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URANIUM RESOURCES AND GEOLOGY OF NORTH AMERICA

PROCEEDINGS OF A TECHNICAL COMMITTEE MEETING
ORGANIZED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
AND HELD IN SASKATOON, CANADA, 1–3 SEPTEMBER 1987

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FOREWORD

Since about the mid seventies, the International Atomic Energy Agency has held meetings on the geology and uranium resources of different geographic regions of the world. These meetings included the ones held in Lusaka 1977, Lima 1978, San Luis 1981, Niamey 1984 and Djakarta 1985 on Africa, South America and Asia and the Pacific respectively.

As a continuation of this series the Technical Committee Meeting on Uranium Resources and Geology of North America was held between 1 - 3 September 1987 in Saskatoon, Canada. The meeting took place in the University of Saskatchewan, hosted by the Department of Geological Sciences in cooperation with Department of Energy, Mines and Resources Canada. Thirtysix technical papers were presented to a group of over 85 participants from seven countries. These papers provided an excellent coverage of uranium occurences and deposits and their geological framework in Canada and the USA, with analogies from other parts of the world.

The Agency extends its appreciation to the authors of the papers and to their respective employers for their efforts in preparing and presenting the papers. Special thanks are due to the Department of Geological Sciences of the University of Saskatchewan and Department of Energy, Mines and Resources Canada for hosting the meeting and making the excellent arrangements. Fred F. Langford of the University of Saskatchewan and also the General Chairman of the meeting, and Vlad Ruzicka of the Geological Survey of Canada were the principal organizers of the meeting.

The Agency's responsible officer was E. Müller-Kahle, Division of Nuclear Fuel Cycle.

EDITORIAL NOTE

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INTRODUCTORY REMARKS

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This is one of a series of regional meetings on uranium resources and geology the Agency has organized over the years, to collect and disseminate information on these topics for the benefit of the geological community of the world. As the number of uranium papers in geological journals has declined over the last years, we believe it is a very important activity of the Agency to continue holding the uranium community together, motivate workers to draft papers on the different aspects of uranium exploration, geology, resources, mining and metallurgy and to publish these contributions.

North America, the region dealt with in this meeting, is of eminent significance for the world's uranium production and the nuclear industry, as will be shown in the following remarks on uranium resources, exploration, supply and demand.

Total WOCA U-resources according to the classification developed by the IAEA and the Nuclear Energy Agency of OECD are periodically collected by these two organisations for their report on Uranium Resources, Production and Demand. Currently, and I use this term to indicate that resource numbers are not static quantities, but variables depending mainly on economics, currently total WOCA known U resources recoverable at costs of less than \$130/kg U or \$50/lb U_3O_8 amount to 3.5 million t U, of which about 25% are located in North America, while the remainder is equally divided among Africa, Australia and the rest of WOCA (Asia, Europe, South America).

In view of the present market conditions with estimated average U-prices of about \$ 80/kg U or \$50/lb U_3O_8, special emphasis should be placed on this lowest cost category of which about 2.5 million t U are known to exist in WOCA. Of this, North America hosts about 16%, with Canada contributing the lion's share of about three quarters. The remaining 84% of WOCA's lowest cost U resources are about equally divided among Africa, Asia and the rest of WOCA.

Uranium exploration as we all know has decreased from the peak of end 70s/beginning of the 80s. Data collected for the 1987 NEA-IAEA report "Uranium Resources, Production and Demand", indicate that total WOCA exploration expenditures in 1987 US-dollars decreased between 1981 and 1986 from about 670 million US dollar by about 80 % of the peak.In the same time, exploration expenditures made by companies in countries other than their respective home countries, have fared better as these expenditures declined from 208 million US dollar in 1981 "only" by about 65%. This means that in 1981 less than one third of total exploration expenditures were incurred by companies in countries other than their home bases, while in 1986 this share has increased to over 55%. As regards future projections there are indications that the total WOCA exploration budgets level off at about 150 million US dollar, of which about one third is being expended in Canada and the US alone.

Looking at the exploration from the North American point of view, we see that in 1981 over 50% of all WOCA exploration expenditures were expended in this region, while this percentage dropped to 33% in 1986. However, it is noteworthy that the level of Canadian exploration expenditures expressed as a percentage of the total WOCA remained constant at about 16%, while the US share decreased from 34 to 17%.

As regards the uranium production development for the same period 1981 - 1986. The total WOCA production decreased from over 44.000 t U to nearly 37.000 t U or by 17%. In the role of the two North American producers Canada and the USA a drastic shift has taken place in this 5 year-period: while the US production decreased from nearly 15.000 t or 34% of the total to 4.900 t or 13% of the total, the Canadian production increased from 7.700 t to 11.700 t and reached with 32% of the total in 1986 nearly the position the US held in 1981. We all know the reasons for this change and one of the speakers will probably provide us with more details on this development. In summary, however, the North American U production decreased slightly from over 50% in 1981 to 45% but occupies still the first place among the WOCA U producing regions, followed by Africa with Gabon, Namibia, Niger and South Africa with a combined share of about one third of the total WOCA production.

Now to the short term uranium supply-demand situation; this is a time frame we are quite certain about as the demand comes from nuclear power plants which are existing, under construction or firmly planned. You know that we have recently achieved a supply-demand balance. Actually, the U production since 1985 is somewhat lower than the demand. This gap amounting to about 1000 to 3000 t U per year based on existing and firmly committed mines and mills, can, through the beginning of the early nineties be easily filled from inventories which were build up during the times of uranium over-supply. Thereafter the supply gap is expected to increase from about 5500 t in 1995 to more than 15.000 t in the year 2000 and implies that somewhere in the mid-nineties additional production will be needed, which is expected to come from presently known resources presumably of the low cost category.

Longer-term supply-demand projections, which have a higher degree of uncertainity than the short-term forecasts, indicate that additional low cost resources may be needed some time in the first decade of the next century.

What implications does this have for the U-exploration with its long lead times to discover new resources and convert them to mineable reserves? Assuming discovery costs of 10.000 $/t U, the total WOCA 1986 exploration expenditures of about 130 million $ suffice for the discovery of only 13.000 t U per year or about one third of the present production. Although this is not critical, we have, however, to monitor closely the supply-demand and respond in a timely way, considering among others the fact that not all resources, listed in our WOCA data base will eventually be mined and enter the market. This is not encouraging for many countries, but it seems to be a realistic projection, that the future uranium producers will not drastically differ from the current suppliers. The concentration of present uranium exploration efforts in just a few countries supports this view.

In summary, North America is a region of outmost importance for the uranium supply of WOCA. It contains about 16% of the lowest cost known uranium resources in an environment highly attractive for mining development. The region's U potential is so attractive that presently one third of all WOCA exploration expenditures are expended here, most of which funded by foreign based companies searching for a long term assurance of supplies. The result

of all this work has resulted in a number of producing mines and mills which currently produce 45% of WOCA's uranium production, representing an estimated value of 1.300 million US $ per year.

This picture is by far not a negative one at all. The uranium industry has left the boom and bust period and entered a stage of maturity. Its main feature is a quite predictable demand with still above average annual growth rates of about 2% through the year 2000. We believe that another feature of this mature industry will be the need for an optimization of all methods from exploration through production, an important measure in a highly competitive market. At present the uranium mining industry is a significant industrial sub-sector with an estimated annual turnover of 3.000 million US$ and we can be assured that this region will continue to play a leading part in the future uranium supply for the benefit of a large share of WOCA's population.

A COMPARATIVE STUDY OF THE US AND CANADIAN URANIUM INDUSTRIES

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Abstract

This paper describes statistical data on the uranium industries in the United States and Canada, as well as a quantitative analysis of the costs relevant to the industry in each country.

Comparative data on the U.S. and Canadian uranium industries are presented in the following three subject areas: (1) the uranium raw materials situation in each country, focusing on uranium deposits and ore reserves, uranium mining operations, uranium concentrate production rate, the status of uranium mills and other production facilities, industry employment, and trends in mining and milling practices; (2) uranium prices, production capabilities, imports and exports of uranium, and industry ownership and control; and (3) comparative data on uranium production costs and costs due to institutional differences such as the effects of the U.S. and Canadian corporate tax structures.

The major uranium-producing States and provinces -- New Mexico, Wyoming, Texas, Saskatchewan, and Ontario -- are listed separately in most of the tables in this paper. The remainder are aggregated into "others" for both the United States and Canada.

Introduction

I am pleased to be here with you this morning to discuss a recent Energy Information Administration study of the uranium industries in the United States and Canada. As many of you may be aware, the Energy Information Administration is an independent organization within the U.S. Department of Energy, with responsibility for gathering and analyzing energy data. We do not make policy decisions.

In 1986, the Bureau of Mines, U.S. Department of the Interior, was requested by a congressional office to prepare a study on the potential implications for the U.S. mining industry of implementing the proposed United States-Canada Free Trade Agreement. Subsequently, the Bureau of Mines asked the Energy Information Administration (EIA) for assistance in preparing the section on uranium for that study. A brief summary of the resulting report on the uranium industries in the United States and Canada is provided in this paper, as well as statistical data relevant to the industry in each country.

Resource Base

The EIA estimates that 82 percent of the $30 per pound uranium resources in the United States are in New Mexico, Wyoming, and Texas, with the remaining 18 percent located in other States: Arizona, Colorado, Nebraska, Nevada, South Dakota, Utah, and Washington (Table 1).

No comparable data are available for Canadian provinces. The data that have been published by the Canadian government for reserves plus potential resources combined assign 49 percent to Saskatchewan and 45 percent to Ontario. Data from company annual reports on their individual properties and from the Canadian Nuclear Association indicate that 73 percent of the reserves are in Saskatchewan and 27 percent in Ontario.

At a forward cost of $30 per pound of U_3O_8, 65 percent of the U.S. Reasonably Assured Resources (RAR) could be mined by underground methods, 17 percent by open-pit methods, and the remainder by other methods, including in situ leaching. Open-pit minable reserves are primarily in Wyoming and Texas.

Table 1

U.S. Reasonably Assured Resources (RAR) at $30 per Pound U_3O_8 by States, and Canadian Uranium Reserves by Provinces

Location	Million Pounds U_3O_8	Percent of Total
United States (RAR)[a]		
New Mexico	184	53
Wyoming	83	24
Texas	18	5
Other[b]	60	18
Total	345	100
Canada (RAR)	403	100
Canada (Reserves)		
Ontario[c]	325	27
Saskatchewan		
Cluff Lake[d]	38	--
Key Lake[d]	174	--
Cigar Lake[d]	385	--
Collins Bay B[e]	31	--
Eagle North and South[e]	130	--
Midwest Lake[f]	56	--
Dawn Lake[f]	66	--
MacLean Lake[f]	15	--
Total Saskatchewan	896	73
Total Ontario and Saskatchewan	1,221	100

[a]Source: Energy Information Administration, Uranium Industry Annual 1985.

[b]Includes Arizona, Colorado, Nebraska, Nevada, South Dakota, Utah, and Washington.

[c]Source: Norman Aspin, President, Canadian Nuclear Association, "Uranium Production and Prospects in Canada," presented at the Atomic Industrial Forum Seminar, October 1983.

[d]Source: Saskatchewan Mining Development Corporation, Annual Report 1985.

[e]Source: Eldorado Resources, Ltd., Annual Report 1985.

[f]Source: Key Lake Board of Inquiry Report, January 1981.

Note: Totals may not equal sum of components due to independent rounding.

In Canada, all of the reserves in Ontario would be mined by underground methods and about 60 percent of the Saskatchewan reserves would also be mined by that method. The balance of Saskatchewan and other areas would be mined by the open-pit method.

Many Canadian uranium deposits (especially in Saskatchewan) are higher grade, thicker, shallower, and larger than those in the United States, although the total U.S. Reasonably Assured Resources (RAR) of 345 million pounds U_3O_8 in the $30 per pound forward cost category are only a little less than the total Canadian RAR of 403 million pounds U_3O_8 (Table 1). In the United States, most uranium production is from many small mines, while in Canada seven large mines account for all the uranium production. U.S. uranium production has been declining since 1981, while Canadian production has generally shown an upward trend, surpassing U.S. production in 1984 to make Canada the world's largest uranium producer.

Employment

For the 6 years covered by data published by Energy Mines and Resources Canada, employment in Canada's uranium industry (Table 2) has remained nearly constant. For 1984, the employment was only 4 percent less than the reported total for 1980. The slack period of employment reflected in the 1982 Canadian total, down by 21 percent from 1980, had nearly disappeared by 1984. In 1984, employment in the Canadian uranium industry was about 5,800 person-years expended, as new mines and mills replaced production centers that had ceased operation.

Table 2

Employment Trends in the Canadian Uranium Industry[a]
(Person-Years Expended)

Location	1980	1982	1984
Ontario			
Agnew Lake Mines, Ltd.	79	53	0
Denison Mines, Ltd.	2,027	2,027	2,200
Rio Algom, Ltd.			
Panel	771	713	669
Quirke	1,404	1,271	1,069
Stanleigh	0	0	818
Madawaska	381	9	0
Saskatchewan			
Cluff Mining	241	304	309
Eldorado Resources, Ltd.			
Beaver Lodge	845	120	0
Rabbit Lake	320	330	319
Key Lake Mining Corp.	0	0	427
Total	6,068	4,827	5,811

[a]Includes number of employees for mine, mill, and general. Does not include employees for exploration.

Source: Energy Mines and Resources Canada, Uranium in Canada: 1984 Assessment of Supply and Requirements.

In contrast, mining and milling employment in the U.S. uranium industry (Table 3) has declined from 16,000 person-years in 1979 to 1,730 in 1985 -- about 11 percent of the 1979 level. The 1985 employment levels are the lowest reported by the industry in the past 19 years. Wyoming, New Mexico, Colorado, and Utah accounted for 75 percent of the total employment in the industry for 1985. Arizona, Colorado, and Utah also reported significant mine and mill employment in activities related to the uranium industry.

Mining

In the United States, as markets and prices for uranium have fallen drastically, the trend has been for companies to close

Table 3

Employment in U.S. Uranium Mining and Milling Activity by State, 1967-1985
(Thousand Person-Years Expended)

	State				
Year	New Mexico	Wyoming	Colorado and Utah	Other[a]	Total
1967	2.45	0.85	2.04	0.12	5.46
1968	2.56	1.21	2.05	0.34	6.16
1969	2.70	1.37	2.04	0.32	6.43
1970	2.75	1.39	1.56	0.41	6.11
1971	2.42	1.48	1.59	0.38	5.87
1972	2.20	1.62	1.00	0.44	5.26
1973	2.22	1.61	0.84	0.37	5.04
1974	2.48	1.55	1.27	0.34	5.64
1975	3.71	1.87	1.45	0.59	7.62
1976	4.88	2.31	2.00	0.63	9.82
1977	6.29	3.31	2.64	0.83	13.07
1978	7.15	4.20	2.71	1.07	15.13
1979	6.83	4.95	2.86	1.36	16.00
1980	6.82	4.36	2.59	1.25	15.02
1981	4.22	2.53	2.21	0.88	9.84
1982	2.61	2.00	1.71	0.70	7.02
1983	1.34	1.38	1.16	0.44	4.32
1984	0.83	0.86	0.69	0.28	2.66
1985	0.43	0.44	0.42	0.43	1.73

[a]Includes Arizona, Texas, South Dakota, and Washington.

Note: Excludes exploration, byproduct, and *in situ* employment.

Sources: •1967-1983--U.S. Department of Energy, Grand Junction Area Office, *Statistical Data of the Uranium Industry*, GJO-100 (Grand Junction, Colorado, 1969-1983). •1984-1985--Energy Information Administration, Form EIA-858, "Uranium Industry Annual Survey" (1984, 1985).

their conventional mining and milling operations. At the same time, there has been a movement toward the use of lower-cost nonconventional methods of uranium recovery, such as *in situ* leach, heap leach, and byproduct at some locations. Commercial *in situ* operations have been primarily in Texas, but there are announced plans for such operations in Wyoming, New Mexico, and Nebraska.

In Canada, all the uranium is extracted by means of conventional mining and milling techniques. In contrast to the large number of small mines in the United States, there are a relatively few, large mines in Canada (Table 4). In Ontario, large-scale underground mining and milling will probably continue, since all the production is committed to long-term contracts. In Saskatchewan, nearly all current mining is from open-pit mines, with production processed by conventional acid leach milling. Since some of the newer deposits are deeper than the older ones, a larger proportion of the future uranium production will probably be mined underground. The in situ and heap-leach methods of uranium extraction are little used in Canada.

In situ leaching requires less investment of capital, and results in lower operating costs than conventional mining and milling does. However, mine recovery is about 60 percent when

Table 4

Number of Producing Mines, 1975-1985

	United States[a]					Canada		
Year	New Mexico	Wyoming	Texas	Others[b]	Total	Ontario	Saskatchewan	Total
1975 ...	27	16	11	115	169	2	2	4
1976 ...	36	19	14	212	281	3	2	5
1977 ...	39	18	20	237	314	3	2	5
1978 ...	45	35	25	286	391	3	2	5
1979 ...	49	32	30	321	432	4	2	6
1980 ...	66	32	34	256	388	4	2	6
1981 ...	54	33	33	134	254	4	3	7
1982 ...	34	23	23	126	196	5	3	8
1983 ...	19	16	10	60	135	5	3	8
1984 ...	6	6	14	24	50	4	3	7
1985 ...	8	4	12	17	41	4	3	7

[a]Including byproduct facilities.

[b]Includes Arizona, Colorado, Florida, Utah, and Washington.

Sources: •United States, 1975-1983--Estimated by staff of the Nuclear and Alternate Fuels Division, Office of Coal, Nuclear, Electric and Alternate Fuels, Energy Information Administration, from U.S. Department of Energy, Grand Junction Area Office files. •United States, 1984-1985--Energy Information Administration, Form EIA-858, "Uranium Industry Annual Survey" (1984, 1985). •Canada--Uranium mining company annual reports.

in situ leaching is used, in contrast to the 80 to 90 percent recovery that is usually expected from open-pit or underground mines. The current trend is to apply in situ leaching to exploit uranium reserves in properties where conventional methods were originally intended. If this trend continues, the U.S. uranium reserve base will be depleted at a faster rate than it would be if conventional methods were used for the same level of uranium concentrate production.

New Mexico was the leading U.S. producer of U_3O_8 through 1983, although its level of production and percentage of the total domestic production of U_3O_8 began to decline by 1981. Wyoming was the largest producer in 1984 and 1985, but its production, like that of New Mexico, has declined since 1981. Texas, where in situ leach predominates, has increased its share of total domestic U_3O_8 production in recent years, although its total level of production has been declining since it reached a peak in 1980. In contrast to the declining U.S. production trend, Canadian production of uranium concentrate has increased steadily (except for the decline in 1983), reaching an all-time high of 29 million pounds U_3O_8 in 1984 (Figure 1), surpassing the U.S. production to become the world's largest producer.

Milling

At the end of 1985, the United States had 4 uranium mills operating and 17 that were inactive, for a total of 21 operable mills. Among the 17 inactive mills, 4 produced for one or more months during the year, although one of the four shut down permanently at the end of the year. Annualized, the utilization

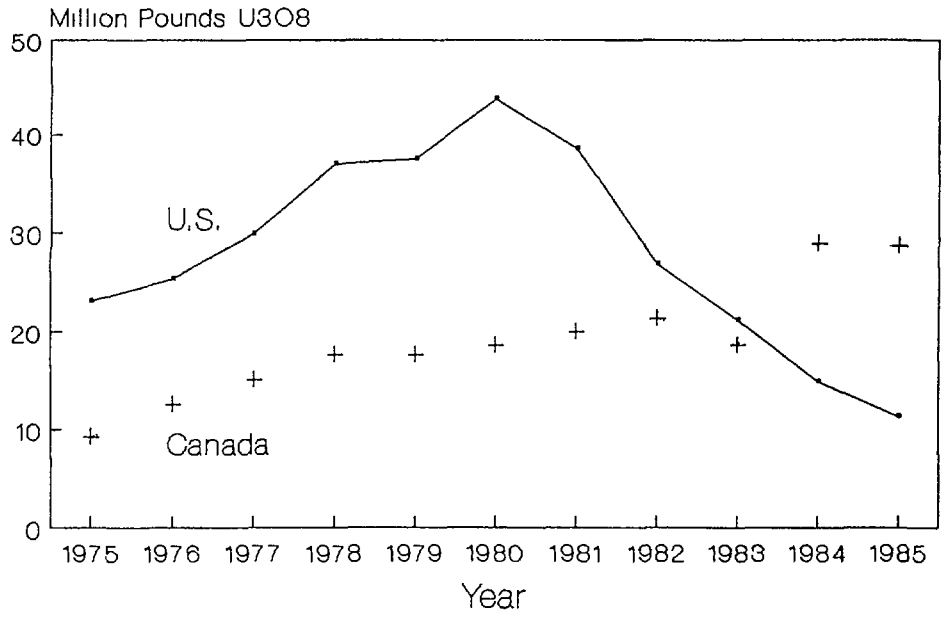

FIG.1. Uranium concentrate production 1975–1985.

of mills in 1985 was 12 percent of the available total capacity (Figure 2), whereas in 1984 it had been 25 percent and in 1981 it had been 77 percent.

The U.S. capacity for producing uranium concentrate by nonconventional methods includes 16 facilities for in situ leaching and byproduct recovery. Of the 14 facilities operated

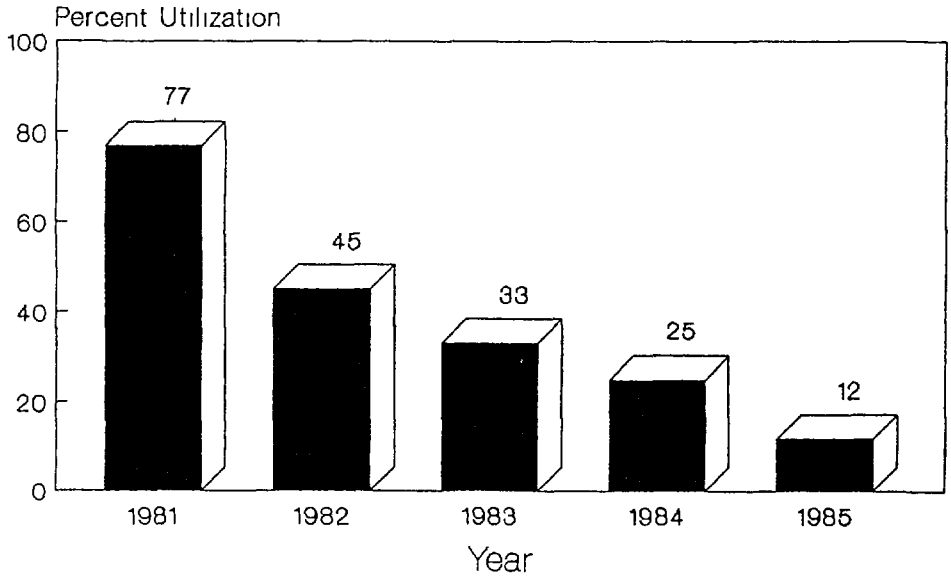

FIG.2. US uranium mill utilization rates as percent of total production capacity — end-of-year 1981–1985.

during all or part of 1985, 7 were for *in situ* leaching and 7 were for byproduct recovery from phosphate ore and copper waste dumps. The total U.S. capacity for *in situ* leaching and byproduct recovery is estimated at 7.1 million pounds U_3O_8 per year. The facilities that operated sometime during 1985 accounted for 6.0 million pounds of U_3O_8 production capacity, or about 85 percent of the total combined *in situ* capacity and byproduct recovery capacity.

