and Pederson, 1975).

The immediate host rock is a massive, fine-grained, chloritic rock with about 65 percent chlorite and relatively high contents of hematite and sericite.

Mineralization. Pitchblende is the main ore mineral. It occurs in the center of the orebody in massive form (one core sample 1 m long contained 72 percent U_3O_8) and in a disseminated, lower grade halo around the high-grade core. Accessory minerals are galena, chalcopyrite, marcasite, pyrite, bornite, chalcocite, covellite, and traces of gold and vanadium. Gangue minerals are practically absent, unless one considers the chlorite a gangue mineral. Secondary minerals, including coffinite, curite, sklodowskite, kasolite and rutherfordine, occur in small amounts.

Weathering extends to a depth of 5 m in host rocks and to about 15 m within the ore zone. The water table fluctuates within this range and has redistributed uranium, producing a broader but lower grade deposit near the surface.

Geochronology. Pitchblende has been dated at 920 m.y. and a younger generation at 400 to 500 m.y. (Hills and Richards, 1976).

Ore Control and Metallogenesis. The ore is controlled first by structure and then by chemical-lithologic factors. Mineralization occurs immediately below the Middle Proterozoic unconformity and is limited to 85 m in depth by a dolerite sill. It is not known if the dolerite pre-dates or post-dates the ore. Graphite zones have reportedly been encountered in proximity to the ore during recent mining operations. The hiatus between the age of metamorphism at 1800 m.y. and the oldest pitchblende at 920 m.y. suggests ore formation is not related to metamorphism.

Shape and Dimensions of Deposit. The orebody is situated in a breccia zone striking north-northwest and dipping 30 to 45 degrees east. Its strike length at the surface is 830 m. The orebody is sheetlike with irregular boundaries. Its thickness is variable up to 20 m with an average of about 10 m. The deposit extends to 85 m below the surface, but the bulk of the ore is between surface and a depth of 45 m.

Production and Reserves. During the dry season of 1980, the deposit was completely mined out, and the ore was stockpiled so that presumably no reserves remain. Reserves had been previously estimated at about 600,000 mt ore at a grade of 1.84 percent U_3O_8 for 12,000 mt of contained uranium (Nuclear Fuel, March 31, 1980). Needham and Roarty (1980) note reserves of 9,550 mt U_3O_8, with an ore grade of 1.84 percent U_3O_8.

Rum Jungle District. Berkman, 1968; Berkman and Fraser, 1979; Dodson et al, 1974; Fraser, 1975, 1979; Heier and Rhodes, 1966; Richards, 1963; Rhodes, 1965; Roberts, 1960; Stephansson and Johnson, 1976; Walpole et al, 1968; Warner, 1976.

The Rum Jungle district lies about 60 km south of Darwin. Both road and railroad connect the two locations. The topography is gently to moderately undulating, with extensive plains broken by several minor ridges.

The district contained eight polymetallic prospects, of which four orebodies, Dysons, White's, Intermediate, and Rum Jungle Creek South, were mined from

1953 until 1971. The additional prospects are Brown's, Mount Fitch, Mount Burton, and Area 55. Rum Jungle was discovered in 1949 by a prospector, although records of mineralization go back to 1869.

Geologic Setting of Mineralization. Rum Jungle is situated on the western flank of the Pine Creek Geosyncline. The local geologic setting is dominated by two Archean domes which are unconformably mantled by Lower Proterozoic metasediments (Fig. 66).

The two domes, the Rum Jungle Complex to the north and the Waterhouse Complex to the south, comprise various granitic facies with intercalations, xenoliths, and belts of gneisses, schists, migmatites, and metadolerite. Leucocratic granitic rocks contain 10 to 28 ppm uranium; metadolerites contain 2.8 to 4.5 ppm uranium (Heier and Rhodes, 1966).

The Lower Proterozoic metasediments are subdivided into four sequences (from bottom to top):

(1) Batchelor Group (Beestons Formation, Celia Dolomite, Crater Formation, Coomalie Dolomite) is an alternating sequence of arkoses, sandstones, conglomerates, and dolomites/magnesites which were deposited in a littoral-neritic environment. The Batchelor sediments are in transition with the overlying sediments.

(2) Namoona Group/Masson Formation (formerly Goodparla Group) contains the ore-bearing Golden Dyke Formation. Sediments are composed of pyritic and carbonaceous black shales of euxinic origin, amphibolite, and dolerite. An unconformity separates these rocks from the overlying sediments.

(3) Mount Partridge Group, with Acacia Gap Sandstone (formerly Acacia Gap Tongue), is partly hematitic quartzite breccia and pyritic black shales with chert nodule beds. They are transitional with the overlying sediments.

(4) Finnis River Group with Burrell Creek Formation (formerly Burrell Creek and Noltenius Formation) is hematitic and chloritic graywackes and siltstones.

A hematite-quartzite breccia (HQB), with intercalated mudstone and sandstone, was found locally overlying the upper dolomite-magnesite of the Coomalie Dolomite, the hanging wall unit of the Batchelor Group. The lithology is such that Walpole et al (1968) compare these sediments with the Carpentarian/Middle Proterozoic/Kombolgie Formation. There are also similarities with the basal rocks of the Middle Proterozoic Athabasca Formation in Saskatchewan. The HQB also is considered to be a regolith.

According to Needham et al (1979a), the Lower Proterozoic metasediments are overlain unconformably by the Carpentarian (?) Depot Creek Sandstone Member, and the Rum Jungle deposits are situated near its present eastern limit. The unit is mostly quartz sandstone, with minor pebble conglomerate beds. It contains no interbedded volcanics.

The Lower Proterozoic sediments were metamorphosed and folded at about 1800 m.y. The grade of metamorphism is in the lower greenschist facies. The Golden Dyke host sediments are graphitic, chloritic, and sericitic schists and amphibolites. Dolerite dikes intruded the metasediments. The weathering zone extends from surface to a depth of about 30 m.

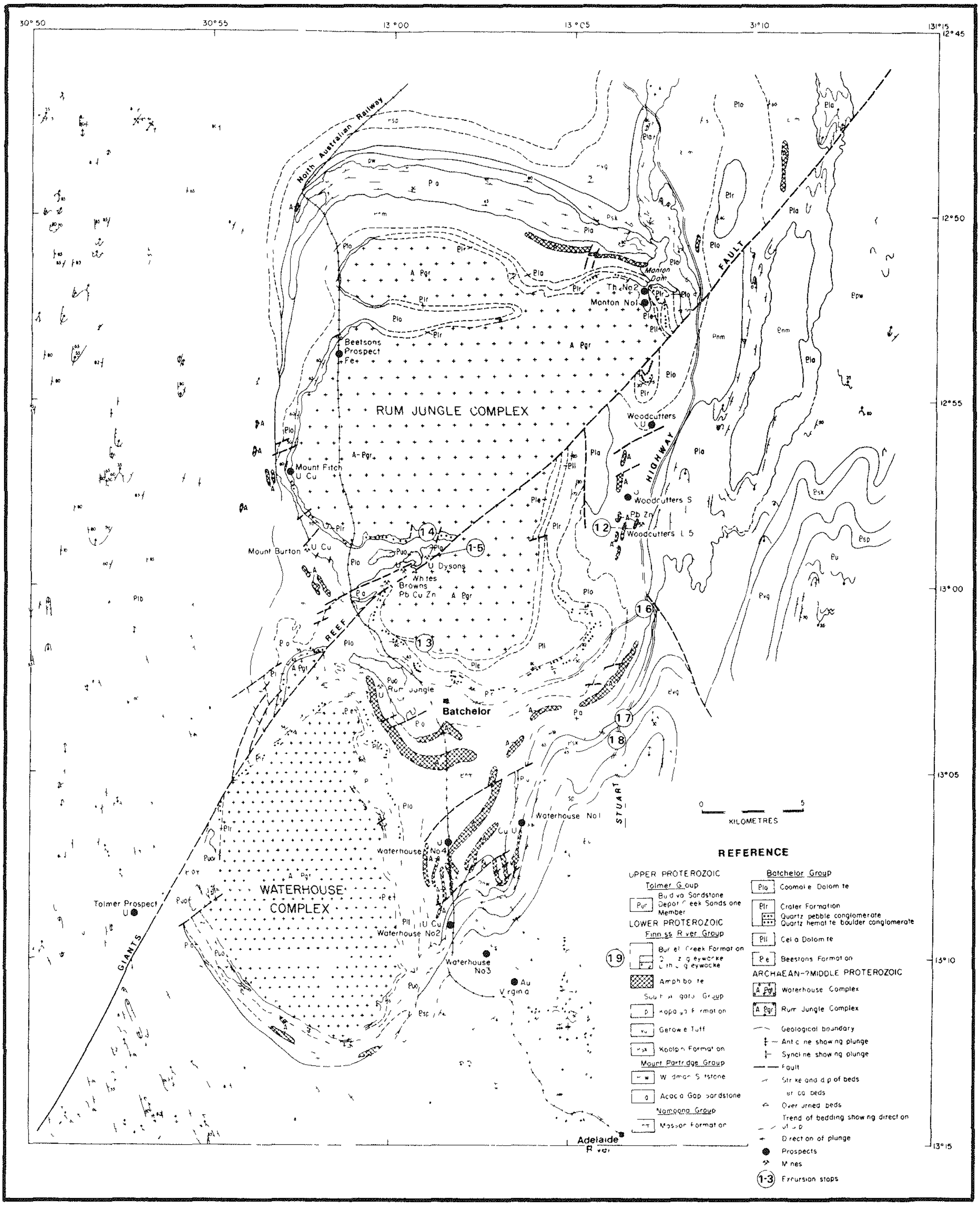

Figure 66. Geologic map of the Rum Jungle area (from Needham et al, 1979b, modified from Stephansson and Johnson, 1976).

According to Berkman and Fraser (1979), disseminated, fine-grained uraninite and chalcopyrite, in concentrations of a few hundred ppm, were found through the two upper shaly magnesites of the Coomalie Dolomite, and in all the Masson Formation rocks except the uppermost schist in the Mount Fitch area.

The regional strike of the sediments is north to south. In the vicinity of the Archean domes it changes, however, and wraps around the domes with dips between 40 and 65 degrees. Between the Rum Jungle and Waterhouse Complexes, therefore, the metasediments form a syncline with subsidiary folds and flexures.

The crystalline basement is cut by the regional northeast-southwest trending Giants Reef Fault. It displaces the rocks horizontally and vertically, as well. The northwest block is displaced about 2 to 3 km to the northeast. At Rum Jungle, this offset pushed a wedge-shaped mass of metasediments, called the embayment, into the southwest margin of the Rum Jungle Complex. Numerous minor or local faults, shear and breccia zones are present in the mineralized area.

Alteration. The host rocks show chloritization, sericitization, and hematitization.

Mineralization. The principal host rocks for mineralization are chloritic, sericitic schists and, in part, graphitic schists of the Golden Dyke Formation. In Mount Fitch, dolomite hosts the mineralization. Most of the ore occurs in fissures and shear zones, and less commonly as disseminations, immediately above the Coomalie Dolomite/Batchelor Group. Eight mineralized areas, of which the first four listed below occur in the "embayment", were discovered, including six with uranium (see Table 21):

Dysons (U)
White's (U, Cu, Pb, Co, Ni)
Intermediate (Cu, U)
Brown's (Pb, Zn, Cu, Co, Ni)
Mount Fitch (U, Cu)
Mount Burton (U, Cu)
Rum Jungle Creek South (U)
Area 55 (Pb, Zn)

The principal uranium ore mineral is colloidal and sooty pitchblende. In the weathering zone, secondary minerals such as torbernite, phosphuranylite, autunite, saleeite, sklodowskite, gummite, and johannite are present. Base metal minerals include chalcopyrite, chalcocite, covellite, digenite, bornite, azurite, malachite, native copper, pyromorphite, gersdorffite, linneite, carollite, galena, sphalerite, cerussite, and pyrite.

According to Roberts (1960), two mineral parageneses exist: (a) pitchblende and pyrite followed by deformation and the formation of (b) copper, cobalt, and lead sulfides. Mineralization is concentrated along the metapelite-dolomite contact. The richest ores, such as in Dysons orebody, were associated with strongly hematitic dolomite.

The polymetallic orebodies exhibit a zoned, concordant metal distribution. For example, the White's orebody (Spratt, 1965) was composed of three zones

Table 21. Mineralogy and geological/structural setting of major orebodies of the Rum Jungle district (modified from Fraser, 1979).

	MINERALOGY OXIDIZED	MINERALOGY PRIMARY	GEOLOGICAL & STRUCTURAL SETTING
White's	Narrow gossanous zone of torbernite, autunite, phosphuranylite gummite, saleeite, and johannite	From 8 m depth, 4 conformable zoned layers from base: (1) Pitchblende, chalcocite. (2) Chalcopyrite, chalcocite digenite, bornite, covellite. (3) Linnaeite, carollite, gersdorffite. (4) Galena, linnaeite.	Host rocks are sheared graphitic, sericitic, chloritic and pyritic shales of Coomalie Dolomite contact. Coomalie Dolomite forms core of recumbent anticlinal structure. HQB in complementary syncline; possible regolith.
Dysons	Saleeite, autunite, sklodowskite to 40 m + depth	From 25 meters pitchblende high grade in hematitized dolomite	Host rocks are sheared graphitic shales of Coomalie Dolomite contact. Coomalie Dolomite forms core of anticlinal structure capped by HQB. Possible regolith.
Intermediate	Malachite, native copper to 10 m, chalcocite to 20 m	From 20 m depth chalcopyrite minor pitchblende	Host rocks are sheared and brecciated graphitic and talcose shale. Close to Coomalie Dolomite contact, inflection in contact.
Rum Jungle Creek South	Three small pods saleeite in strongly weathered shales	From 30 m depth pitchblende fine sooty coating on cleavage and joints, some massive veins	Host rocks are pyritic, chloritic shale overlying graphitic shale in synclinal structure close to Coomalie Dolomite contact. HQB downfaulted on eastern limb of syncline. Amphibolite overlies Coomalie Dolomite on western limb of syncline.
Brown's	Minor galena, cerussite, malachite, azurite, pyromorphite	From 30 m depth finely divided galena, chalcopyrite, sphalerite, linnaeite-carollite, gersdorffite	Host rocks are sheared graphitic and sericitic shales close to Coomalie Dolomite contact, inflection in contact. Orebody divided by irregular lense of near-barren blocky chloritic shales and amphibolite. Amphibolite on hanging wall.

arranged from the shale-dolomite contact upwards (Fig. 67): (a) uranium-copper (18 m thick); (b) copper-cobalt, cobalt-nickel (together up to 15 m thick); and (c) cobalt-lead (5 m thick).

A reconstruction of the tectonic setting prior to the displacement by the Giants Reef Fault reveals that six of the orebodies (the Mount Fitch and Mount Burton deposits are further to the northwest) were originally situated along the axis of a syncline between the two granitic complexes, aligned in an arc parallel to the periphery of the Waterhouse dome (Fig. 68). The metals are zoned with uranium towards the east and base metals towards the west.

The major ore accumulations, namely Dysons, White's, and Intermediate, and also Brown's, were found in the central part, i.e., in the "embayment". These orebodies are aligned over a distance of 1.5 km at spacings of about 400 m. They appear as pearls on a string, essentially strata-bound and interconnected by zones of low-grade uranium. With this structural reconstruction, Rum Jungle Creek South also lines up to the east with the other orebodies.

Geochronology. Reported whole-rock age dates for leucocratic granites of the Rum Jungle Complex gave 2400 m.y. Analyses of zircons from three different locations in the Rum Jungle Complex yielded ages of 2550 m.y. (Richards et al, 1966). Page (1976) reports a 2400 m.y. Rb-Sr isochron for the Waterhouse Complex.

A post-Archean magmatic event is indicated by quartz-tourmaline veins which, near the center of the Rum Jungle Complex, extend into the overlying Lower Proterozoic metasediments which were metamorphosed at about 1800 m.y.

Richards (1963) obtained lead ages of 1520 m.y. on samples from the White's and Brown's orebodies. Other ages suggest events between 1340 and 990 m.y. One pitchblende yielded an age of 1015 m.y. Richards (1963) considers that age, on the basis of the mineralogical investigations of Roberts (1960), to be anomalously young due to considerable alteration.

Ore Control and Metallogenesis. Several features appear to have been important ore controls.

(1) All orebodies are found in fractures, breccias, or shear zones, close to and on the northwest side of the Giants Reef Fault.

(2) Six of the deposits, including all major orebodies, occur along the axis of the syncline of Lower Proterozoic metasediments between two Archean granitic domes.

(3) A paleogeography/paleotectonic control is suggested by the occurrence of the six orebodies along a trend around, and equidistant from, the Archean Waterhouse Granitic Complex (based on a pre-Giants Reef Fault reconstruction). The Mount Fitch and Mount Burton occurrences are in a similar position but adjacent to the Rum Jungle Granitic Complex.

(4) All mineralization is concentrated along the contact between Lower Proterozoic metapelites and dolomite/magnesite. The preferred host rock is chlorite-sericite schists adjacent to graphitic schists. Graphite, schist, and dolomite are locally host rocks.

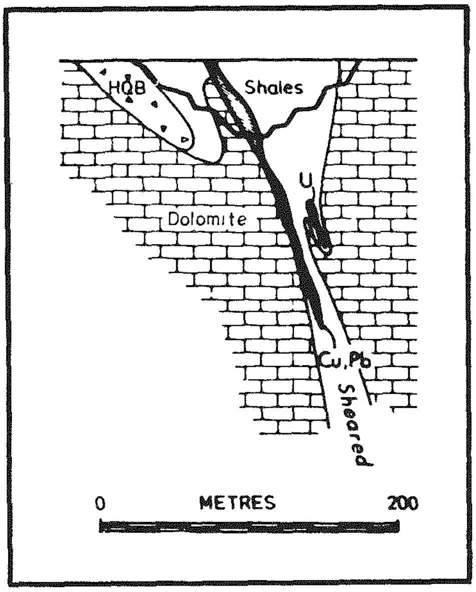

Figure 67. Diagrammatic cross section of the White's deposit, Rum Jungle (from Fraser, 1980).

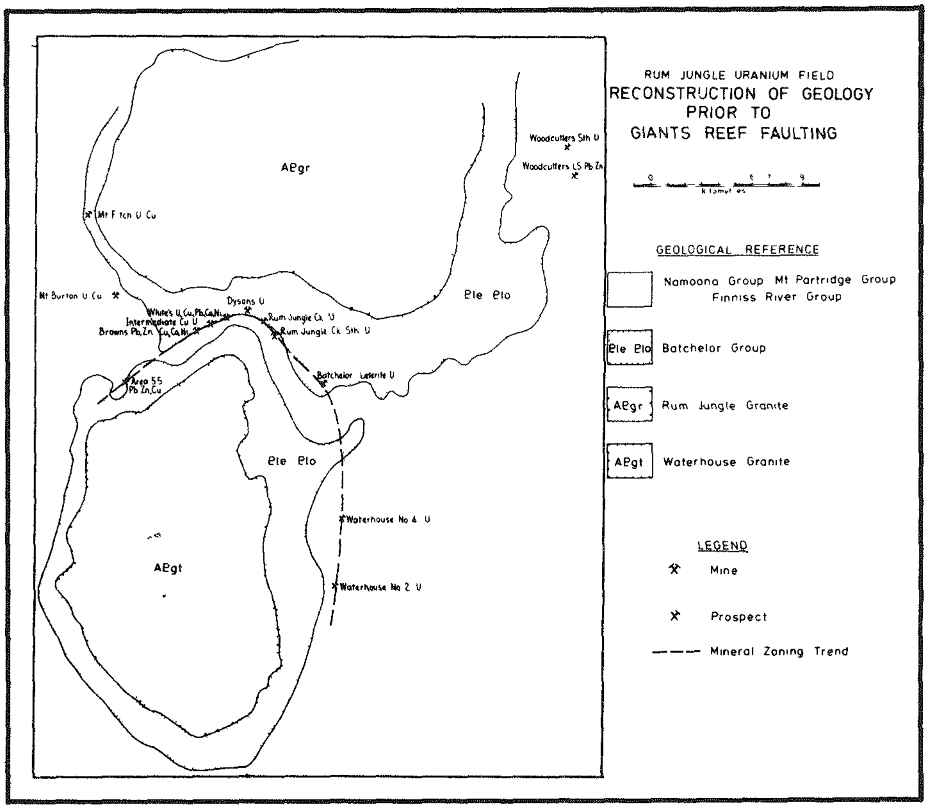

Figure 68. Reconstruction of the geology of the Rum Jungle area prior to pre-Giants Reef faulting (from Fraser, 1980).

(5) High uranium background concentrations occur as primary constituents in leucocratic granites of the Archean domes (10 to 28 ppm; Heier and Rhodes, 1966) and in the metasediments (few hundred ppm in the form of uraninite, Berkman and Fraser, 1979).

(6) Finally, the ore-bearing Lower Proterozoic metasediments are overlain unconformably by quartz sandstones, which contain minor pebble conglomerate beds, of the Carpentarian (?) (Middle-Upper Proterozoic ?) Depot Creek Sandstone Member. All orebodies at Rum Jungle are situated near the present eastern limit of the Depot Creek Sandstone and are at, or are immediately below, the projected plane of the unconformity. The Depot Creek Sandstone does not have interbedded volcanics as are found in the time equivalent (?) Kombolgie Formation in the eastern part of the Pine Creek Geosyncline.

With respect to genesis, Fraser (1975) suggests the following metallogenic evolution:

(1) Synsedimentary introduction of metals into Lower Proterozoic sediments. W. N. Thomas (personal communication, 1980) suggests that the uranium and the base metals were transported into two lagoonal basins separated from each other by a minor ridge.

(2) Weak remobilization of ore during updoming (uplift) of the Archean Complexes.

(3) Weathering with formation of a regolith, the hematite-quartz breccia (HQB), and further supergene concentration of ore, particularly uranium.

(4) Activation of Giants Reef Fault resulting in flexurelike dragging of HQB. This resulted in the remobilization of ore with transportation and emplacement in the structural positions in which it is now found.

Shape and Dimension of Deposits. Uranium occurred in lenses of irregular shape in the four deposits that have been mined.

The general strike of the deposits was northeast, and the dip was vertical to steep to the southeast. Lenses with high-grade ore were surrounded by a halo of low-grade mineralization up to several hundred ppm.

The lengths of the individual uranium orebodies were between 60 m (Dysons) and 245 m (Rum Jungle Creek South) (Figs. 69 and 70). Copper and lead mineralization extended beyond these limits. Widths varied between a few meters and 60 m. Economic uranium grades rarely extended to more than 100 m in depth whereas base metal mineralization was found down to several hundreds of meters (see Table 22).

Production and Reserves. The Rum Jungle district produced a total of 1.4 million mt ore containing about 4,300 mt U_3O_8 plus copper and lead (Needham and Roarty, 1979). The average grades of the various orebodies were on the order of 0.6 to 0.4 percent U_3O_8, 1 to 3 percent Cu and up to 6 percent Pb. Co, Ni and Zn were not recovered.

South Alligator River District. Ayres and Eadington, 1975; Crick et al, 1979; Foy and Miezitis, 1977; Hills and Richards, 1976; Needham et al, 1979a; Prichard, 1965; Taylor, 1969; Walpole et al, 1968.

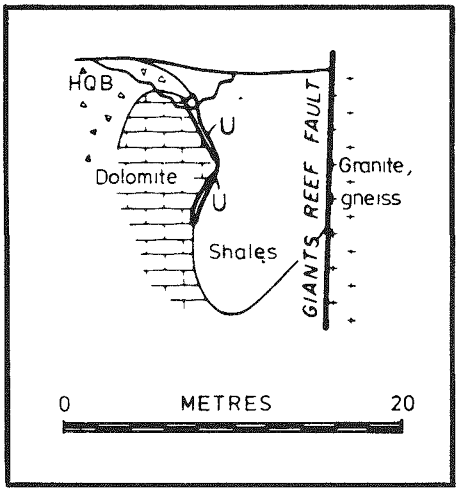

Figure 69. Diagrammatic cross section of the Dyson's deposit, Rum Jungle (from Fraser, 1980).

The uranium district is about 220 km southeast of Darwin. It parallels the South Alligator River Valley over a northwest-southeast distance of almost 60 km and a width of 10 to 20 km. The topography is controlled by deeply eroded strata and resistant ridges up to 200 m high. About 30 uranium prospects were found following the initial discovery by ground radiometrics in 1953. Thirteen mines were in operation until 1964 when mining ceased. Twelve of the mines were in the narrowest part of the valley, spread along a distance of 20 km. The thirteenth deposit, Sleisbeck, is 32 km to the southeast. The district was of minor economic importance (< 1,000 t U).

Regional Geology. The area is underlain by a northwest-trending belt, 10 km wide and 60 km long, of tightly folded metasediments of Lower Proterozoic age (Fig. 71). The basement rocks were covered by Middle Proterozoic-Carpentarian felsic volcanics and sandstone. These Carpentarian rocks fill basins on either side of the metasedimentary belt. Crick et al (1979) and Walpole et al (1968) have described the geology, and the following description is largely from these publications.

The Masson Formation is the oldest unit in this part of the Pine Creek Geosyncline, and it is composed of mainly carbonaceous shale, siltstone, carbonate, calcarenite, and sandstone. The pelitic rocks, particularly the carbonaceous ones, are iron-stained to brick red shale at the surface. The maximum thickness of the Masson Formation is about 2,800 m. The Stag Creek Volcanics (1,000 m thick) conformably overlie the Masson Formation and are a sequence of poorly exposed altered basaltic breccias, flows and tuff, and dark green tuffaceous shale. The Mundogie Sandstone, composed of feldspathic quartzite and conglomerate, is generally 300 m thick on the western limb of the syncline, but thickens to about 1,000 m on the eastern limb. It is overlain by the Wildman Siltstone, a 1,500 m sequence of color-banded siltstone, shale, quartz sandstone, and quartz graywacke. Drilling has intersected carbonaceous sediments locally underlying red shale rubble.

This lower sequence is overlain unconformably by the Koolpin Formation composed of 1,050 m of interbedded dolomite, siltstone, and carbonaceous shale. The base of the Koolpin Formation is commonly occupied by a massive, chert-banded ferruginous siltstone (carbonaceous shale with carbonate bands at depth). South of Saddle Ridge and in the northern part of the region, massive dolomite with algal structures occupies this stratigraphic position. Tuff and argillite of the Gerowie Tuff become increasingly interbedded with the upper part of the Koolpin Formation. Stratigraphically upwards, the Koolpin beds become thinner, and the Gerowie Tuff reaches a maximum thickness of about 700 m. A 100 to 300 m thick flow of andesite-diorite (Showvel Billabong Andesite) is present near the base of Gerowie Tuff and is probably genetically related to it. The youngest Lower Proterozoic unit in the area is the Fisher Creek Siltstone which contains siltstone, feldspathic sandstone, phillite, graywacke, and arkose. It is faulted against older rocks north of El Sherana, and relations to other units in the south are obscure. The thickness has been estimated at 5,200 m.

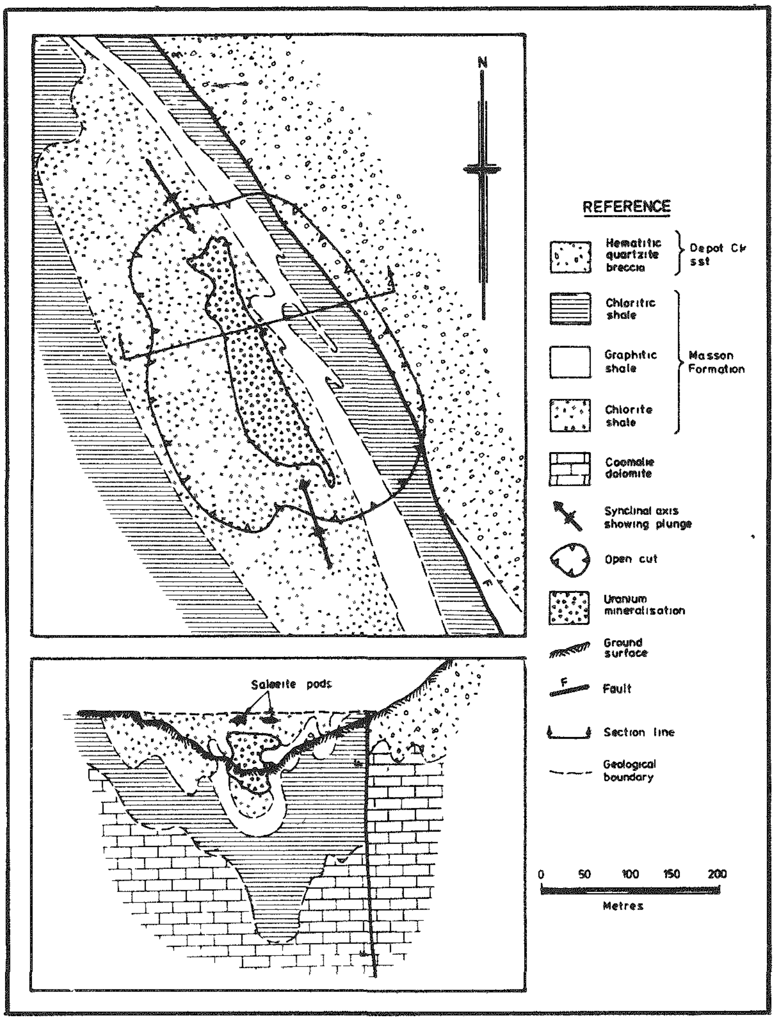

Figure 70. Geologic sketch map and cross section for the Rum Jungle South deposit, Rum Jungle (from Fraser, 1980, modified from Berkman, 1968).

Table 22. Some characteristics of the uranium deposits in the Rum Jungle district, Australia (from Fraser, 1979, and Needham et al, 1979b).

Orebody	Length	Width	Depth	Reserves	Grade	Remarks
White's	150 m	28 m	300 m	396,000 t	0.27% U_3O_8 2.7% Cu	U, Cu terminates at 180 m depth
				295,000 t	2.8% Cu 0.3% Co	deepest mining level 112 m 0.92 oz Ag
				87,000 t	5.1% Pb 0.8% Cu 0.3% Co	
Dyson's	60 m	8 m	100 m	157,000 t	0.34% U_3O_8	mined to 65 m
Intermediate	150 m	40 m	350 m	359,000 t 367,000 t	2.7% Cu 1.7% Cu	mined to 70 m minor pitchblende below 20 m
Rum Jungle Creek South	245 m	60 m	80 m	663,500 t 115,800 t	0.43% U_3O_8 0.06% U_3O_8	mined to 70 m
Brown's	700 m	50 m	450 m	20,500,000 t	5.4% Pb 0.3% Zn 12 g/t Ag	not mined
Mount Fitch (two bodies)	110 m 160 m	30 m 110 m	20 m 100 m	3,500,000 t 290,000 t	0.04% U_3O_8 0.6% Cu	not mined
Mount Burton	?	?	?	6,000 t	0.17% U_3O_8 1.3% Cu	not mined

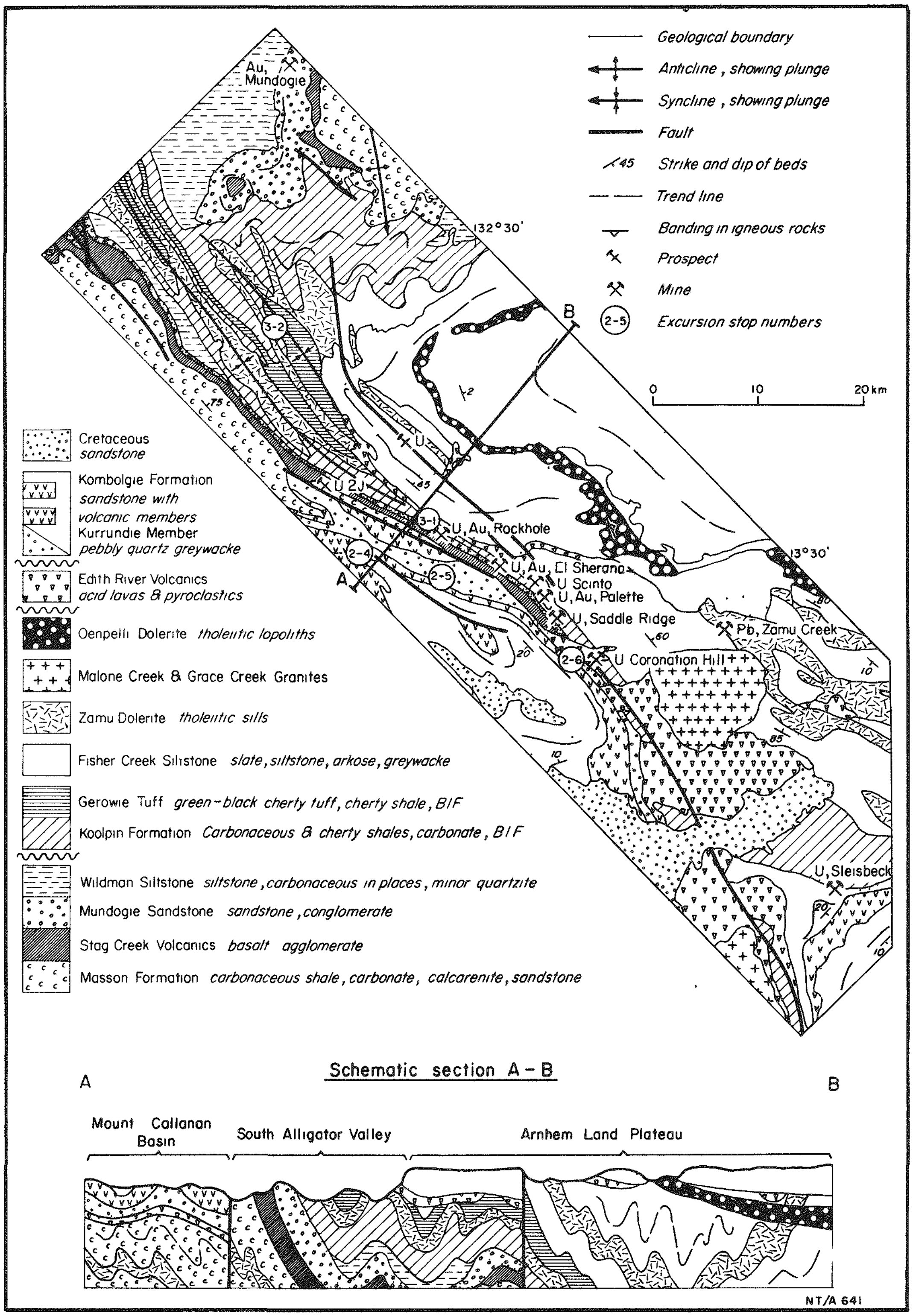

Figure 71. Generalized geology and idealized cross section of the South Alligator River Valley area (from Needham et al, 1979b).

The Zamu Dolerite is present as extensive sills in the Koolpin Formation and to a lesser extent in the other Lower Proterozoic units with which it was folded.

During the orogenic event at 1800 m.y., the Lower Proterozoic rocks were metamorphosed to low-grade rank and isoclinally folded. Sedimentary textures are generally preserved, and pelitic rocks have a well-developed slaty cleavage and contain sericite, chlorite, and rare epidote. Late orogenic granitoids were emplaced in the southern part of the area. The Malone Creek Granite (age about 1750 m.y.; Compston and Arriens, 1968; Walpole et al, 1968) and the Grace Creek Granite are interpreted to be the intrusive equivalents of the Edith River Volcanics which include felsic volcanics and associated pyroclastics, in places up to 1,200 m thick.

Sedimentary relations between the Edith River Volcanics and the overlying Kombolgie Formation range from conformable to strongly unconformable. Angular unconformities in areas of strong faulting suggest instability during deposition. Intermixing of the two lithologies had been thought to indicate contemporaneity, but an age of 1688 m.y. for the Oenpelli Dolerite (Page et al, 1979), which locally underlies the Kombolgie Formation, indicates a significant time lapse between the eruption of the Edith River Volcanics (1760 m.y.; Walpole et al, 1968) and deposition of the Carpentarian Kombolgie Formation.

The Kombolgie Formation is comprised of more than 1,500 m of sandstone, graywacke, and volcanics in the Mount Callanan Basin southwest of the South Alligator River. On the basement platform to the northeast, there is less than 600 m of sandstone. A coarse, pebbly quartz graywacke (the Kurrundie Member) is at the base of the Mount Callanan Basin Sequence and is probably equivalent in age to the medium to coarse quartz sandstone and interbedded conglomerates northeast of the river. The Plum Tree Creek Volcanic Member occurs above the Kurrundie Member and is comprised of about 360 m of ignimbritic material overlain by about 1,000 m of fine to medium quartz sandstone with conglomerate beds. A 50 m thick andesite of the Mount Callanan Member occurs in the center of the basin.

Geologic Setting of Mineralization and Alteration. The host rocks of ten of the deposits consist of silicified, ferruginous siltstones and carbonaceous and pyritic, and locally chloritic, shales of the Lower Proterozoic Koolpin Formation. Two deposits (Coronation Hill and Saddle Ridge) occur in carbonaceous shales and sandstones associated with the Middle Proterozoic Edith River Volcanics. Coronation Hill is supposedly associated with a diatreme. One deposit with secondary uranium mineralization (Scinto 6) is described as occurring in syenite of the Zamu Dolerite. Crick et al (1979) consider that the ore of the Sleisbeck Mine is probably in the predominantly chloritic siltstone of the Masson Formation.

Secondary uranium mineralization was found, in several of the mines, in sandstones and volcanics of the Edith River Volcanics and in sandstones of the Kombolgie Formation above uraniferous carbonaceous shale. All deposits occur immediately adjacent to the Lower/Middle Proterozoic unconformity and extend not more than 90 m below the paleosurface.

The principal ore mineral is pitchblende occurring dominantly as massive lenses and veins within structures adjacent to carbonaceous schists. In some deposits, gold was present in economic amounts. Galena, chalcopyrite, pyrite, marcasite, niccolite, gersdorffite, clausthalite, coloradoite, and rutherfordine occur as accessory minerals. Numerous secondary minerals are present within the weathering zone including uranyl-phosphates such as metatorbernite, autunite, phosphuranylite, uranophane, soddyite, and gummite. Quartz and siderite comprise the rare gangue mineral suites.

Geochronology. Threadgold (1960) described two microscopically identifiable uranium phases. Cooper (1973) subsequently reported two pitchblende ages at 815 to 710 m.y., and 530 m.y. Hills and Richards (1976) suggest that the upper age limit for the pitchblende is 800 to 900 m.y.

Ore Control and Metallogenesis. The mineralization is epigenetic and to an extent chemically and lithologically controlled. All primary ore occurs (a) along a major northwest-trending lineament, (b) as lenses and veinlike masses in fractures and structures. Furthermore, ore occurrences are (c) immediately below the Lower/Middle Proterozoic unconformity, (d) extend less than 90 m below this horizon, and (e) are adjacent to or within carbonaceous and pyritic shales and ferruginous cherts of the Lower Proterozoic Koolpin Formation. Finally, the deposits are (f) within a uraniferous province where Lower Proterozoic carbonaceous shales generally contain about 30 ppm uranium with occasional values up to 300 ppm (it should be mentioned that these samples were taken from mine areas, thus, high uranium values may be due to epigenetic mineralization). The Middle Proterozoic Edith River Volcanics contain 8 to 35 ppm uranium and the Malone Creek Granite 35 ppm (Ayres and Eadington, 1975).

Several metallogenic concepts have been proposed for the South Alligator River deposits. Condon and Walpole (1955) propose a syngenetic origin, whereas Taylor (1969) favored a hydrothermal origin. Foy (1975) regards the Edith River Volcanics as source for the uranium. Ayres and Eadington (1975) consider that ground waters percolated through the uranium-bearing Edith River Volcanics, dissolved uranium, and transported it to the underlying comparatively impermeable Lower Proterozoic metasediments. Precipitation occurred in structural traps with reducing agents. Crick et al (1978) consider the anomalously radioactive Gerowie Tuff as a uranium source for the northern half of the district. A vague link with Middle Proterozoic diatremes is suggested by Crick et al (1979), since mineralization was found at the Coronation Mine in such a structure. They point out, however, that the younger age of the mineralization, and its absence in other diatremes, do not strongly support this hypothesis.

These concepts, which derive the uranium of the deposits from the Middle Proterozoic volcanics, do not seem unreasonable, particularly when one considers the relatively small size of individual orebodies (maximum of 250 t U). It remains to be shown why the ages of mineralization are about 900 to 800 m.y. It may have been related to epeirogenic crustal movements, the stage of erosion, or possibly the end of diagenetic processes. In some respects, the South Alligator River mineralizations appear similar to occurrences in the Middle Proterozoic volcanics near Baker Lake, N.W.T., Canada.

On the other hand, the geologic-tectonic setting of the deposits is similar to those of the East Alligator Rivers deposits further to the north in the Pine Creek Geosyncline. Perhaps a combined uranium source of both Lower Proterozoic metasediments and Middle Proterozoic (Edith River) volcanics provided the uranium for the deposits. The emplacement of granites, equivalent to the Edith River Volcanics, may also have affected ore formation.

Shape and Dimension of Deposits. In general, the deposits occur as discontinuous lenses and veins, with lateral and vertical dimensions in the range of one to several tens of meters, and thicknesses in the range of millimeters to centimeters, rarely meters (see Table 23). Figures 72 and 73 show the geologic settings of the El Sherana and Palette deposits.

Production and Reserves. Altogether the South Alligator River district produced about 795 mt U_3O_8. The deposits of El Sherana, El Sherana West, Coronation Hill, and Palette yielded in addition 11,570 oz Au (Needham and Roarty, 1980). The individual deposits are summarized in Table 23.

Table 23. Production grade and tonnage and vertical extent of the principal deposits in the South Alligator River Valley (modified from Ayres and Eadington, 1975; and Crick et al, 1980).

Mine	Ore (mt)	Grade (% U_3O_8)	U_3O_8 Content (mt)	Vertical Extent (m)
Coronation Hill	25,700	0.3	77	55
Saddle Ridge	29,800	0.2	60	24.4
El Sherana	38,400	0.8	192	36.6
El Sherana West	21,300	0.8	170	?
Rockhole-Teages	13,200	1.1	145	61
Palette	4,700	2.5	117	30.5
Scinto 5	5,700	0.4	23	?
Scinto 6	1,700	0.15	3	36.6
Koolpin Creek	2,300	0.12	3	15.2
Skull	530	0.5	3	?
Sleisbeck	600	0.4	2	?
	143,930	0.55	795	

Other Uranium Prospects in the Pine Creek Geosyncline. In addition to the economic and potentially economic deposits, numerous other uranium occurrences are known in the region. Whereas many of them appeared insignificant, others received detailed investigations. The following occurrences are recorded in the literature:

Adelaide River: pitchblende in shears and joints in sandstones and siltstones of the Lower Proterozoic Burrell Creek Formation.

George Creek: pitchblende in shears and joints of sandstones and siltstones of the Lower Proterozoic Burrell Creek Formation.

Brocks Creek: (Fleur de Lys Mine) pitchblende and Cu-sulfide impregnations in graphite schists.

ABC-Prospect: secondary uranium minerals in joints, shears and as impregnations in intercalated tuffs and basalts of the Middle Proterozoic McAddens Creek Volcanics.

Caramel: pitchblende disseminated in chloritic schists of Lower Proterozoic Koolpin Formation, above and below a dolerite dike.

Beatrice: secondary uranium minerals in chloritic schists of Lower Proterozoic Koolpin Formation.

Ormac: uranium in Lower Proterozoic sediments of Cahill Formation (0.13 percent U over 3 m thickness).

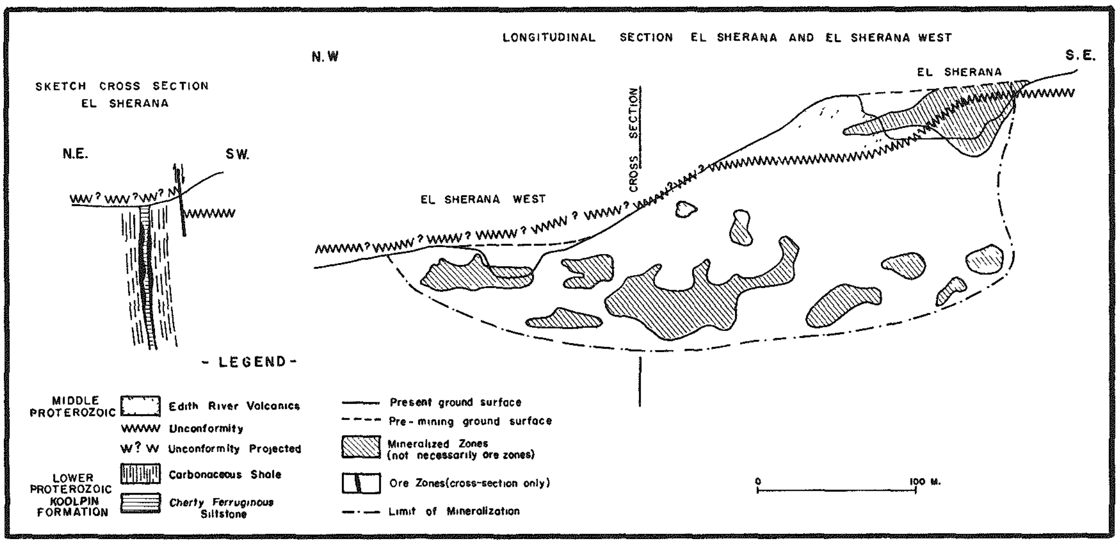

Figure 72. Longitudinal projection of El Sherana and El Sherana West, and cross section of El Sherana West (from Crick et al, 1980).

Background Values of Uranium and Other Metals in Potential Source Rocks

No comprehensive region-wide studies on the lithologic-chemical distribution of uranium and other metals in the Pine Creek Geosyncline rocks have yet been published. Several authors, however, have addressed the subject on a more local scale. A brief synopsis of these data is given below.

Ferguson et al (1979a) reviewed uranium concentrations in granitic Archean and Lower/Middle Proterozoic rocks and concluded that, with the exception of the Nimbuwah Complex, uranium is enriched in all granitoids in the Pine Creek Geosyncline by 2 to 6 times the average abundance (4.8 ppm) for such rocks (Taylor, 1964). The late orogenic granitoids have, on the average, a higher uranium content than the granitoids in the complexes, and S-type granitoids have a slightly higher uranium content than the I-types. The Nimbuwah Complex is anomalous for its low average uranium content of less than 4 ppm.

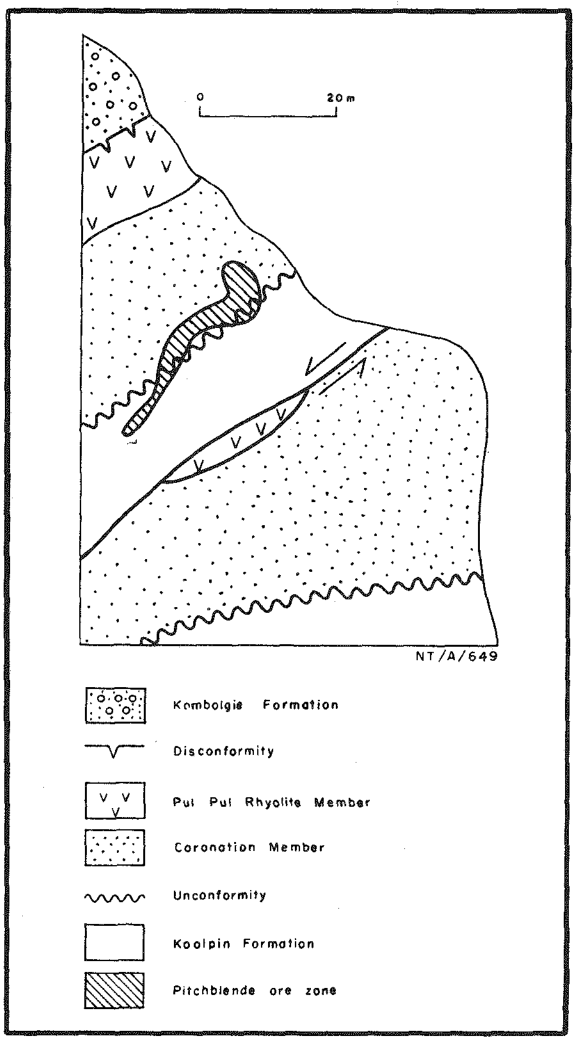

Figure 73. Generalized cross section of the Palette deposit (from Crick et al, 1980).

The uranium distribution in the granitoid complexes and late orogenic granitoids of the Pine Creek Geosyncline is shown in Figure 74.

Binns et al (1979a, 1979b) investigated the uranium content of the metamorphosed and retrograded host rock sequence at Jabiluka for evidence of uranium enrichment and depletion. Their results (tabulated below) do not indicate uranium depletion in the chloritized rocks in the vicinity of ore that could account for the uranium in the latter.