At the end of 1985, Canada had seven operating mills in Ontario and Saskatchewan. The four mills in Ontario that process lower-grade ore are very large. By contrast, the three mills in Saskatchewan process relatively few tons per day because the ore there is of a high grade, compared to average grades in Ontario. As a result, the Saskatchewan mills, which make up only 10 percent of the total Canadian milling capacity, can produce a larger amount of yellowcake than is produced in Ontario.

The only reported nonconventional operation in Canada is at Medicine Hat in Alberta, where phosphate rock from Idaho is processed. The small amount of uranium recovered from wet-process phosphoric acid at Medicine Hat is returned to the United States.

Ownership

The control of uranium reserves, in both countries, rests with several types of companies. In the United States, about 2 percent of the reserves rated at $30 per pound are on Government withdrawn lands in Colorado and Utah, but uranium mining activities are entirely controlled by private companies;

governments do not engage in mining. The remaining reserves are on public and private lands and are mined by private companies. In Canada, the Federal Government controls and mines some of the uranium reserves. Complete control of the Rabbit Lake mine/mill complex was purchased by Eldorado Mines, Ltd., a Crown (Federal) company, from Gulf and Uranerzbergbau. Eldorado also acquired an interest in the Key Lake deposit, but Eldorado is not the operator. The Saskatchewan provincial government, participating through Saskatchewan Mining Development Corporation (SMDC), has declared its right to acquire up to 50 percent interest in any uranium venture in the province. SMDC's interests include 20 percent of the Cluff Lake and 50 percent of the Key Lake operations.

In the United States, all three uranium enrichment facilities are owned by the Department of Energy. Overall U.S. enrichment capacity is about 205 percent of U.S. requirements for 1985. Canada does not have any enrichment capacity. Uranium hexafluoride (UF_6) conversion facilities and fuel fabrication facilities in the United States are owned and operated by private corporations, and have excess production capacities. The Canadian chemical conversion plant at Port Hope, which produces UF_6 for export, is owned and operated by Eldorado Nuclear, Ltd., a Crown (federal) company. Canada fabricates fuel for the CANDU reactor, a heavy-water-moderated plant design that uses natural uranium. All Canadian reactors except one are of the CANDU design. Fuel fabrication in the United States is predominantly for light-water reactors, which require enriched uranium.

In 1985 the prices of uranium delivered by U.S. suppliers to U.S. utilities averaged $31.43 per pound U_3O_8 (Figure 3). The weighted average price per pound for 1985 deliveries for contracts signed that year was $15.13. Settlement of market price contracts averaged $29.88 per pound U_3O_8; however, for settlements in which the contract had no floor price, the average settled price was $15.46 per pound U_3O_8.

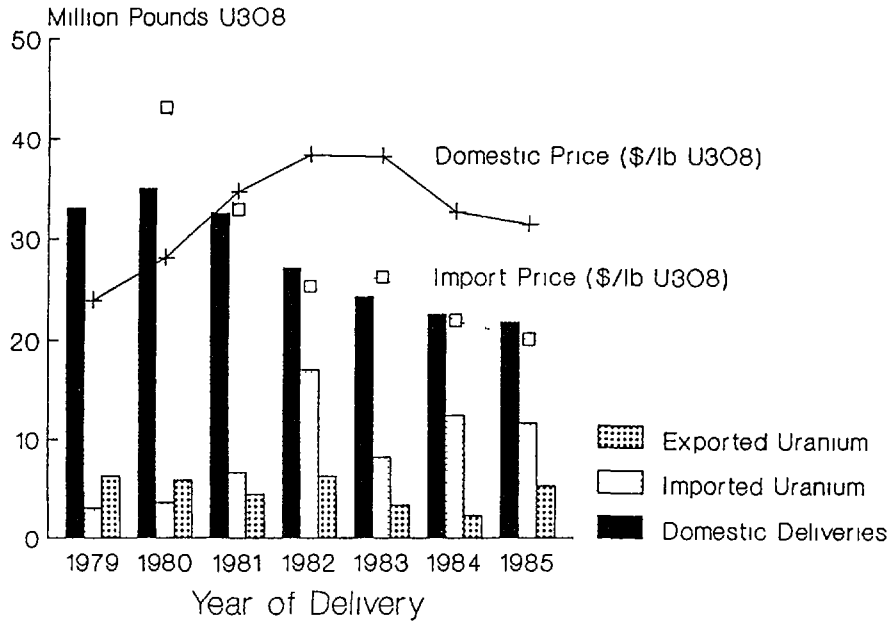

FIG.3. US uranium marketing activities 1979–1985.

Imports of uranium by the United States from foreign suppliers totaled 11.7 million pounds in 1985 (Figure 4). The average price (Figure 3) was $20.08 per pound, down by $1.78 per pound from 1984. Of the 1985 total, Canadian sales to the United States were 6.8 million pounds U_3O_8, at an average price of $20.66 per pound.

Of the uranium imports into the United States, imports from Canada during the 1983-1985 period made up more than half the

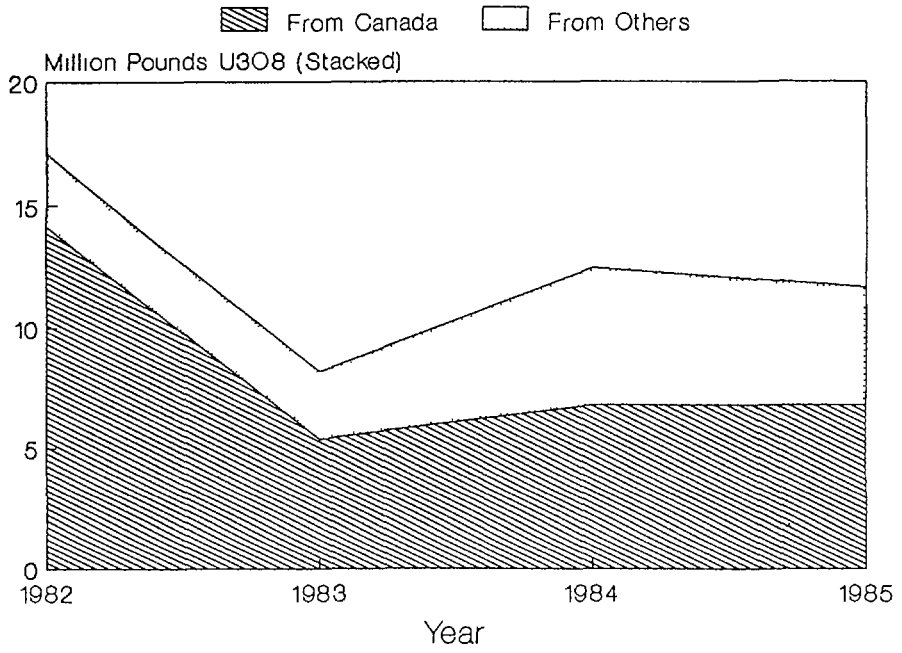

FIG.4 US imports of uranium.

total. As you know, Canada provides all the uranium needed by Canadian reactors; no uranium is imported into Canada.

Most of Canada's reactor requirements are covered by long-term contracts with Elliot Lake producers Rio Algom and Denison. Also, long-term contracts were signed in 1978 with Ontario Hydro and other utilities with nuclear plants to assure a lifetime supply of fuel. This means that potential Canadian production seeking a market in the United States is the high-grade, low-cost uranium from northern Saskatchewan.

Production Capability

Projected production capability, based on known reserves, suggests that the United States could increase its uranium production from 11.3 million pounds U_3O_8 in 1985 to more than 45 million pounds in 1995, given the proper market incentive. It has been estimated that the current Canadian production capability, 33 million pounds U_3O_8 per year, could increase

only moderately to 42 million pounds in 1995. About 60 percent of the projected production is from the lower cost reserves in northern Saskatchewan and would be available for export.

Costs

Production costs, estimated for the Energy Information Administration by International Energy Associates, Ltd., are significantly higher for the major producing areas in the United States than for any of the Canadian production regions. In particular, production costs in Saskatchewan are estimated to be only a small fraction of those for any other area in Canada or any area of the United States.

Finally, a comparison of the effects of differences in tax structures on the production costs for U.S. and Canadian uranium, prepared for this report by the Nuclear Assurance Corporation, indicates that, as of December 1985, both the United States and Canada had a maximum federal tax rate of 46 percent with credits for investment, depreciation, and depletion on capital assets. However, the Canadian resource allowance of 25 percent and tax rate abatement of 10 percent for mining companies serve to reduce the effective tax rate for uranium mining companies from 46 percent to approximately 27 percent.

Comparison of tax law provisions at the State or provincial and local levels in the United States and Canada is more difficult than a comparison of the federal tax statutes. Taxes vary from State to State in the United States and from province to province in Canada. For example, in Canada the existence of provincial taxes subjects the uranium mining industry to four tiers of taxation. First is the Canadian federal income tax,

as mentioned earlier, at an effective rate of 27 percent. In addition, the same income is subject to provincial income taxes at rates ranging from 4 to 16 percent. Third, each of the provinces where uranium is produced imposes a mining tax, minerals royalty, or a similar levy on some measure of production profits or revenues. Finally, there are the indirect taxes that mining companies pay. In Ontario, for example, the cumulative provincial tax structure imposes a graduated income tax with marginal rates as high as 30 percent. The cumulative impact of this system is that provincial taxes in Canada absorb a higher percentage of revenues than do federal income taxes.

Principal State and local taxes on uranium mining in the United States include property taxes, severance taxes, State income taxes, and sales taxes. In the aggregate, these taxes represent about 40 percent of the total taxes paid by the industry. However, the federal tax law provisions permit the dollar value of these taxes as an offset in the determination of federal tax liability. In contrast, as noted above, Canada does not offer a similar deduction. The combination of high local taxes and low federal taxes in Canada appears to be approximately equal to the low local taxes and high federal taxes in the United States. A definitive comparison can only be made, however, by a closer examination of typical mining companies located in the two countries.

The new U.S. Tax Code was signed into law on October 22, 1986 (after the completion of this study). Under the new law, U.S. industries will see a lower marginal tax rate of 34 percent, compared to a previous maximum rate of 46 percent. However, the 10 percent Investment Tax Credit will be eliminated, and

the depreciation schedule will be stretched to as long as 15 years instead of 5 years. In addition, the deduction for intangible drilling costs will be trimmed from 80 percent to 70 percent. The new law also requires tighter standards for the Alternative Minimum Tax. Therefore, despite the lower marginal tax rate, most U.S. uranium companies will wind up paying more taxes due to new restrictions on exemptions and deductions.

AN ANALYSIS OF URANIUM DISCOVERY IN CANADA, 1930-1983

Rates of discovery, exploration expenditures, discovery costs and geological deposit types

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Abstract

In 1932, Canada emerged as the world's second important source of uranium and in 1958 became the major uranium producer. Surpassed by the United States in terms of uranium production in 1959, Canada retained its role as leading exporter. It was not until 1984, however, that Canada again became the western world's leading uranium producer.

During the past 40 years, enormous market pressures, unprecedented in any other major mineral commodity, caused levels of uranium exploration and rates of discovery in Canada to fluctuate considerably.

Blessed with a large and growing inventory of known high-grade deposits, Canada has maintained its status as leading uranium exporter and focus of international uranium exploration activity. With average discovery costs in Saskatchewan, Canada's foremost uranium-producing province, of $Cdn 1.53 per kilogram of uranium and the potential for many additional major discoveries, Canada is assured of being able to supply its own uranium needs and those of its customers well into the 21st century.

INTRODUCTION

The deposit that became Canada's first uranium mine and the world's second significant uranium producer was discovered by Gilbert La Bine on the shore of Great Bear Lake, Northwest Territories, in May 1930. La Bine was prospecting, not for uranium but for silver. During the 1930s and early 1940s, the deposit was operated as the Port Radium mine of Eldorado Gold Mines, Limited; it yielded radium, uranium, silver, polonium, copper, cobalt and lead. The uranium compounds produced at Eldorado's refinery at Port Hope, Ontario, were in demand as a colouring agent for glass and for ceramic glazes.

Closed from 1940 to 1942 because of disruptions in world radium markets, the Port Radium mine was reopened and ownership

was transferred to Canadian government-owned Eldorado Mining and Refining Limited. Uranium for nuclear purposes became the significant product. The economic importance of radium decreased when most of its uses were captured by reactor-produced radioisotopes. Uranium ore was exhausted at the Port Radium mine, which closed in 1960 (the mine yielded silver and copper again from 1977 to 1982).

Since 1932, Canada has been a major world uranium producer and supplier. With the need for uranium for nuclear purposes, a considerable number of new Canadian uranium deposits were discovered, beginning in the late 1940s; the most remarkable of these is the large, very high-grade Cigar Lake deposit discovered in Saskatchewan in 1981. Discovery of high-grade deposits in Saskatchewan together with a sharp decline in uranium production in certain other countries because of low uranium prices led to Canada once again becoming the world's largest uranium producer in 1984. Additional known high-grade Canadian deposits will be able to support even higher production rates should market conditions improve.

The effects of changing market conditions on exploration and discovery in Canada have been much greater in the case of uranium than they have for other major mineral commodities, because:

(i) Demand for uranium was, until the discovery of nuclear fission in 1938, limited to use as a colouring agent for glass and ceramic glazes. Although steady, the need was easily met by the by-product uranium from the world's two significant radium mines at Port Radium and in Zaire (then the Belgian Congo).

(ii) The application of nuclear fission introduced an instantaneous demand for uranium for defence purposes beginning in 1942. In their efforts to accumulate large stocks of an element for which known sources were few, the governments of the United States and United Kingdom offered both premium prices and bonuses for uranium. By 1959, the uranium so accumulated far exceeded short-term requirements. Moreover, the total uranium production capacity that had been developed in Canada, the United States, Australia, and South Africa in particular, was much too large with respect to foreseeable world requirements.

As sufficient domestic uranium production capacity had been developed in the United States, that country did not take up options for further uranium purchases from foreign sources, so that other than honouring existing contracts, the U.S. effectively excluded foreign-produced uranium from U.S. markets for almost 20 years.

The effects of uranium market conditions on the Canadian uranium exploration and discovery record are further examined below.

A RECORD OF URANIUM PRICES

Because of the strategic military importance of uranium, only the Canadian government was permitted to search for uranium deposits from 1944 to 1947. During that period, uranium exploration in Canada was therefore restricted to Eldorado Mining and Refining Limited (now Eldorado Nuclear Limited) and the Geological Survey of Canada. The ban on private prospecting for uranium in Canada (similar to those in effect in Australia and the United States) was lifted in 1947, and various incentives were offered to encourage uranium exploration and production, including guaranteed prices and development allowances.

Eldorado was the sole purchaser of privately-produced Canadian uranium, acting on behalf of the United States Atomic Energy Commission (USAEC) and the United Kingdom Atomic Energy Authority (UKAEA). In March 1948, the first schedule of prices for Canadian uranium was published. This provided for a price* of $7.15/kg U ($2.75/lb U_3O_8) contained in ores or concentrates. Development and milling allowances were later added to bring the price up to $18.85/kg U ($7.25/lb U_3O_8) but no uranium was forthcoming at these prices.

In 1953, special prices were offered and uranium purchase agreements negotiated with several companies. Under these contracts the average price of uranium contained in concentrates was about $27.30/kg U ($10.50/lb U_3O_8). Such prices were available until 1956, when the USAEC announced that it had fully contracted for its immediately foreseeable needs and would not offer any new contracts.

As sales of Canadian-produced uranium for commercial purposes were not permitted until 1958, there was no market for Canadian uranium beyond that already under contract. In 1959 the USAEC indicated that it did not intend to exercise any of the options it had under various contracts, all of which had been scheduled for completion between 1962 and 1966. Arrangements were made with the USAEC to stretch out deliveries and to transfer contracts from higher-cost to lower-cost operations. Subsequently, in 1962, the UKAEA contracted for more Canadian uranium to meet a commitment in a letter-of-intent that it had signed during the 1950s. The average price of $13.08/kg U ($5.03/lb U_3O_8) - plus an escalation clause to cover cost increases - was just sufficient to cover operating costs. Later, two stockpiling programs were negotiated between Canadian producers and the Government of Canada, at prices that averaged $12 and $12.75/kg U ($4.60 and $4.90/lb U_3O_8) respectively, plus escalation for increased costs of labour and materials. These were intended to keep some mines in production to help support the communities of Uranium City,

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* Prices are in current Canadian dollars per kg U and current Canadian dollars/lb U_3O_8 unless otherwise noted; the equivalent current U.S. dollar/lb U_3O_8 prices may be found in Table 1 for comparison.

Saskatchewan, and Elliot Lake and Bancroft, Ontario, until commercial markets developed. A third stockpile, the joint venture stockpile, was agreed upon between the federal government and Denison Mines Limited in 1971; the government acquired a 76 per cent ownership in the stockpile by paying Denison $11.85/kg U ($4.56/lb U_3O_8) against a book value of $15.60/kg U ($6.00/lb U_3O_8).

Canada's first commercial contract was negotiated by a Canadian producer in 1966 and by the end of 1967, six such contracts had been signed by Canadian companies. Contract prices were not released owing to highly competitive market conditions. By the late 1960s, sufficient numbers of commercial contracts were being negotiated throughout the world that the Nuclear Exchange Corporation (NUEXCO), a California brokerage firm, began publishing a price index, referred to as the NUEXCO Exchange Value (EV). It is defined as "NUEXCO's judgement of the price at which transactions for significant quantities of natural uranium concentrates could be concluded" as of the date indicated.

In the United States, the principal price series for the pre-commercial contract period is one for the average price paid each year for U_3O_8 in concentrates purchased by the USAEC. This series provides a reasonable indication of costs of production in the United States, the world's major producer and consumer of uranium during the 1950s and 1960s. It also provides some indication of prices likely to have prevailed if normal market conditions had existed. The average USAEC price was reasonably consistent with the $27.30/kg U ($10.50/lb U_3O_8) price available for Canadian uranium in the 1950s, as well as with the NUEXCO EV around 1969 when the NUEXCO series began.

A second U.S. price series is available from the United States Department of Energy (USDOE) beginning in the early 1970s. This series provides the price of actual deliveries made under contracts between U.S. suppliers and U.S. utilities; prices are given for contract-specified and settled market-price procurements.

Table 1 presents a composite U.S. price series prepared from: (i) the average price paid to the United States producers by the USAEC from 1948 to 1970 inclusive, and (ii) the average contract price and market price settlements for actual deliveries from 1971, compiled by the USDOE. Table 2 presents a composite Canadian unit value series prepared from: (i) the value of Eldorado's uranium deliveries from 1944 to 1955, and (ii) the value of all Canadian producers' shipments from 1956 onwards. In Figure 1, these two series are expressed in constant (1985) Canadian dollars per kilogram of uranium.

For long-term commercial contracts that provide uranium consumers with a reliable source of supply, Canadian producers have generally been able to obtain prices higher than the NUEXCO EV. In 1974, prompted by concerns about domestic security of supply, the Government of Canada announced revisions to its uranium export policy designed to ensure that the needs of Canada's growing nuclear power program would be met.

TABLE 1: UNITED STATES URANIUM PRICES

YEAR	USAEC/ USDOE ($US/lb U3O8)	EXCHANGE RATE ($US in $C)	PRICE (CURR. $C/lb U3O8)	IMPLICIT GNE PRICE DEFLATOR	MULTI-PLIER FOR 1985 $	PRICE (1985 $C/lb U3O8)	PRICE (1985 $C/ kgU)
1948	$7.14	1.0025	$7.16	0.513	5.998	$42.93	$111.61
1949	$8.53	1.0308	$8.79	0.535	5.751	$50.57	$131.47
1950	$9.11	1.0892	$9.92	0.548	5.615	$55.72	$144.84
1951	$10.10	1.0528	$10.63	0.610	5.044	$53.64	$139.44
1952	$11.28	0.9798	$11.05	0.637	4.830	$53.39	$138.79
1953	$12.35	0.9834	$12.14	0.636	4.838	$58.76	$152.76
1954	$12.27	0.9723	$11.93	0.646	4.763	$56.83	$147.73
1955	$12.25	0.9863	$12.08	0.650	4.734	$57.20	$148.69
1956	$11.51	0.9841	$11.33	0.674	4.565	$51.71	$134.43
1957	$10.49	0.9588	$10.06	0.688	4.472	$44.98	$116.94
1958	$9.45	0.9706	$9.17	0.698	4.408	$40.43	$105.12
1959	$9.12	0.9590	$8.75	0.712	4.322	$37.80	$98.26
1960	$8.75	0.9697	$8.48	0.721	4.268	$36.21	$94.14
1961	$8.50	1.0132	$8.61	0.724	4.250	$36.60	$95.15
1962	$8.15	1.0689	$8.71	0.734	4.192	$36.52	$94.94
1963	$7.82	1.0785	$8.43	0.748	4.114	$34.69	$90.19
1964	$8.00	1.0786	$8.63	0.766	4.017	$34.66	$90.11
1965	$8.00	1.0780	$8.62	0.791	3.890	$33.55	$87.21
1966	$8.00	1.0773	$8.62	0.826	3.725	$32.11	$83.46
1967	$8.00	1.0787	$8.63	0.859	3.582	$30.91	$80.36
1968	$8.00	1.0775	$8.62	0.887	3.469	$29.90	$77.74
1969	$6.99	1.0768	$7.53	0.926	3.323	$25.01	$65.02
1970	$5.74	1.0440	$5.99	0.969	3.175	$19.03	$49.47
1971	$7.20	1.0098	$7.27	1.000	3.077	$22.37	$58.16
1972	$7.47	0.9905	$7.40	1.050	2.930	$21.68	$56.37
1973	$7.10	1.0001	$7.10	1.146	2.685	$19.07	$49.56
1974	$7.90	0.9780	$7.73	1.321	2.329	$18.00	$46.79
1975	$10.50	1.0173	$10.68	1.463	2.103	$22.47	$58.40
1976	$16.10	0.9861	$15.88	1.604	1.918	$30.46	$79.18
1977	$19.75	1.0635	$21.00	1.723	1.786	$37.51	$97.52
1978	$21.60	1.1402	$24.63	1.838	1.674	$41.23	$107.19
1979	$23.85	1.1715	$27.94	2.027	1.518	$42.41	$110.26
1980	$28.15	1.1690	$32.91	2.258	1.363	$44.84	$116.58
1981	$32.20	1.1990	$38.61	2.497	1.232	$47.58	$123.68
1982	$39.82	1.2341	$49.14	2.755	1.117	$54.89	$142.69
1983	$37.81	1.2324	$46.60	2.901	1.061	$49.42	$128.49
1984	$32.38	1.2948	$41.93	2.982	1.032	$43.26	$112.47
1985	$30.79	1.3652	$42.03	3.077	1.000	$42.03	$109.28

SOURCES:

United States Atomic Energy Commission (USAEC) data to 1970 inclusive.
United States Department of Energy (USDOE) data from 1971 onwards.
Bank of Canada "average noon spot" exchange rate.
Statistics Canada implicit deflator of the Gross National Expenditure (GNE).