	Uranium content in ppm (log-normal means)		
Rock Type	Graphite Schist	Psammitic Schist	Pelitic Schist
1. Unaltered amphibolite facies schists distant from Jabiluka	-	7	9
2. Retrogressed schists remote from mineralization	13	8	8
3. Retrogressed schists close to mineralization	39	10	7
4. Immediate hosts to veins (with veins removed)	250	250	220

No discrete uranium-rich phases were noted in any of these rocks, and the increase in uranium towards ore is interpreted to represent mineralization extending out from the deposit.

In contrast to a uranium source within the sediments, Binns et al (1979b) suggest that an extraneous source is strongly indicated, and they suggest a concealed intrusive. They point out that the Jabiluka ores are enriched in elements such as Be, Sc, Y, Nb, Sn, Mo, Bi, and possibly B (Binns et al, 1979a; Ferguson and Winer, 1979), as well as in Hg (Ryall and Binns, 1979) and total REE (McLennan and Taylor, 1979). Lithium is enriched in both ores and the retrogressed aureole, and thorium is low. These geochemical relations suggest to them that pneumatolytic-hydrothermal systems associated with acid magmas were involved.

Uraninite-bearing two-mica granitic gneisses, such as those described at Koongarra by McAndrew and Finlay (1979), represent a potential source rock for mineralizing solutions. Binns et al (1979b) submit that a model deriving uranium from hydrothermal solutions released from deeper granitic intrusives would account for many characteristics of Jabiluka mineralization, such as retrogression and fracturing. This model does not explain, however, the abundant magnesium that has been added to the retrograde chlorite zones, nor the dolomites replaced by magnesite.

Hochman (1979) investigated the composition of various rock types in the Mount Bundey area of the Alligator Rivers area (see Table 24). The apparent enrichment of uranium in the Mount Goyder and Mount Bundey plutons is noteworthy. The "sediments" also appear to contain anomalous uranium concentrations.

The paucity of analyses for representative samples of the various rocks in the Pine Creek Geosyncline does not permit conclusions regarding the abundance and distribution of uranium. The granitoids are apparently enriched, but samples of the metasediments do not convincingly represent the various lithologies in their various states of metamorphism, retrogression, alteration, and uranium mineralization.

Previous Metallogenic Models

Some previous concepts regarding ore formation and controls have been presented with the discussions of individual deposits. In this section, we review some of the more general and comprehensive views on the origin of the deposits.

Mosher et al (1979), in summarizing the geologic characteristics of the deposits, emphasize their occurrences within the same stratigraphic succession and the following characteristics:

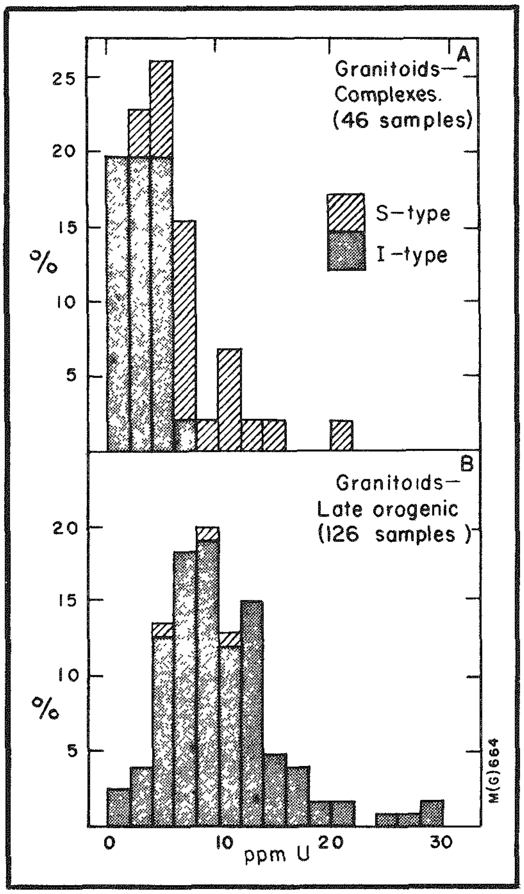

Figure 74. Uranium distribution in the granitoid complexes of later orogenic granitoids of the Pine Creek Geosyncline (from Ferguson et al, 1979a).

Table 24. Analyses of various rock types in the Mount Bundey area, Australia (from Hochman, 1979).

	GRANITOIDS				APLITE	VOLCANICS		DOLERITES			SEDIMENTS		
	[1] Av.Mt. Goyder syen.	[2] Av.Mt. Bundey gran.	[3] Av. gran.	[4] Av. syn.	549/018	549/T1	549/LR	549/78	549/54	549/75	549/74	549/010	549/40
SiO_2	61.18	71.16	71.2	60.19	76.13	75.27	84.57	60.01	44.59	60.56	0.49	62.95	15.78
Al_2O_3	14.33	13.57	14.7	16.28	12.67	13.40	7.93	12.41	13.72	17.56	0.14	18.39	0.96
Fe_2O_3	5.20	2.71	3.60	6.02	0.91	1.33	0.56	9.59	13.59	7.26	0.52	2.49	72.20
MnO	0.09	0.04	0.05	0.14	0.02	0.02	0.02	0.15	0.28	0.21	0.05	0.02	0.16
MgO	2.98	0.74	0.55	2.49	0.16	0.31	0.11	3.73	6.92	3.36	20.80	1.23	0.05
CaO	3.27	1.52	2.00	4.30	0.46	0.56	0.80	4.35	8.55	1.43	30.57	0.03	0.03
Na_2O	3.94	3.72	3.54	3.98	4.00	5.63	3.19	1.10	2.74	1.16	0.11	0.10	0.08
K_2O	6.40	5.05	4.18	4.49	5.12	3.10	0.50	4.47	1.27	4.16	0.04	4.93	0.05
TiO_2	0.67	0.31	0.40	0.67	0.08	0.16	0.09	0.46	3.19	0.63	0.01	0.63	0.05
P_2O_5	0.53	0.14	0.16	0.28	0.01	0.03	0.02	0.47	0.55	0.06	0.08	0.05	0.86
LoI	0.48	0.48	-	1.16	0.30	0.39	2.36	2.31	3.82	2.75	45.88	8.92	9.53
Total	99.07	99.44	100.38	100.00	99.86	100.19	100.14	99.35	99.22	99.14	98.69	99.74	99.73
Ba	2780	902	600	-	215	660	76	340	730	225	< 1	185	22
Sr	1615	430	285	-	190	170	58	86	225	120	240	59	10
Rb	215	279	145	-	305	120	34	180	30	185	1	240	10
Y	19[5]	16[6]	40	-	13	17	26	-	33	-	-	-	13
Zr	585	212	180	-	89	125	104	55	135	72	ND	155	3
Nb	52	26[7]	-	-	30	11	7	11	21	18	2	15	4
Ce	280	135	57	-	35	99	59	66	56	77	16	84	24
Nd	99	41	-	-	15	44	21	46	29	31	4	37	11
Sc	12[5]	4[5]	-	-	1	3	3	-	25	-	-	13	8
U	13[5]	12[5]	4	-	11.5	6	4	5	0.4	3.7	-	7.7	14.1

Trace elements in ppm.
ND Not Detected.

[1] Average of 4 samples unless otherwise indicated.
[2] Average of 10 samples unless otherwise indicated.
[3] Taylor, 1968.
[4] Daly, 1933.
[5] Average of 3 samples; [6] Average of 8 samples; [7] Average of 9 samples

(1) Host rocks are pervasively chloritized (i.e., magnesium metasomatism) in the vicinity of mineralization.

(2) Most mineralization is generally structurally controlled, particularly as pen space fillings, but ore zones are broadly conformable with the host rocks.

(3) Pitchblende is the main ore mineral and is accompanied by variable amounts of disseminated sulfides and locally gold.

(4) Deposits are spatially related to the Middle Proterozoic unconformity and the erosional margin of the Kombolgie Formation.

(5) Deposits are spatially related to underlying granitic migmatite complexes.

(6) Deposits are regionally associated with, but are not within, carbonate-bearing strata.

(7) A major mineralizing event (900 m.y.) occurred well after the deposition of the Kombolgie Formation.

Hegge and Rowntree (1978) summarize their views on the formation of the deposits as follows:

(1) Erosion of uraniferous, granitic Archean highlands during Lower Proterozoic time led to deposition of clastic and chemical sediments in a miogeosynclinal marine environment. Uranium became enriched in the reduced carbonaceous shales and impure carbonates, such as the Cahill Formation.

(2) Regional metamorphism, folding, and faulting at around 1700 to 1800 m.y. were accompanied by the formation of a migmatized mantle of basal Lower Proterozoic sediments adjacent to reactivated Archean basement complexes. Initial uranium remobilization was associated with the local silicification of carbonates which produced open-space, collapse structures.

(3) Magnesium metasomatism produced chlorite during retrograde metamorphism to greenschist facies. Uranium was dissolved in presumably carbon dioxide-rich and chlorine-rich brines from which it precipitated upon the release of carbon dioxide in open-space structures.

(4) Following uplift and erosion, deposition of the Kombolgie Formation began at about 1600 m.y.

(5) Uranium was remobilized principally around 900 m.y., but also around 500 m.y. The deposits that formed near the unconformity remained protected until recent erosion and the removal of the Kombolgie Formation.

In contrast to Hegge's (1977) mechanism of breccia formation by solution and collapse, Binns et al (1979b) favor hydraulic fracturing resulting from excessive pressure of either the retrogressive or the earliest mineralizing fluids.

It is important to establish relations between uraninite and CSQ (chlorite-septechlorite-quartz), because both are dominant components of most significant deposits. Binns et al (1979b) conclude that uraninite formed at a comparatively late stage, replacing CSQ and coffinite. The CSQ assemblage itself is locally distinctly uraniferous (> 1,000 ppm U), particularly where uraninite is lacking. They suggest that uranium was first introduced at Jabiluka with the CSQ replacement, and that uraninite subsequently crystallized from uranium dispersed in this assemblage. Some data suggest that magnesium chlorite characterizes uraniferous CSQ, whereas Fe^{+2} is more abundant in chloritized rocks from which uranium has been removed.

The fluids which produced the CSQ were relatively oxidized and presumably capable of transporting uranium (Binns et al, 1979b). Graphite has been oxidized in the vicinity of CSQ veins and breccias, and pyrites of adjacent schists are altered. Anhydrite and chalcocite, locally replacing chalcopyrite, are restricted to CSQ. They view the CSQ event as a later oxidizing event that evolved from the more reduced, retrogressive metamorphic event which developed the aureole around Jabiluka mineralization. Relative ages are supported by the formation of brannerite by reaction of the uraniferous CSQ fluids with anatase in chloritized biotite, the latter having formed in the earlier retrogressive event. They note, however, mineralogic (e.g., septechlorite) and textural similarities between CSQ replacements in and near veins or breccias, and retrogressive alteration in more remote schists. CSQ grades into retrogressive assemblages without definite evidence of replacement, suggesting to them that retrogressive metamorphism and the formation of uraniferous CSQ were related and essentially contemporaneous. The fluids of the system become more oxidized with time, hence the slightly younger paragenesis of the CSQ.

Binns et al (1979b) consider the model for late formation of uraninite from uraniferous CSQ explains the diverse U-Pb and Pb-Pb ages of uraninite and galena in the Jabiluka deposit (Hills and Richards, 1976; Gulson and Mizon, 1979). The 1800 m.y. isochron, obtained by Gulson and Mizon (1979) from lead-bearing sulfide lenses within graphitic schists, suggests an early stage of uranium mineralization. This uranium would have been available for retrogressive metamorphism believed to have formed very soon after the 1800 m.y. regional metamorphism. The younger uraninite Pb ages, which are comparable to an 800 m.y. model Rb/Sr age for fine-grained white mica from a Jabiluka greisen (Riley et al, 1979), may reflect the final release of uraninite from CSQ. Binns et al (1979b) acknowledge that these interpretations require both pre- and post-Kombolgie retrogressive metamorphisms, for which there is currently no petrographic evidence.

Stable isotope data reported by Binns et al (1979b) do little to resolve the genetic uncertainties. They state:

> At present it does not appear essential to appeal to contributions from meteoric water. For example, dolomites from both marbles and the common type of drusy vein have similar $\delta^{18}O$, close to +15 (SMOW). At the low temperatures suggested by fluid inclusions in drusy quartz (ca 100°C: Ypma and Fuzikawa, 1979) these values conform to possible equilibration with low-latitude meteoric water ($\delta^{18}O$ = 6). However the same $\delta^{18}O$ ~15 could equally be achieved in marble either by equilibration with typical high grade regional metamorphic fluids ($\delta^{18}O$ = 12) at 600°C or with

magmatic fluids ($\delta^{18}O = 7$) during greenschist facies retrogression at 300°C. Derivation of drusy carbonate by solution of marble under low fluid-rock conditions would allow retention of the same isotopic ratio.

Mumme et al (1979), based on their structural and chemical studies of uranium in the Pine Creek Geosyncline, describe a sequence of geologic events which they consider to have formed the uranium deposits. They contend, as do Hegge and Rowntree (1978), that granitic rocks in the Archean basement provided uranium that was accumulated in the sediments of the Pine Creek Geosyncline around 1800 x 10^6 years ago. They note the lack of volcanic rocks within the Lower Proterozoic sequence. Uranium accumulated from the dilute solutions by adsorption and related processes. Reducing conditions in the basin of sedimentation, maintained by the abundant organic material now reflected in graphitic schists, led to the reduction of sulfate and the precipitation of iron, copper, lead, and zinc sulfides. Following sedimentation, partial melting of the Archean basement, due to the substantially higher concentration of radioelements than at present, produced doming, intrusion, and metamorphism. The rising granitic masses also domed, fractured, and brecciated the metasediments. Pyrite and uranium were precipitated in the resulting open spaces. They suggest that transport of uranium may have been aided by dissolved hydrocarbons.

In the opinion of Mumme et al (1979), the precipitation and concentration of U as pitchblende, in fractures and breccia zones in carbonaceous and chloritic shales, largely around 700-800 million years ago, was affected by strong reducing conditions created by pyritic material already deposited in such zones.

Page et al (1979) have studied Rb-Sr, K-Ar, and U-Pb isotopes in order to establish the geochronology and evolution of the Late Archean basement and Proterozoic rocks in the Alligator Rivers Uranium Region. The most important ages are summarized in Table 20.

Basement ages in the Rum Jungle area indicate that the Rum Jungle and Waterhouse Complexes are older than 2400 m.y. (Richards et al, 1966; and Page et al, 1979).

In the Alligator Rivers region, no clear contacts with basement are exposed, and the age of the basement Nanambu Complex has been obtained by regional geochronology. Massive biotite granite in the center of the complex, on the basis of the Rb-Sr whole-rock method, is as old as 2470 $\pm$ 32 m.y., and the low initial $^{87}Sr/^{86}Sr$ ratio 0.7043 $\pm$ 0.0013 suggests that this is the actual age of the granite.

Most samples from the complex, mainly from muscovite-rich gneiss, show evidence of complete or partial mixing of the Sr isotopes, and yield isochron ages between 1750 m.y. and 1980 m.y., with high and variable initial Sr ratios (0.71 to 0.79). They consider these to be Archean rocks which were incompletely homogenized in the 1800 m.y. amphibolite-grade regional metamorphism. In addition to the Archean granite and reworked gneiss, the basement Nanambu Complex is comprised of pegmatoid leucogneiss, quartzite, and schist which are interpreted to be Lower Proterozoic arkosic sediments accreted to the granitoid complex during the 1800 m.y. regional metamorphism.

The formation of the granitoid rocks within the Nimbuwah Complex was apparently related in time to the regional metamorphism (Page et al, 1979). This is confirmed by U-Pb dates from zircons which yield 1870 ± 20 m.y., and a maximum age of 1905 ± 28 m.y. The metamorphic event is recorded in numerous dates, all of which cluster around 1800 m.y. Post-tectonic granites, in the Pine Creek Geosyncline, yield rubidium-strontium ages in the range of 1760 to 1780 m.y., compatible with the age of metamorphism. The age of the ore-bearing metasediments, therefore, is bracketed between 1870 and 2470 m.y.

An age date for the Oenpelli Dolerite of 1688 ± 13 m.y. (rubidium-strontium), provides a maximum age for the Kombolgie Formation, which unconformably overlies it.

The ages of metasomatic events are considered by Page et al (1979) in some detail. They point out that if the chloritization in the vicinity of the uranium deposits in the Alligator Rivers region is a result of the same event that chloritized the Oenpelli Dolerite and the 1780 m.y. Nabarlek Granite, it cannot be older than 1688 m.y.

> Rb-Sr data on chloritic and sericitic schist from the alteration zone at Nabarlek do not conform to a perfect isochron, but nevertheless provide clear evidence of isotopic re-equilibration about 1610 m.y. ago. This is consistent with the dolerite age, and is statistically the same as the age of alteration reflected in the Nabarlek Granite Rb-Sr total-rock results. It strongly suggests that at least part of the Nabarlek chloritization took place at this time. Rb-Sr total-rock data on chloritic schist from within and outside the mineralized zone at Jabiluka record what may be the same low-temperature metasomatic event, the average model age in this situation being 1600 m.y.

They suggest that the 1600 m.y. metasomatic event was not widespread, because K-Ar and Rb-Sr ages on muscovite from outside the Nabarlek alteration zone reflect the 1800 m.y. metamorphism, or are partly updated, and give ages of about 1750 m.y. Eight K-Ar muscovite ages from within and outside the alteration-mineralization zone at Jabiluka consistently yield 1804 ± 7 m.y. They conclude, on the basis of estimated threshold temperature of about 350°C for retention of Ar in the K-Ar muscovite system, that any subsequent metasomatism and mineralization of the Jabiluka schist occurred at substantially lower temperatures.

Page et al (1979) also report evidence for one or more additional metasomatic events between 1600 and 1700 m.y. These are tabulated in Table 20 and indicate that these alteration events affected not only the metasediments but the Oenpelli Dolerite and the Carpentarian granites.

Some Late Carpentarian dikes were also investigated by Page et al (1979). A phonolite cutting the basement complex yielded an age of 1316 ± 50 m.y. A post-Kombolgie Dolerite yielded an age of 1200 ± 35 m.y., while another dolerite near Ranger One gave a K-Ar date of 1370 m.y. This age provides a minimum age for the Kombolgie, and therefore brackets the age of this formation between 1680 and 1370 m.y.

Ferguson et al (1979b) reviewed the geologic characteristics of the Alligator Rivers Uranium District and developed a model for the formation of the deposits. They accept the anomalous uranium concentrations in the Archean basement rocks as a precursor to uranium enrichment in the Lower Proterozoic sediments discussed by other authors. Referring to the work of Ferguson and Winer (1979), they note that the highest uranium concentrations are in pyritic, carbonaceous black shales of the Koolpin, Masson, and Cahill Formations, but syngenetic mechanisms were insufficient to produce ore deposits, and all significant deposits post-date the regional metamorphism at 1800 m.y. They find no evidence for the concentration of uranium during the metamorphic event. Their model, outlined below, for subsequent geologic events is based on the Jabiluka, Ranger, and Koongarra deposits, which they consider to be similar.

A major period of erosion followed the metamorphism of the Lower Proterozoic sediments. They propose that associated with this peneplanation a karst topography developed within the carbonate-rich sequences at Jabiluka, Ranger, and Koongarra, leading to the collapse structures and brecciation which characterize the ore zones. They suggest that the principal period of mineralization occurred after brecciation but before the deposition of the Kombolgie Formation. Magnesium-rich clays and/or chlorite and possibly organic material may have accumulated in, or washed into, these collapse structures. These materials tend to adsorb uranium, hence they may have contributed to the formation of the deposit. Ground waters flowing through the structures would have slowly upgraded the deposits.

With the intrusion of the Oenpelli Dolerite at 1688 $\pm$ 13 m.y., Ferguson et al (1979b) suggest that under a thin alluvial cover the deposits were heated to approximately 266 $\pm$ 40°C, as indicated by stable isotope data, which caused complexed uranium to be released from the clays to form uraninite at about 1700 m.y. As an example of this event, they refer to age dates on disseminated uraninite in the Ranger deposit which record the 1700 m.y. event. It is unclear in their minds whether chlorite had accumulated within the collapse structures, or whether it was formed upon the emplacement of the Oenpelli Dolerite. They suggest that circulating fluids, associated with the intrusion of the Oenpelli Dolerite, were very saline, in contrast to the fluid inclusions of Ypma and Fuzikawa (1979), which may represent the fluids related to the formation of primary mineralization. Petrographic work by Ewers and Ferguson (1979) demonstrates that this disseminated uraninite was redistributed as stringers and colloform uraninite. Ferguson et al (1979b) suggest that this could probably have been effected by mild hydrologic conditions, which might have been expected to accompany the 800 to 900 m.y. event that is correlated only with epeirogenesis.

As a mechanism for the primary accumulation of uranium, Ferguson et al (1979b) favor the adsorption of uranium, particularly on clays, but they acknowledge that other mechanisms such as redox reactions, pH changes, and the loss of CO_2 might have been involved. The high uranium to thorium ratios suggest that uranium was transported in oxidizing solutions. Other elements associated with uranium, based upon correlation matrices (Ferguson and Winer, 1979), include tungsten, arsenic, niobium, molybdenum, lead, lithium, scandium, and cobalt. McLennan and Taylor (1979) independently demonstrated that the HREE are concentrated in the ore zone, and they suggested that they were transported as carbonate complexes.

Ferguson et al (1979b) find the occurrence of graphite and sulfides in the ore zones difficult to explain. They note that there is no evident correlation between the amount of uranium and the presence of carbon. Similarly, the absence of a general correlation between sulfur and uranium suggests to them that reduction of uranyl complexes by sulfide was not an important ore-forming process.

Nabarlek differs from Jabiluka, Ranger, and Koongarra, in that there is no evidence of massive, bedded carbonates in the vicinity of the deposit. Graphitic horizons were reportedly encountered, however, during recent mining. According to Anthony (1975), the deposit occurs in a strong breccia zone, and hematite is a major constituent of the host rock together with chlorite in the heart of the deposit. They suggest that perhaps the structural zone was the site for washed-in clays and/or chlorite and iron hydroxides which subsequently altered to hematite. This assemblage may have had sufficient sorptive capability to form the very high-grade deposit at Nabarlek.

Gabon, Africa

The uranium deposits of the Franceville Basin in Gabon, occurring as they do in unmetamorphosed sandstone, do not properly belong to the veinlike-type deposits. They may represent, however, a type of uranium mineralization which may have been present in the middle to upper Lower Proterozoic sediments in Australia and Canada prior to their metamorphism. The deposits of Gabon may provide, therefore, a link in the evolution of veinlike-type deposits, and it is on this basis that we include them in this study.

Franceville Basin - General

Baud, 1967; Bernazeaud, 1959; Bonhomme et al, 1965; Bonhomme and Weber, 1969; Bourrel and Pfiffelmann, 1972; Boyer et al, 1975; Branche et al, 1975; Chauvet, 1975; Donnot and Weber, 1969; Drozd et al, 1974; Favre-Mercuret, 1965; Gangloff, 1970; Gauthier-LaFaye et al, 1975; Gauthier-LaFaye, 1977; Geffroy, 1975; Geffroy et al, 1964; LeCoq et al, 1958; Molina and Besombes, 1975; Morin and Tardieu, 1972; Naudet et al, 1975; Pfiffelmann, 1975; Weber and Bonhomme, 1975.

The Franceville Basin is in southeastern Gabon about 500 km southeast of Libreville. It is one of several Lower to Middle Proterozoic, intracratonic, sedimentary basins of Central Africa. Its shape is elliptical with a northwest-trending long axis of approximately 90 km. The basin covers an area of almost 2,500 km. All deposits found to date cluster along the southwestern edge of the basin immediately adjacent to the Massif du Chaillu. The deposits occur in two groups: the northwestern group includes Boyindzi, Mounana, Oklo, and Okelobondo; the southwestern group contains Mikouloungou and Kaya-Kaya. The two districts are 30 km apart. The Mounana deposit is depleted, and the Oklo deposit is in operation.

Stratigraphy and Lithology. The Franceville Basin was formed as an intracratonic structural depression during Upper Lower to Lower Middle Proterozoic. It is surrounded by Archean-Lower Proterozoic crystalline complexes: to the southwest by the Massif du Chaillu, to the northeast by the Ondili uplift, to the northwest by the Matsatsa, and to the southeast by the Mopata basement highs. The contact between sediments and crystalline basement is commonly faulted.

The crystalline basement consists predominantly of granites and gneisses, which were dated about 2600 m.y. in the Massif du Chaillu. Other rock types are pyroxenites, amphibolites, and mica schists.

The age of the Franceville sediments is dated at 1740 $\pm$ 20 m.y., but pitchblende dates for the Oklo deposit yield ages of up to 2000 m.y. The sediments transgressed the crystalline basement in two major psammite-pelite sedimentary cycles. The lower cycle comprises the FA Formation and the overlying FB 1 Formation (Fig. 75). The FA consists of fluvial and fluvio-deltaic (arkosic) sandstones. Its thickness is about 50 m along the edge of the basin and increases to 1,000 m towards the center. The basal part consists of quartz pebble conglomerates and coarse-grained arkosic (microcline) sandstones with a siliceous, chloritic, sericitic, or dolomitic matrix. Locally, the conglomerates contain thorium-rich heavy mineral concentrations. The conglomerates grade progressively upwards into medium- to coarse-grained sandstones with dolomitic matrix. They in turn are succeeded by a succession of alternating fine-, medium-, and coarse-grained sandstones, with occasional intercalations of conglomeratic lenses. The matrix of these younger, feldspar-poor sandstones consists of silica or organic material, the latter imparting a blackish color to the sandstones. The individual sandstone layers reveal, besides cross-bedding and ripple marks, rapid lateral facies change. All uranium deposits occur in this upper sandstone of the FA Formation.

The FB 1 Formation overlies the FA Formation and is comprised of 0 to 600 m of pelitic sediments. A conglomerate is locally present at the base of FB 1. The sand content decreases progressively upwards in this formation, giving way to shales. A distinct increase in organic material occurs up through the section. In places, sand-filled paleochannels with pebbles of shales and dolomites are scoured into the pelites. The manganese deposits of Moanda are at the top of the FB 1 Formation.

The upper cycle is comprised of the FB 2a to FE Formations. It commences with approximately 100 m of well-sorted, fine- to medium-grained sandstones (FB 2a) reportedly derived from the erosion of FA clastics. Overlying the FB 2a is the FB 2b Formation, which consists of 30 to 40 m of organic pelites similar to those of the FB 1. The FB 2b is overlain by a 40 m thick succession of alternating cherty layers with organic pelites and some intercalated dolomites and tuffs.

The FC Formation consists of two, 30 to 60 m thick, organic pelitic horizons separated by a 50 m thickness of intercalated tuffs and organic pelites. The top of the sequence is occupied by the FE Formation, more than 100 m in thickness, consisting of five gray-green feldspathic sandstones alternating with micaceous greenish pelites.

An iron, lateritic duricrust formed during Eocene on top of the sediments. The sediments are slightly folded along a northwest to southeast-striking fold axis. Deformation of the Franceville Basin provided a northwest to southeast-trending fracture system along which the northeast blocks are generally downfaulted relative to the southwest blocks. A second fault direction is oriented north-south, producing, in combination with the northeast-trending set, fragmentation of the basin into rhombic blocks. A third set of faults trends east to northeast and is associated with dolerite dikes dated about 530 to 545 m.y., 715 to 730 m.y., and 870 m.y. (Weber and Bonhomme, 1975). Fault movement apparently re-occurred several times.

The northwestern group of deposits contains the major orebodies (Oklo, Mounana, Boyindzi and Okelobondo) and is immediately adjacent to the granite-gneiss horst of Mounana, a tectonic outlier of the Chaillu massif. The eastern edge of the horst comprises a zone of predominantly north-south trending, 70 degrees to 80 degrees east-dipping fractures. They separate the granites and gneisses from the FA and FB 1 sediments. The faults produced displacements of up to several hundred meters. The development of the various segments caused tilting of the sedimentary strata towards the east, forming a monoclinelike structure with dips 45 degrees to the east.

Mineralization. All deposits in the Franceville Basin are sandstone-type uranium deposits and most show some structural control. Based on local geologic features, Pfiffelmann (1975) identified three types of deposits: stratiform deposits (e.g., Oklo), veinlike deposits (e.g., Mounana, Boyindzi), and mixed stratiform-tectonic deposits (e.g., Mikouloungou).

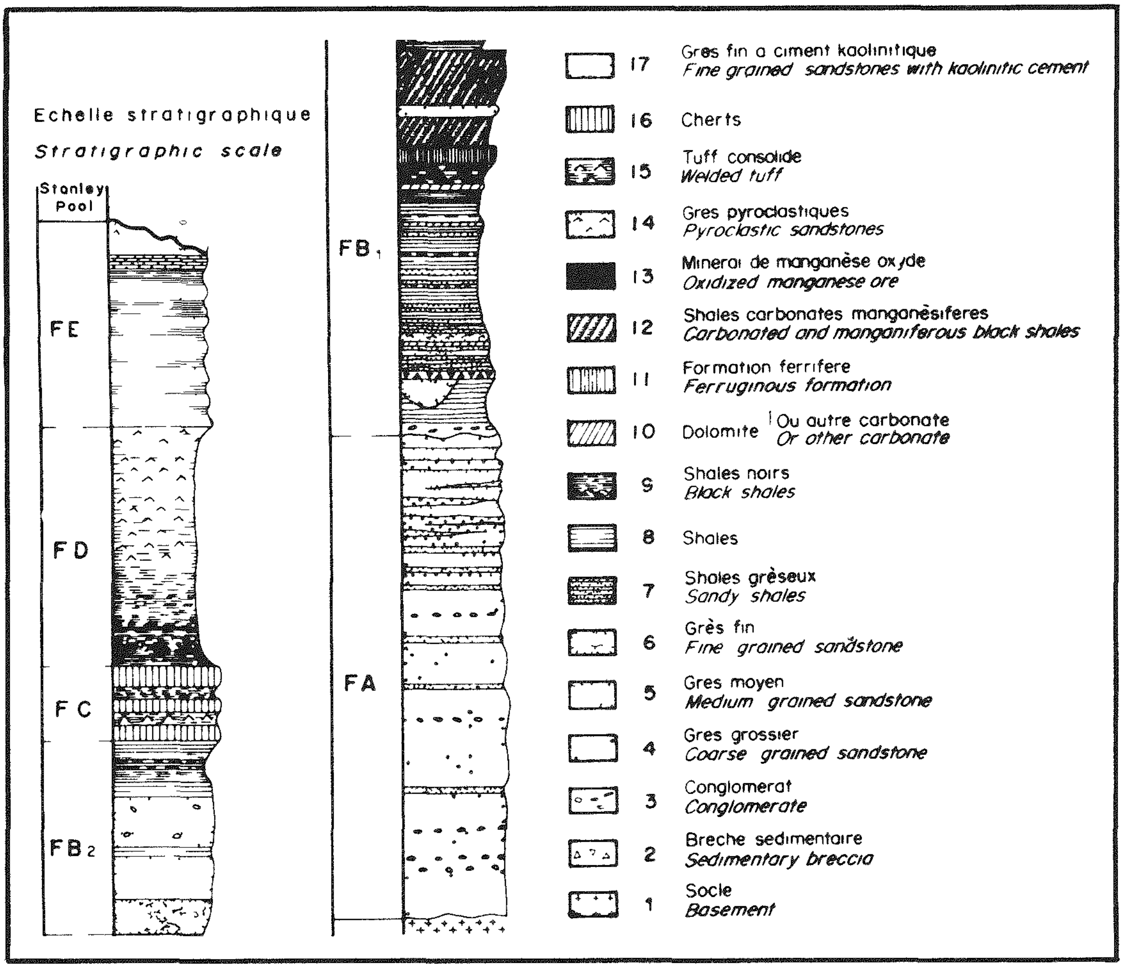

Figure 75. Stratigraphic section of the Francevillian series in the Franceville Basin, Gabon (from Gauthier-Lafaye et al, 1980).

In the primary ore, the principal minerals are pitchblende and coffinite. In the area of the natural reactor at Oklo, pitchblende is recrystallized to uraninite. Associated and gangue minerals include karelianite, montroseite, and roscoelite. There are also minor amounts of pyrite, galena, sphalerite, chalcopyrite, marcasite, melnikovite, barite, and calcite as fissure fillings.

In the oxidized ores, the principal minerals are francevillite, vanuralite, uranocircite, autunite, torbernite, and renardite. Associated minerals include vanadinite, chervetite, and brackebuschite.

Production and Reserves. Production from the deposits of the Franceville Basin has amounted to about 10,000 t uranium. Reserves (average grade between 0.2 and 0.4 percent U), are tabulated below:

Type of Reserves	Forward Cost Category	
	80 $/kg U	80-130 $/kg U
Reasonably assured	20,000 t U	
Estimated additional	5,000 t U	5,000 t U
Total	25,000 t U	5,000 t U

Uranium Deposits

Oklo.

Geology and Mineralization. The deposit is 1.5 km to the south of Mounana. It has a north-south length of 900 m and a maximum east-west width of 600 m (Fig. 76). The ore horizon plunges with dips between 15 and 60 degrees to the east and then flattens at depth. The maximum depth is 300 m. The mineralization covers an area of approximately 280,000 m .

The uranium is concentrated in the upper 5 to 10 m of the FA Formation. This part of the sequence in the Oklo deposit is subdivided into two units. The lower n + 3 unit is 30 m thick and contains the weakly and irregularly mineralized C 2 horizon. The overlying n + 4 unit is 4 to 10 m thick and contains the main ore horizon (C 1). Both units grade from fine-grained, in part pelitic, sandstone at their bases to coarse-grained sandstones and conglomerates at their tops, i.e., they are inverse sedimentary cycles. The top of n + 4 is covered, with a very slight unconformity, by green- and black-banded pelites of the FB 1 Formation.

The main ore horizon (C 1) consists of a series of lenses of cross-bedded fluvial sandstones with a conglomeratic interbed. The C 1 was deposited immediately above the upper conglomerates and a fine-grained pelitic bed of the unit n + 3. Uranium is concentrated predominantly in sandy zones in the form of microcrystalline pitchblende within an organic matrix. Mineralization appears to avoid pelitic horizons. In the zones of the natural reactors, uranium was found in association with chlorite. Some uranium concentration was found associated with a dolerite dike which cut the Francevillian sediments in the southern third of the deposit. In contrast to Mounana (see later paragraph), no vanadium is associated with uranium at Oklo.

The natural reactors of Oklo (Boyer et al, 1975) are a unique phenomenon among uranium deposits of the world. They are characterized by a depletion of U^{235} from 0.72 percent to between 0.62 percent and 0.296 percent. Six reactors have been found which occupied a total area of 3,500 to 4,000 m^2 (1.5 percent of the total mineralized area). The individual reactors covered from a few meters up to 10 m and 20 m each in ore thicknesses up to 1 m. At each locality, uranium was enriched to more than 50 times the normal concentration with extreme values up to 60 percent U. The reactors are located at places where the overlying pelites are cut by sand-filled paleochannels. About 800 t of natural uranium was destroyed by the reactors.

Ages of ore from the nuclear reaction zones are dated at 2000 m.y. by Devillers et al (1975) and 1700 to 1900 m.y. by Cowan et al (1975), which predates the age of 1740 m.y. of the host sediments. The period of criticality lasted at least 200,000 years. At the time the reactors were active, U^{235} amounted to almost 3 percent of the total uranium (compared with 0.7 percent today).

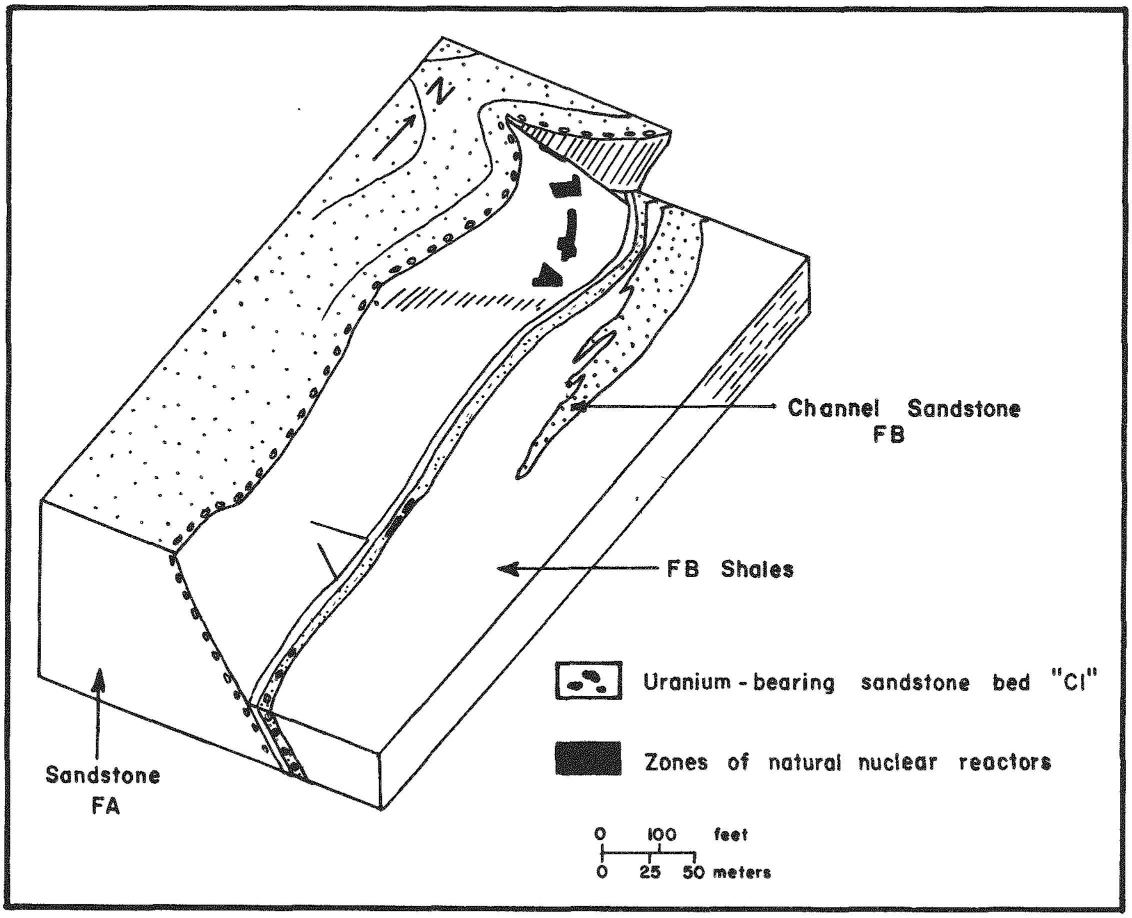

Figure 76. Schematic block diagram for the Oklo deposit, Gabon (modified from Gauthier-Lafaye et al, 1980).

Ore Control. The Oklo ore shows a strong lithologic-stratigraphic control. Within the fluvial-deltaic sandstones of the C 1 zone, uranium seems to be concentrated on the flanks or rims of paleochannels or where intermediate thicknesses of sandstone are combined with high concentrations of organics and moderate interbedding. The mineralization decreases in zones of thick sandstone and in low concentrations of organic material. There also seems to be some relationship to dip, the best ore occurring in sediments with a dip of about 30 degrees.

A regional ore control may be related to the western bounding fault of the Franceville Basin and the crystalline Massif du Chaillu less than 1,000 m to the west of the deposit.

Production and Reserves: The total of reserves plus production is about 13,000 t U and the grade about 0.4 percent U. The major part of the deposit has been exploited.

Mounana.

Geology and Mineralization. Mounana occurs in the same regional structural setting as Oklo. It lies immediately east of the fault separating the crystalline wedge of the Massif du Chaillu from the Franceville sediments (Fig. 77). Another fault zone borders the orebody to the east.

The ore is concentrated in the same C 1 horizon as in Oklo. Here the sandstone is heavily fractured and referred to as the Mounana Sandstone. The sandstones dip steeply, possibly due to drag on the fault. The orebody was about 100 m long, 40 m wide, and extended to a depth of 120 m. Quartz and microcline, 1 to 4 mm in size, constituted 90 percent of the sandstone. The matrix contains organic material and is silicified.

In the oxidized upper 40 m of the deposit, the ore consisted of uranyl vanadates. Primary mineralization then occurred down to a depth of 120 m.

The ore control is structural as well as chemical-lithological. Mineralization is restricted to the FA sandstones where organic material is abundant. A reported ore control is the occurrence of the orebody on the west flank of a paleochannel that is scoured into the upper FA Formation. Later tectonics, however, have strongly overprinted this sedimentological control. Structure is expressed by marginal faults and fractures that separate ore from nonmineralized rocks and by structures within the deposit that separate rich from poor mineralization.

Production and Reserves. The original reserves were about 6,000 t U, at 0.4 percent U, but the deposit has been mined out.

Boyindzi.

Geology and Mineralization. The Boyindzi deposit is just north of the Mounana deposit in a similar structural position. The orebody is not exposed at the surface and occurs at depths between 150 and 230 m. Its northwest-southeast length is approximately 150 m, the width 20 m to 40 m. The mineralization occurs in tilted (dragged?) sandstones of the uppermost FA Formation and dips with the strata to the northeast (Fig. 78). The orebody is limited on the southwest by the northwest-striking fault that dips steeply northeast and abuts the crystalline basement. The northeast boundary of the deposit is controlled by a sedimentary pinchout (?) between FA and FB 1 Formations. The top of the deposit is an overthrust of FA sandstones over FB 1 pelites. Below the mineralization, the sandstones are silicified. To the north, the orebody wedges out along east to west-trending faults.

The deposit is in the uppermost 60 to 70 m of the FA Formation. The basal portion of this section consists of 30 m of fine- and coarse-grained, greenish sandstones. They are overlain by 20 m of gray or black, coarse-grained

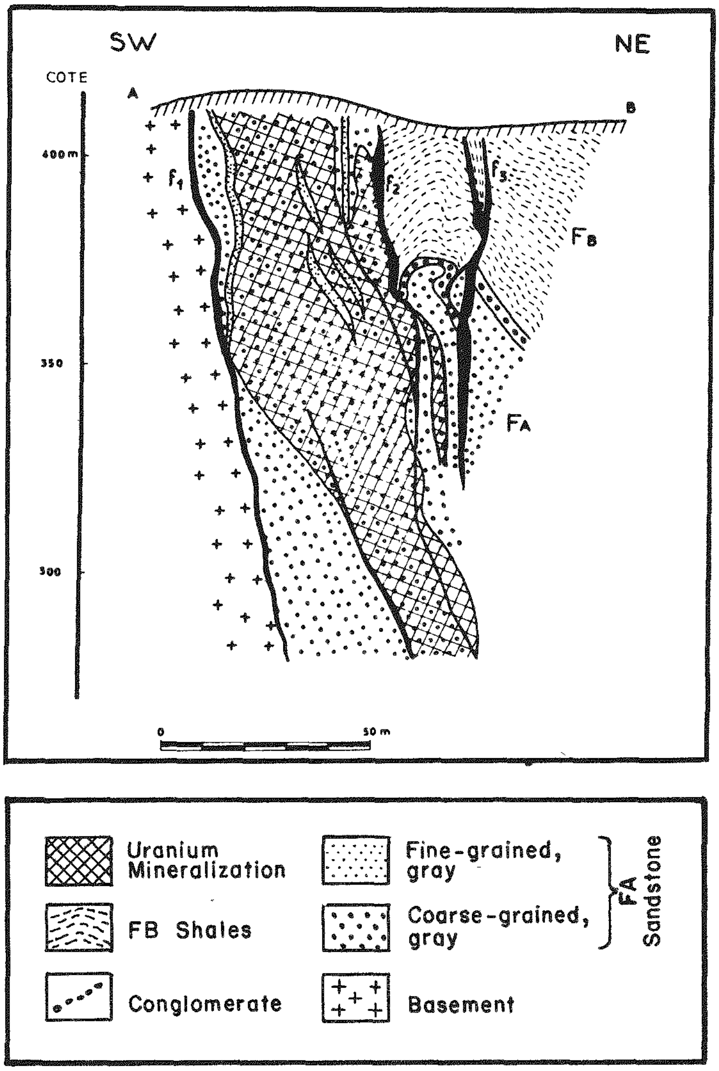

Figure 77. Schematic cross section of the Mounana deposit, Gabon (from Gangloff, 1970).

sandstones with one or two interbedded layers of fine-grained sandstone. This unit encloses the main ore horizon. The upper part of the FA consists of 15 to 20 m of alternating fine- and coarse-grained sandstones. The overlying pelitic sediments of the FB 1 Formation contain a sandy conglomeratic bed at their bases.

The control for this deposit is structural as well as lithologic. The mineralization is confined to the upper FA sandstone, which is equivalent to the host at Mounana and probably at Oklo. Organic substances occur within or adjacent to the host rocks. At depth, the mineralization is bounded by silicified sandstone. The structural control is expressed by faults bounding the sides of the orebody.

Production and Reserves are estimated to be 3,000 t U, and 0.3 percent to 0.4 percent U.

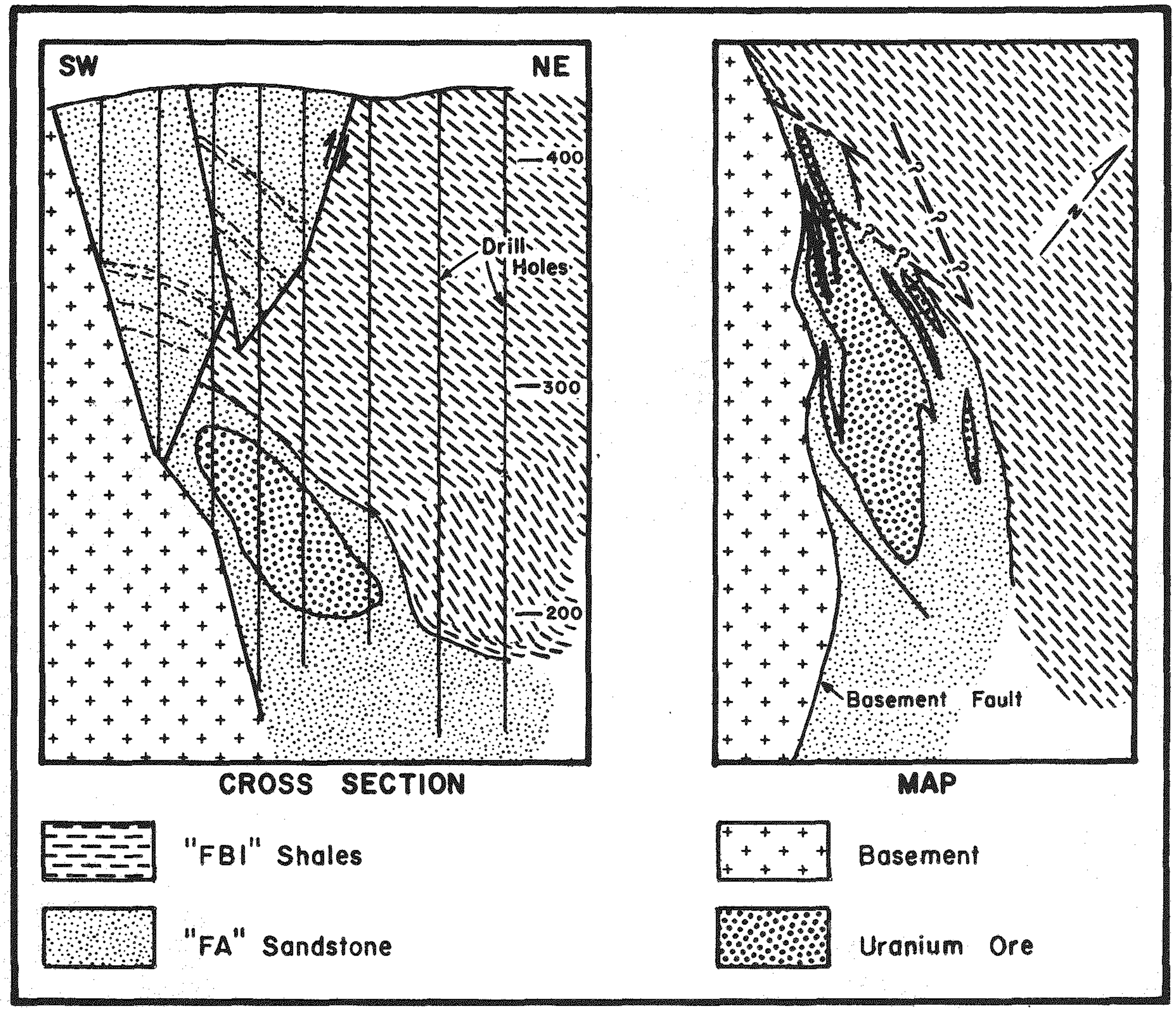

Figure 78. Geologic plan map for the 240 level and a cross section for the Boyindzi Mine, Gabon (from Pfiffelmann, 1975).

Okelobondo. The deposit, discovered in 1974, is immediately south of, and similar to, Oklo. It consists of two separate orebodies that extend to a depth of about 500 m.

Reserves are supposed to be on the order of 4,000 t U, at a grade of 0.3 to 0.4 percent U.

Mikouloungou.

Geology and Mineralization. Mikouloungou and the nearby Kaya-Kaya deposits are located about 60 km southeast of the Mounana and Oklo deposits. These deposits are not at the edge of the Franceville Basin but are almost 20 km from the crystalline basement.