TABLE 2: CANADIAN URANIUM UNIT VALUES *

YEAR	DOMESTIC DELIVERY SHIPMENT (tU)	VALUE (CURR. $C x 000)	VALUE (1985 $C x 000)	UNIT VALUE (CURR. $C/kgU)	IMPLICIT GNE PRICE DEFLATOR	MULTI-PLIER FOR 1985 $	UNIT VALUE (1985 $C/ lb U3O8)	UNIT VALUE (1985 $C/kgU)
1944-6	539	$2,842	$21,381	$5.28	0.409	7.523	$15.27	$39.70
1947	238	$3,539	$23,829	$14.84	0.457	6.733	$38.43	$99.92
1948	115	$4,050	$24,292	$35.10	0.513	5.998	$80.97	$210.51
1949	188	$7,497	$43,119	$39.87	0.535	5.751	$88.20	$229.31
1950	169	$6,980	$39,190	$41.20	0.548	5.615	$88.99	$231.34
1951	168	$6,966	$35,138	$41.57	0.610	5.044	$80.66	$209.69
1952	187	$8,703	$42,038	$46.64	0.637	4.830	$86.65	$225.28
1953	283	$11,897	$57,557	$42.02	0.636	4.838	$78.19	$203.28
1954	678	$26,300	$125,271	$38.78	0.646	4.763	$71.05	$184.71
1955	725	$23,288	$110,242	$32.14	0.650	4.734	$58.53	$152.16
1956	1,754	$45,732	$208,780	$26.07	0.674	4.565	$45.77	$119.00
1957	5,105	$136,304	$609,605	$26.70	0.688	4.472	$45.93	$119.42
1958	10,311	$279,538	$1,232,292	$27.11	0.698	4.408	$45.97	$119.52
1959	12,226	$331,143	$1,431,077	$27.09	0.712	4.322	$45.02	$117.05
1960	9,807	$269,938	$1,152,011	$27.53	0.721	4.268	$45.19	$117.47
1961	7,417	$195,692	$831,689	$26.39	0.724	4.250	$43.13	$112.14
1962	6,485	$158,184	$663,121	$24.39	0.734	4.192	$39.33	$102.26
1963	6,425	$136,909	$563,194	$21.31	0.748	4.114	$33.72	$87.66
1964	5,604	$83,509	$335,455	$14.90	0.766	4.017	$23.02	$59.85
1965	3,418	$62,361	$242,587	$18.25	0.791	3.890	$27.30	$70.98
1966	3,025	$54,335	$202,407	$17.96	0.826	3.725	$25.74	$66.92
1967	2,876	$53,022	$189,928	$18.44	0.859	3.582	$25.40	$66.05
1968	2,847	$52,285	$181,375	$18.36	0.887	3.469	$24.50	$63.70
1969	2,965	$53,151	$176,614	$17.93	0.926	3.323	$22.91	$59.57
1970	3,157	$55,745	$177,016	$17.65	0.969	3.175	$21.56	$56.06
1971	3,160	$52,623	$161,922	$16.65	1.000	3.077	$19.71	$51.25
1972	3,755	$70,600	$206,892	$18.80	1.050	2.930	$21.19	$55.10
1973	3,504	$78,696	$211,298	$22.46	1.146	2.685	$23.20	$60.30
1974	4,021	$109,378	$254,773	$27.20	1.321	2.329	$24.37	$63.36
1975	5,273	$205,351	$431,897	$38.94	1.463	2.103	$31.51	$81.91
1976	5,438	$241,829	$463,908	$44.47	1.604	1.918	$32.81	$85.31
1977	5,787	$349,219	$623,649	$60.35	1.723	1.786	$41.45	$107.77
1978	8,211	$617,528	$1,033,805	$75.21	1.838	1.674	$48.43	$125.90
1979	6,530	$616,165	$935,343	$94.36	2.027	1.518	$55.10	$143.24
1980	6,739	$702,038	$956,674	$104.18	2.258	1.363	$54.61	$141.96
1981	7,507	$794,212	$978,691	$105.80	2.497	1.232	$50.15	$130.37
1982	7,643	$837,468	$935,350	$109.57	2.755	1.117	$47.07	$122.38
1983	6,823	$667,672	$708,179	$97.86	2.901	1.061	$39.92	$103.79
1984	10,272	$901,573	$930,295	$87.77	2.982	1.032	$34.84	$90.57
1985	10,029	$957,660	$957,660	$95.49	3.077	1.000	$36.73	$95.49
	181,403	TOTALS	$18,509,544	AVG. UNIT VALUE		($C/kgU) 1944-85=		$102

* Unit values reflect average annual prices received for Canadian uranium deliveries.

SOURCES:
Eldorado Nuclear Limited uranium deliveries data from 1944 to 1955.
Statistics Canada producers' shipments data from 1956 onwards and implicit deflator of the Gross National Expenditure (GNE).
Bank of Canada "average noon spot" exchange rate.

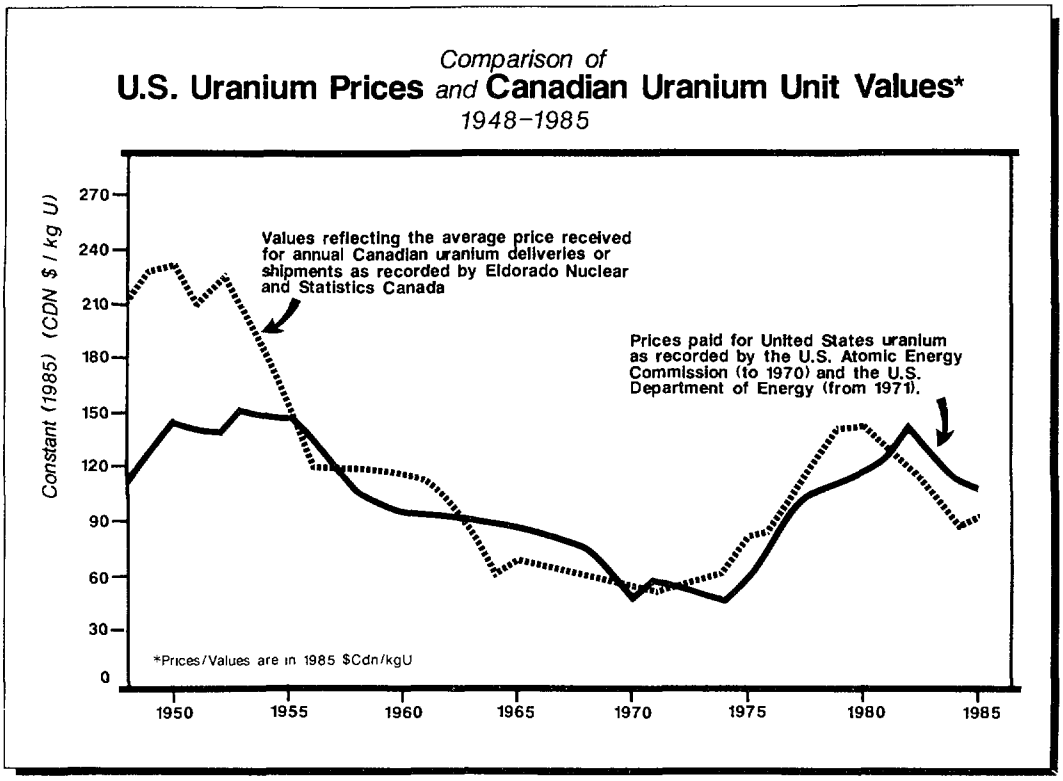

FIGURE 1

As part of this policy, EMR's Uranium Resource Appraisal Group (URAG) was established to annually audit Canada's uranium resources and provide the information base required to implement Canada's uranium export policy. As part of this annual exercise, URAG calculates the average price of all export deliveries made by Canadian producers in a given year. Table 3 presents the URAG price series from 1974 to 1985. URAG prices differ markedly from those of the NUEXCO EV series but are more representative of long-term Canadian marketing realities.

The price series presented here are only a general indication of price trends that have been a major factor in influencing the search for uranium deposits in Canada.

CANADIAN URANIUM DISCOVERIES AND RATES OF DISCOVERY (1930-1983)

Figure 2 indicates the quantities of uranium (essentially equivalent to measured, indicated and inferred resources) discovered in Canada per three-year period over the 54 years from 1930 to 1983 inclusive, together with the names of the deposits discovered in each period.

TABLE 3: URAG * CANADIAN URANIUM PRICES

YEAR	URAG PRICE ($C/kgU)	URAG PRICE ($C/lb U3O8)	IMPLICIT GNE PRICE DEFLATOR	MULTI-PLIER FOR 1985 $	URAG PRICE (1985 $C/kgU)	EXCHANGE RATE ($US in $C)	URAG PRICE ($US/lb U3O8)	URAG PRICE (1985$US/ lb U3O8)	NUEXCO EV DEC. 31 ($US/ lb U3O8)
1974	$39	$15.00	1.321	2.329	$91	0.9780	$15	$36	$15.00
1975	$52	$20.00	1.463	2.103	$109	1.0173	$20	$41	$35.00
1976	$104	$40.00	1.604	1.918	$200	0.9861	$41	$78	$41.00
1977	$110	$42.25	1.723	1.786	$196	1.0635	$40	$71	$43.20
1978	$125	$48.00	1.838	1.674	$209	1.1402	$42	$71	$43.25
1979	$130	$50.00	2.027	1.518	$197	1.1715	$43	$65	$40.75
1980	$135	$52.00	2.258	1.363	$184	1.1690	$44	$61	$27.00
1981	$110	$42.25	2.479	1.241	$137	1.1990	$35	$44	$23.50
1982	$115	$44.25	2.755	1.117	$128	1.2341	$36	$40	$20.25
1983	$100	$38.50	2.901	1.061	$106	1.2324	$31	$33	$22.00
1984	$90	$34.40	2.982	1.032	$93	1.2948	$27	$28	$15.25
1985	$91	$35.00	3.077	1.000	$91	1.3652	$26	$26	$17.00

* The Uranium Resource Appraisal Group (URAG) of Energy, Mines and Resources, Canada, (EMR).

NOTE: URAG figures are based on the average price under all export contracts made by Canadian producers for deliveries in the given year; prices are rounded.

The Nuclear Exchange Corporation (NUEXCO), a California-based uranium brokerage firm, publishes a monthly exchange value (EV) reflecting NUEXCO's judgement of the price at which transactions for significant quantities of natural uranium concentrates could be concluded as of the last day of the month.

SOURCES:

URAG uranium export prices.
Statistics Canada implicit deflator of the Gross National Expenditure (GNE).
Bank of Canada "average noon spot" exchange rate.
NUEXCO December 31 Exchange Values.

Following the Port Radium discovery, other silver-cobalt-nickel-arsenide deposits were discovered in the region, none of which had an economically significant content of uranium. Minor radium-uranium occurrences and deposits were found in the vicinity of Bancroft, Ontario, during the 1930s, but none of them were of economic significance. Pitchblende occurrences were found in the 1930s in Saskatchewan, north of Goldfields, during prospecting of the region for gold. The Geological Survey of Canada and Eldorado Mining and Refining were attracted to Beaverlodge Lake by these pitchblende occurrences, and in 1948 Eldorado discovered the principal orebody of what soon became its Ace-Fay-Verna mine. Another thirteen uranium deposits were found in the Beaverlodge Lake district between 1948 and 1974, all but two of them between 1948 and 1954; the most important of these was the Gunnar mine discovered on the north shore of Lake Athabasca in 1952. As a group, these thirteen additional deposits contained about half as much uranium as did Eldorado's Ace-Fay-Verna mine, about 60 per cent of that half was in the Gunnar mine. Twelve of these yielded some uranium.

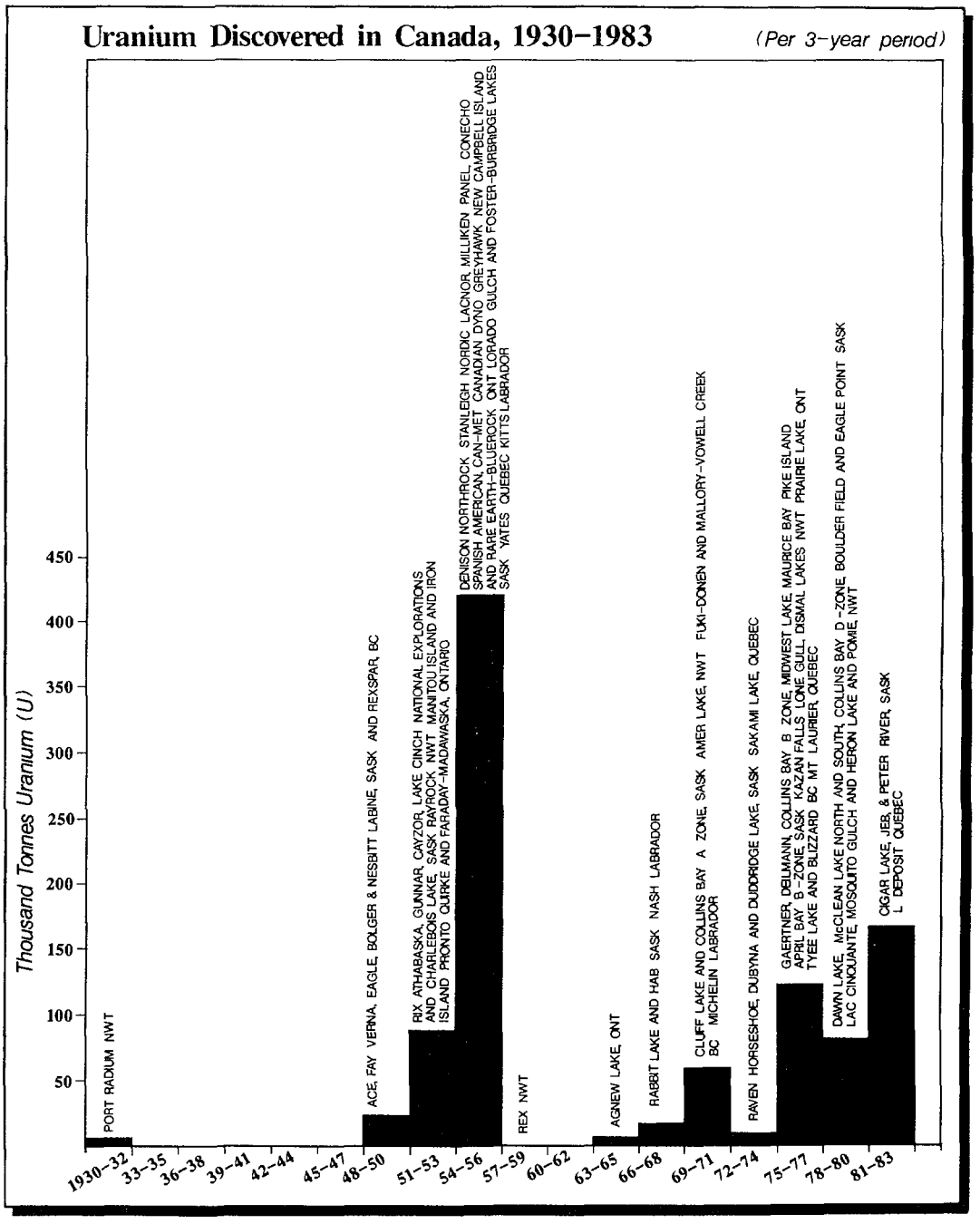

FIGURE 2

Exploration in the Bancroft district of Ontario resulted in the discovery of the Faraday (later Madawaska) mine in 1953. Four other deposits had been discovered in the Bancroft district by 1956, the most notable of them the Bicroft mine.

Canadian geologist Franc Joubin recognized the similarity of quartz-pebble conglomerates near Blind River, Ontario, to the Witwatersrand gold-uranium-bearing conglomerates of South Africa. This rapidly led to the discovery, between 1953 and 1955, of more than ten major low-grade uranium deposits in the vicinity of Elliot Lake, Ontario, one of the world's major uranium districts.

Once the ban on private uranium prospecting in Canada was lifted in 1947, Canadian uranium exploration continued at a rapid pace until 1956. That year, the USAEC announced that it would not enter into negotiations for new uranium purchase contracts, so that the market for Canadian uranium disappeared for the foreseeable future. As a result, exploration for new uranium deposits in Canada came to a virtual halt, with no significant uranium discoveries from 1956 to 1965 (Figure 2).

Expressed in 1985 Canadian dollars, the price paid by the USAEC to U.S. uranium producers declined from $153.00/kg U ($59.00/lb U_3O_8) in 1953 to an all-time low of $50.00/kg U ($19.00/lb U_3O_8) in 1973. This continuous price decline provided little incentive for resumption of uranium exploration in Canada (Table 1).

In the early to mid-1960s, concerns were expressed that as nuclear power generation increased, the world's known resources of uranium would be inadequate to meet demand without new discoveries. Anticipation of increased world requirements for uranium led to a limited resumption of uranium exploration, that resulted in the discovery of deposits at Agnew Lake in Ontario, Rabbit and Cluff Lakes in Saskatchewan, in Labrador and elsewhere in Canada (Figures 2 and 3). But uranium markets did not improve as rapidly as had been predicted; as a result, Canadian uranium exploration declined from the late 1960s to the early 1970s and the rate of uranium discovery in Canada dropped sharply between 1972 and 1974.

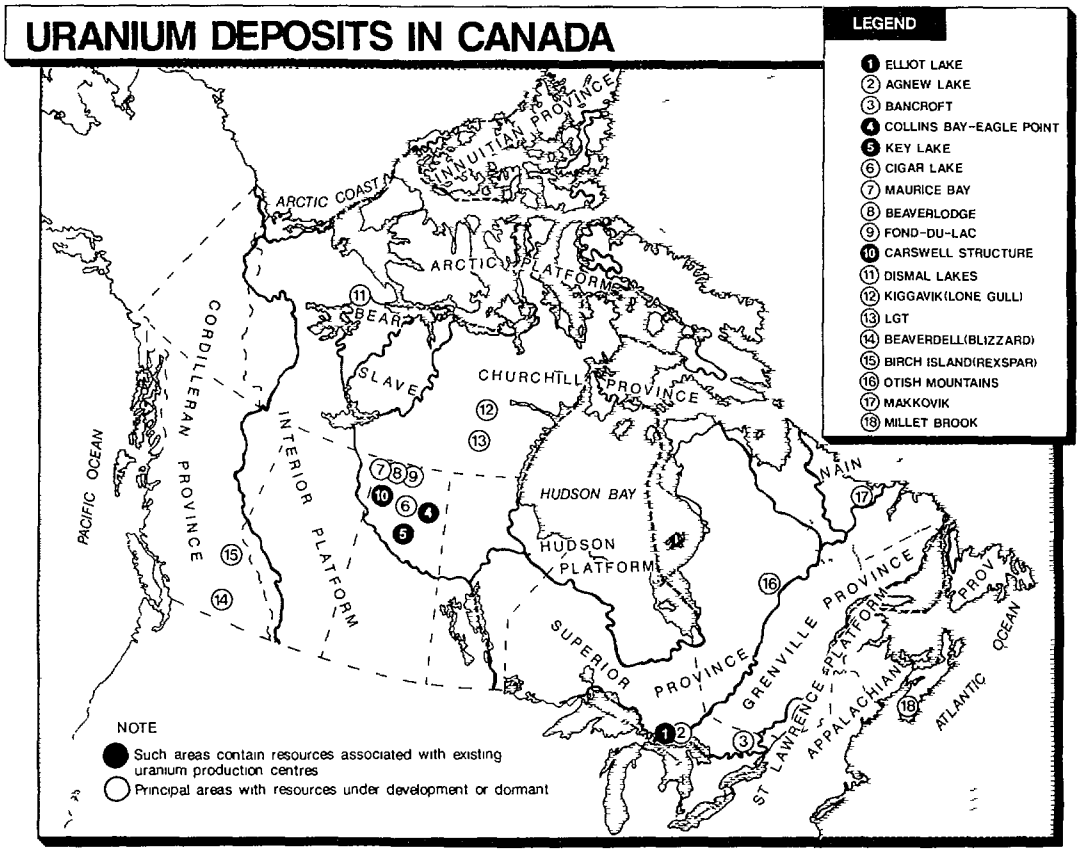

FIGURE 3

However, from 1973 to 1978 the spot market price of uranium, as reflected by the NUEXCO EV expressed in 1985 Canadian dollars, surged almost five-fold, from $45/kg U ($17.45/lb U_3O_8) to $215/kg U ($82.83/lb U_3O_8), respectively. In comparison, the average Canadian uranium export price, in 1985 Canadian dollars, more than doubled from about $91/kg U ($35/lb U_3O_8) in 1974 to about $209/kg U ($80/lb U_3O_8) in 1978.

The sharp price increase, together with the recent discovery of several mostly high-grade Canadian uranium deposits, led to a 26-fold increase (10-fold in annual constant dollar terms) in Canadian uranium exploration expenditures between 1973 and 1979 when uranium exploration expenditures peaked at $130 million. Since 1971, the first year for which relevant statistics were gathered, Canadian uranium exploration expenditures have closely followed the changing price of uranium (Figure 4).

In 1981, some 160 000 tonnes of uranium were discovered in Canada, second only to the roughly 300 000 tonnes discovered in 1954. About 150 000 tonnes of the uranium discovered in 1981 is in the Cigar Lake deposit in the Athabasca Basin of northern Saskatchewan.

Uranium prices, which had peaked in 1978, declined precipitously from 1979 on, (see Table 3) so that by 1983 uranium exploration expenditures in Canada were less than one quarter of the expenditures in 1979 measured in constant dollar terms. In recent years a higher proportion of the expenditures has been for surface development drilling of deposits already discovered, but such activity is estimated to account for no more than 5 per cent of the total drilling expenditures. Although the inclusion of such expenditures may tend to inflate the cost of discovery, these costs are likely more than offset by sizeable additional expenditures (e.g., for land acquisition or the work of consultants) which have not been included here.

URANIUM EXPLORATION EXPENDITURES IN CANADA

In 1976, URAG commenced a uranium exploration expenditure survey that gathered expenditure data back to 1971. Although the 1971-1975 expenditures were collected on a national rather than on a provincial basis, data for subsequent years were gathered for each province and territory of Canada. Saskatchewan accounted for 55 per cent of the total $1.05 billion (1985 $Cdn) spent on uranium exploration between January 1, 1976, and December 31, 1985 (Figure 5).