The Mikouloungou mineralization extends for 30 m along an east-west striking overthrust that dips 45 degrees north. Its width reaches 20 m, and it extends to a depth of more than 250 m.

North-dipping, FB 1 pelites in the upper plate of the thrust overlie horizontal to gently southwest-dipping FA sandstones in the lower plate (Fig. 79).

The FA Formation is more than 500 m thick. It is subdivided into four alternating sequences of fine- and coarse-grained sandstones. Uranium occurs principally in sequence two. It is 175 m thick and comprises 21 beds of several tens to hundreds of centimeters in thickness, each of alternating fine- and coarse-grained, feldspathic sandstones. Near the overthrust, the host rocks are shattered by micro-fractures, and feldspars are kaolinized. The sandstones are variably silicified. Sequence two is overlain by sequence one which is composed of 75 m of fine-grained sandstones. Mineralization occurs: (a) along the footwall of the thrust zone independent of the lithology and (b) extending southward as tonguelike projections for 5 to 20 m from the thrust zone into the coarse-grained sandstone horizons of sequence two. In plan, the ore tongues show irregular, amoeba-like shapes.

The ore consists of a mixture of pitchblende and clay minerals accompanied by pyrite and, in fissures and joints, calcite.

The ore controls are structural and lithologic. Mineralization is sharply separated from the adjacent pelites by the overthrust. It only occurs on the footwall side of the fault zone within coarse-grained kaolinized sandstones. Within the sandstone beds, joints with gouge partly control the mineralization. A change in alteration is observed within the host rocks from a barren, fresh feldspathic sandstone to a sandstone impregnated with pitchblende and clay minerals close to the fault. It appears that the kaolinitization developed along micro-fractures which also could have been conduits for the uranium. A chemical control was possibly provided by the overthrusted pelites.

Their organic material may have produced a reducing environment that precipitated the uranium. A lithologic control appears to be the affinity of the ore for sequence two of the FA Formation. Several generations of silicification appear to have influenced the distribution of the uranium. Reserve estimates indicate almost 10,000 t U at a grade of nearly 0.2 percent U.

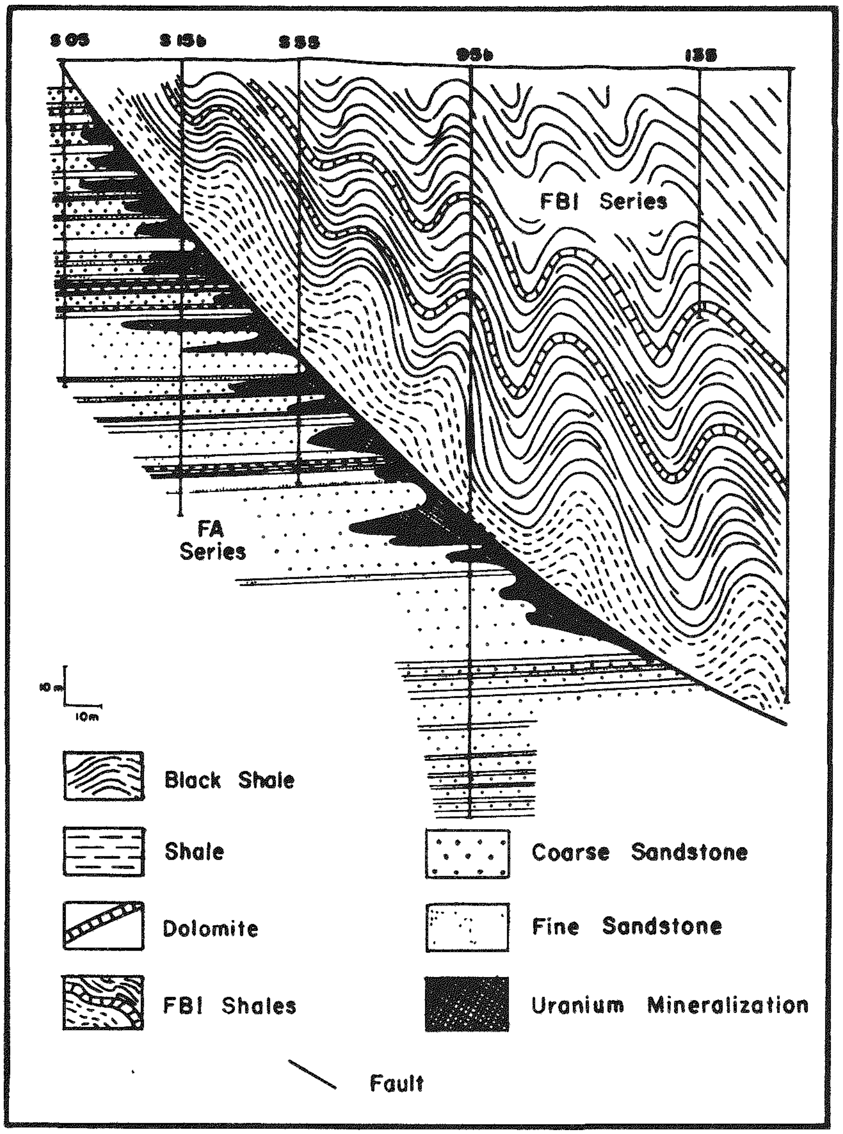

Figure 79. Schematic cross section of the Mikouloungou deposit, Gabon (from Gangloff, 1970).

SYNTHESIS

Working Model

The geologic descriptions of veinlike deposits presented in the preceding sections demonstrate that, although the various Lower to Middle Proterozoic uranium deposits are similar in many respects, there are strong differences among them. The similarities suggest that they experienced some of the same ore-forming processes; the significant differences suggest that their geologic histories are not identical. In the following section, we attempt to resolve the accumulated data into a working model that establishes relationships between the different types of veinlike deposits.

The data and interpretations of the preceding sections do not support a simple or convincing single interpretation for the formation and control of the veinlike deposits. We believe this reflects (a) the lack of some important descriptive data, and (b) the complex sequence of processes which formed these deposits. Although the interpretations will probably become more simple with time, several sequential and locally superimposed geologic processes likely led to the formation of the various veinlike deposits. We have grouped the different deposits into types and subtypes based largely on the nature of their host rocks and the processes believed important in their formation. The model of geologic ore-forming processes is presented in the following paragraphs and shown graphically in Plate IV. The principal uncertainties in the model, and directions for further study, are then discussed.

Stage I

In middle to upper Lower Proterozoic time, between 2200 and 1900 m.y., uranium was transported in solution into basins formed on the Archean craton (see Plate IV). The uranium was most likely derived from uraniferous Archean granites, and it became preferentially concentrated in the sediments deposited around the granitic highlands and close to the underlying Proterozoic-Archean unconformity. The uranium accumulated in somewhat calcareous psammitic and pelitic rocks, particularly in association with organic (algal?) accumulations. An excellent example of this type of occurrence is the Franceville Basin in eastern Gabon which is the only known unmetamorphosed, ore-bearing Lower to Middle Proterozoic sedimentary sequence. There the uranium occurs in the form of pitchblende in a basal sandstone sequence above the Archean basement. The ore-bearing horizon is partly carbonaceous and overlain by organic-rich shales and underlain by dolomitic sandstones. Figure 76 shows a block diagram of the Oklo deposit, the largest, primarily strata-controlled deposit of the Franceville Basin.

Uranium is also found as high background concentrations associated with a variety of lithologies in the metamorphic belts (Wollaston Belt, Pine Creek Geosyncline) which host the important districts. Common associations are biotite-hornblende gneisses, aluminous (sillimanite and cordierite) gneisses, quartz-feldspar gneisses (meta-arkose?), marbles, and metadolomites. These occurrences suggest that uranium had accumulated in the unmetamorphosed equivalents of these rocks and remained immobile or moved only locally during metamorphism. Both interpretations are probably applicable to certain rock types. Possible examples of these associations are, respectively, the mineralization in black shales and carbonates at Rum Jungle and the close association of uraniferous lenses and veins with carbonates in the area of the Rabbit Lake deposit, Saskatchewan.

Stage II

Stage II encompasses the metamorphism of the uraniferous sediments in some basins to amphibolite and locally granulite facies. It is subdivided into two substages. Stage II-A applies to those settings where late-stage retrograde metamorphism appears to have occurred in a closed system, whereas Stage II-B applies to those areas for which geologic relations suggest an open system. We interpret the closed system to be one in which there was no significant metamorphic modification, and transportation of the uranium accumulated during sedimentation. This was due, presumably, to the limited development of structures, negligible fluid movement, and relatively low thermal gradients. These environments are characterized by an absence of granitic and mafic intrusions which otherwise might have promoted the mobilization and transportation of uranium into structures. In contrast, field relations suggest that the deposits formed in open systems occur close to Late Hudsonian granitic intrusives and/or to migmatitic zones, associated with Archean basement highs, which were mobilized by Hudsonian palingenesis. It is also possible that major mafic intrusions, such as the Oenpelli Dolerite in Northern Territory, Australia, may have contributed to the mobilization and transportation of uranium into structures.

Stage II-A

During metamorphism in a closed system, uranium became recrystallized in the original sedimentary layers so that it is now found in the form of strata-bound uraninite essentially without associated alteration. The mineralization may crop out at the surface and may extend to considerable depths depending on stratigraphy and structural setting. This type of mineralization is not localized in structures but is essentially strata bound. Examples of this type of deposit would be the Kitts and Michelin deposits in Labrador, although the latter is associated with volcanics.

In the Athabasca region, uranium enrichment in the metasediments occurs in hornblende- and biotite-rich horizons, strata rich in albite, mafic- or iron-rich zones, in lithologies rich in apatite, marble and/or calc-silicate minerals, and in cordierite and sillimanite-rich horizons, probably reflecting aluminous, pelitic sediments. In such settings, the typical original metamorphic uranium mineral is euhedral uraninite in the Athabasca Region, the Pine Creek Geosyncline, and in analogous belts of the world. Some of these types of occurrences are shown in Figure 43. These occurrences are locally of very high grade but are generally only small, subeconomic deposits.

Stage II-B

The geologic setting for Stage II-B is noticeably different from that in Stage II-A. Intrusions and/or zones of migmatization, commonly accompanied by zones of shearing and faulting, have produced mobilization and local reconcentration of the original uranium in the sediments. Although structures are present, there is still a very strong element of strata control as, for example, in the Jabiluka and Koongarra deposits. The stratigraphic continuity of the mineralization suggests that the primary mineralization may not have moved far to form these deposits. The importance of structural control is demonstrated in the Ranger One deposit by the well-developed shear and breccia zones and the associated intense chloritization. We interpret the deposits at Beaverlodge to reflect an intimate association of structural and stratigraphic control. In the Verna Mine, for example, horizons of mineralization wrap around fold noses suggesting sedimentological units of primary uranium enrichment. In the Fay Mine, by contrast, a major amount of the uranium is distinctly within structures but still within the same gross stratigraphic sequence. Nabarlek poses a particular problem. Although it occurs in close proximity to a 1600 million year old granite, and is itself structurally controlled, yet an age date on pitchblende from the deposit yields only 900 million years. If the age date is representative of the deposit, it may reflect a totally new uranium accumulation formed at that time or the reconstruction of an older deposit. The Gunnar deposit may represent the extreme case of uranium remobilization. The deposit occurs now within a quartz-deficient, albitized granite of Late Hudsonian Age and may represent the advanced stages of uranium redistribution in proximity to intrusives and zones of palingenesis. The deposit has received limited study, and this hypothesis is unconfirmed.

Proterozoic sediments exposed to high-grade metamorphism in an open system are locally characterized by the developments of zones of anatexis and partial melting. The metasediments may become annealed to Archean cores, and numerous pegmatites may be developed within the metasedimentary pile. Metasomatism of various types is also characteristic of the rocks and uranium deposits formed in these environments. In the Athabasca region, for example, sodium metasomatism has been noted, whereas in the Alligator Rivers region magnesium metasomatism is more common.

Stage III

Following post-orogenic erosion, some deposits of the types formed in Stage II-B were covered by early Middle Proterozoic sediments. These sediments were oxidized, continental clastic sequences deposited in areas of contemporaneous block faulting. They occur over basement rocks on which practically no regolith was developed. These relations are typical of the Beaverlodge region where the Martin Formation overlies the metasediments. By contrast, in the Alligator Rivers district, a thin regolith was developed, probably leading to the local remobilization and enrichment of some shallow uranium occurrences. In the Baker Lake region, the sedimentary sequence includes arenaceous sediments with interbedded uraniferous volcanics represented by the Christopher Island and Pitz Formations. These extrusive rocks are in contrast to the basic igneous rocks in the Beaverlodge region, which also include some felsic flows, dikes and sills. The deposition of these sediments prior to any period of intense weathering of the basement rocks preserved the outcropping and near-surface uranium mineralization.

Stage IV

In Precambrian terrains of paleo-subtropical latitude, a long period of intense weathering developed a strong regolith on the Archean-Aphebian crystalline basement and the overlying early Middle Proterozoic sediments.

For example, south of the Beaverlodge district in northern Saskatchewan, where the Martin sediments were absent, the basement is characterized by a regolith which locally extends to depths of 100 meters in the metamorphics. It is presumed that this regolith represents a period of intense chemical weathering prior to the deposition of the Athabasca sandstone. Where the Martin Formation was present, the basement rocks were protected from weathering. Paleomagnetic data support the interpretation that this region was at approximately 30°N during the time prior to the deposition of the Athabasca sandstone. The basement rocks were likely exposed, therefore, to deep chemical weathering under a humid, warm to temperate climate. The intense chemical weathering mobilized many elements including uranium, much of which was probably lost from the region in surface and ground waters. Some, however, may have precipitated in sites which were accessible to the ground and surface waters. Shear and fault zones in or near uraniferous metasediments and lacustrine sediments rich in carbonaceous material overlying uraniferous basement are two such possible sites. The host sediments for the D orebody at Cluff Lake have been interpreted as carbonaceous sediments deposited in a lacustrine (?) environment, although recent mapping has not confirmed this interpretation. It is uncertain whether uranium-concentrating processes operated in such environments to form protores, or even orebodies, prior to the deposition of the Athabasca. We consider it likely that they did, but field relations are now dominated by later, possibly masking, geologic events.

In addition to the possible formation of new uranium concentrations at the unconformity, one might expect that where Beaverlodge-type deposits were present at or near the surface, these processes may have led, under certain circumstances, to their enrichment and the superposition of unconformity-type mineralization on synsedimentary or strata-structure-bound deposits. There are some indications that this type of setting may be represented by the Rabbit Lake deposit.

Following the development of the regolith, and its partial erosion from hills and ridges and possible reaccumulations and preservations in valleys, the Athabasca Formation was deposited over the basement rocks in a broad continental clastic sedimentary basin.

In the Baker Lake region, the regolith affected the interbedded volcanic and sedimentary cover sequence over the metamorphic basement and probably formed unconformity-type deposits. These deposits, however, are of small size probably because of the limited amount of uranium in the source rock. In the region west of Baker Lake, the regolith is developed on Aphebian metasediments, and unconformity-type deposits, of which the Gull Lake may be an example, were apparently developed.

Stage V

In northern Saskatchewan, following the deposition of the thick Athabasca Formation, diagenetic processes affected the distribution of uranium in the immediately underlying regolith and Aphebian metasediments. Deposits within structures and pre-Athabasca lacustrine (?) sediments, that had become protores or even orebodies prior to Athabasca deposition, may have experienced only minor remobilization and recrystallization. Some protore occurrences may have been upgraded to viable deposits, while some deposits may have been further enriched or redistributed. These processes could have persisted throughout the period of Athabasca deposition.

Athabasca sedimentation was finally interrupted by broad epeirogenic uplift which was accompanied by the emplacement of diabase dikes. This event is believed to have terminated the diagenetic processes and ore formation, and it is the last major stage in the formation of the uranium deposits. It is this event, furthermore, which established the common radiometric dates characteristic of many of these deposits.

Stage VI

Subsequent to the important Middle Proterozoic ore-forming event, periodic mild disturbances and reactivation of structures caused local redistribution of mineralization. This is reflected in younger age dates in some deposits and the introduction of uranium up into the Athabasca sandstone, presumably remobilized from earlier concentrations in the basement. At Key Lake, for example, primary mineralization is restricted to the basement, and only sooty pitchblende and coffinite occur within the Athabasca sandstone. The ages of this redistributed mineralization are younger than 300 m.y.

In summary, the veinlike deposits display different combinations of geologic characteristics reflecting, in our opinion, different intensities and different combinations of geologic processes. The four important stages in the evolution of these deposits appear to have been (a) during the deposition and diagenesis of the Aphebian sediments, (b) during the metamorphism of these sediments, (c) during the erosion and weathering (regolith development) of these metasediments, and finally (d) during the deposition and diagenesis of the overlying cover sediments. Not all stages are represented in all deposits. Many deposits appear to reflect the syngenetic uranium accumulation in only one of the subsequent upgrading processes. We suggest, however, that the various subtypes are related in the manner discussed in preceding paragraphs. Divergent opinions, as discussed in the text, are numerous, and they will continue to find support due, in part, to inadequacies in the data and ambiguities in their interpretation. Some of the more important uncertainties and remaining problems are briefly outlined in the following section.

Discussion of the Working Model

The working model presented in the preceding section is at best a preliminary, simplified interpretation of the most prominent ore-related geologic data. It is based, in many instances, on drill hole information rather than outcrops or mine workings, and includes limited information for areas outside the actual deposits. The following paragraphs discuss some of the important uncertainties of the model and identify topics for further research that could help confirm or correct the model. Since the working model will be used in exploration and resource studies, comments and recommendations are slanted toward those applications.

Archean Source Rocks for Strata-bound Uranium in Middle to Upper Lower Proterozoic (Aphebian) Sediments

There are only limited representative analyses for the Archean-Lowest Proterozoic basement rocks that are generally considered to have been the source for the metals in the deposits of the Middle to Upper Lower Proterozoic metasediments. It is not possible to state, with certainty, therefore, that the

Archean granites adjacent to the districts were adequate sources, and that they provided the uranium in the sediments. Similarly, Lowest Proterozoic uraniferous oligomictic conglomerates, another possible source rock, have only locally been identified in the basement rocks close to the uranium districts. The recognition of fertile source rocks is a fundamental guide to these types of deposits. The recognition of such source rocks, and the evaluation of their leaching characteristics, are potentially important criteria for exploration and resource studies. Useful studies might proceed along the following lines:

(1) Identify the types of Archean and lowest Lower Proterozoic rocks that were capable of supplying the uranium and other metals in the deposits.

(2) Identify the mineralogy, metal contents, and uranium-leaching characteristics of these rocks.

(3) Determine the major and minor element contents of the leached and unleached potential source rocks.

(4) Investigate the possible effects of outcrop area, relief, and climate in the source rock area on uranium availability.

Lower Proterozoic (Aphebian) Source Rocks for the Formation of the Veinlike Uranium Deposits

The uranium contribution of the Aphebian metasediments to the large Lower Proterozoic deposits has been neither convincingly documented nor unanimously accepted. Much attention has been placed on identifying high uranium background concentrations in the metasediments of both the Canadian and Australian districts, largely without success. Less attention has been directed to the growing number of uranium anomalies or occurrences in certain metasedimentary horizons, and the numerous small, high-grade uranium accumulations in pegmatites, meta-arkoses, mafic gneisses, calc-silicates, and other lithologic settings. Although many such occurrences have been prospected and rejected as uneconomic occurrences, they have been somewhat overlooked for the geochemical enrichments they probably reflect. It now seems likely that much of the dispersed uranium incorporated in the sediments at deposition was mobilized and moved to, or was only preserved in, certain lithologic sites during metamorphism. Evidence of a uraniferous protolith, therefore, is probably the numerous remnant, economically marginal, and insignificant uranium occurrences throughout these metasediments. This observation becomes an important criterion in the search for, and evaluation of, potential areas.

An additional source of syngenetic uranium may have been uraniferous volcanics which occur interbedded with Aphebian sediments in, for example, the Michelin deposit in Labrador. In the other districts, Aphebian uraniferous volcanics are not reported, or are younger than the Aphebian uranium-bearing sediments. Although the uranium contribution of the younger volcanics to the unconformity-bound deposits might have been possible at some places, for example Baker Lake and Thelon Basins, Northwest Territory, their contribution was probably minimal. They suggest, nonetheless, that the region was within a uraniferous province.

In order to resolve important remaining questions regarding the source of uranium in the deposits, and clarify recognition criteria, the following types of studies would be useful:

(1) Establish if a high uranium background content in the source rocks (several tens to thousands of ppm) is necessary for the formation of high-grade, large-tonnage deposits, or if normal concentrations (i.e., a few ppm) are sufficient. The distinction should be made between leachable uranium and that bound in refractory minerals.

(2) Investigate the fate and uranium-leaching characteristics of refractory minerals such as monazite, xenotime, sphene, and others during magmatic, metasomatic, and palingenic-anatectic processes.

(3) Investigate the fate of uranium released by processes ranging in intensity from supergene alteration to palingenesis in terms of the likely mode and distance of uranium transport, and mechanisms of re-accumulation.

(4) Identify those analyses and/or observations that most reliably indicate the former background uranium concentrations of potential source rocks (e.g., uranium in zircon and radiogenic lead in galena).

Depositional Environment of the Lower Proterozoic (Aphebian) Host Sediments

The sediments now represented by the metasediments of the uranium districts were probably deposited as coarse to fine clastics with interbedded carbonaceous material and chemical sediments. These sedimentary sequences are now found immediately (within a few tens to hundreds of meters) above Archean basement and in close proximity to Archean prominences or highlands. These relations suggest deposition in a shallow, marginal-marine to lagoonal setting. The general geometry of the basins of sedimentation has not been established because of deformation and metamorphism. The basins may have been linear depressions in the Archean crust or broad intracratonic basins.

The morphology of the sedimentary basins within the vicinity of the deposits is also not known. For example, was uranium precipitated in sub-basins or lagoons, or merely in a broad shallow sea? The presence of abundant carbonaceous material and carbonates in various parts of the stratigraphic sequences suggests that lagoons and/or sub-basins, possibly flanked by reef-like zones may have controlled sedimentation. Some basins might have accumulated ore-grade material, whereas others received only low-grade mineralization. At Rum Jungle, the occurrence of uranium and copper in some of the deposits, and uranium, lead, and zinc in others, suggests that metal accumulation may have occurred in two sub-basins. The original distribution of uraniferous sediments may, therefore, have been very restricted and irregular. It is also possible that these metal distributions are entirely the result of post-depositional processes. The proximity of the ore-bearing Aphebian metasedimentary sequences to the underlying Archean prominences seems inviolate, but this and the original metal distributions should be established through studies of the depositional environments of the original sediments.

Lithologies of Lower Proterozoic Host Sediments

The metasedimentary sequences which host the deposit include schists, graphitic schists, feldspar gneisses, feldspar-quartz gneisses (meta-arkoses), and (dolomitic) marbles which were probably deposited in a marginal-marine environment. The stratigraphy and lithologies of the Lower-Middle Proterozoic Franceville Basin, Gabon, appear to be unmetamorphosed equivalents of these metasediments. The Franceville Basin may provide, therefore, an opportunity to study the regional and local geologic settings of a Lower Proterozoic basin, as well as the pre-metamorphic lithology and chemical composition of the sediments and basement rocks. Integrated geologic studies of this basin could provide important guides for regional and detailed exploration.

Volcanic-rich sediments have not been identified within the principal ore districts of the Northern Territory, Australia, and Northern Saskatchewan, Canada. On the other hand, uranium deposits are associated with Lower Proterozoic volcanics in Labrador and with Middle Proterozoic volcanics in Northwest Territory, Canada, and the South Alligator River district in Australia. Volcanics are also described within the Lower Proterozoic rocks in the southwestern portion of the Pine Creek Geosyncline, indicating that volcanism probably occurred during the deposition of the host rocks in the Alligator Rivers district. Volcanism may have contributed uranium to the Lower Proterozoic sediments, but this could only be verified through careful lithologic and chemical studies of the sediments. The Franceville Basin, Gabon, offers a possible site to study these features in unmetamorphosed equivalents (?) of the metasediments.

Pre-Metamorphic Diagenesis of Lower Proterozoic Sediments

The behavior of uranium during compaction and lithification of the uraniferous Lower Proterozoic sediments is not known. Judging from the importance of diagenetic and post-lithification processes in the formation of uranium deposits of the Mesozoic and Cenozoic sandstones, it is likely that much redistribution and reconcentration of uranium occurred. This may have been an important stage in the formation of these deposits and could best be studied, as with previous topics, in the unmetamorphosed sediments of Gabon.