EXPENDITURE TRENDS OF MAJOR COMPANY GROUPS EXPLORING FOR URANIUM IN CANADA

During the mid-to-late 1970s, uranium exploration in Canada was carried out by five groups of companies: (i) petroleum companies, largely the multinationals, (ii) Canadian and multinational mining companies, (iii) foreign utility-backed exploration companies, (iv) federal and provincial government-owned mineral exploration and mining companies, most notably Saskatchewan Mining Development Corporation, Eldorado Nuclear Limited, Société québécoise d'exploration minière (SOQUEM) and

Société de développement de la Baie James, and (v) Canadian "junior mining companies" (small mineral exploration firms without producing mines).

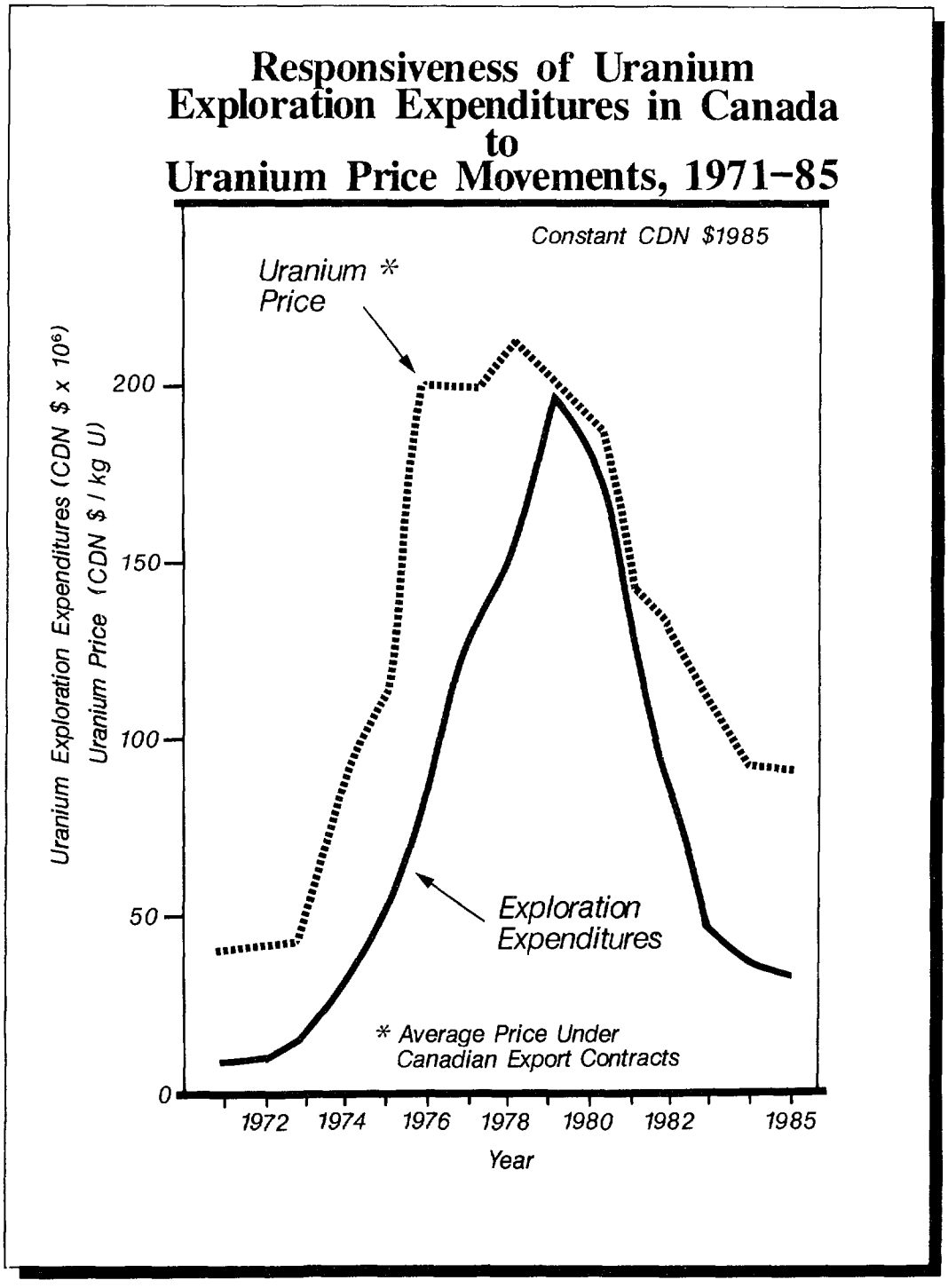

FIGURE 4

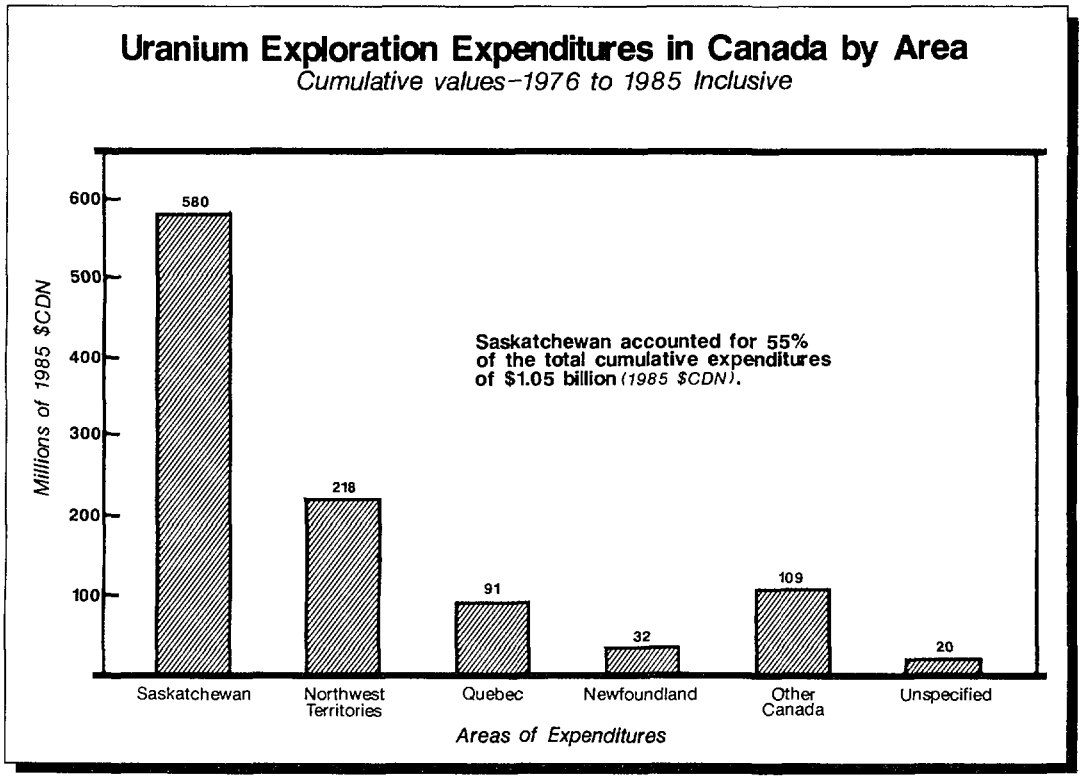

FIGURE 5

With the decline in the price of uranium beginning in the late 1970s, it is largely the activities of state-sponsored and private, utility-linked exploration firms that have maintained any level of uranium exploration in Canada. Most of these are non-U.S. foreign companies that are relatively less concerned about current low prices, focussing rather on long-term security of supply. Figure 6 indicates the expenditure trends of the major groups of companies exploring for uranium in Canada in recent years.

URANIUM DISCOVERIES BY GEOLOGICAL DEPOSIT TYPE

Percentages of total Canadian uranium discovered in each deposit type, and examples of major deposits of each type, are as indicated in Table 4. Rates of discovery of uranium in Canada by geological deposit type are depicted in Figure 7.

CANADIAN URANIUM DISCOVERY COSTS

Barnes* (1972) calculated that during the period 1965-1970, Canadian discovery costs for newly discovered orebodies amounted to about $2.60/kg U ($1.00/lb U_3O_8). In 1985 dollars, this equals $9.30/kg U ($3.60/lb U_3O_8). But Barnes' calculation

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* F. Q. Barnes, "Uranium Exploration Costs" in, Bowie, S.H.U; Davis, M; Ostle, D; editors, Uranium Prospecting Handbook, proceedings of a NATO-sponsored Advanced Study Institute, Institution of Mining and Metallurgy, London, 1972.

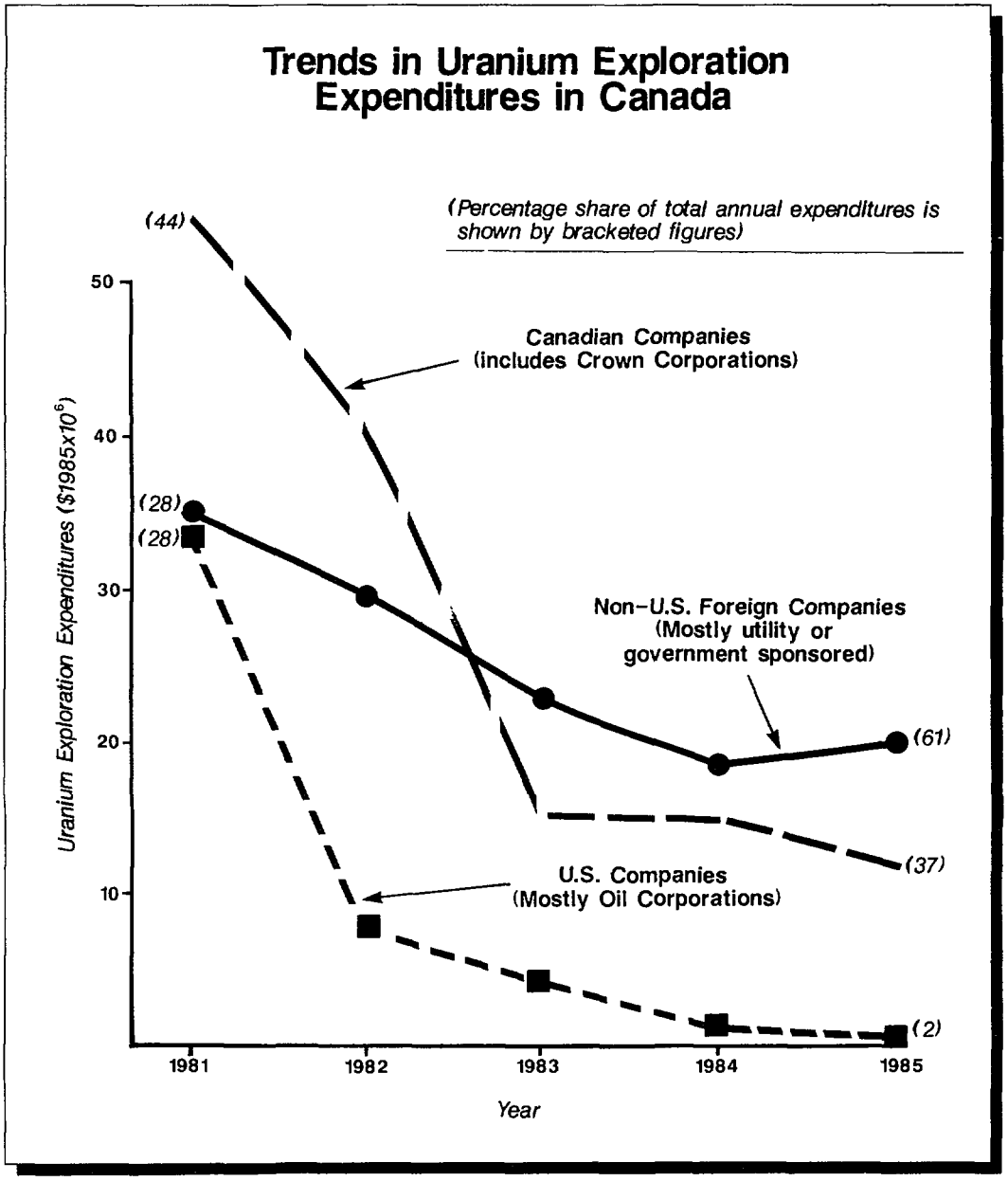

FIGURE 6

was based on his assumption that the Rabbit Lake and Agnew Lake deposits were the only discoveries made between 1965 and 1970. He was apparently unaware of the following discoveries: Hab in Saskatchewan, Fuki-Donen and Mallory-Vowell Creek in British Columbia, Michelin and Nash in Labrador, and Amer Lake in the Northwest Territories, which contain roughly as much uranium again as Barnes had considered to be contained in the Rabbit Lake and Agnew Lake deposits. If these additional uranium discoveries had been taken into account, the discovery cost calculated by Barnes would have been lower. Another uncertainty in his cost calculations concerns the reliability of his estimates of Canadian exploration expenditures during the period, data on which are undoubtedly incomplete.

TABLE 4

PERCENTAGES OF CANADIAN URANIUM DISCOVERIES BY GEOLOGICAL DEPOSIT TYPE

Uranium Deposit Types (and Major Examples)	% of Total Canadian Uranium Discovered
1. Quartz-pebble conglomerate (and other placer) deposits (chiefly Elliot Lake, Ontario)	50
2. Unconformity-related deposits (mostly in the Athabasca Basin, Saskatchewan)	41
3. Vein deposits (Beaverlodge district, Saskatchewan)	5
4. Disseminated magmatic, pegmatitic and contact deposits in igneous and metamorphic rocks (Bancroft, Ontario)	> 1
5. Volcanogenic deposits (Makkovik, Labrador)	1
6. Proterozoic-stratabound and remobilized deposits in continental sedimentary environments	< 1
7. Sandstone deposits	< 1
8. Uranium in carbonatites	< 1
	100

The URAG exploration expenditure data, noted above, were used in the calculation of various uranium discovery costs for the period 1971-1983 inclusive. (Discoveries have been made since 1983, both in Saskatchewan and elsewhere in Canada, but the size and grade of these deposits are still being assessed; as such they are not included in this cost analysis. However, Cigar Lake is included as it was discovered in 1981.) By dividing exploration expenditures by the amount of uranium discovered, an approximate cost per kilogram of uranium can be derived, as shown below.

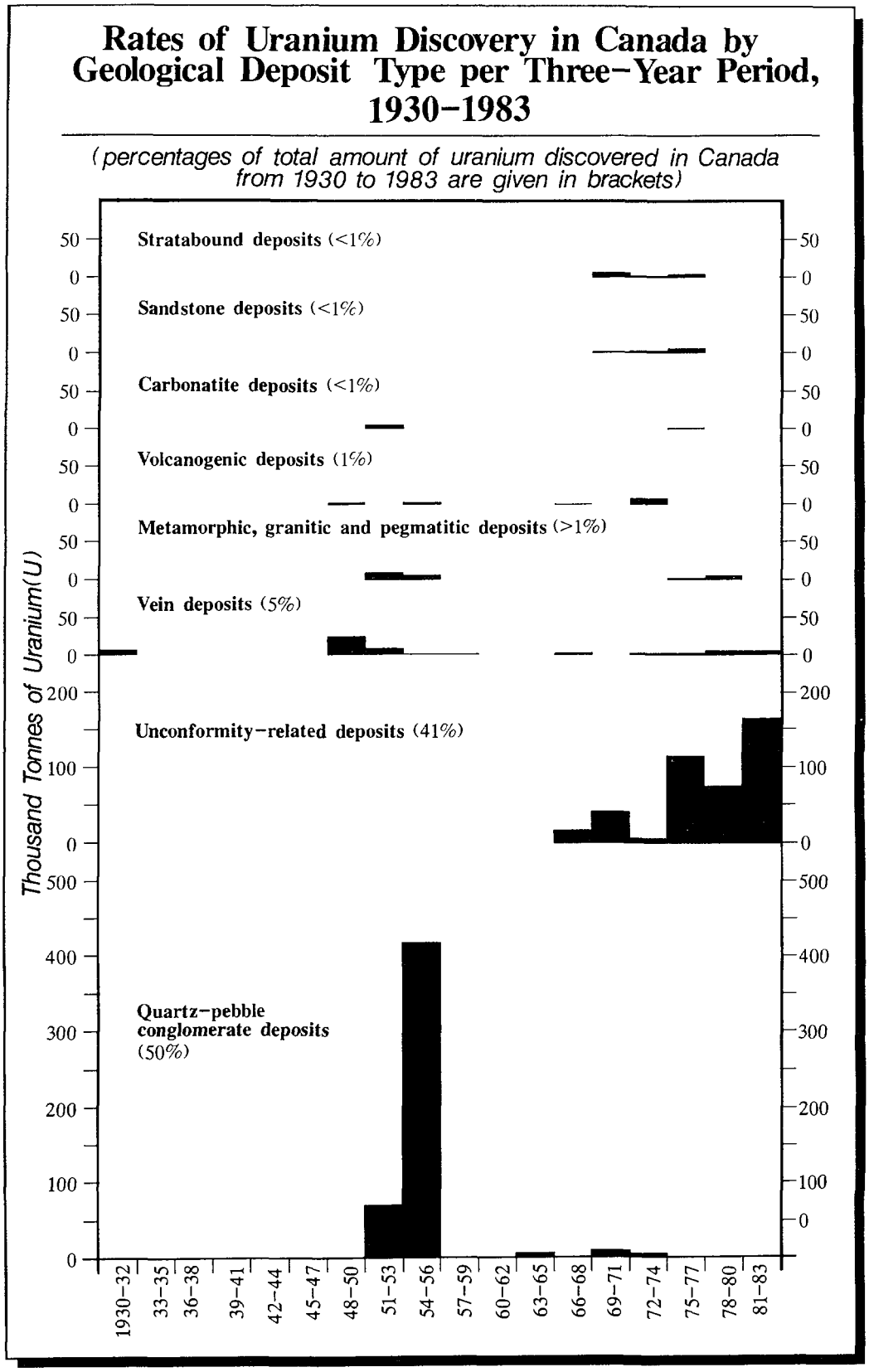
Rates of Uranium Discovery in Canada by Geological Deposit Type per Three-Year Period, 1930-1983
(percentages of total amount of uranium discovered in Canada from 1930 to 1983 are given in brackets)
Thousand Tonnes of Uranium(U)
Stratabound deposits (<1%)
Sandstone deposits (<1%)
Carbonatite deposits (<1%)
Volcanogenic deposits (1%)
Metamorphic, granitic and pegmatitic deposits (>1%)
Vein deposits (5%)
Unconformity-related deposits (41%)
Quartz-pebble conglomerate deposits (50%)
1930-32
33-35
36-38
39-41
42-44
45-47
48-50
51-53
54-56
57-59
60-62
63-65
66-68
69-71
72-74
75-77
78-80
81-83

FIGURE 7

1. **Overall Canadian Discovery Costs For Uranium (1985 $Cdn)**

   - Total uranium exploration expenditures, 1971-1983 inclusive: $1 096 million
   - Total uranium discovered in Canada, 1971-1983 inclusive: 421 200 tonnes
   - Cost per kg U discovered in Canada = $2.60

2. **Discovery Costs for Uranium in Saskatchewan (1985 $Cdn)**

   - Uranium exploration expenditures in Saskatchewan, 1971-1983 inclusive : $588 million
     (assuming 50 per cent of Canadian expenditures for years 1971-1975 in Saskatchewan)
   - Uranium discovered in Saskatchewan, 1971-1983 inclusive: 383 800 tonnes
   - Cost per kg U discovered in Saskatchewan = $1.53

3. **Discovery Costs in Canada Excluding Saskatchewan (1985 $Cdn)**

   - Uranium exploration expenditures in Canada excluding Saskatchewan, 1971-1983 inclusive: $508 million
   - Uranium discovered in Canada excluding Saskatchewan, 1971-1983 inclusive: 37 400 tonnes
   - Cost per kg U discovered in Canada excluding Saskatchewan = $13.58

In 1985, it was estimated that the Cigar Lake deposit could contain 150 000 tonnes U, which amounts to 36 per cent of the total uranium discovered in Canada from 1971-1983 and 39 per cent of that discovered in Saskatchewan. Such a major single discovery has a considerable effect on discovery costs both for Saskatchewan and for Canada as a whole. If Cigar Lake had not been discovered, costs for Canada as a whole would have been $4.04/kg U, and for Saskatchewan alone $2.51/kg U (both in 1985 $Cdn).

THE OUTLOOK FOR FUTURE CANADIAN URANIUM DISCOVERIES

Additional uranium deposits have been discovered in Saskatchewan and elsewhere in Canada after 1983, but it is still too early to properly assess their size and significance. The probability is very high that additional high-grade deposits will be found in the Athabasca Basin, but the number of these will be dependent on the geographical extent of the favourable geological environment, which is not yet clear. Similarly, the potential for additional discoveries elsewhere in Canada is also high. As new concepts are developed concerning the genesis of uranium deposits, perhaps related to new-found mineralization elsewhere in the world, other favourable environments for uranium may be recognized in Canada that lead to still more discoveries.

The fact that uranium discovery costs have been much lower in Saskatchewan than in other parts of Canada should not be considered as being indicative of future discovery costs in either area. Costs for the rest of Canada could decline if major new uranium environments and deposits are discovered. The costs calculated here are averages, but competent innovative explorationists may continue to discover uranium at costs well below average. It is clear that uranium exploration and discovery in Canada still have a bright future.

SUMMARY AND CONCLUSIONS

Since 1930, in excess of 1 000 000 tonnes of uranium have been discovered in Canadian deposits sufficiently attractive to have warranted the expenditure required to establish their tonnage and grade.

Canada has produced uranium since 1932, and has continued to be the major exporter. In 1984, Canada regained its position as the Western world's largest producer and is likely to remain so for some years, thanks to its large inventory of known high-grade deposits. Although many of these deposits are not viable at current uranium prices, most of the uranium in deposits not currently in production could be produced profitably within the range of prices, expressed in constant dollars, that has occurred over the past 40 years.

Levels of uranium exploration and rates of discovery in Canada have gyrated wildly over the past 40 years, as a result of unprecedented market distortions introduced by: (i) the changing needs and priorities of the USAEC, (ii) the still relatively immature state of world uranium markets, and (iii) sharp cutbacks in world plans for nuclear generation of electrical power. Markets for other major mineral commodities have not been affected in this fashion.

Exploration for uranium in Canada has gone from boom-to-bust and back again, the first such peak in exploration and discovery activity occurring between 1947 and 1955, the second beginning in 1974 and ending in the early 1980s. Another, but less significant, exploration-discovery peak occurred in the second half of the 1960s.

Half of the uranium discovered in Canada from 1930 to 1983, inclusive, was in quartz-pebble conglomerate deposits nearly all at Elliot Lake, Ontario, and most of the rest was found in unconformity-related deposits in the Athabasca Basin of northern Saskatchewan.

For the period 1971 to 1983, Canadian uranium discovery costs (in 1985 Canadian dollars) have averaged $2.60/kg U. In Saskatchewan the cost has been only $1.53/kg U, whereas in the remainder of Canada the cost has averaged $13.58/kg U.

Discovery of uranium in Canada has continued since 1983, and although it is too early to properly evaluate uranium exploration success in the three-year period for 1984 to 1986, it is known that at least four new Canadian uranium discoveries were made despite the decline in annual uranium exploration expenditures. It is also clear that there is still considerable potential for discovering additional uranium in Canada, at a reasonable cost.

CONCEPTUAL GENETIC MODELS FOR IMPORTANT TYPES OF URANIUM DEPOSITS AND AREAS FAVOURABLE FOR THEIR OCCURRENCE IN CANADA

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Abstract

Conceptual genetic models for the formation of known Canadian uranium deposits, developed for the purpose of uranium resource evaluation, have been formulated for: (1) deposits of Lower Proterozoic pyritic quartz-pebble conglomerates; (2) deposits associated with Proterozoic unconformities; (3) uraniferous veins; (4) disseminated mineralization in orthomagmatic, anatectic and metamorphic rocks; (5) volcanogenic deposits; (6) sediment-hosted deposits; (7) surficial deposits; and (8) deposits of other types.

In Canada all active mines and the bulk of presently known recoverable uranium resources are confined to deposits of the first two types, although deposits of the remaining types contain resources which may be recoverable in the future.

Conceptual genetic models are of value not only for concise representation of geological and genetic features of various deposit types, but also for delineation of areas favourable for mineralization and thus for selection of exploration targets. Because of the present economic importance of the conglomeratic and unconformity-associated uranium deposits the greatest attention is paid to the conceptual genetic models for these deposits.

The conceptual model for the Lower Proterozoic uraniferous pyritic conglomerates involves placer concentrations of uranium minerals in the oldest (>2.25 Ga) supracrustal rocks, derived from Kenoran granitoids, and deposited in pericratonic or intracratonic basins. Environments favourable for such deposits occur in pericratonic basins of the Southern Structural Province and in some intracratonic basins of the Churchill Structural Province.

In the conceptual model for deposits associated with Proterozoic unconformities it is postulated that the uranium was also derived from Kenoran granitoid rocks (>2.5 Ga), was accumulated during subsequent sedimentary and magmatic processes (between 1.8 and 1.7 Ga), underwent major reconcentration by diagenetic processes combined with hydrothermal events related to emplacement of diabase dykes (between 1.3 and 0.8 Ga) and was rejuvenated in at least two later periods (at about 300 to 200 Ma and at about 80 Ma). Environments favourable for unconformity-associated uranium deposits in Canada occur in the Athabasca Basin, Baker Lake - Thelon Basin, Coronation Homocline and Otish Basin regions.

Conceptual genetic models for the remaining deposit types incorporate magmatic, hydrothermal, sedimentary or supergene processes in various proportions. Environments favourable for their formation occur in the Canadian Shield and in Phanerozoic orogenic belts of Canada.

Introduction

Conceptual genetic models are useful not only for concise representation of geological and genetic features of various deposit types, but also for delineation of areas favourable for mineralization and thus for selection of exploration targets.

A general model accounting for formation of a uranium deposit

[1] incorporates proposed mechanism for:

(a) Primary concentration of uranium and its geochemical availability, i.e. source, from which uranium can be liberated and introduced into geochemical cycle either in discrete solid form, for example within detritus, or in dissolved form, for instance in supergene or hypogene solutions.

(b) Transport of uranium from the site of origin or pre- concentration to the site of deposition; this can involve either mechanical or chemical processes.

(c) Concentration and deposition of uranium which can occur in structural or lithological traps due to: sedimentation, absorption, precipitation (as a result of evaporation, redox changes, or P-T changes). The processes involved in the concentration and deposition of uranium may take place either syngenetically with the rock-forming processes or epigenetically, i.e. after lithification of the sedimentary rocks, solidification of the igneous rocks or in the post-metamorphic stage in the case of metamorphic rocks.

(d) Modification of uranium deposits due to accretion, during diagenesis, due to prograde or retrograde metamorphism, by oxidation etc.

(e) Preservation of uranium deposits from destruction (retention of sufficient resources to represent an exploitable deposit).

Current work by a group of consultants (D.P. Harris, W.I. Finch and V. Ruzicka),to the International Atomic Energy Agency (IAEA) which is at present (1987) preparing a 'Manual for Estimation of Undiscovered Uranium Resources' [2], is resulting in further modification of a sequential scheme of processes participating in formation of uranium deposits. The modification consists essentially in redefinition of the first ('source') stage of the general model [1] and includes: 'Precursor processes', 'Host-rock formation', 'Host-rock preparation' and 'Uranium source development'.

Conceptual genetic models for known Canadian uranium deposit types (according to a modified NEA/IAEA classification [3]), which have been developed for the purpose of uranium resource evaluation, are for:

(1) deposits of Lower Proterozoic (Huronian) pyritic quartz- pebble conglomerates;

(2) deposits associated with unconformities;

(3) uraniferous veins;

(4) deposits consisting of disseminated mineralization in orthomagmatic, anatectic and metamorphic rocks;

(5) volcanogenic deposits;

(6) sediment-hosted deposits;

(7) surficial deposits; and

(8) deposits of other types (e.g. associated with carbonatites).

In Canada all active mines and the bulk of presently known recoverable resources are confined to deposits of the first two types. Deposits of the remaining types, however, contain resources, which may be recoverable in the future. Resources of a classical representative of the polymetallic vein type (Eldorado deposit at Port Radium) are mined out.

Location of areas with deposits associated with existing uranium Production centres and with deposits containing resources under development or dormant is shown in Fig. 1.

Deposits in Lower Proterozoic (Huronian) quartz-pebble conglomerates occur in the basal part of the Huronian Supergroup. There is an active production centre at Elliot Lake, Ontario (1)*; remaining resources in the Agnew Lake area, Ontario (2), are dormant.

Deposits associated with the Middle Proterozoic unconformity occur in the Collins Bay-Eagle Point area (4): Collins Bay 'A','B','D', Eagle Point 'N','S', Raven, Horseshoe and West Bear; at Key Lake (5), in the Cigar Lake - McClean Lake area (6): Cigar Lake, Midwest, Dawn Lake, McClean Lake; at Maurice Bay (7), Fond-du-Lac (9) and in the Carswell Structure (10): Claude, Dominique-Peter, Dominique-Janine, N, R, and OP; all of them in the

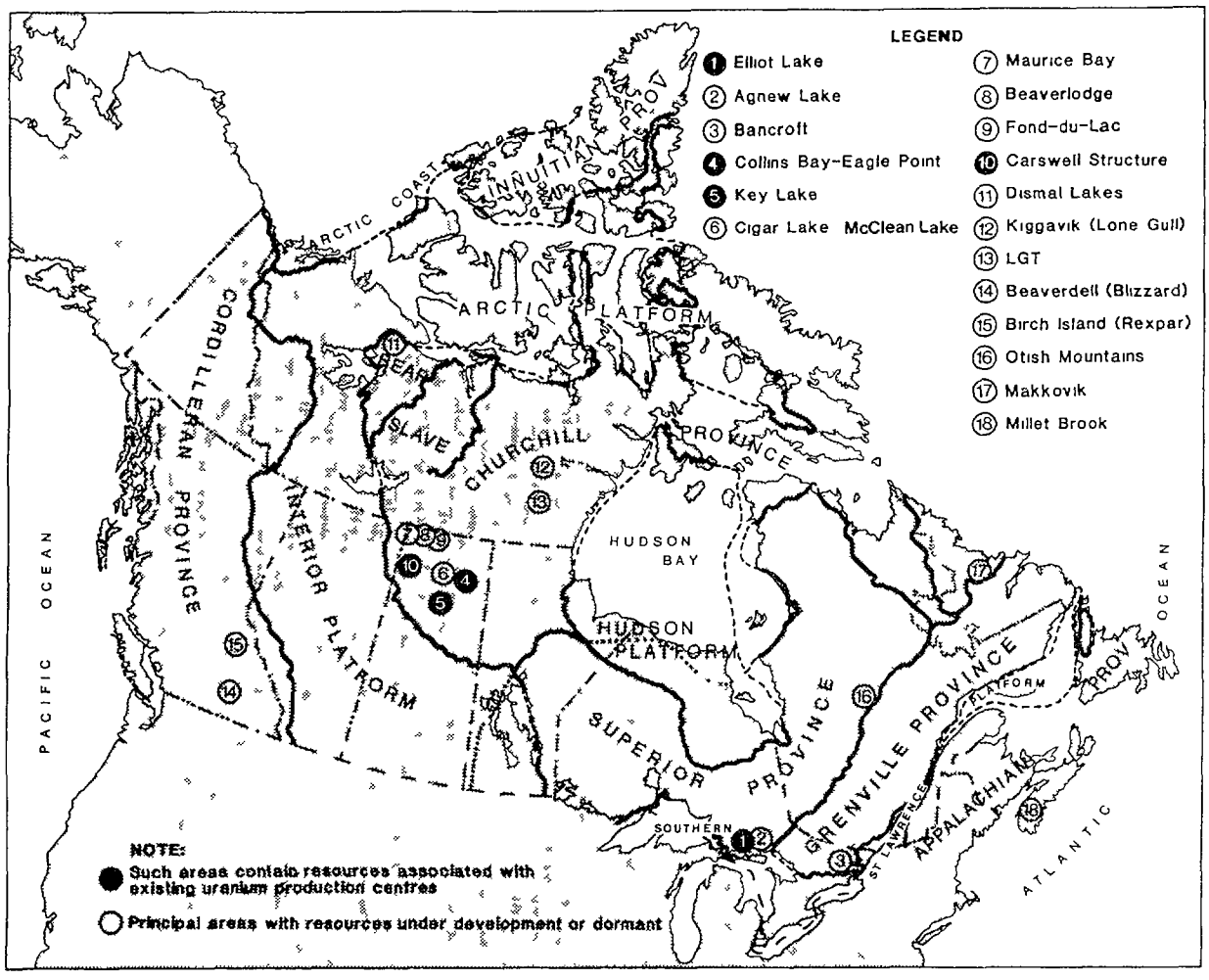


Figure 1: Areas with uranium resources in Canada (1987).

* Numbers in parentheses are keyed to numbers in Fig. 1.

Athabasca Basin region, Saskatchewan. The Key Lake and Collins Bay B deposits and some deposits in the Carswell Structure are being exploited; the Eagle Point and Cigar Lake deposits and some deposits in the Carswell Structure are being developed for production; the remaining deposits are dormant. In the Northwest Territories uranium resources of the Kiggavik (formerly Lone Gull) deposit (12) are under advanced exploration.

Uranium resources in the vein deposits, which are commonly also associated with unconformities, occur in Saskatchewan in the Carswell Structure (10), where they are under exploration, development and exploitation; in the Beaverlodge area (8) the remaining resources are dormant. In the Northwest Territories the LGT (Lac Cinquante) deposit (13) is dormant. In the Central Mineral Belt of Labrador the Kitts deposit near Makkovik (17) and in Nova Scotia the Millet Brook deposit (18) are dormant.

Low grade and irregularly distributed uranium resources in deposits consisting of disseminated mineralization in anatectic rocks occur in the Bancroft area, Ontario (3), particularly in the dormant Faraday (Madawaska) mine.

Uranium resources in deposits of volcanogenic origin are in the Central Mineral Belt of Labrador: the Michelin deposit near Makkovik (17) and in the Cordillera: the Rexspar deposit (15) near Birch Island, British Columbia. Their resources are dormant.

The dormant Mountain Lake uranium deposit (11) in the Dismal Lakes area, Northwest Territories, is hosted by Precambrian sedimentary rocks. In the Beaverdell area, south-central British Columbia, the Blizzard deposit (14), which occurs in Tertiary unconsolidated and semiconsolidated sedimentary rocks, is dormant too.

Occurrences in which the uranium has been concentrated by surficial processes (e.g. occurrences of the so-called 'young uranium') are common in the Beaverdell-Kelowna area (14), south-central British Columbia. Their exploration is also dormant.

The Otish Basin in Quebec (16) hosts uranium occurrences of several types [55]. However only the 'L' deposit, classified as belonging to the group of 'Other types', contains (at present dormant) uranium resources. The deposit is associated with a zone of deuteric alteration (epidote - chlorite - albite - carbonate) in gabbroic intrusions and with a contact between altered (carbonatized and/or silicified) sandstone and carbonate rocks of Proterozoic age.

Lower Proterozoic uraniferous conglomerates

Sedimentary and volcanic rocks of the Huronian Supergroup, which contain the uraniferous pyritic quartz-pebble conglomerate deposits, occur in a belt at least 430 kilometres long and as much as 130 kilometres wide that extends in Canada between the towns of Sault Ste. Marie and Noranda [4]. The Huronian rocks were deposited 2.5 - 2.1 Ga ago, as indicated by radiometric ages for the Archean granitoid basement rocks and for Nipissing Diabase that has intruded the Huronian sequence [5;6;7;8].

In the Blind River - Elliot Lake area the rocks of the Huronian Supergroup were deposited in a pericratonic basin in four major sedimentary cycles, which were controlled by syndepositional faulting and differential movements of basement blocks [5;8]. The lowermost part of the sequence, the Matinenda Formation, which hosts the uraniferous conglomerates, was deposited during a series of regressive marine periods, which were locally interrupted by mafic volcanism [9]. Roscoe [8;50] recognized four members of the Matinenda Formation (Fig. 2).

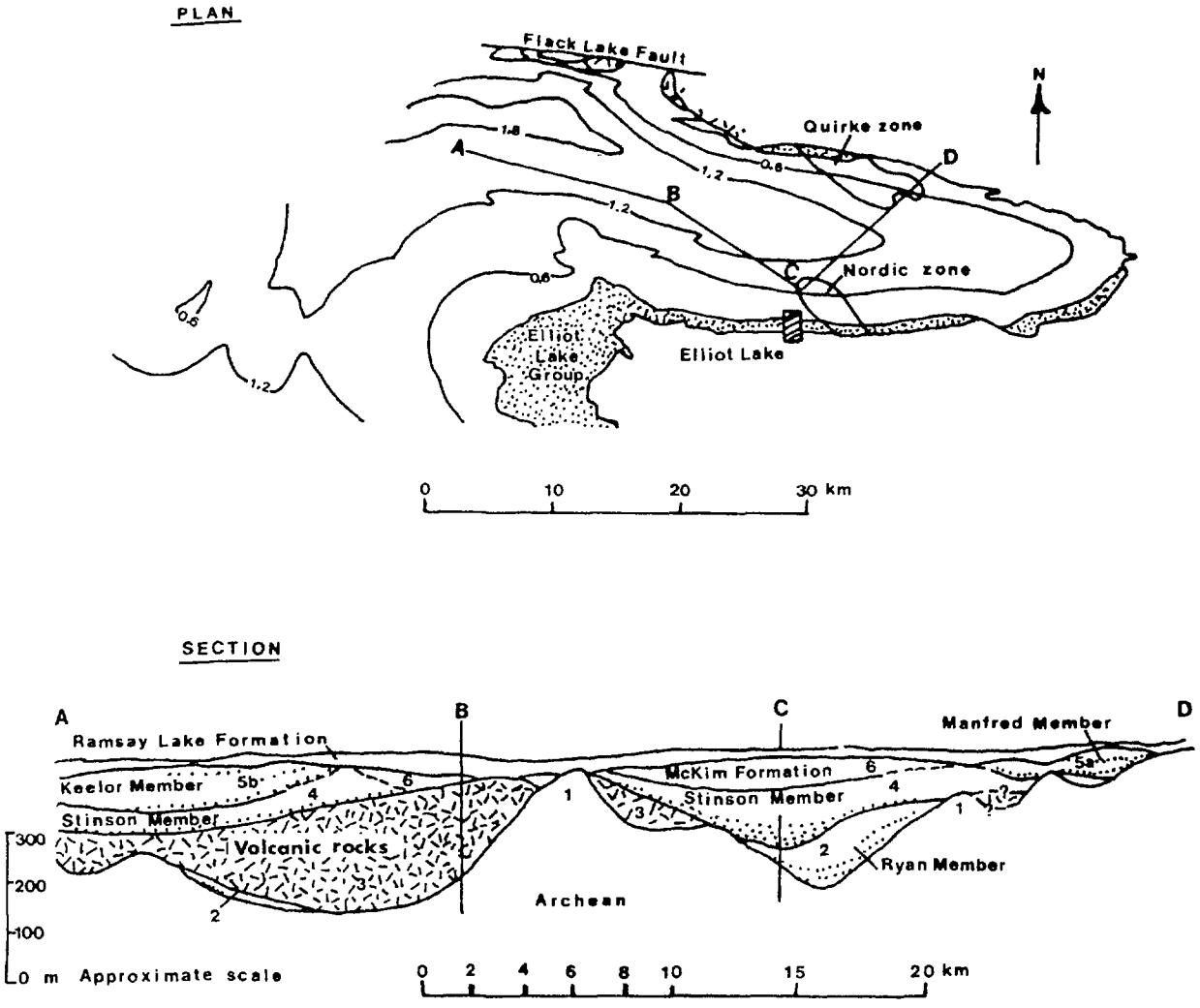


Figure 2: Elliot Lake area, Ontario. Plan of the distribution of the Matinenda Formation with contours (in km) of its top below the present surface and a section of the Matinenda and Ramsay Lake formations at Elliot Lake, Ontario; (1) Archean granitic, metasedimentary and metavolcanic rocks; (2,4,5a and 5b) Clastic sedimentary rocks of Matinenda Formation; (3) Dollyberry volcanic rocks. After Roscoe [50].

During deposition of the Huronian Supergroup the atmospheric conditions changed from oxygen deficient (10^{-6} PAL)[Present Atmospheric Level] to oxidizing [10].

The uraniferous conglomerate consists mainly of quartz pebbles embedded in an arkosic/sericitic matrix with abundant pyrite, uraninite, 'brannerite', monazite, zircon and other heavy minerals (Fig. 3). Most of the metallic components of the conglomerate indicate detrital origin (Fig. 4a,b); however some minerals, such as coffinite, at least one generation of pyrite, 'brannerite', chalcopyrite and galena (derived from radiogenic lead) are authigenic and crystallized during diagenesis of the conglomerate.

Sedimentological, geochemical and petrographic studies of the Huronian sequence indicate that both the host rocks and the mineralization were derived from an Archean terrane, which extends to the north and northwest from the Blind River - Elliot Lake Basin. The presently exposed Archean terrane is characterized by belts and patches of metavolcanic and

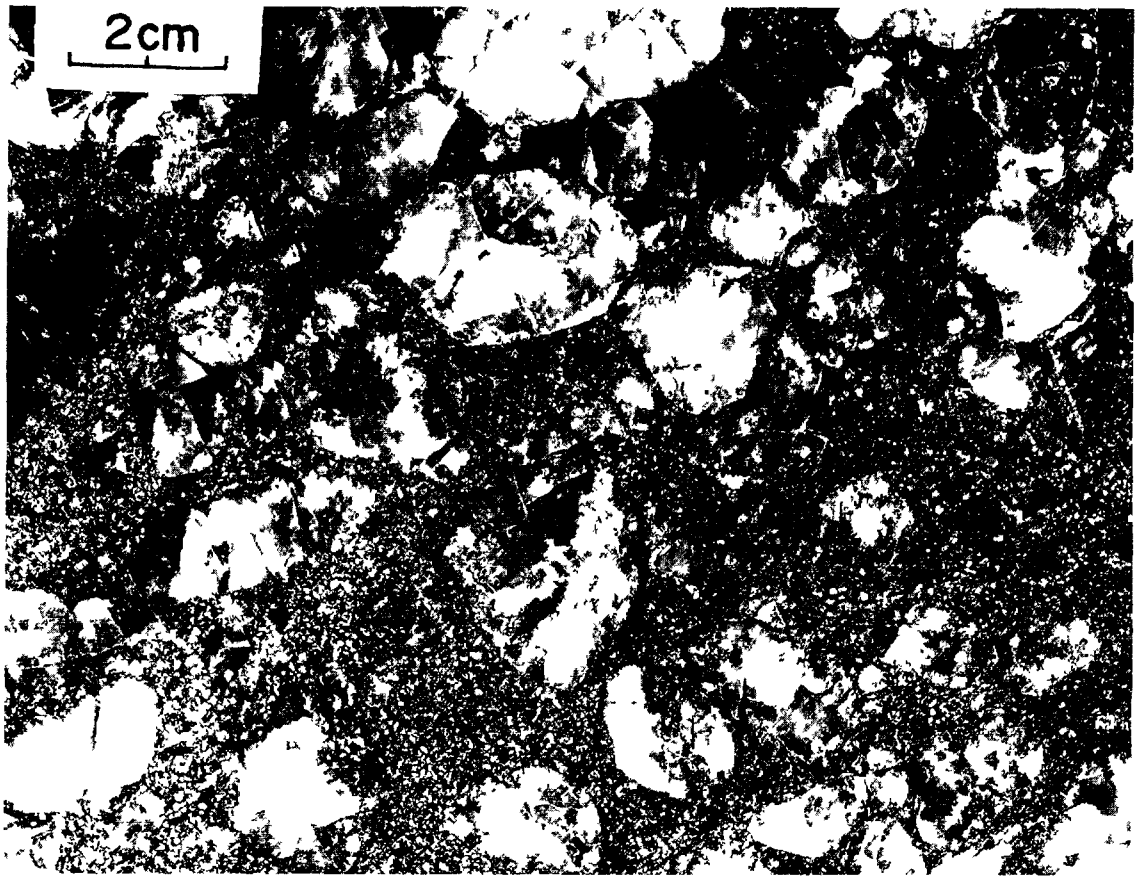


Figure 3: Uraniferous conglomerate from 'A' Reef, Denison mine, Elliot Lake, Ontario. Quartz pebbles (q) are embedded in arkosic/sericitic matrix with pyrite, uraninite, 'brannerite', monazite, zircon and other heavy minerals.

metasedimentary rocks and metagabbro, within predominantly granitic rocks. The metasedimentary rocks include iron-formations, which are locally jaspilitic [11]. The granitic rocks were emplaced during the Kenoran Orogeny (2.70 - 2.65 Ga ago) [8]. Their heavy mineral accessories include hematite, magnetite, ilmenite, titanite, rutile, anatase, zircon, apatite, allanite, monazite, uraninite, microlite-pyrochlore and thorite [12;8;9;13]. Robinson and Spooner [14] speculated that the uraninite, which represents a substantial constituent of the Elliot Lake ores, was derived from a pegmatitic, potassic (alaskitic) granite similar to the uraniferous alaskites of the Roessing deposit in Namibia. However such an actual source rock has not been identified yet. Uraninite-bearing Kenoran rocks also occur elsewhere in the Superior Structural Province, e.g. at the Richard Lake (New Campbell Island) deposit that contains about 500 tonnes of uranium [15] in magnetite-bearing pegmatite dykes in which uraninite is the principal uraniferous mineral. Uraninite occurs in several other occurrences in the Kenora - Dryden area, such as Kenoramatic, Hawk Lake (Fig. 5), Ascot, Coulee and Headway [16]. Robertson [16] reported concentrations of uraninite from several localities in Algoma District, Ontario and Roscoe [8] from the Kippawa region, Quebec, which are parts of the assumed source area for the host sequence containing the Elliot Lake - Blind River deposits.