Host Rocks

Much information is now available on the unaltered and altered host rocks of the major districts. There are, however, important unanswered questions regarding the suitability of unmetamorphosed and metamorphosed sediments as source rocks and sites for ore formation. These considerations could affect exploration and resource studies and might be pursued by the following types of studies:

(1) Lithologic investigations of the carbonaceous (graphitic) and carbonate-rich sequences to establish their characteristics, distribution, organic or inorganic origin, and the significance of these rocks for primary and/or secondary uranium accumulation.

(2) Stratigraphic studies to determine what relations exist between lithologic sequences and primary and/or secondary accumulations of uranium. For example, the not uncommon occurrence of generally dolomitic carbonates

preferentially below or lateral to ore-bearing horizons may reflect ore controls, but this has not been established. At Key Lake, sedimentary cycles are reversed with pelitic sediments (schists) grading upwards into psammitic sediments (quartz-feldspar gneisses, feldspathic quartzites). The significance of this to protore uranium accumulation, if any, has not been established.

(3) Chemical studies of the major and minor elements in the host sediments, particularly in the unmetamorphosed deposits, might provide information on the character of the provenance, the depositional environment, and the suitability of the rocks for re-accumulations of uranium in protore or economic accumulations. The importance of factors such as climate on the accumulation of the uraniferous sediments (i.e., will Aphebian sediments deposited at all paleolatitudes contain comparable uranium concentrations?) should be investigated.

Impact of Metamorphism on Uranium Mineralization

The behavior of uranium during metamorphism has not been investigated in sufficient detail, either theoretically or experimentally. Likewise, the effect of metasomatism, whether related to intrusions, metamorphism, or anatexis-palingenesis, on strata-bound uranium is not yet understood. Field observations suggest, but do not prove, that premetamorphic concentrations of uranium in some stratigraphic settings were relatively immobile during metamorphism, whereas concentrations in other settings appear to have moved. Even under seemingly comparable metamorphic grades, local geologic conditions appear to have produced different results, which we have designated as closed and open systems. Whereas the field relations suggest such a subdivision, it is undoubtedly oversimplified and should be critically reviewed. It may be important that deposits of the strata-structure-bound type (Beaverlodge, Jabiluka, etc.), i.e., those which formed in open systems, occur in close proximity to Late Hudsonian granitic intrusives or migmatitic complexes. It is an open question whether these felsic bodies, or perhaps even basic intrusions such as the Oenpelli Dolerite in the Alligator Rivers district, developed the thermal circulating systems that mobilized uranium and transported it into structures.

At the Gunnar deposit, Saskatchewan, the precise relations between metasomatism, alteration, and mineralization within the zone of the "episyenite" have not been convincingly established. It is conceivable that the Gunnar deposit formed under conditions similar to those that produced the uranium deposits in the Massif Central in France (see Leroy, 1978; and Cuney, 1978). On the other hand, a supergene origin cannot be ruled out until more comprehensive data are available on this deposit.

Metasomatism

Two types of metasomatism have been recognized in close association with the veinlike deposits in Canada and Australia. The first is dominated by the introduction of sodium (e.g., albitization) and potassium that are restricted to the metasediments and which were probably related to late metamorphic-orogenic fluids. The relations between this metasomatism and uranium mineralization, particularly the strata-structure-bound (Beaverlodge, Jabiluka) subtype, are unknown. Characteristics of these deposits might usefully be compared with deposits in the Soviet Union which are described as occurring with albitites (for example, Avrashov, 1980).

The second type of metasomatism is dominated by some combination of magnesium, lithium, and boron that formed authigenic minerals such as magnesium-rich clays, magnesium-chlorite, and tourmaline, in the metasedimentary basement and in the overlying sandstones (i.e., Athabasca and Kombolgie Formations). This metasomatism is probably the result of diagenetic solutions, but the source of these elements is unknown and they are not found in all deposits. Magnesium-rich minerals are abundant at Rabbit Lake but have not been reported at Collins Bay. Two possible sources might be (a) magnesium-, lithium-, and boron-bearing primary minerals in the crystalline basement; or (b) evaporitic brines which formed prior to or during the early deposition of the Athabasca and Kombolgie sediments (both sandstones indicate deposition during a semi-arid to arid climate). In either case, the origin and/or movement of the fluids must have been restricted because the alteration is apparently present in only certain deposits. The distribution of this type of metasomatism and its relation to particular subtypes of the unconformity-bound deposits, if any, needs to be established. Relations between the distribution of alteration zones, particularly in the overlying sandstone, and the location, size and grade of the deposit, might be important to exploration and resource studies. In this connection, J. Hoeve (personal communication, 1980) is investigating the various alteration minerals that occur in the Athabasca Sandstone as halos around deposits. He considers that certain clay minerals formed within the halos can be used as exploration guides.

Pre-Athabasca Uranium Mobilization and Precipitation

The unconformity-related veinlike deposits are believed by some authors to have formed, in part at least, by the mobilization of uranium during deep weathering and regolith formation prior to the deposition of the overlying Middle Proterozoic sandstones. During the period immediately prior to sandstone deposition, some regolithic material may have been locally or regionally redistributed and washed into structure-controlled valleys and lacustrine basins. Mobilized uranium may have contemporaneously accumulated in these depressions through the reduction by carbonaceous matter and sulfides, adsorption on clays, or possibly other mechanisms. These processes are suggested by some field relations, but they have not been established and need to be tested with the following types of studies:

(1) Determine if depressions and valleys on the paleosurface are related to structures and if evidence exists for the redistribution of regolithic material.

(2) Investigate the influence of graphitic horizons on the development of structures, and the role, if any, of graphite and pyrite in the reduction and precipitation of uranium.

(3) Determine if karst structures developed below the unconformity, their time of formation, and relations to uranium deposits. If such structures formed before the deposition of the Kombolgie Formation as has been interpreted by some investigations in the Alligator Rivers district, relatively undeformed Kombolgie sediments should be found within these structures. If the structure developed after the Kombolgie deposition, in-filling should be chaotic. These relations have not yet been described.

(4) Regolith development is presumed important for the formation of unconformity-related deposits at the Lower-Middle Proterozoic paleosurface. Thus, such deposits should be absent where regolith is absent under cover sediments such as the Martin Formation. Also, if the uraniferous basement is important to ore formation, regoliths developed on cover rocks such as the Martin Formation should not have associated deposits unless the rocks contain uraniferous volcanics or other uranium sources. These tentative conclusions appear to be supported by field relations but should be tested where field conditions present thick regoliths or unweathered uraniferous Lower Proterozoic metasediments.

Influence of Cover Sediments on Uranium Mineralization

Interpretations of geologic relations suggest that the lithologic nature and time of sedimentation of the cover sediments may have had considerable impact on the nature and distribution of uranium deposits. Two types of geologic relations at the unconformity are recognized. In the first, sediments rest unconformably on the metasediments on which a regolithic weathering zone is not developed; in the second a regolith is present.

Unconformities without regoliths suggest that either (a) the climate was inappropriate for the development of a regolith, (b) the cover sediments were deposited before a regolith could develop, or (c) whatever regolith formed was subsequently eroded. In the case of the Beaverlodge district, the relatively old age of the Martin Formation suggests it was deposited early, after only physical erosion of the basement, and that it protected the metasediments from weathering. Whereas this setting permits the occurrence of Beaverlodge-type mineralization essentially up to the unconformity, it precludes the development of true unconformity-related deposits. Where not protected by suitable sandstone cover, for example in the South Athabasca Region, the upper portions of strata-structure related deposits are interpreted to have been destroyed during regolith development. It is uncertain, however, whether the formation of the Beaverlodge-type deposit involved any post-metamorphic processes, in particular post-Kombolgie diagenetic processes. Sassano et al (1972b) have found evidence that non-magmatic fluids affected the Beaverlodge mineralization. If these processes were operative, their effects on the deposits, if any, have yet to be determined. The Bolger deposit, for example, occurs at the unconformity, but it is uncertain whether its genesis is more related to late metamorphic or later diagenetic processes.

With respect to unconformity-related deposits that are associated with strongly weathered basement rocks, there are numerous important unresolved questions, the most important of which include:

(1) What effect does the composition and depositional environment of the cover sediments have on ore-forming processes? Will important ore occurrences be limited to metasediments below continental sandstones?

(2) What factors affect the preservation of regoliths and any uranium concentrations they might have contained? Presumably the rapid deposition of cover sediments, avoiding long periods of exposure, would be most favorable. What other geologic conditions might have been important?

(3) If, as Hoeve et al (1979) suggest, the uranium in the deposits was derived from the overlying sandstone through leaching by diagenetic and other solutions, the development of the regolith and the length of time between its formation and sandstone deposition are unimportant. Accumulating field evidence suggests that this is not the case, but its importance to exploration requires that remaining uncertainties be resolved.

(4) If the uranium deposits formed from the upgrading of uranium preconcentrations in regolith by post-Athabasca diagenetic solutions, as suggested by Pagel et al (1979), then the same primary ore minerals should be found in both the basement and the overlying sandstone. This is not the case at Key Lake, at least. The importance of these processes, and the conditions under which they might have played a role in ore formation, have yet to be established.

(5) If the unconformity-related deposits were formed from diagenetic solutions that derived the uranium from unweathered uraniferous basement without regolithic processes, as suggested by some authors, then deposits such as the Key Lake deposits should also be found below, for example, the Martin and Kombolgie Formations. It is possible that the Bolger orebody in the Beaverlodge region is an example of this type of deposit. Furthermore, deposits might then be expected in uraniferous basement under sandstones of other ages. The 1000 m.y. old Fond du Lac sandstone in Michigan, which overlies uraniferous Aphebian metasediments, might then be expected to overlie such deposits even though no regolith is present below the unconformity. The absence of such deposits thus far suggests that the regolith processes are important to the formation of unconformity-related veinlike deposits.

Diagenetic Processes

As discussed briefly above, many authors believe diagenetic processes played an important role in the formation of unconformity-related deposits. Some authors, such as Pagel (1975b) and Pagel et al (1979), assign to diagenetic processes the major role in ore-deposit formation, deriving the uranium from protore concentrations in the regolith. Other authors, by contrast, believe the effects of diagenesis were mainly the alteration and recrystallization of existing mineralization formed by earlier supergene processes (Dahlkamp, 1978). Criteria have not yet been developed to evaluate the relative importance of these processes. They both require, however, that the uranium have been present in the basement rocks prior to sandstone deposition. It seems important to establish the relative importance of these processes because their associated geologic characteristics would then provide guides for identifying favorable areas. Some geologic characteristics possibly important for resolving these relations include:

(1) Magnesium, lithium, and/or boron metasomatism occur both in the basement and the overlying sandstones in the Athabasca and Alligator Rivers regions. The distribution of these elements within both basement and sandstone indicates the processes occurred after sandstone deposition.

(2) The presence of magnesium chlorite at Rabbit Lake and Jabiluka, where it also occurs in the overlying Kombolgie sandstone, indicates that this type of chlorite formed after regolith development and sandstone deposition.

(3) The basal part of the cover sandstones and the gangue-mineral assemblage within the deposits contain some minerals in common and minerals with similar fluid inclusions (Pagel, personal communication, 1980). This indicates that the fluids moved within the basement and the sandstones and may have affected uranium distribution. However, Pagel (1975b) and Pagel et al (1979) point out that their studies have not identified fluid inclusion-bearing gangue minerals that are clearly paragenetically related to uranium ore minerals. The relations between uranium mineralization and these diagenetic alterations are, therefore, still uncertain.

Mineralogy, Mineral Chemistry, and Crystallography

The identification of ore and gangue minerals within veinlike deposits is generally incomplete. Mineral assemblages and parageneses and the isotopic and chemical composition of the various phases have not been systematically studied. Crystallographic and mineral-chemical studies of the various uranium oxide phases (uraninite, pitchblende, tetragonal α U_3O_7) and their genetic relations to different metamorphic grades and metasomatic and/or diagenetic processes are lacking. It has been observed, near Key Lake, for example, that cubic crystals of uraninite are present as disseminated protore occurrences in the Wollaston Belt. In the deposit itself, however, uraninite was not detected, only colloidal pitchblende and tetragonal α U_3O_7. Crystalline uraninite also occurs in the Beaverlodge district and has yielded a radiometric age of 1700-1800 m.y., i.e., equivalent to the Hudsonian Orogeny.

Based on the occurrences mentioned above, it seems probable that cubic uraninite is the product of higher temperatures of formation, presumably during metamorphism. On the other hand, it is not clear what temperature represents the maximum temperature of formation of pitchblende. The clarification of these relations is important to studies of ore formation and control. As presently interpreted, cubic uraninite is an important indicator of primary uraniferous metasediments; but, in itself, it is not an indicator of the presence or proximity of uranium deposits.

The gangue mineralogy of some deposits has been described by previous authors in considerable detail. Some investigators have also described mineral assemblages and parageneses, particularly for the ore stages. Thorough studies are still limited, however, to a few deposits, and only in the case of the Beaverlodge district, and to some extent the Rabbit Lake deposit, are studies based on extensive exposures in mine workings. These studies have contributed significantly to the description and understanding of these types of deposits, but many of the observations and conclusions are still preliminary, and it is uncertain how successfully they will be extended to other deposits. Although many of the general interpretations and conclusions are likely to survive, many concepts will doubtless require revision as more complete data become available. Mineralogic and geochemical studies could now provide answers to some of the numerous, important remaining questions regarding the genesis and controls of these deposits. Some of these include:

(1) Were sulfide minerals involved in any way in the formation of the deposits? Are sulfides indicative of favorable environments? Did sulfide oxidation lead to the reduction and precipitation of uranium at any stage in the complex history of the deposits?

(2) Did graphite play an important role directly or indirectly in the precipitation of uranium, as is assumed by some authors?

(3) Did methane, which is presently observed at Rabbit Lake, Collins Bay, and other places, form from graphite, or did it form from other forms of carbon such as unmetamorphosed organic material in pre-Athabasca sediments as described by Pagel et al (1979)?

(4) Was organic material important in the accumulation of uranium, either through reduction or adsorption, in the unconformity-related deposits such as the D orebody at Cluff Lake?

(5) Regolith is interpreted to form under conditions of abundant moisture with strong chemical but negligible mechanical weathering. By contrast, the overlying sandstones were presumably deposited under more arid conditions which may have led to the development of evaporitic brines. Verification of these interpretations could help explain the diagenetic metasomatism recognized in some deposits and its possible impact on ore formation.

(6) Evidence suggests that uranium in the Alligator Rivers district, Australia, correlates with arsenic, niobium, molybdenum, lead, lithium, scandium, and cobalt (Ferguson et al, 1979b). Is this or any other element suite typical of all veinlike deposits or certain subtypes of deposits, or does the associated element suite only reflect local geologic conditions?

(7) In some deposits uranium is associated with other elements such as nickel (Key Lake), gold (Jabiluka), lead and copper (Rum Jungle), etc. What controls these associations; what information do they provide about ore formation and distribution?

(8) Studies of stable isotopes and fluid inclusions for ore-related minerals have already revealed distinct varieties among them. Attempts have been made to relate the results to certain genetic processes. Further studies are required to establish the genetic relations between the uranium-ore minerals and those minerals for which fluid inclusion and isotope data have been collected. Combined with thin and polished section study of ore and host rocks, these investigations should help resolve many of the unsolved problems regarding the ore-forming fluids (hypogene, supergene, and/or diagenetic ?) and conditions of ore formation.

(9) Formation of the unconformity-related deposits, by whatever model, involves numerous reactions between solutions and rock components during processes such as weathering and diagenesis. The chemical behavior of uranium and related elements during these various process stages needs to be understood if a reasonably accurate model of ore formation is to be developed.

(10) Sodium-potassium metasomatism is well documented in the vicinity of several veinlike deposits, but its origin and relations to uranium concentrations are open to question. Does it simply reflect proximity to anatexis-palingenesis, or does it reflect sediments of particular compositions within the Lower Proterozoic rocks? What is the importance of such metasomatism to the formation of the uranium deposits?

(11) Data from uranium-lead isotope studies of Cluff Lake ore are interpreted (Gancarz, 1979) as evidence that uranium was introduced from an outside source into the D orebody at Cluff Lake at 800-900 m.y. This mineralization is definitely younger than the earlier pitchblende (about 1200 m.y.). The source of this additional uranium and the reason for its transport into already-existing (?) orebodies are unknown. What was the nature of the ore-bearing fluids, and is this event reflected in other unconformity-related deposits?

(12) Conditions of formation of the Gunnar deposit are even more uncertain than most of the veinlike deposits. Was it formed by metasomatic processes, as mentioned in (10) above, by supergene processes, or by intragranitic hydrothermal processing as described by Cuney (1978) and Leroy (1978) for uranium deposits in the Massif Central in France? "Episyenites" are present at Gunnar and in the Massif Central and in Vendée in France, but did they form by similar processes? Mineral-chemical studies such as those conducted by B. Poty indicate the types of investigations that will contribute to the understanding of the formation and ore controls of this type of deposit.

Age Determinations

Reliable age dates for minerals of the various stages that formed the veinlike deposits would establish the relations between the process stages and other geologic events. However, the superposition of stages and processes and the high mobility of uranium have produced complex geologic relations and masked or obliterated earlier events. This has led to a possible overemphasis of late ore-forming events and difficulty in recognizing those events related to metamorphism and basement erosion and weathering.

Age dates have, nonetheless, been useful in studies of the veinlike deposits. For example, it is known that the rocks which host these deposits (below the Lower-Middle Proterozoic unconformity) are of essentially identical metamorphic ages in all the districts (1900 to 1700 m.y.). Age dates on the oldest ore mineralization at Beaverlodge, in particular uraninites but also pitchblende, yield dates of almost 1.8 billion years, i.e., time-equivalent to the orogenic event. Uranium-lead determinations establish the next important ore-forming event at about 1.2 billion years in the unconformity-related deposits.

Documentation of these ore-forming events is based upon limited geologic data, and it is now important to date those uranium and gangue minerals which appear to have been formed during other possible stages. For example, cubic uraninite of the low-grade protores of the Wollaston Fold Belt and equivalent mobile belts should be dated. Such uraninite may be expected to yield ages for the Hudsonian metamorphic event.

The interpretation of uranium-lead age dates poses problems in open systems such as the strata-structure-bound deposits and the unconformity-related deposits appear to have been. Separation of uranium from lead during the multiple remobilization offers considerable opportunity for ages that are younger than the original introduction of the uranium. Locally abundant galena with high concentrations of radiogenic lead at Key Lake, for example, is evidence for this type of uranium-lead separation. It is expected that future studies of carefully selected and prepared samples will ultimately identify samples that have remained sufficiently closed to reflect most, if not all, of the stages in the formation of these important and complex deposits.

RECOGNITION CRITERIA

The geologic data for veinlike deposits summarized in this report have identified numerous geologic features that are characteristic of one or more of the deposit subtypes. The working model presented in a preceding section emphasizes those ore-forming processes and stages that appear to have been most important in the formation of economic deposits of the various subtypes. With this background, it would be useful to summarize those geologic characteristics or recognition criteria that are most diagnostic for the presence or absence of veinlike deposits in unexplored areas. Such recognition criteria could be applied in resource studies and exploration to estimate the geologic favorability of areas for the occurrence of veinlike deposits.

The differences between veinlike deposits, and our inadequate understanding of aspects of ore formation and ore controls, introduce major uncertainties into the selection of recognition criteria and in their application to exploration and resource investigations. If the geologic characteristics of each subtype of deposit were better documented and understood, detailed criteria could be more confidently selected and applied. In lieu of this, we have limited our recognition criteria to some general geologic features which are based largely on observations, hence are less sensitive to variations in interpretation. These criteria should prove useful even though the details of ore formation and control are incomplete.

A recognition criterion for a type of deposit is simply a geologic observation that has been shown to be predictably related to that type of deposit. To be useful in resource studies or exploration, recognition criteria are chosen so that: (a) when they are present or "favorable", the chances of a deposit being present are significantly increased, i.e., they are important "good news" for the occurrence of a deposit; or (b) when they are absent, or unfavorable, the chances of a deposit being present are significantly decreased, i.e., the negative criteria are important "bad news". Some recognition criteria have both attributes and are thus particularly useful. By using only criteria that significantly affect the likelihood of a deposit being present or absent, one avoids the distraction of including geologic observations which are too ubiquitous or undiagnostic to be useful guides to the favorability of an area.

The eight major geologic recognition criteria for the subtypes of Lower to Middle Proterozoic veinlike deposits are tabulated in Plate II. The presence or absence of each criterion is important to one or more of the fourteen subtype examples (a through n) that are shown in Plates I, II, and IV. Some criteria are important to several of the deposit subtypes. To these criteria is added anomalous uranium concentrations in Archean granitoids and Lower to Middle Proterozoic sediments, the presence of which is important to all veinlike deposits.

The evaluation of areas for the types of deposits discussed in this report first must determine if Lower to Middle Proterozoic uraniferous sediments are present. Where such sediments are identified, the eight criteria in Plate II can be used to determine which deposit subtypes, if any, are likely to be present. Reference to the more extensive discussions of these criteria in the text will provide some indication of the degree of geologic similarity with better described districts, hence some indication of the likelihood that a deposit is present.

The significance of anomalous uranium concentrations and the eight recognition criteria of Plate II to favorability for veinlike deposits may be briefly summarized as follows:

(1) Uranium Anomalies--Veinlike uranium districts are characterized by strata-bound uranium concentrations and widespread occurrences of uranium in pegmatites, calcsilicate rocks, and other preferred lithologies. These anomalous concentrations, generally presumed to be the source of the uranium in the deposits, provide an important criterion for exploration and resource studies.

(2) Host Rocks--Veinlike districts occur preferentially in carbon-rich metasediments composed of mixed pelites, psammites, and carbonate rocks. Less important for most subtypes are volcanic-bearing sediments.

(3) Alterations--Albitization, magnesium, boron, and lithium metasomatism, and magnesium and iron chloritization are variously associated with some of the deposit subtypes. The recognition of these alterations are important criteria for establishing favorability for certain subtypes of veinlike deposits.

(4) Unconformity--Essential for the unconformity-related deposits. The presence of sandstone above the unconformity (see text) may be necessary for certain types of unconformity-related deposits.

(5) Paleosols--All clearly unconformity-related deposits occur with well-developed regolith, suggesting it is an important criterion for these deposit subtypes.

(6) Depth Extension--The position of veinlike uranium occurrences with respect to an unconformity suggests the subtype to which the occurrence belongs. Deposits that extend several hundred meters below an unconformity, or that are unrelated to an unconformity, are most likely strata-related or strata-structure-related deposits. Identification of the style and subtype of mineralization provides considerable guidance for further exploration.

(7) Proximity to Archean Domes--Veinlike deposits occur on the flanks of present-day Archean domes. This relation offers a useful exploration guide which can be exploited with geophysical methods.

(8) Proximity to Hudsonian Intrusives--Only a few of the deposit subtypes appear to occur in proximity to Hudsonian intrusives and zones of anatexis and palingenesis. These features are apparently unfavorable for the occurrence of other deposit subtypes.

Each recognition criterion is discussed in various parts of the text with respect to the geology of major veinlike deposits and districts. Reference to this material is necessary to augment the cursory descriptions presented in Plate II. Although each criterion is an empirical observation based on the field relations discussed in the text, together they suggest ore-forming processes that operated during Lower to Middle Proterozoic sedimentation (uranium anomalies and proximity to Archean domes), during metamorphism (albitization and possibly other alterations), during erosion and weathering (paleosol development), and after the deposition of the cover sediments (alterations and mineralization which occur both in basement and cover rocks).