The source rocks underwent intensive weathering and disintegration during pre-Huronian time. This led to development of detritus, in which the uranium and thorium minerals were physically liberated but essentially

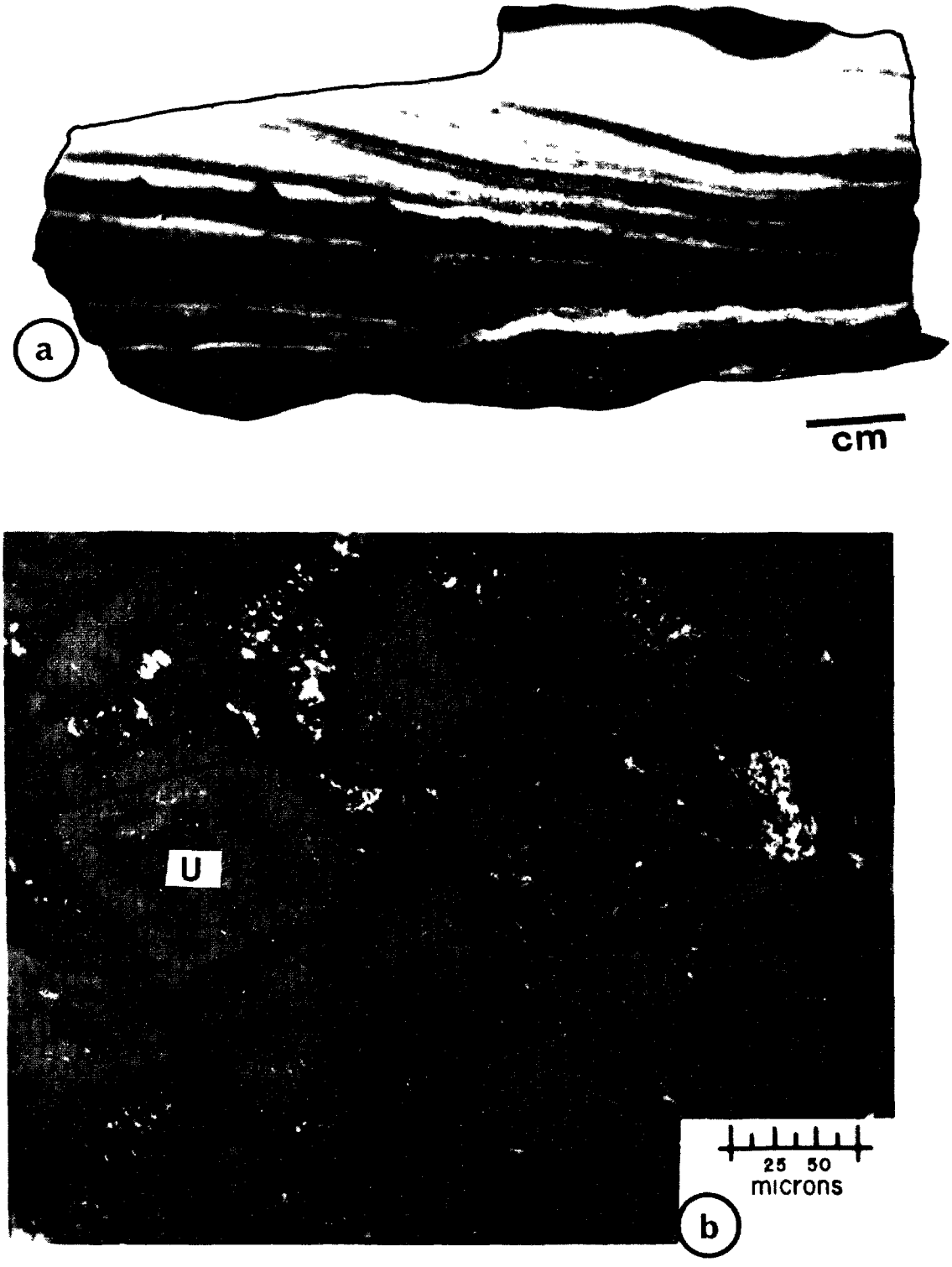


Figure 4: Stratified uraninite from Quirke 1 mine, Rio Algom Limited, Elliot Lake, Ontario; (a) autoradiograph (positive image) showing laminae of uraninite (white); (b) photomicrograph of detrital uraninite (U) from a lamina in (a). (Cf. Figs. 27.8 and 27.9 in [13]).

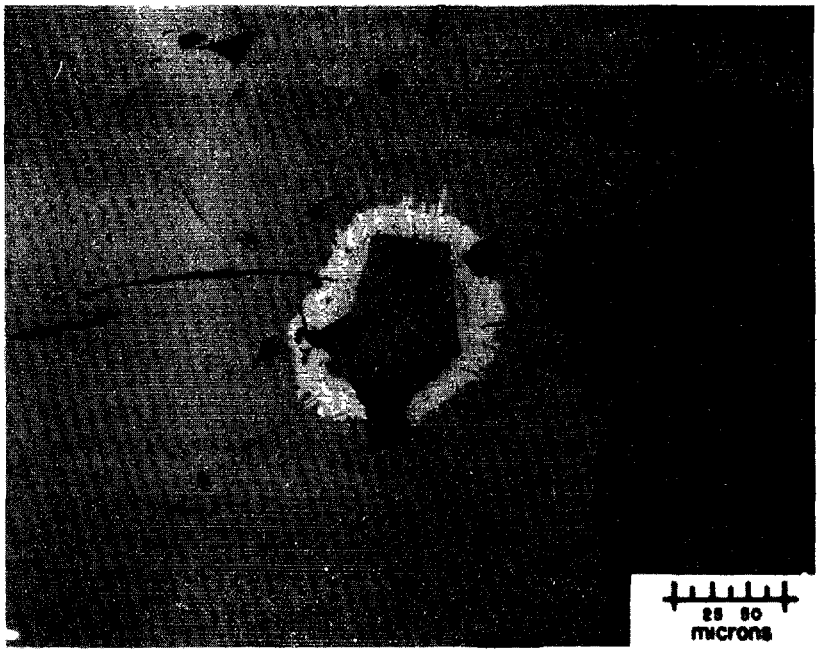


Figure 5: Crystal of uraninite embedded in magnetite and rimmed by hematite from Kenoran granite pegmatite. Byberg occurrence at Hawk Lake [15], Kenora-Dryden area, Ontario.

chemically intact. Part of the detritus was eroded and part remained in situ and developed as paleosol or regolith [17]. Paleosols of the Elliot Lake area consist of sericite, quartz and chlorite with rutile or leucoxene as principal accessories [18]. Relative to parent rocks the paleosols are typically enriched in titanium compounds, but commonly depleted in total iron throughout the paleosol profiles. Locally, however, the paleosol is enriched in iron at the base, i.e.just above the contact of the paleosol with the underlying parent rock [18].

The conceptual model presented here includes the proposal that both the detritus, which was directly derived from the Archean rocks, and the paleosol, which developed as a weathering product on the parent rocks, were the source material for the host conglomerate, and also for the bulk of uranium mineralization. In the conceptual model it is also suggested that the heavy mineral composition of the ores reflects the heavy mineral composition of the rocks in the source area.

The detritus derived directly from the rocks and the material derived from the paleosol were transported by fluvial systems and well sorted during transport. The size of the pebbles in the conglomerate decreased with decreasing depositional energy gradient, e.g. for the Quirke zone from northwest to southeast [19]. The detritus was deposited generally in upward-fining cycles (Fig.6). In general, the pebble size also changed with the stratigraphic position of the beds: the largest pebbles were deposited at the bottom of the Matinenda Formation, e.g. in the Pronto deposit near Blind River, which is stratigraphically at the bottom of the sequence, and the smallest pebbles at the top of the Matinenda Formation, e.g. on the south shore of Elliot Lake at Spine Road within the Elliot Lake townsite.

Quartz pebbles account for more than 95 per cent of all pebbles in the conglomerate. Theis [19] demonstrated that the pebble size is proportional to the grain size of pyrite (correlation coefficient 0.93), which indicates

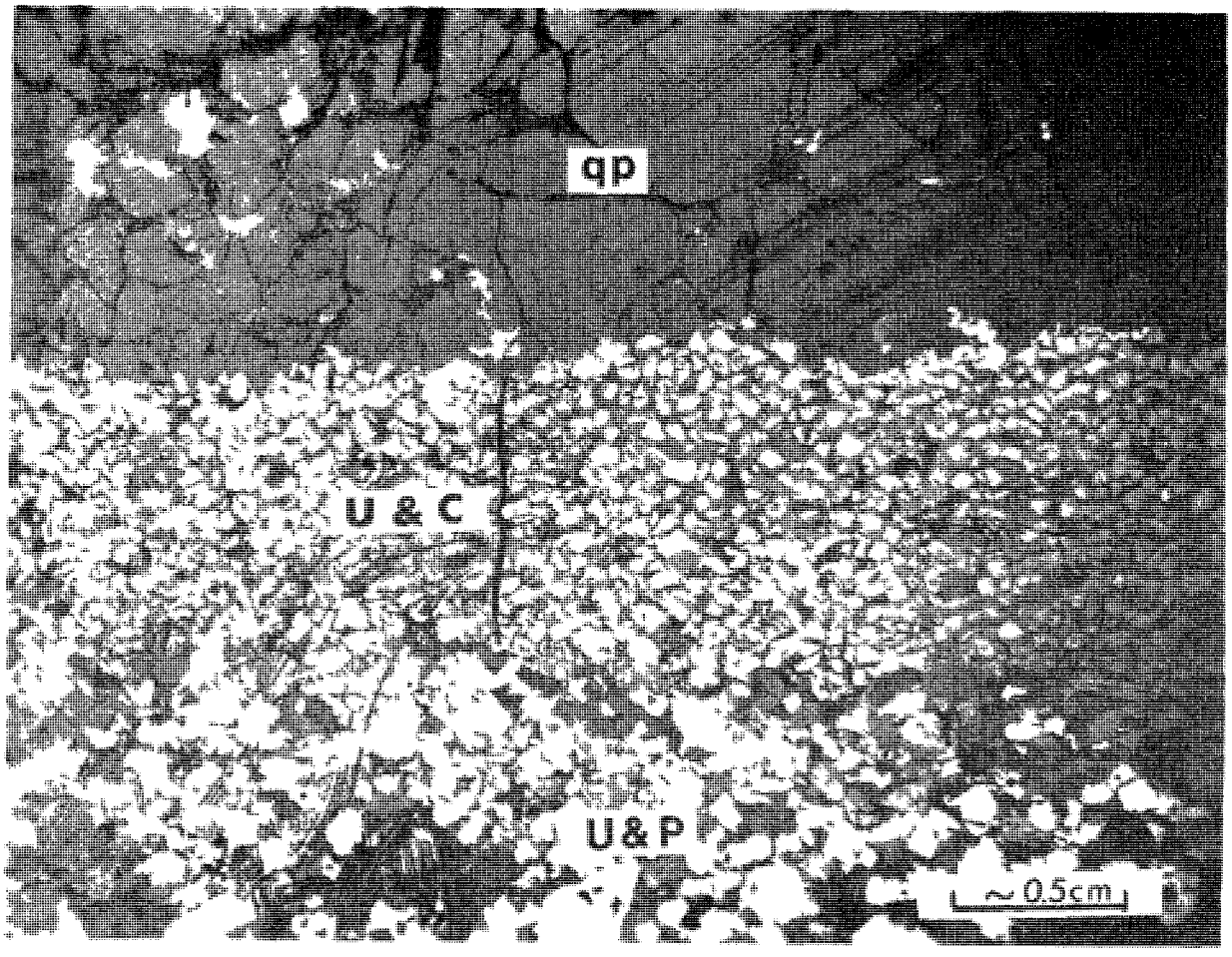
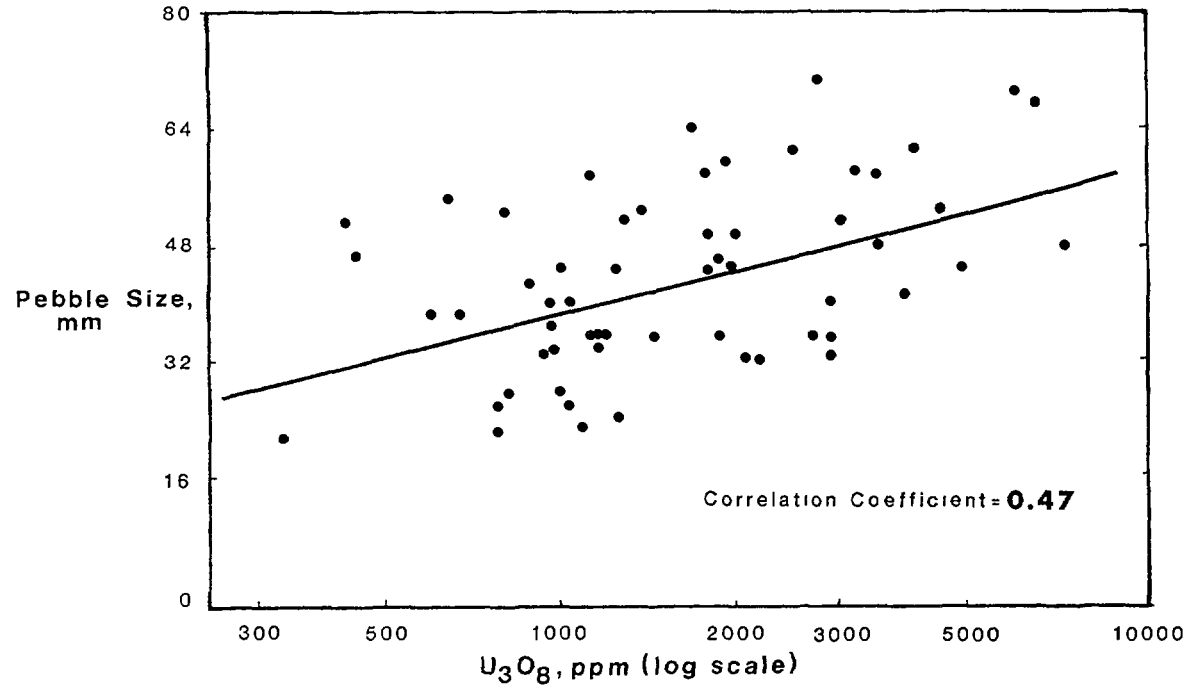


Figure 6: Upward-fining texture of uraniferous quartz-pebble conglomerate. (U&P) uraninite-brannerite-pyrite assemblage grading upwards into (U&C) uraninite and carbon /kerogen/. (qp) densely packed quartz pebbles with some pyrite /white/ are at the base of the next depositional cycle. 'A' Reef, Denison Mine, Elliot Lake, Ontario. (Photomicrograph, reflected plain light.)

that deposition of much of the pyrite was controlled by the same mechanism that controlled deposition of the quartz pebbles. A similar, but less strict correlation (coefficient 0.47) was observed by Theis [19] between the U_3O_8 content and the pebble size in selected ore samples (Fig.7). The detritus was deposited in several cycles corresponding to cyclical uplift and subsidence of the source area and the depositional sites [20]. The sedimentation process included deposition of algal mats [21; 22] that are at present apparently represented by layers of stratiform kerogen [23].

The uraniferous conglomerates were modified after their deposition. Observations on uranium-titanium aggregates (so called 'brannerite') show that both uranium and titanium were present in the solutions. Uranium was commonly adsorbed by titanium minerals from the connate waters ('Pronto-Reaktion' of Ramdohr,[24]), but the process took place also in reverse and both uranium and titanium-bearing phases have been observed at the periphery of a grain of an unidentified mineral with high niobium contents [13]. The diagenetic solutions also reacted with the matrix of the conglomerate and caused formation of other authigenic compounds, such as a U-Ti-Si phase (Fig. 8)[25] and coffinite.



U_3O_8 plotted against pebble size

Figure 7: U3O8 contents plotted against size of quartz pebbles in conglomerate ore; Denison Mine, Elliot Lake, Ontario. After Theis [19].

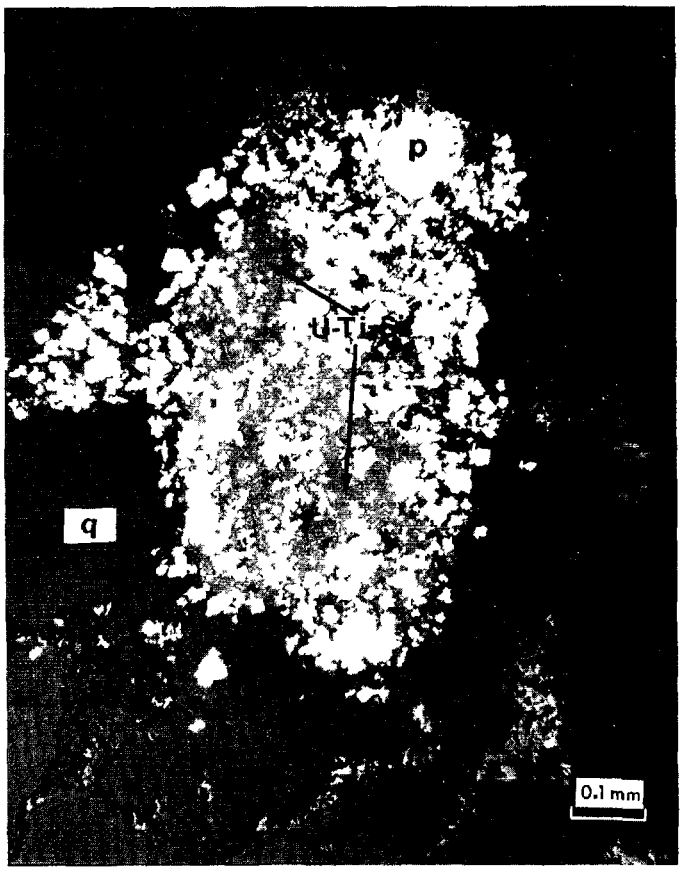


Figure 8: A U-Ti-Si phase, commonly called 'brannerite' from Quirke mine, Rio Algom Limited, Elliot Lake, Ontario. Photomicrograph, reflected plain light. U-Ti-Si (light grey) = 'brannerite'; p (white) = pyrite; q (dark grey) = quartz.

In general the mineralization process resulted, on one hand, in enrichment of some elements in addition to uranium, such as arsenic, rare-earth elements, lead, copper, molybdenum, silver and zirconium, and, on the other hand, impoverishment or depletion of other elements, such as strontium and manganese.

Apparently also during the diagenetic stage the stratiform kerogen has been remobilized and redeposited within the sequence in a globular form.

Modelling studies on the Elliot Lake deposits indicate that the bulk of the uranium minerals (principally uraninite) was deposited syngenetically with the rocks, but the mineralization was modified during the diagenetic stage mainly by authigenic crystallization of a Ti-U phase ('brannerite'). Therefore the uranium deposits in the Huronian pyritic quartz-pebble conglomerates can be classified as "Modified Paleoplacers".

In addition to the Blind River - Elliot Lake area the uraniferous pyritic quartz-pebble conglomerates occur in the Agnew Lake area near Sudbury, Padlei area in the Northwest Territories and Sakami Lake area, Quebec.

Unconformity-associated uranium deposits

Uranium deposits associated with the pre-Helikian unconformity occur in the Athabasca Basin region, Saskatchewan (Fig 9).

This region is a part of the Churchill Structural Province of the Canadian Shield. It consists of Archean granitoids flanked by Aphebian metasedimentary rocks which were deposited in shallow intracratonic basins. The metasedimentary sequence includes graphitic, pyritic, non-graphitic and aluminous pelites and semipelites, calc-silicate rocks, banded iron-formation, volcanic rocks and greywackes [26;29]. The crystalline rocks underwent peneplanation with development of a regolith prior to deposition of Helikian supracrustal rocks of the Athabasca Group. Deposition of clastic sedimentary rocks within the Athabasca Basin was accompanied intermittently by explosive volcanism [27]. Locally the sedimentary rocks contain phosphates, layers of sulphides and organic substance. The crystalline basement rocks and the rocks of the Athabasca Group have been intruded by diabase dykes.

The structural pattern of the crystalline basement is dominated by northeasterly trending faults and shear zones. However the most important structures, which control distribution of the mineralization, are the sub-Athabasca unconformity and intersecting extension faults and fracture zones [26].

The orebodies are associated with zones of alteration which developed in at least three stages [28]: (i) development of regolith on the basement rocks, which took place before deposition of the Athabasca Group rocks; (ii) diagenetic alteration which was coeval and even cogenetic with the mineralization; and (iii) post-ore alteration, which was associated with movements of the groundwaters.

The alteration processes included [28]: argillization of the basement rocks; illitization, kaolinization and chloritization of the host rocks; dissolution or corrosion of quartz grains; silicification of the sandstone in a distant aureole; limonitization, hematization or bleaching of the host rocks.

Brecciation and development of collapse structures in the immediate vicinity of the orebodies accompanied the mineralization processes.

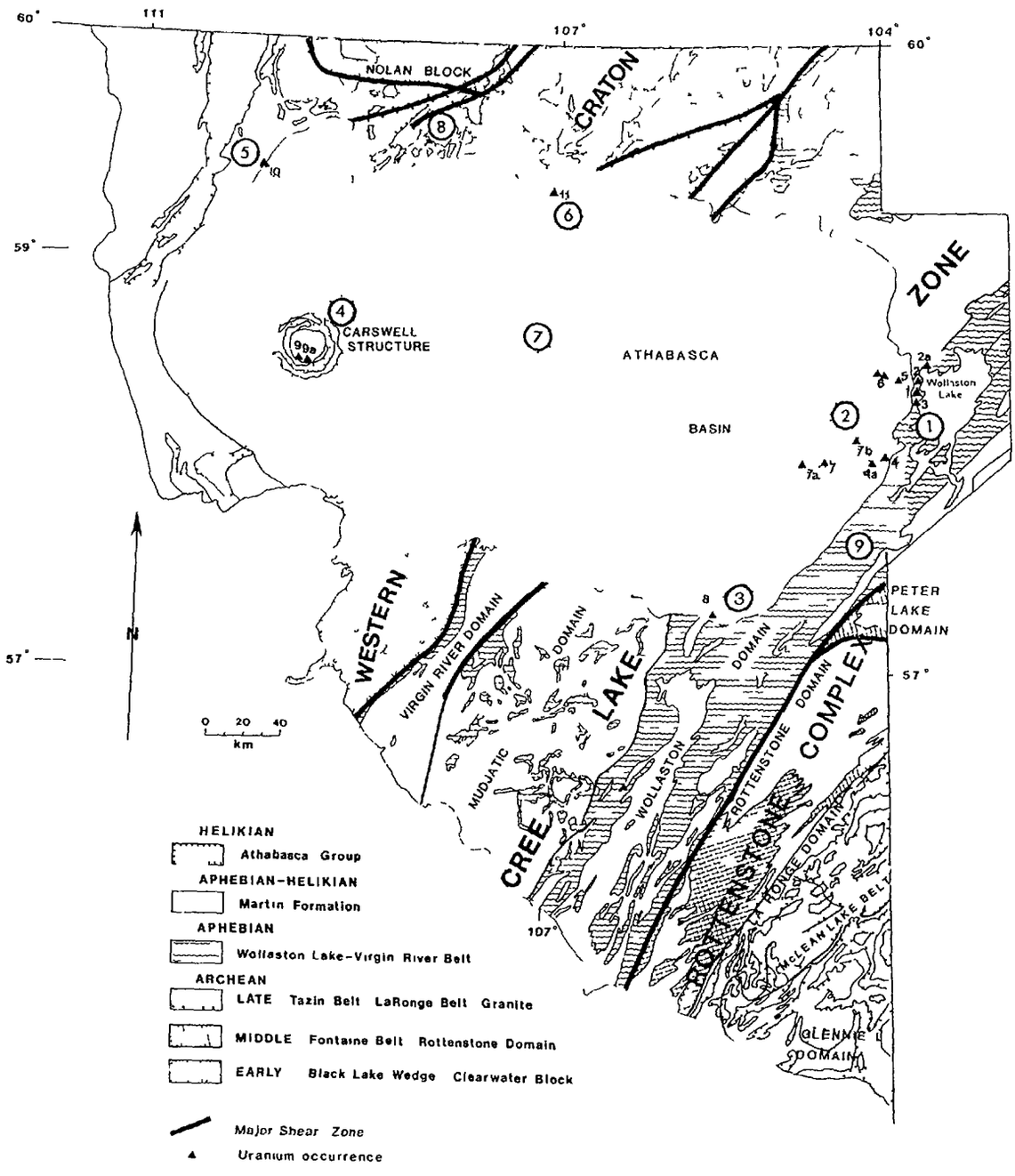


Figure 9: Major crustal units, structural domains, uranium-bearing areas and deposits in the Athabasca Basin region, Saskatchewan. Base map modified after Lewry and Sibbald [26]. Areas and deposits: (1) Rabbit Lake - Collins Bay area: 1 - Rabbit Lake; 2 - Collins Bay 'A','B' and 'D'; 2a - Eagle Point 'N' and 'S'; 3 - Raven and Horseshoe; 4 - West Bear; 4a - Sand Lake and Wolf Lake; (2) Cigar Lake - McClean Lake area: 5 - McClean Lake; 6 - Midwest and Dawn Lake; 7 - Cigar Lake; 7a - Close Lake; 7b - Natona Bay; (3) Key Lake area: 8 - Key Lake; (4) Carswell Structure (Cluff Lake area): 9 - Dominique-Peter and Dominique-Janine; 9a - Claude, 'N', 'R', 'D'(depleted); (5) Maurice Bay area: 10 - Maurice Bay; (6) Fond-du-Lac - Stoney Rapids area: 11 - Fond-du-Lac; (7) Inner segment of the basin; (8) Beaverlodge area; (9) Wollaston Belt.

The uranium deposits contain either monometallic (uranium only) or polymetallic (e.g. uranium + nickel + cobalt ± silver ± molybdenum ± gold) mineralization.Unlike the polymetallic vein occurrences in the Beaverlodge area (e.g. the Nicholson mine) the unconformity-associated deposits in the Athabasca Basin region do not contain platinum group elements in recoverable grades.

The ore formed in the main mineralization period about 1.3 to 0.8 Ga ago with rejuvenations at 300 to 200 Ma and about 80 Ma ago [16].

A conceptual genetic model, which accounts for formation of the unconformity-associated deposits includes features as follows (Figs. 10 and 11):

(a) The deposits occur in a uranium metallotect within the Churchill Structural Province, where uranium was introduced into the geochemical cycle by granitic magmatism during the Kenoran Orogeny about 2.5 Ga ago.

(b) Further concentration took place in Aphebian sedimentary rocks and in pegmatites at about 1870 Ma.

(c) Major epigenetic concentration of uranium minerals in veins at about 1740 Ma was associated with waning of the Hudsonian Orogeny.

(d) Peneplanation with associated lateritic weathering resulted in liberation of uranium and associated metals from the pre-Helikian rocks and their introduction into the sedimentary cycle. This resulted in formation of a reservoir of metallic elements incompatible with the rock-forming minerals of the clastic sedimentary rocks.

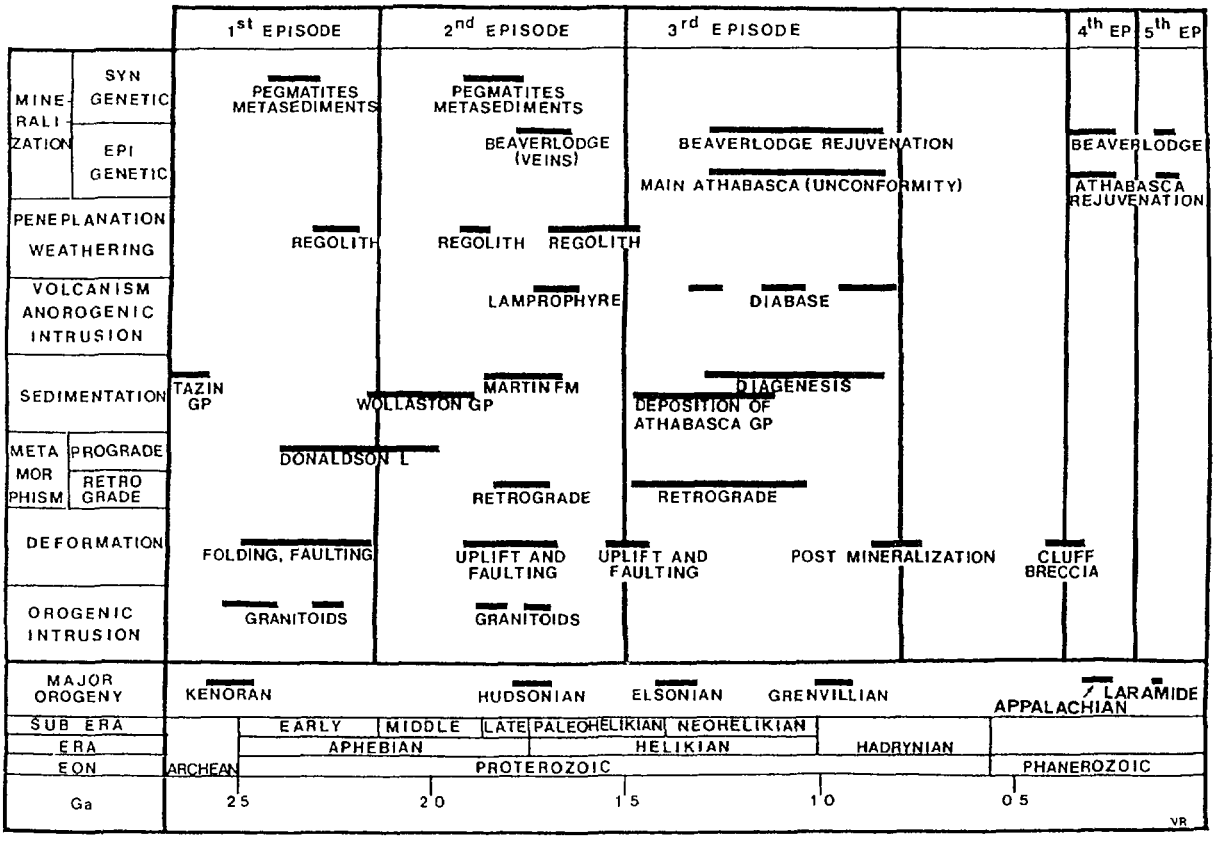


Figure 10: Uranium metallogenic periods in northern Saskatchewan. After Ruzicka and LeCheminant [32].

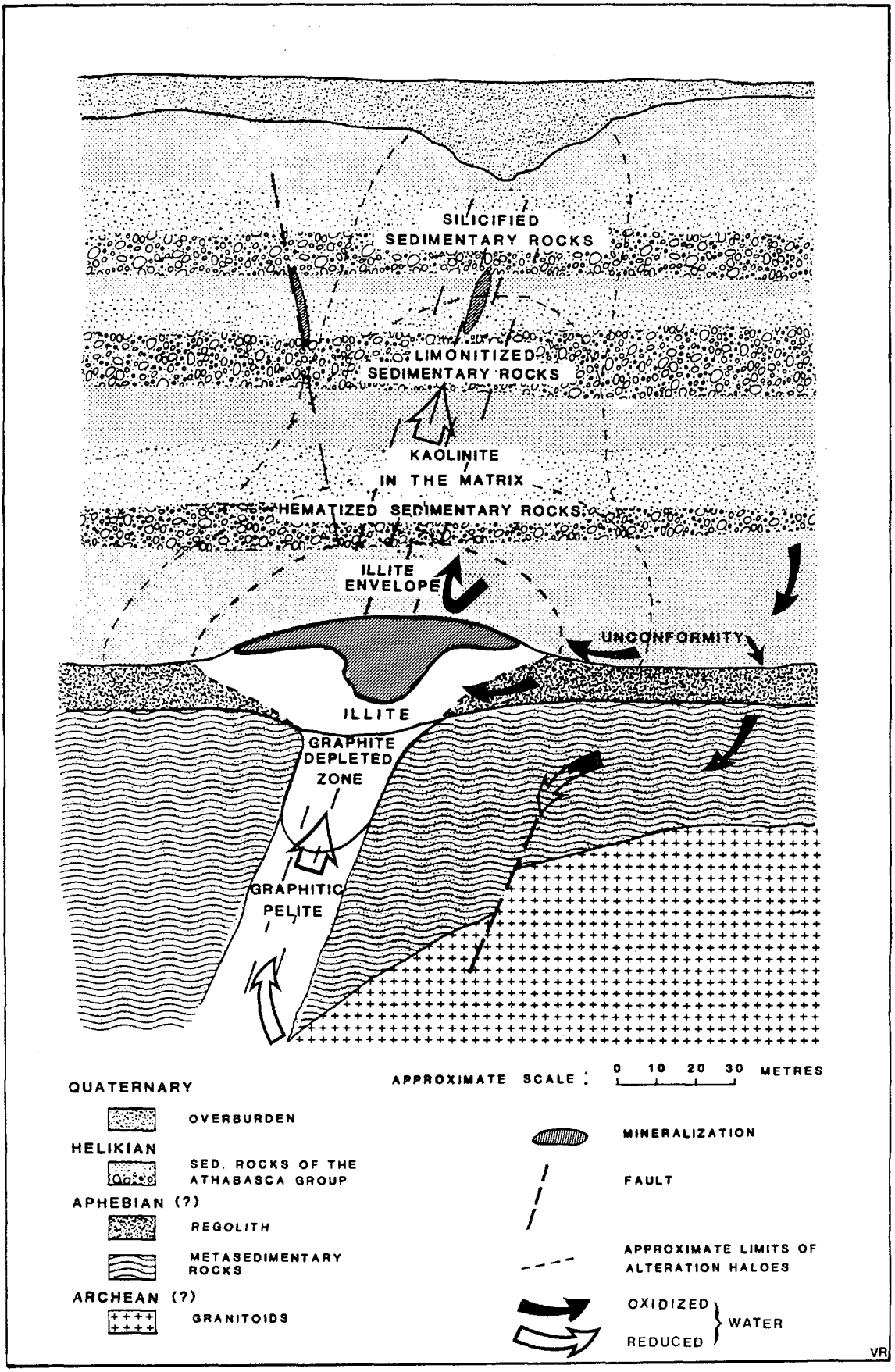


Figure 11: A conceptual model for unconformity-associated deposits. Modified after Ruzicka [28].

(e) The tectonic and thermal events associated with regional faulting and with intrusion of diabase dyke swarms (circa between 1300 and 800 Ma) activated hydrodynamic systems, which mobilized metals from the reservoir and caused their redistribution. The metal-bearing solutions consisted of oxidized connate, ground and vadose waters, which moved laterally or per descensum, and of ascending thermal reduced fluids, which were derived from the same water reservoir, but which had their Eh changed from positive to negative values during deeper percolation through the basement rocks (Fig. 11).

(f) Deposition of the ore-forming minerals took place in areas at the interface of the oxidized and reduced waters, i.e. at the redox front, at temperatures between 130° and 260°C [28], although Pagel [30] and Pagel et al.[31] reported temperatures between 60° and 260°C, as interpreted from their fluid inclusion studies.

(g) The mineralization processes were associated with retrograde metamorphism, which resulted in diaphthoresis of the graphitic metapelites (especially in partial depletion of their graphitic substances) and in argillic alteration (illitization, kaolinization, chloritization) of the host rocks. The argillization was superimposed on preceding lateritization of the basement rocks. The ascending fluids introduced carbonates (dolomite, siderite, calcite), iron oxides, bitumen (kerogen), hydrogen sulphides and methane into the host environment. They also caused corrosion or total dissolution of quartz grains in the clastic sedimentary rocks in the area of mineralization (Fig. 12) on one hand and silicification of sandstone, including crystallization of euhedral quartz in vugs in a distant aureole of the orebodies, on the other hand. Tourmalinization (e.g. impregnation or fracture filling of the host rocks with dravite) and magnesian metasomatism, which commonly took place in the early stages of mineralization, were common companions of these processes.

(h) Deposition of uranium and associated metals was structurally controlled by the unconformity and intersecting faults and fracture systems; lithologically by graphitic and pyritic pelitic rocks beneath, and porous clastic sedimentary rocks above, the unconformity; geochemical controls (Eh, pH, adsorption, complexing) influenced not only deposition of ore-forming minerals, but also the nature of mineral assemblages and apparently also the general zonal arrangement of individual mineralization phases (i.e. polymetallic /U+Ni+Co+As/ immediately at the unconformity (Fig. 13) and monometallic /U/ in the basement rocks (Fig. 14) and in more distant areas in the clastic sedimentary rocks).

(i) The mineralization was rejuvenated in at least two later periods: at about 300 to 200 Ma and at about 80 Ma [32].

(j) The orebodies were protected from destruction by their clay envelopes and by the non-oxidizing nature of the surrounding fluids.

The Athabasca Basin region contains the greatest number of and the most typical uranium and uranium-polymetallic deposits associated with the pre-Helikian unconformity in Canada.

Environments favourable for similar deposits elsewhere in Canada occur in the Baker Lake - Thelon Basin, where at least one deposit (Kiggavik) is known, Coronation Homocline in the Northwest Territories and in the Otish Basin region, Quebec.Environments with similar lithological features, but without known unconformity-associated uranium occurrences also occur in Sibley Basin region near Lake Superior, Ontario.

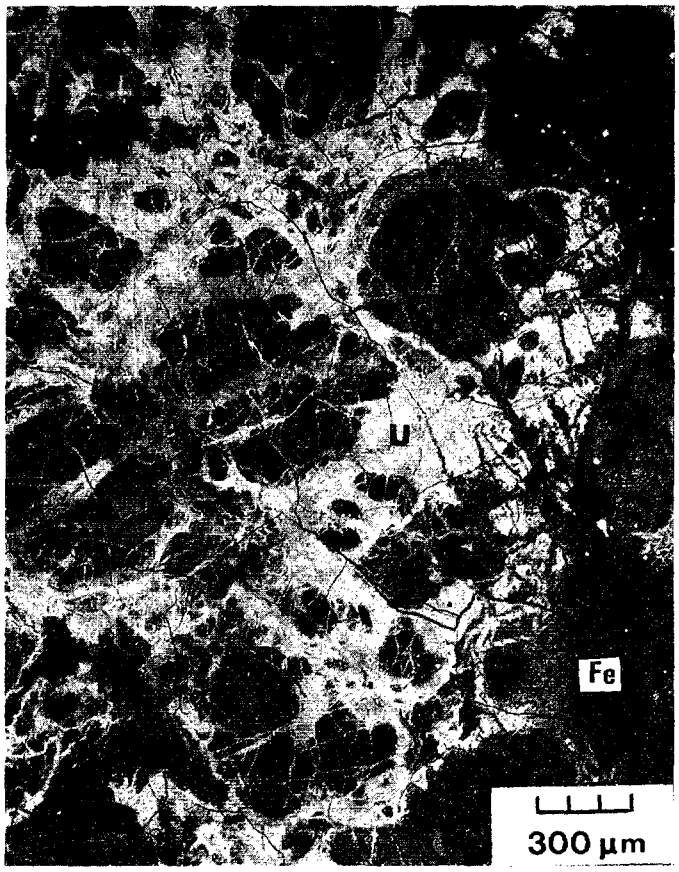


Figure 12: Iron oxides (Fe) replacing pitchblende (U) and corroding quartz grains (Q) in sandstone at the Cigar Lake deposit, Saskatchewan. Drillhole No.78. Reflected plain light. From Ruzicka and LeCheminant [32].

Recent research on processes associated with the formation of unconformity-associated uranium deposits indicates that the conceptual model for the Precambrian deposits can also be applied to some Phanerozoic environments. For instance, some of the Phanerozoic uranium deposits within the Hercynian Orogen in Europe are associated with unconformities. The Pribram uranium deposit in Czechoslovakia [33], for example, exhibits features indicating derivation of the uranium from a reservoir in Phanerozoic sedimentary rocks, which unconformably overlie Precambrian pyritic black shales; precipitation of pitchblende filling fractures in the shales took place after intrusion of the Central Bohemian (Granite) Pluton during the Permian about 270 Ma ago.

Remaining deposit types

The remaining deposit types in Canada include: uraniferous veins; deposits with disseminated mineralization in orthomagmatic, anatectic and metamorphic rocks; volcanogenic deposits; sediment-hosted deposits; surficial deposits; and deposits of other types.

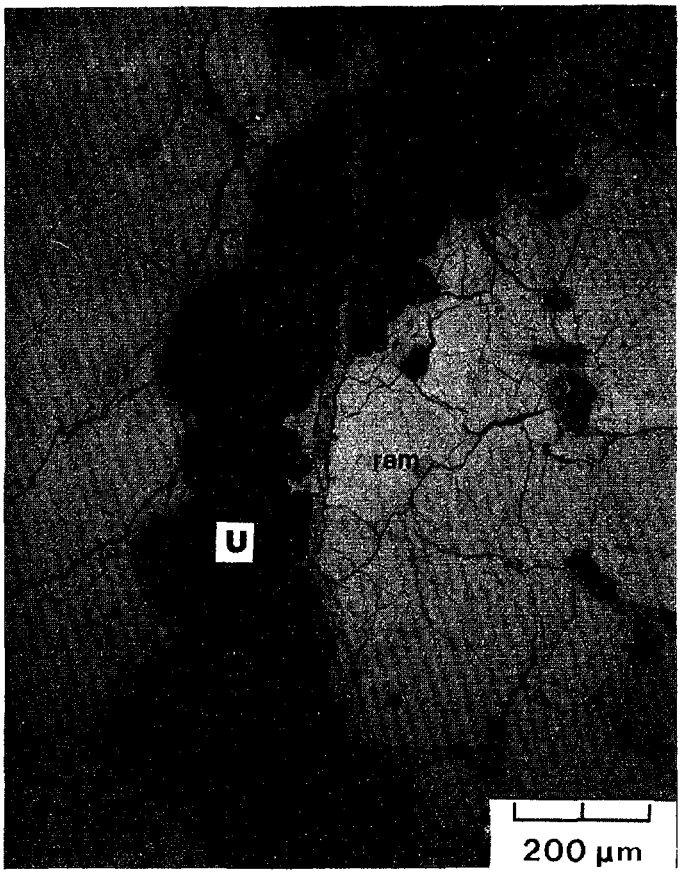


Figure 13: Pitchblende (U) and rammelsbergite (ram) cut by a vein of gersdorffite (g); Cigar Lake deposit, Saskatchewan, drillhole No. 154/439.5 m. Reflected plain light. From Ruzicka and LeCheminant [32].

Vein deposits

Uraniferous veins were important sources of uranium in the past. Vein deposits were exploited in the Great Bear Lake (Port Radium) area, Northwest Territories, and in the Beaverlodge (Uranium City) area, Saskatchewan. Deposits in the Great Bear Lake area contained veins with polymetallic (U+Ni+Co+Bi+Ag+Cu+As) assemblages, whereas the deposits in the Beaverlodge area contained veins with simple (U+Ti) mineralization.

The polymetallic vein deposits are epigenetic concentrations of uranium minerals; arsenides and sulpharsenides of nickel, cobalt and silver; sulphides of base metals; and of native silver and bismuth.

The conceptual genetic model for the polymetallic vein deposits can be demonstrated on the basis of the Eldorado Port Radium deposit [34]: The deposit occurs in a volcano-sedimentary complex. The ore constituents were mobilized from residual brines of the complex by hydrothermal processes; their deposition was controlled lithologically by rocks containing reducing agents and structurally by open fractures associated with major regional faults. The hydrothermal activity was apparently triggered by thermal events

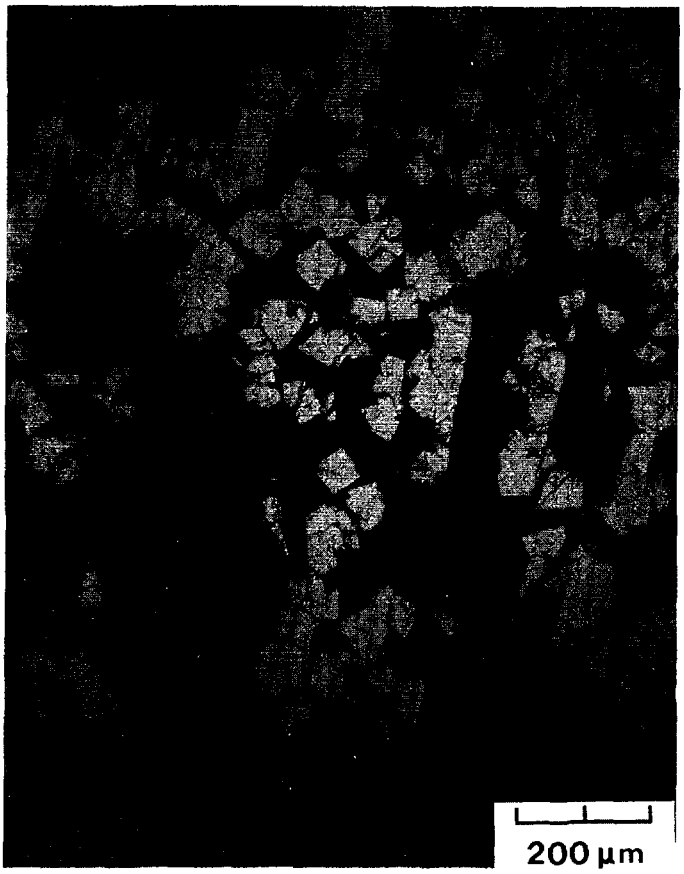


Figure 14: Crystalline pitchblende (thorium-free uraninite or U3O7) in a micaceous matrix. Eagle Point deposit, Saskatchewan; drillhole EP 222/205.2 metres. Reflected plain light. From Ruzicka and LeCheminant [32].

associated with intrusion of dykes in the region as indicated by K-Ar and U-Pb isotope analyses on the dykes and uranium ore minerals respectively [35].