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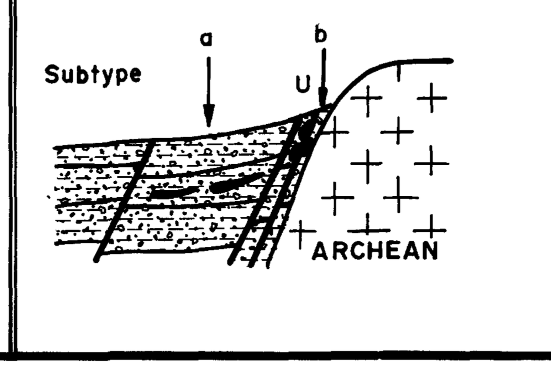
PLATE I

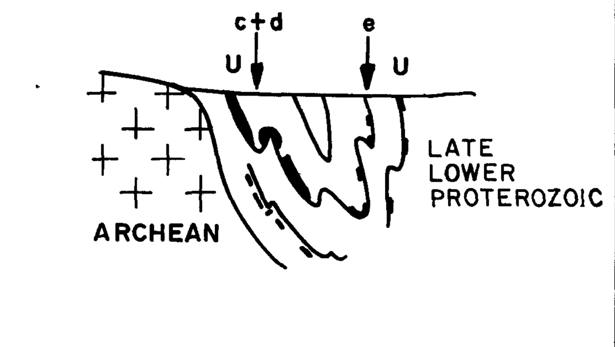
TYPES OF LOWER TO MIDDLE PROTEROZOIC STRATA-RELATED AND UNCONFORMITY-RELATED VEINLIKE URANIUM DEPOSITS AND THEIR GENERAL CHARACTERISTICS

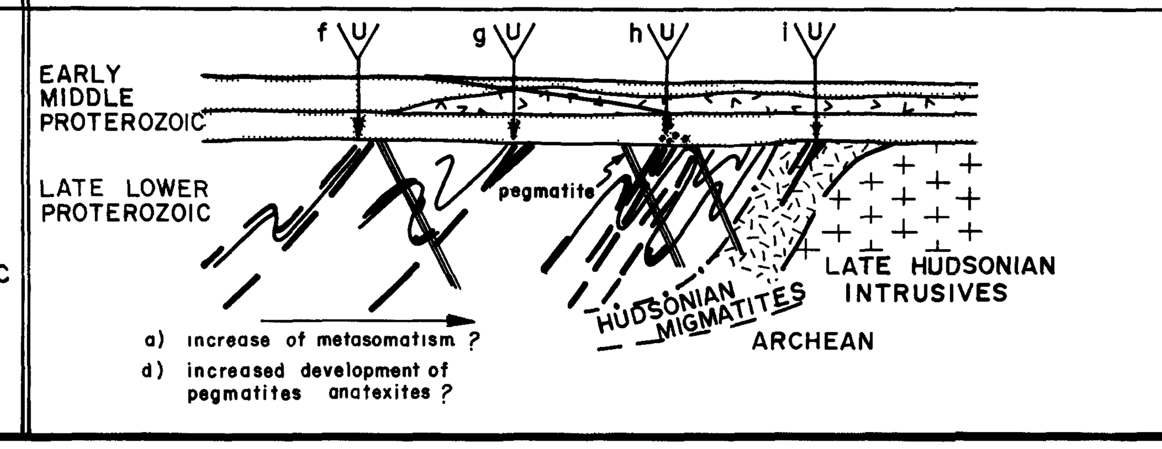
Deposit Types	Host Rocks	Principal Geologic Characteristics	Principal Primary Uranium Mineral	Principal Gangue Mineral: VEIN FILLING	Principal Gangue Mineral: OTHERS (replacement, etc)	ASSOCIATED METALS	Uranium Reserves: DIMENSIONS	Uranium Reserves: TONNAGE DEPOSIT	Uranium Reserves: TONNAGE DISTRICT	Uranium Reserves: GRADE U_3O_8 PERCENT
1. Sedimentary Host Rocks 1.1 Strata-related deposits 1.1.1 Strata-bound subtype a: Oklo 1.1.2 Strata-structure bound subtype b: Mounana	continental sandstones, arkoses, variable carbonaceous material overlain with slight unconformity both subtypes occur in same stratigraphic horizon	(a) Mineralization associated with or adjacent to carbonaceous matter, i.e., primary lithologic control; no alteration or unconformity control (b) Redistribution (?) of primary mineralization related to faults but within same horizon	1.1.1 pitchblende uraninite in zone of natual reactors 1.1.2 pitchblende	- - - - -	chlorite associated with U is found at natural reactor sites - - - -	Vanadium	l <100 m w < 40 m d <120 m l <900 m w <600 m d <300m	up to 6000 t up to 13,000 t	25,000 t	0.2 to 0.5% 0.4% with zones up to 60% U_3O_8
2. Crystalline Host Rocks 2.1 Strata-related deposits 2.1.1 Strata-bound subtype c: Kitts; probably Amer Lake subtype d: Michelin subtype e: Protore in Tazin-Wollaston Belts; Amer Group, Thelon region	(c) metasediments and metavolcanics (d) acid metavolcanics (e) metapelites and metapsammites adjacent to graphitic horizons; apatite-bearing sediments, calc-silicate rocks, metamorphic grade amphibolitic to granulite facies	Mineralization controlled by lithology; no alteration or unconformity control; cover rocks unimportant	2.1.1 (c) uraninite and/or pitchblende (d) uraninite and/or pitchblende (e) uraninite; uranium in lattice or cleavage planes of several minerals (apatite, biotite, etc.)	2.1.1 (c) - (d) - (e) -	- - -	2.1.1 (c) - (d) - (e) Ni, Mo, Pb, Zn	l m to 100s m w cm to 10 m d <200 m l m to >1000 m w cm to m's d >300 m l m to 100 m w cm to m d >1600 m	t to >1000 t t to >3500 t t to >10 t	up to several 1000 t up to several 1000 t up to several 1000 t	ppm to 0.2% ppm to 1% ppm to several %
2.1.2 Strata-structure bound (associated with Lower Proterozoic uraniferous metasediments) subtype f: Jabiluka II; Koongarra subtype g: Ranger One; South Alligator River (?); roots of Rabbit Lake (?); Rum Jungle (?) subtype h: Beaverlodge; Nabarlek (?) subtype i: Gunnar	metapelites and metapsammites adjacent to graphitic horizons with chloritic, argillic, hematitic, and sericitic alteration; original metamorphic grade was amphibolite-granulite facies Increasing influence of anatexis or intrusions: (f) (g) (h) (i) ↓	Mineralization generally adjacent to graphitic horizons in zones of fracturing and alteration; Na and/or Mg metasomatism; no minor paleosol; covered by lower Middle Proterozoic sediments and volcanics; position of mineralization may be related to zones of intrusion and anatexis - palingenesis - migmatization; numerous pegmatites and dikes; mineralization affected by later diagenesis related to cover rocks	2.1.2 (f) uraninite and/or pitchblende (g) uraninite and/or pitchblende (h) uraninite and/or pitchblende (i) uraninite (?) and pitchblende; uraninite was probably formed at high temperatures but has been completely transformed to pitchblende by later processes	2.1.2 (f) - (g) (h) calcite, dolomite, quartz, chlorite (?) (i) quartz (?) chlorite (?)	chlorite, sericite, kaolinite, silica/quartz, carbonate, hematite locally Mg-chlorite, authigenic tourmaline in Kombolgie sandstone and basement epidote	2.1.2 (f) Au (g) Cu, Pb, Zn (h) Co, Ni, Pb, Cu-As, Se, S, Pt, Au, Ag (i)	l >1000 m w > 400 m d > 500 m l > 600 m w < 500 m d > 400 m l m to 100 m w cm to m d >1600 m l up to >100 m w up to >100 m d > 600 m	>200,000 t >50,000 up to 1000s t up to 8000 t	4,000,000 t up to 30,000 t ?	0.2 to 0.4% 0.1 to 0.3% 0.2% 0.1 to 0.3%
2.2 Unconformity-related deposits 2.2.1 Structure-bound (associated with Lower Proterozoic uraniferous metasediments) subtype j: N and Claude, Cluff Lake; Key Lake; Rabbit Lake subtype k: Thelon Basin	a) metapelites and metapsammites, generally adjacent to graphitic horizons; strong fracturing and mylonitization; chloritic, argillic, hematitic, sericitic, and carbonate alteration; intense weathering below unconformity; original metamorphic grade amphibolite to granulite facies b) continental sandstones overlie deposits in basement	Mineralization is in fracture zones immediately below Middle Proterozoic unconformity; crystalline Aphebian rocks are strongly altered by paleoweathering and ore-related processes; paleosol is up to several tens of meters thick; mineralization is commonly in structures which follow graphitic horizons that are close to Archean basement domes; mineralization and regolith are covered by continental sandstones	2.2.1 (j) pitchblende and locally tetragonal α U_3O_7 (Key Lake) and uraninite; uraninite at Cluff Lake possibly formed by high T in conjunction with formation of Carswell structure (meteoric impact?) (k) pitchblende	2.2.1 (j) in minor amounts quartz carbonate (k) ?	Fe-chlorite, kaolinite, silica/quartz, sericite, hematite, locally Mg-chlorite, authigenic tourmaline in Athabasca sandstone and basement ?	(j) Ni (Key Lake) (k) (?)	l up to 1000s m w m to 10s m d <150 m l up to 100s m w m to 10s m(?) d <150 m(?)	up to 75,000 t up to 1000s t	>200,000 t ?	0.2 to 2% up to 1% (?)
2.2.2 Sediment-bound (superjacent to Lower Proterozoic uraniferous metasediments) subtype l: D orebody, Cluff Lake A & B zones, Collins Bay (?) B zone Maurice Bay (?)	pelitic, argillaceous, and psammitic sediments with abundant carbonaceous matter underlying and grading into (?) overlying sandstones	Mineralization occurs strata bound in carbonaceous pelitic sediments which overlie regolith developed on Aphebian metasediments and underlie Athabasca sandstones; some mineralization extends into the Athabasca sandstones	(l) pitchblende and uraninite (see j above)	(l) some quartz and carbonate in veinlets	chlorite	(l) Au, Ag, Te, Se; minor Bi, Co, Ni, Pb arsenides and sulfides (Cluff Lake D orebody)	l 10s to 100s m w 10s m d m to 10s m	up to 1000s t (7000 t at Cluff Lake D ore body)	?	up to sev. %; 10% at Cluff Lake D orebody
2.2.3 Structure-bound (within or adjacent to Middle Proterozoic uraniferous volcanics) subtype m: Baker Lake subtype n: South Alligator River (?) (may also belong to subtype g)	acidic uraniferous volcanics and adjacent metasediments; otherwise similar to 2.2.1	Similar to subtype 2.2.1; this subtype may be similar in some respects to the Phanerozoic Pena Blanca deposits in Mexico; however, hydrothermal processes are considered important at Pena Blanca; the influence of hydrothermal processes in the formation of the Baker Lake mineralization is not known	2.2.3 (m) pitchblende (n) pitchblende	(m) - (n) very minor quartz	- chlorite, silica, uraninite	(m) Au, Pb, Cu, Fe, Ni, S (n) Au, Pb, Cu, Fe, Ni, Co, S	l m to 10s m w mm to m d m to 10s m, max 90 m l m to 10s m(?) w mm to m(?) d m to 10s m(?)	up to 10s or 100s t (?) few to 200 t	? <800 t	up to 1% (?) 0.2 to 2.5% av. 0.55%

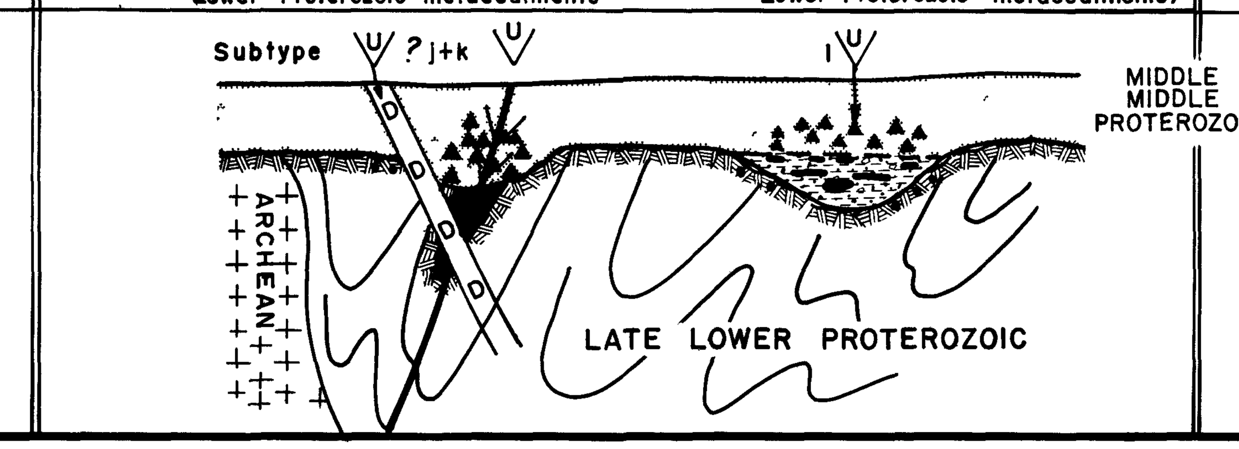
SCHEMATIC GEOTECTONIC SETTING AND MAJOR RECOGNITION CRITERIA FOR THE TYPES OF LOWER TO MIDDLE PROTEROZOIC VEINLIKE DEPOSITS

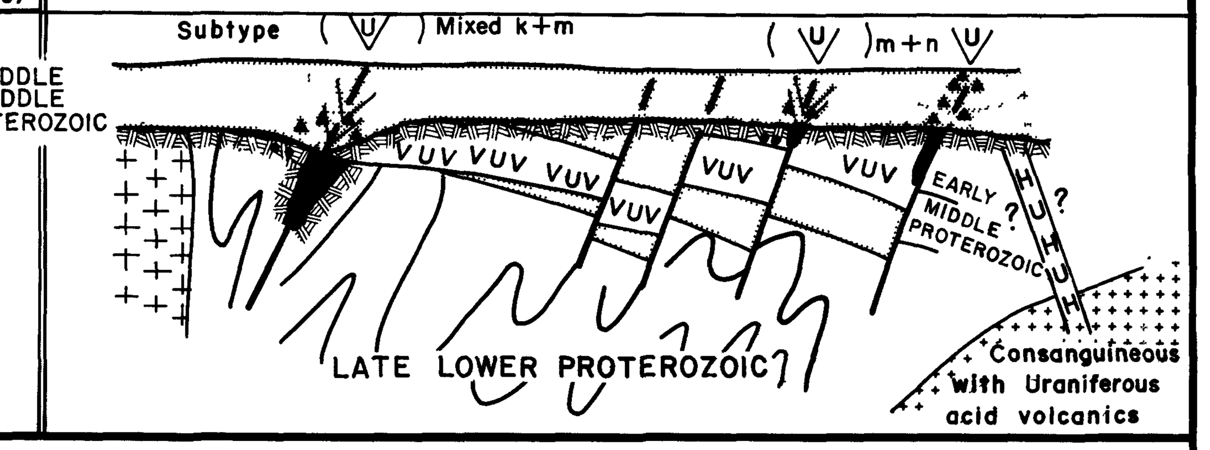
HOST ROCK TYPE	1. Sedimentary Host Rocks	2. Crystalline Host Rocks			
DEPOSIT TYPE	1.1 Strata-related	2.1 Strata-related		2.2 Unconformity-related	
Subtype	1.11 Strata bound; 1.12 Strata-structure bound	2.11 Strata-bound	2.12 Strata-structure bound	2.21 Structure-bound (associated with Lower Proterozoic metasediments); 2.22 Sediment-bound (superjacent to Lower Proterozoic metasediments)	2.23 Structure-bound (associated with Middle Proterozoic Volcanics)











MAJOR RECOGNITION CRITERIA

	(a + b)	(c), (d), (e)	(f, g, h)	(i)	(j, k)	(l)	(m, n, mixed k + m, m + n)
Host rocks	generally carbonaceous sandstones	(c) meta-argillites (generally no graphite); (d) meta-acid volcanic beds (no graphite); (e) meta-pelites/psammites generally adjacent to graphitic horizons	meta-pelites/psammites generally adjacent to graphitic layers	quartz-deficient metasomatized granitic rock (no graphite)	meta-pelites/psammites generally adjacent to graphitic layers	lacustrine (?) sediments with organic matter	acid volcanics and red-bed sandstones; locally metasediments below acid volcanics
Alteration associated with mineralization	some alteration	generally no alteration	strong alteration Na - metasomatism in basement Mg,B,Li - metasomatism in basement and overlying sandstones	strong Na metasomatism (albitization)	strong alteration; Mg, B, and Li metasomatism in basement and overlying sandstones	generally strong alteration	some alteration
Importance of unconformity	not essential	not essential	none	none	essential	essential	essential
Paleosol development	not essential	generally no regolith	regolith minor or absent	no regolith	strong regolith development	strong regolith development	strong regolith development
Depth extension of ore below paleosurface	variable	variable, not limited	variable, not limited	variable	generally less than 150 m below unconformity	along unconformity	generally less than 150 m below unconformity
Protective cover rocks	younger host sediments	no cover rocks necessary	cover rocks essential for protection against erosion or leaching of deposits at/or near unconformity		essential	essential	[illegible]
Vicinity to nearby Archean domes	yes	yes	yes	yes	yes	yes	only for mixed k+m type
Vicinity to nearby Late Hudsonian intrusives or anatexites	no	no	yes ← increase in distance from Late Hudsonian intrusive or anatectic/migmatitic zones		not necessary	not necessary	not established

EXPLANATION

EARLY AND MIDDLE MIDDLE PROTEROZOIC (1700 to 1300 my.)

- Volcanic sediments, sills, dikes
- Sandstones

LATE LOWER TO EARLY MIDDLE PROTEROZOIC (2200 to 1700 m.y.)

- Hudsonian migmatites and quartz deficient metasomatized granitic rocks ("episyenite")
- Granitic intrusion
- Metasediments
- Shales, sandstones, conglomerates (unmetamorphosed)

ARCHEAN TO EARLY LOWER PROTEROZOIC (pré 2200 m.y.)

- Dominantly granitic rocks (uraniferous?)

Symbols:

- Mafic to felsic dike (including pegmatite)
- Diabase dike
- Structure
- Boundary of migmatized Lower Proterozoic sediments
- Regolith
- (a, b, c etc.) Subtypes of deposits

URANIUM OCCURRENCES

- Uranium protore horizon
- U V U V U Uraniferous felsic volcanics
- • • • • Uranium in regolith and pre-Athabasca (?) unmetamorphosed sediments
- ▲▲▲▲ Redistributed uranium
- Strata-bound and strata-structure-bound deposits
- Unconformity-bound deposit
- Carbonaceous sediment-bound deposit
- Hydrothermal uranium veins
- Uranium in outcrop
- Uranium in suboutcrop

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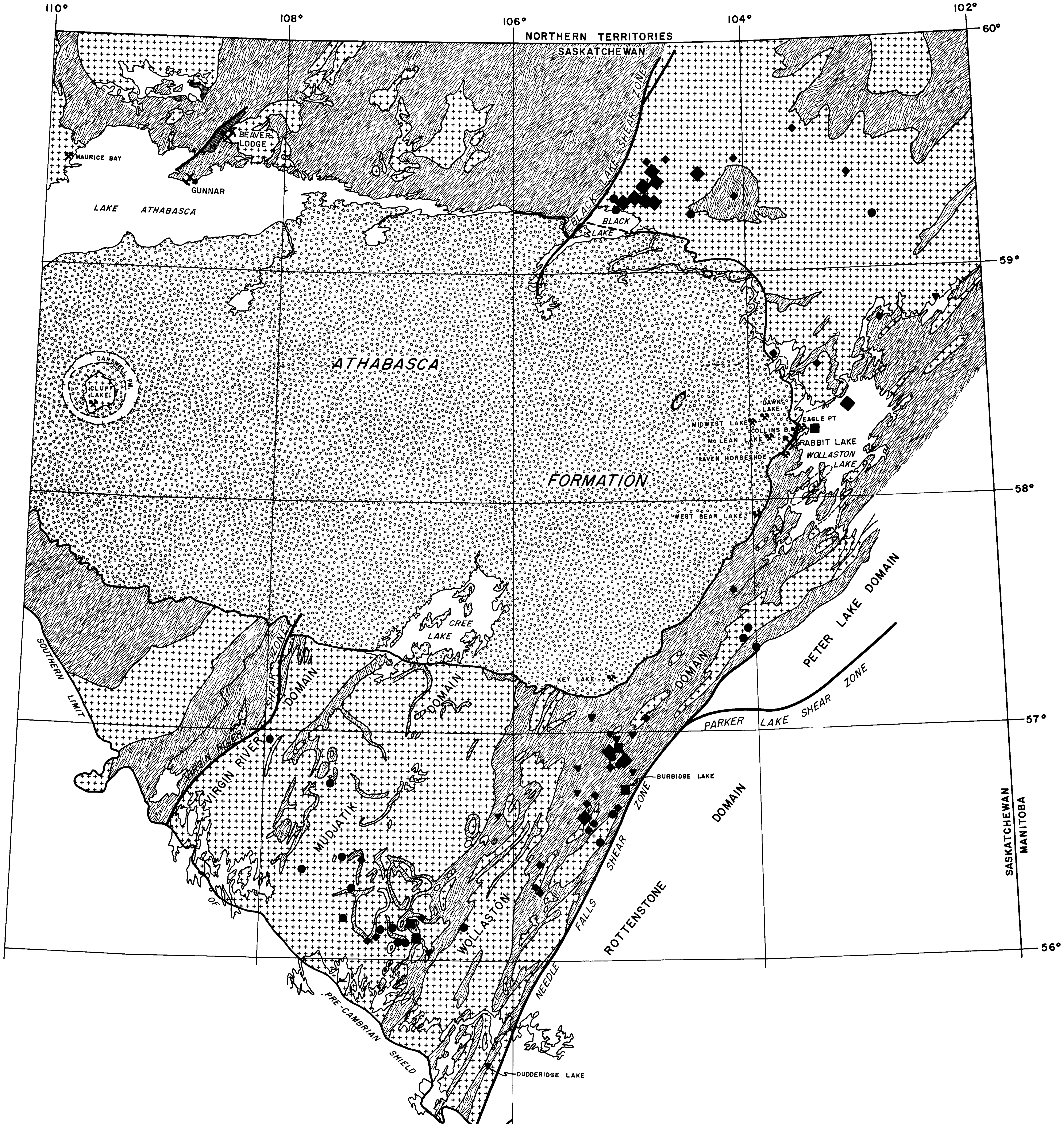
PLATE III



LEGEND

AGE	SYMBOL	DESCRIPTION
NEOHELIKIAN		Athabasca Formation dominantly sandstone and conglomerates
PALEOHELKIAN		Martin Formation
APHEBIAN & ARCHEAN(?)		Supracrustal metasediments and metavolcanics, including pelitic schists and gneisses, psammites, amphibites and hornblende gneisses.
ARCHEAN &/OR APHEBIAN		Granitoids and migmatites

URANIUM MINE

FORMER URANIUM MINE

URANIUM DEPOSIT

URANIUM OCCURRENCES (arranged by host rock type)

- REMOBILIZED BASEMENT SUPRACRUSTAL METASEDIMENTS
- META-ARKOSE
- CALC-SILICATE
- PELITE-PEGMATITE

20 10 0 20 40 60 MI.

10 0 25 50 100 Km.

REGIONAL GEOLOGIC MAP AND URANIUM OCCURRENCES NORTHERN SASKATCHEWAN

NOVEMBER 1980	SCALE 1" = 20 MILES

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Compiled from Thomas (1980); and Whitaker and Pearson (1972)

SCHEMATIC CONCEPT FOR METALLOGENIC EVOLUTION OF LOWER TO MIDDLE PROTEROZOIC VEINLIKE-TYPE URANIUM DEPOSITS

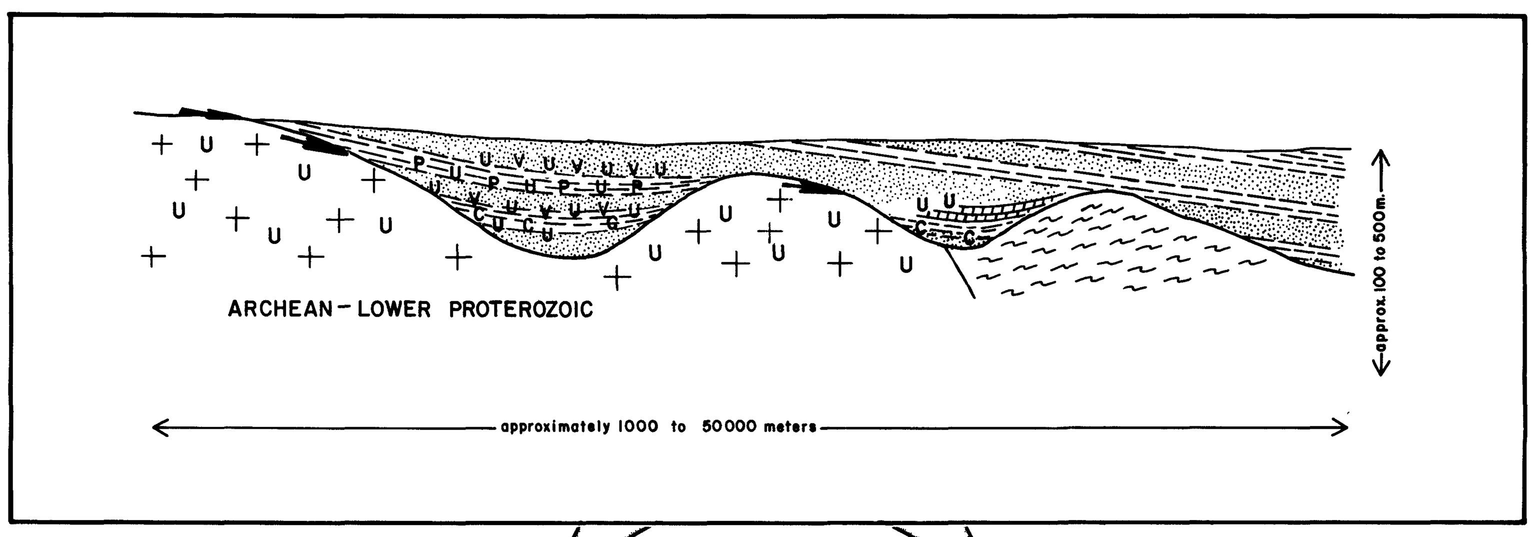
PLATE IV

STAGE I

Deposition and Uranium Enrichment in Favorable Sediments in Restricted Sedimentary Basins

TIME: Middle to late Lower Proterozoic (Aphebian in Canada) (Approximately 2200 to 1900 m.y.)

EXAMPLE: Deposits of Franceville Basin, Gabon



STAGE IIA

Formation of Strata-bound Uranium Deposits in Closed Metamorphic System

TIME: Late Lower Proterozoic (Approximately 1900 to 1800 m.y.)

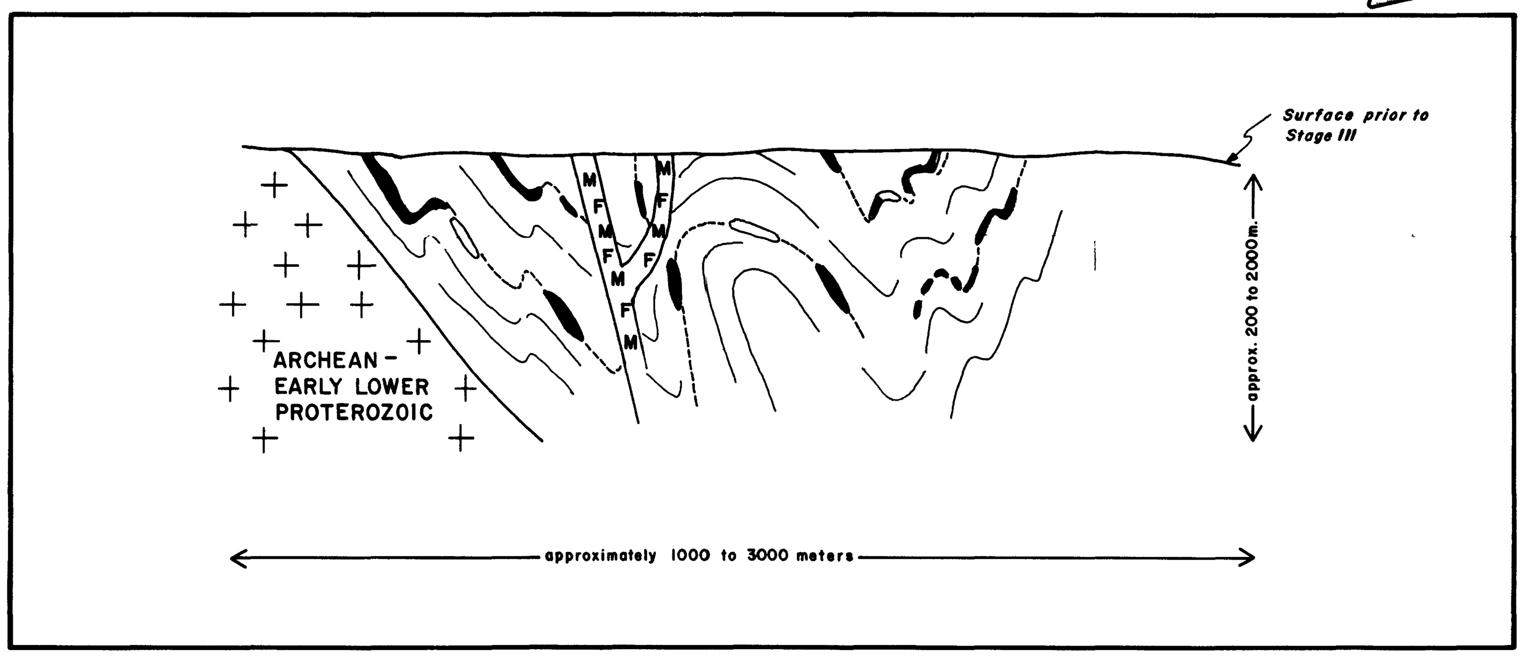
EXAMPLE: Kitts and Michelin deposits, Canada (also protore of uraninite-bearing biotite, apatite, and/or carbonate-bearing gneisses and schists)

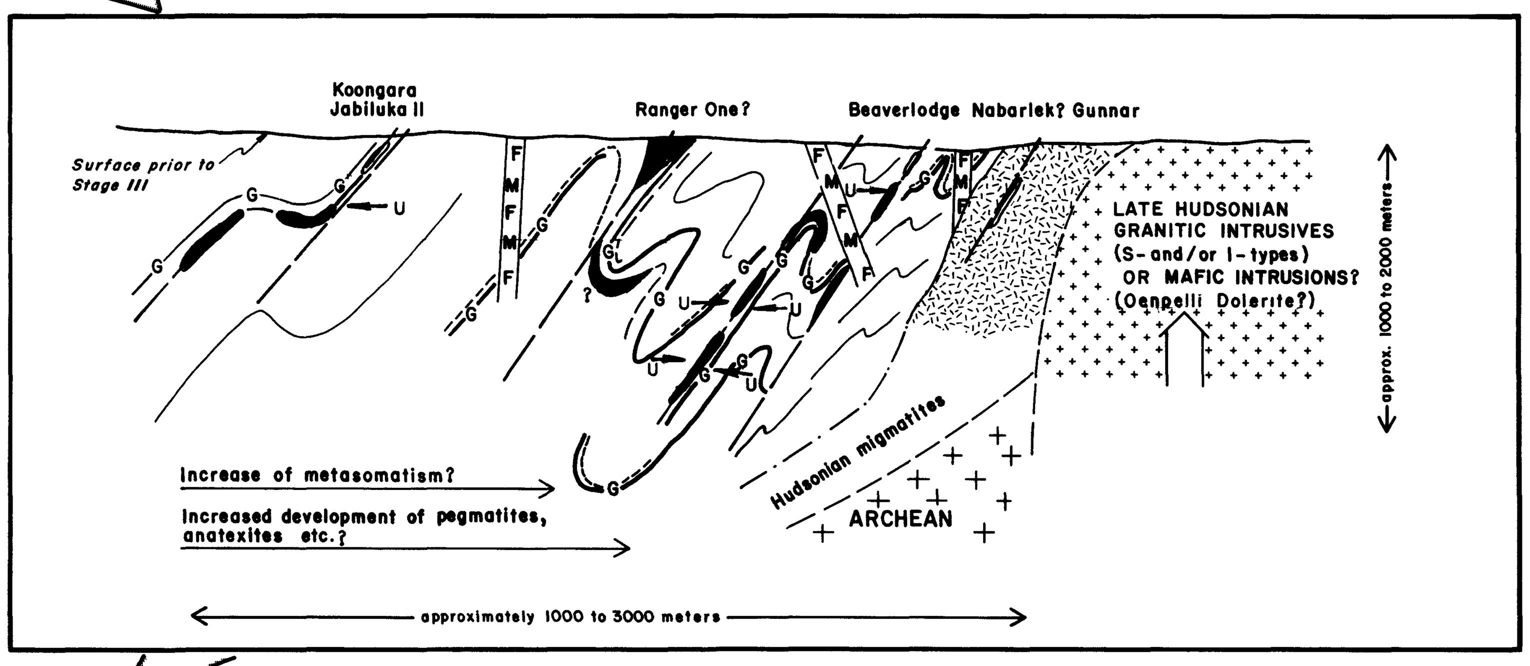
STAGE IIB

Formation of Strata-structure-bound Uranium Deposits in Open Metamorphic System

TIME: Late Lower to early Middle Proterozoic (Hudsonian in Canada) (Approximately 1900 to 1700 m.y.)

EXAMPLE: Deposits of Beaverlodge, Canada and Pine Creek Geosyncline, Australia



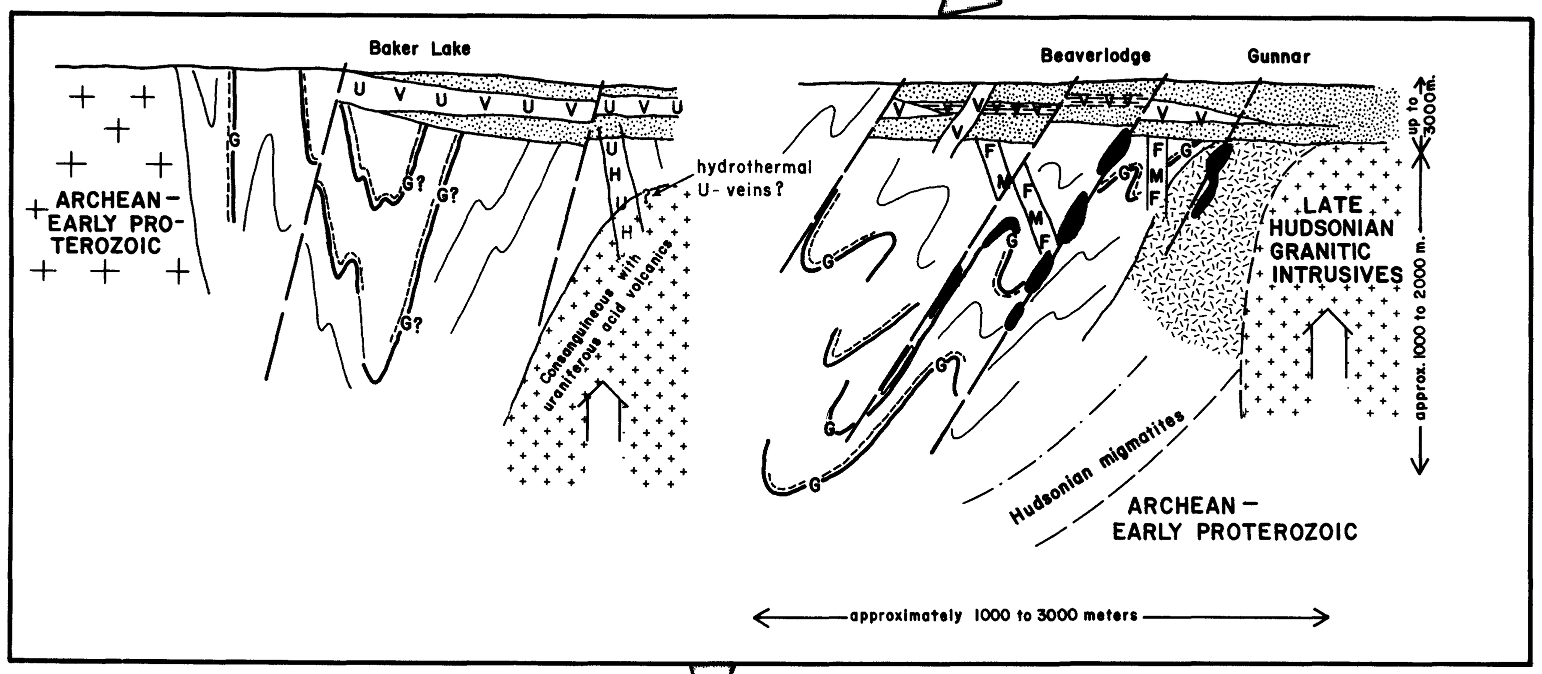


STAGE III

Block Faulting and Deposition of Continental Sediments and Volcanics on Eroded Basement Without Well-developed Regolith

TIME: Early Middle Proterozoic (Early Paleo-Helikian in Canada) (Approximately 1750 to 1500 m.y.)

EXAMPLE: Martin Formation, Beaverlodge Area, and Lower and Middle Dubawnt Formation, Baker Lake Region, Canada; Edith River Volcanics, South Alligator River, and Kombolgie Formation, East Alligator River District, Australia

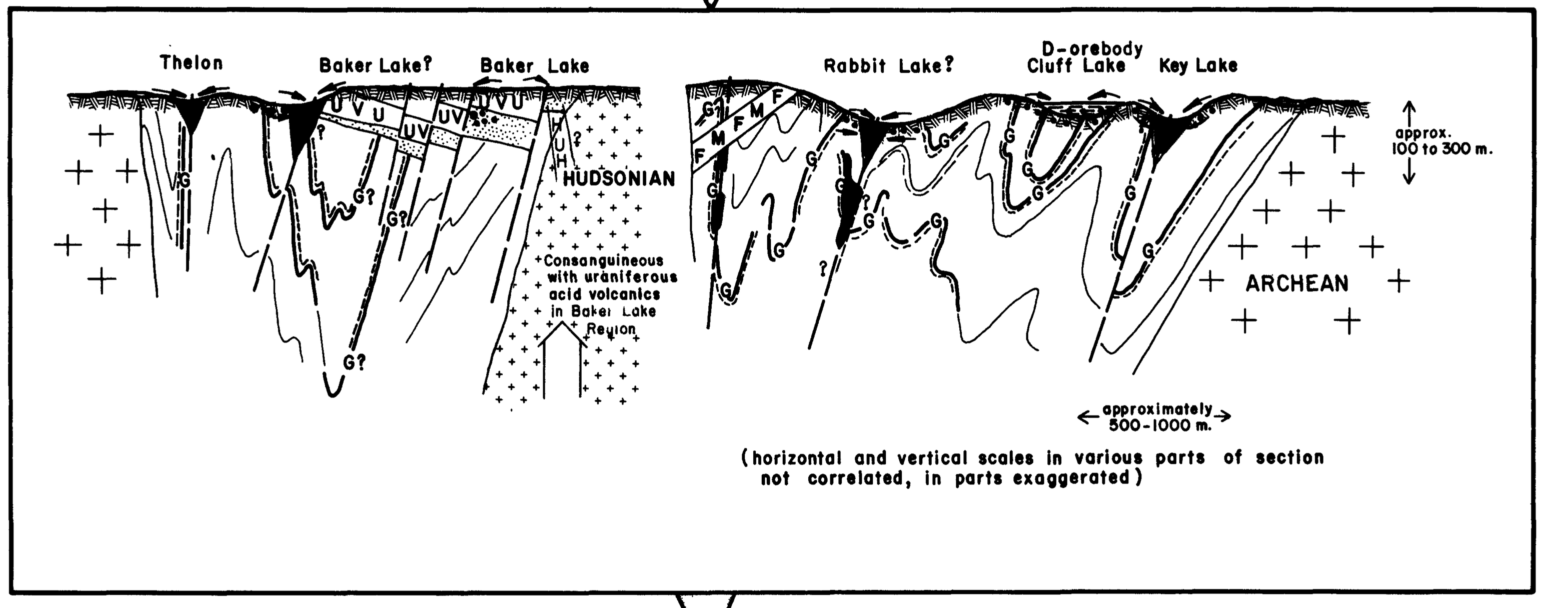


STAGE IV

Leaching of Uranium during Regolith Formation and Concentration in Near-surface Structural and Lithologic Sites

TIME: Early Middle Proterozoic (Paleo-Helikian in Canada) (Approximately 1500 to 1350 m.y.)

EXAMPLE: Southern Athabasca Basin Region, Baker Lake-Thelon Basin Region, Canada

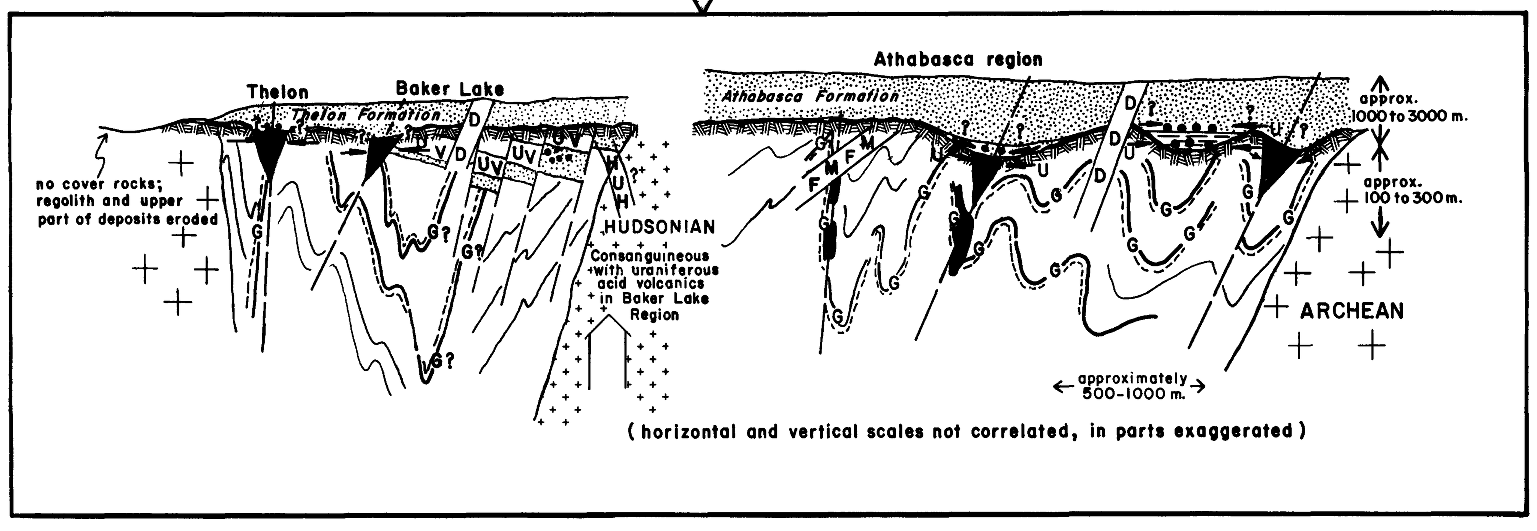


STAGE V

Deposition of Protective Continental Sediments over Deeply Weathered Basement and Diagenetic Overprint on Pre-existing Uranium Deposits or Final Diagenetic Concentration of Uranium in Deposits

TIME: Early to middle Middle Proterozoic (Neo-Helikian in Canada, early Adelaidian in Australia)

EXAMPLE: Athabasca Formation, Athabasca Region; Thelon Formation, Baker Lake-Thelon Region, Canada; Kombolgie Formation, Pine Creek Geosyncline Region, Australia (Note: Basement only slightly weathered before deposition of Kombolgie Formation)

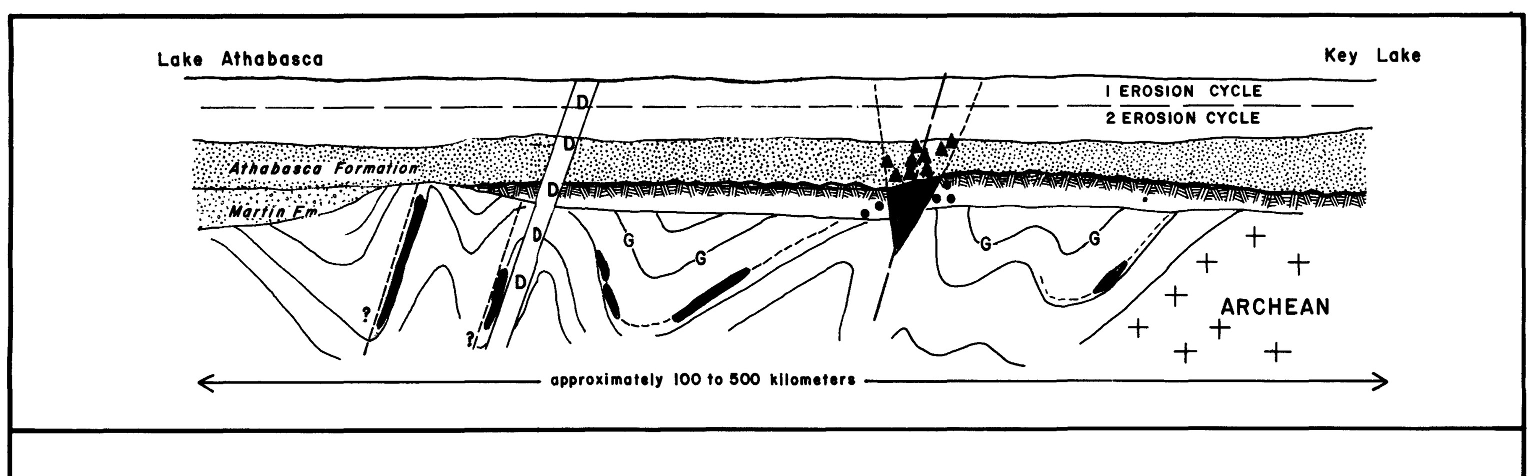


STAGE VIa

Periodic Uplift, Refracturing and Redistribution of Uranium into Overlying Sandstones

TIME: Middle Proterozoic to Late Paleozoic (Approximately 1100 to 200 m.y.)

EXAMPLE: Athabasca Region, Canada

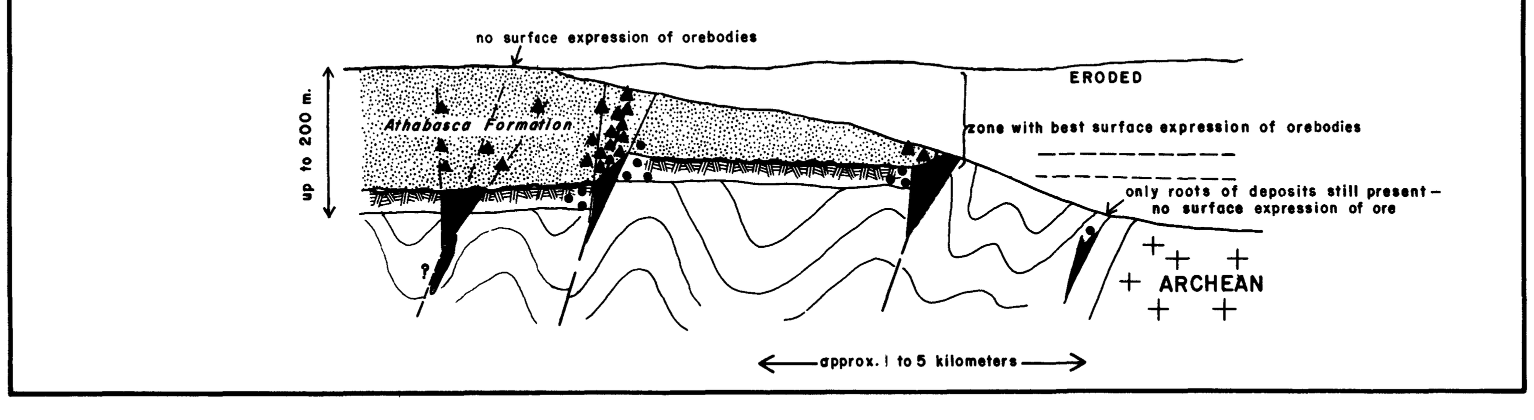


STAGE VIb

Erosional Exposure and Local Destruction of Deposits

TIME: Late Paleozoic to Recent (Approximately 200 m.y. to present)

EXAMPLE: Athabasca Region, Canada



EXPLANATION

LOWER AND MIDDLE MIDDLE PROTEROZOIC (1300 to 1700 m.y.)

- Volcanic sediments, sills, dikes
- Sandstones

LATE LOWER TO EARLY MIDDLE PROTEROZOIC (1900 to 1700 m.y.)

- Hudsonian migmatites and quartz deficient metasomatized granitic rocks (episyenite)
- Granitic intrusion

MIDDLE TO LATE LOWER PROTEROZOIC (2200 to 1900 m.y.)

- Carbonate-bearing rocks
- Dominantly interbedded pelitic and psammitic sediments

ARCHEAN TO EARLY LOWER PROTEROZOIC (pre 2200 m.y.)

- Dominantly granitic rocks (uraniferous)
- Dominantly greenstone belts (non-uraniferous)

- Mafic to felsic dikes including pegmatite
- Diabase dike
- Structure
- Boundary of migmatized Lower Proterozoic sediments
- Graphitic horizon
- Regolith
- P Phosphatic sediments
- C Carbonaceous sediments

URANIUM OCCURRENCES

- Uranium protore horizon
- U V U V U Uraniferous felsic volcanics
- U Uranium occurrence (Concentration range: ppm to percent)
- Uranium movement to structural or lithologic site
- Uranium in regolith and pre-Athabasca (?) sediments
- Redistributed uranium
- Strata and strata-structure-bound deposit (Types f,g,h,i ?)
- Unconformity-bound deposit (Types j,k,m,n ?)
- Pre-Athabasca Sediment-bound (?) deposit (Type l ?)
- Hydrothermal uranium veins

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