The metallic elements were pre-concentrated in a sedimentary environment. The highest concentration of uranium apparently took place in formational brines of the clastic sedimentary rocks of the Hornby Bay Group, which were overlying the basement rocks at the time of mineralization [35;33].

After the initial stage of the hydrothermal activity, the metal-saturated formational brines of low pH and positive Eh descending from the reservoir released uranium at the interface with ascending hydrothermal fluids of higher pH and negative Eh. Both the descending and ascending fluids were apparently derived from the same parent aquifer.

Nickel-cobalt arsenides and most of the native silver and bismuth were deposited in subsequent stages of mineralization in re-opened fractures. Sulphides and some native metals were deposited during the last stages of the hydrothermal process under high pH and negative Eh conditions (Fig. 15).

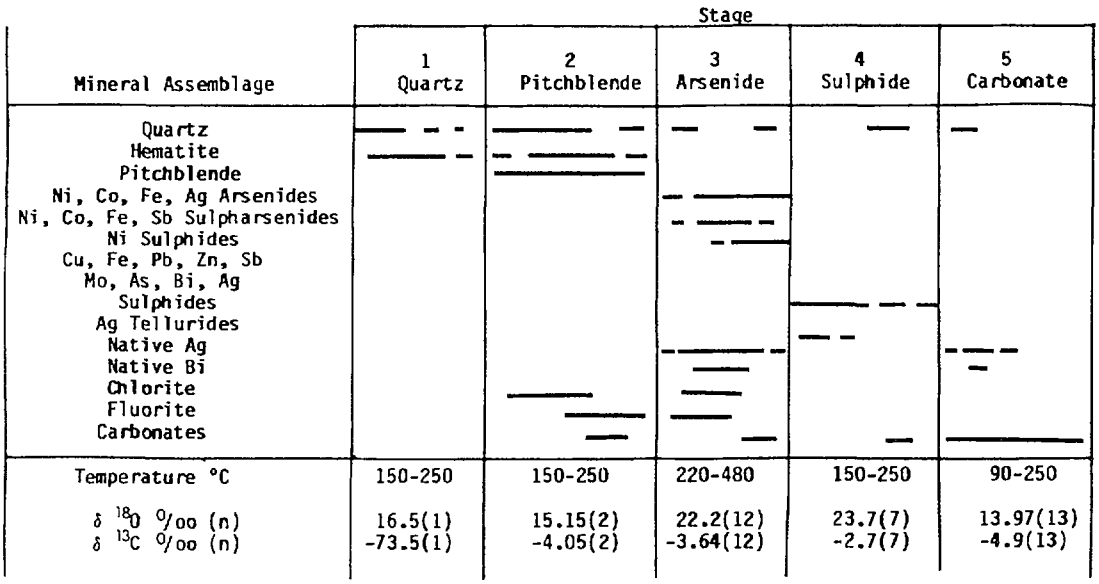


Figure 15: Generalized paragenesis of constituents in the Eldorado and Echo Bay deposits, Great Bear Lake Mining District, Northwest Territories. Compiled after Jory [50], Murski [51] and Changkakoti et al. [52]. Oxygen and carbon isotope values were calculated from data in Changkakoti et al. [52].

The conceptual model for vein deposits with simple (monometallic) mineralization can be demonstrated using the Eldorado Beaverlodge deposits as examples (Fig. 16). The deposits formed during a major metallogenic cycle which started with introduction of uranium into granitoids at the end of the Kenoran Orogeny [37],(Fig. 10). The uranium and associated elements were further concentrated in sedimentary rocks of the Tazin Group, which were mylonitized and faulted during Hudsonian Orogeny. The metals from the sedimentary rocks were remobilized and redeposited by hydrothermal processes in fractures, stockworks and as disseminations in the host rocks.

Distribution of the veins was structurally controlled by major faults and apparently also by the Aphebian-Helikian unconformity. Distribution of the principal (uranium and titanium) minerals was lithologically controlled by the Aphebian and Helikian rocks of the Tazin Group and Martin Formation respectively [36].

The principal metallic minerals in the upper part of the Ace, Fay and Verna deposits (from the surface down to about 500 metres) are pitchblende and coffinite, whereas brannerite is a common additional constituent in the ore in the lower part of the deposit (below the 500 metre depth) [37], (Fig. 17).

Sodic metasomatism (albitization) accompanied the mineralization process in its early stage. However hematization, chloritization, feldspathization and carbonatization are the main forms of alteration associated with the mineralization.

In addition to the Eldorado deposits, monometallic vein deposits also occur in granitoid rocks at Gunnar mine [38] in the same area and in granitic rocks of the South Mountain Batholith in the Appalachian Orogen at Millet Brook, Nova Scotia [39].

None of the above mentioned deposits is at present being mined in Canada, being mined-out or else dormant.

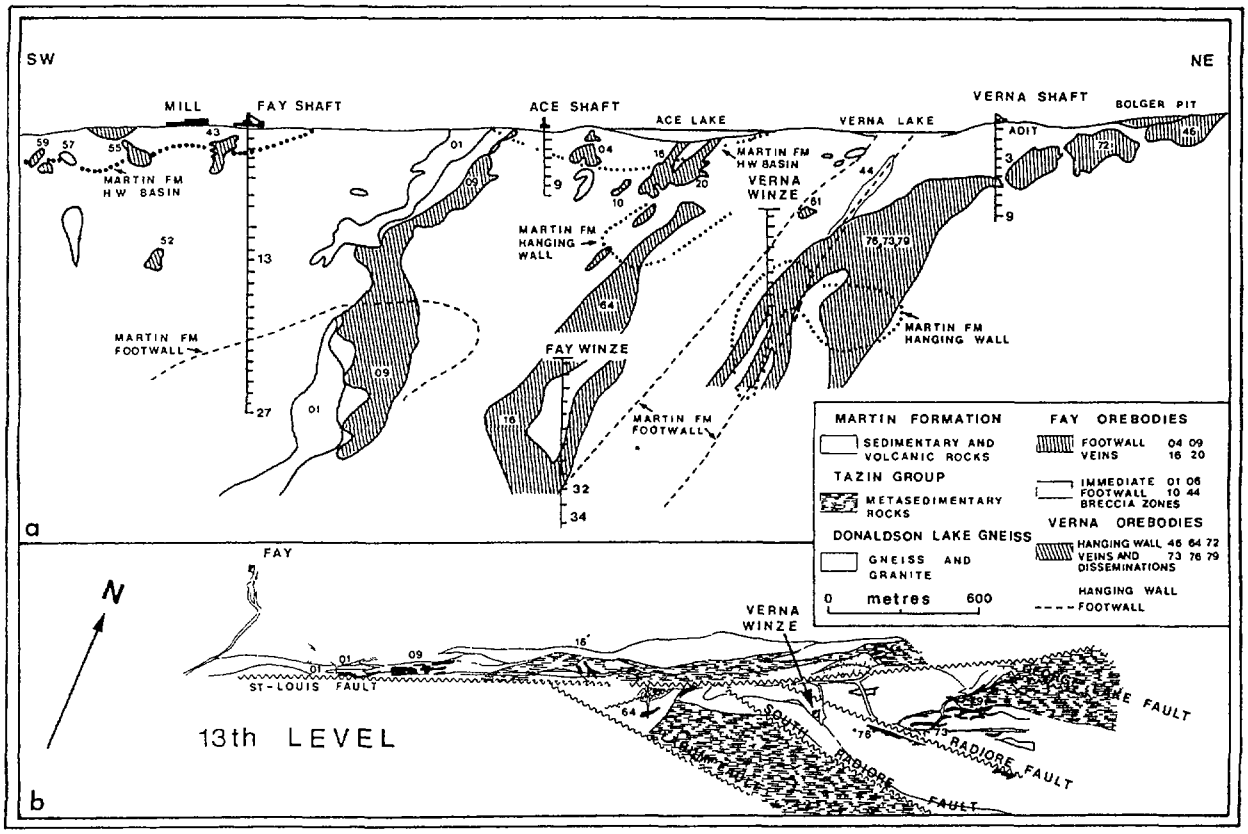


Figure 16: Uranium orebodies of the Ace, Fay and Verna deposits of Eldorado Resources Limited at Beaverlodge, Saskatchewan; (a) longitudinal section; (b) plan of the 13th level. Modified after documentation provided by Eldorado Resources Limited.

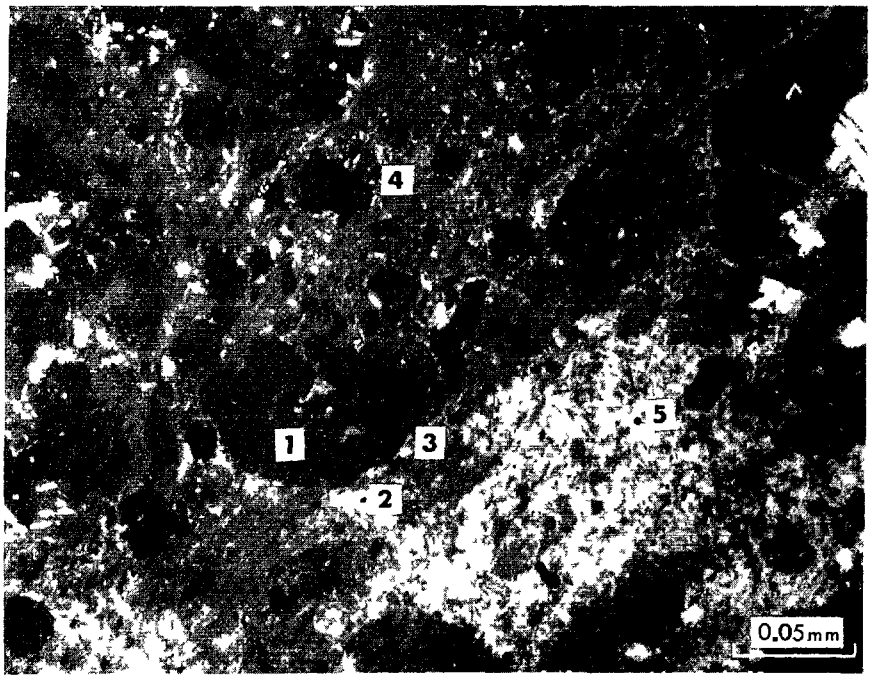


Figure 17: Mineral assemblage of the 09 orebody, Eldorado Beaverlodge operations, 23rd level (cf. Fig. 16a). 1-albite; 2-anatase and minor U,Si,Fe and Ca; 3-U,Ti,Ca,Fe,Si phase; 4-chlorite and brannerite mixture; 5-brannerite with minor Fe,Ca,Si,Pb assemblage. Reflected plain light.

Deposits consisting of disseminated mineralization in igneous and metamorphic rocks

The principal deposits in Canada consisting of disseminated mineralization in igneous and metamorphic rocks are associated with pegmatitic felsic rocks of the Grenville Structural Province. The Faraday (Madawaska) mine at Bancroft, Ontario, is a typical representative of this deposit type (Figs. 18 and 19). It was in operation in two periods: 1956-1964 and 1976-1982 [40].

A conceptual genetic model, based on studies of the Faraday deposit, involves association of uranium mineralization with late differentiates of granitic or syenitic magmas that have commonly been subsequently affected by postmagmatic hydrothermal or metamorphic processes [41]. Uranium tends to be concentrated in the residual hydrous phase, which is saturated with elements incompatible with the magma. These elements were originally present only in trace amounts in the magma. Uranium is concentrated in excess of several times its geochemical background, the U-bearing fluid reacts with the rock-forming minerals and uraniferous minerals crystallize generally in tectonically disturbed zones.

Uraninite, which is the principal uranium mineral, is commonly associated with magnetite; the other radioactive minerals are uranothorite, brannerite and allanite. The brannerite is locally intergrown with albite, chlorite or calcite, which are deuteric minerals replacing the granitic or syenitic mass.

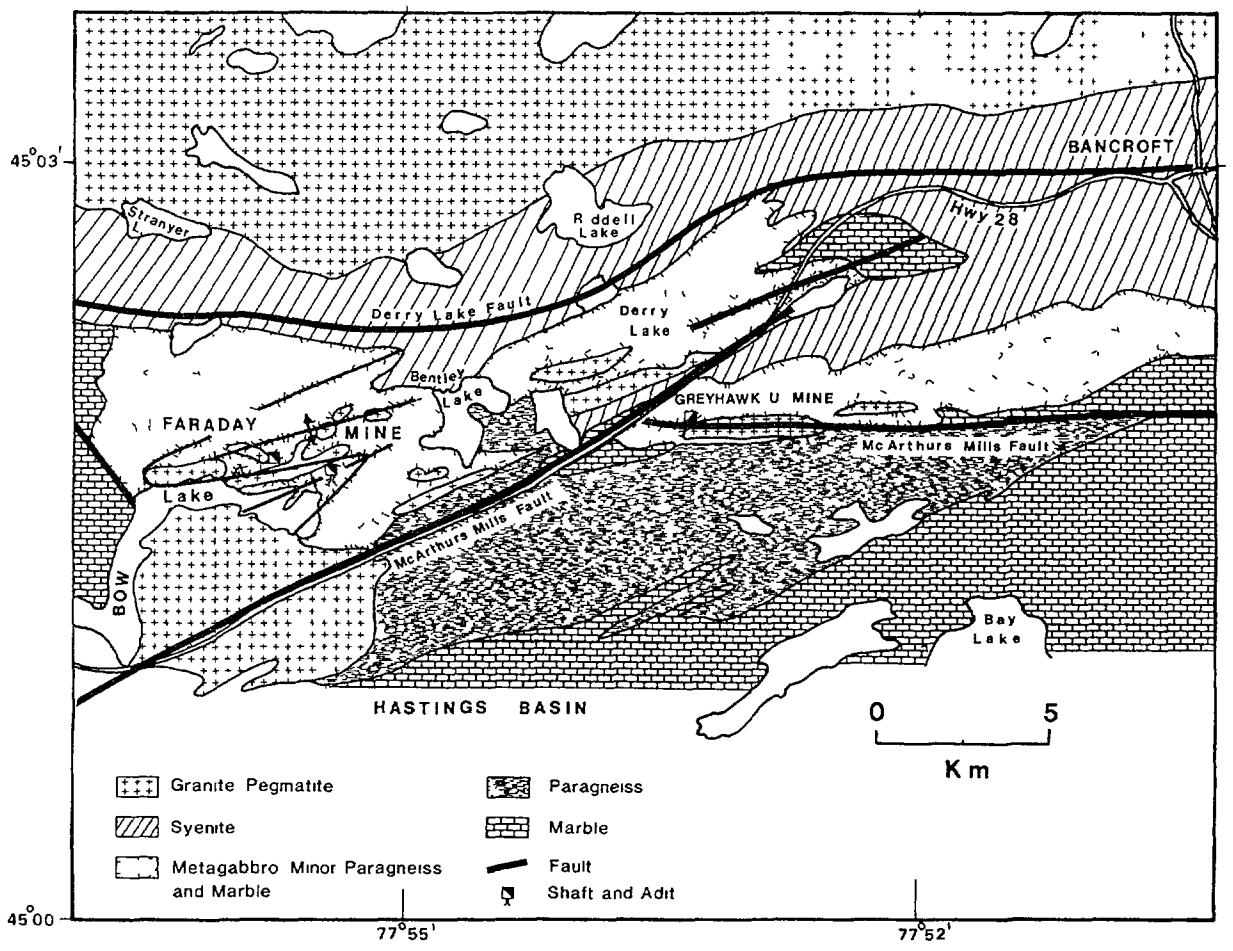


Figure 18: Geological setting of the Faraday (Madawaska) mine at Bancroft, Ontario. Modified after Alexander [40].

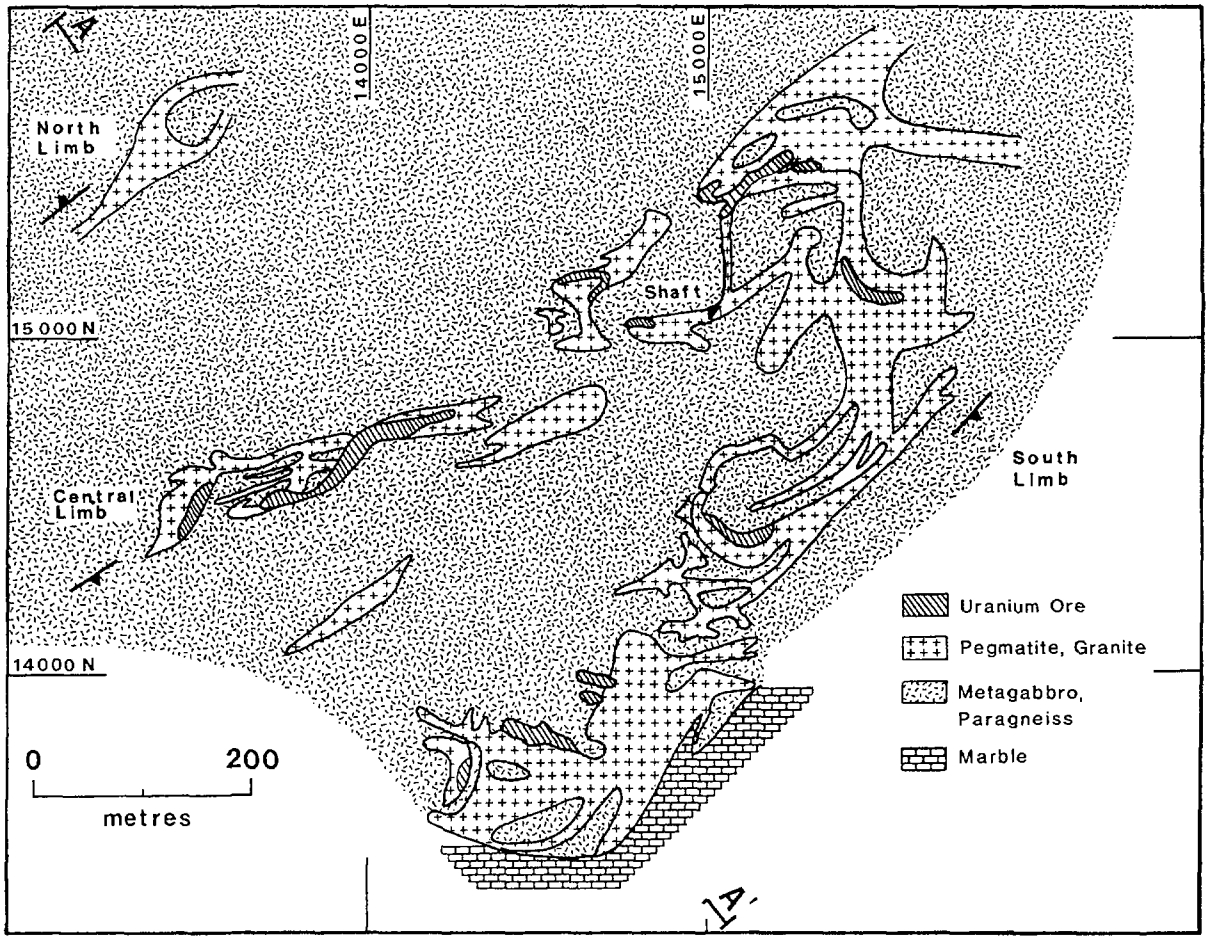


Figure 19: General geology of the 450 foot level, Faraday (Madawaska) deposit at Bancroft, Ontario. Modified after Alexander [40].

In addition to the Bancroft area, the magmatic/anatectic uranium deposits containing disseminated mineralization occur in the Mont-Laurier and Johann Beetz areas of the Grenville Structural Province, in the Kenora-Dryden area of the Superior Structural Province and in several areas of the Churchill Structural Province [42]. All are dormant.

Volcanogenic deposits

Uranium deposits associated with volcanic rocks and related to volcanogenic processes occur in alkalic volcanic rocks, including K- and Na-rich rhyolites, trachytes, latites and phonolites. A primary concentration of uranium is important, but is commonly combined with subsequent deuteric or supergene processes.

In Canada two representatives of this type of uranium deposit are known: the Rexspar deposit at Birch Island, British Columbia, and the Michelin deposit in the Central Mineral Belt, Labrador.

The Rexspar deposit occurs in a trachytic member of alkali-feldspar porphyry, in lithic tuff, tuff breccia and pyritic schists, conformably interlayered with greenschists and fragmental rocks of Upper Permian age (Fig. 20) [43]. The mineralization exhibits pyrometasomatic features, such as intergrowths of rutile and uranothorite [41] and replacement of fluorphlogopite by pyrite [43]. The deposit contains mineral assemblages which resemble those hosted by alkalic volcanic rocks elsewhere, e.g. in the Latium region of Italy [44].

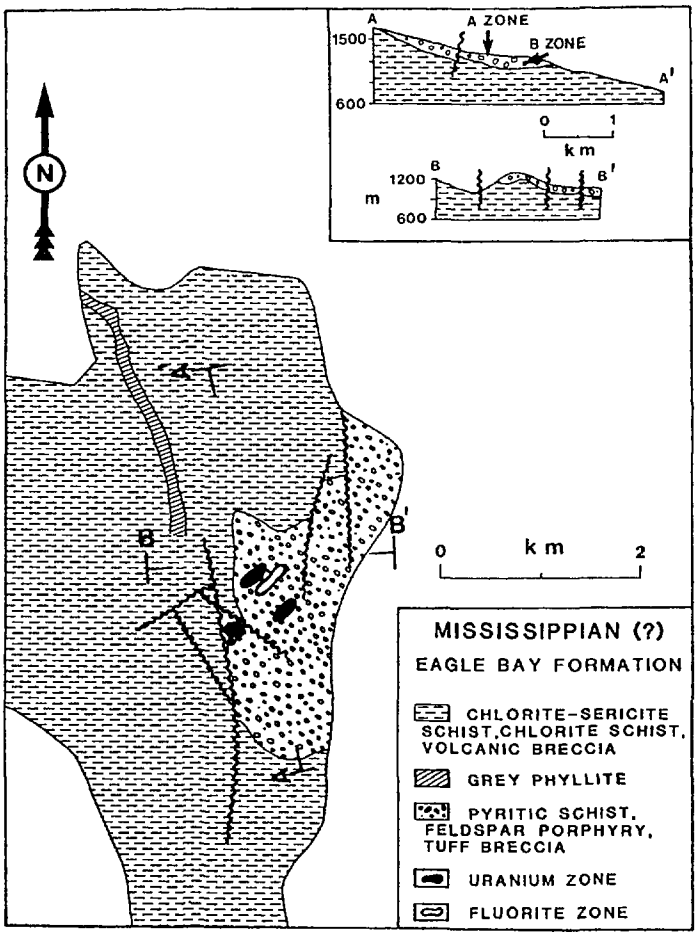


Figure 20: General geology of the Rexspar area, British Columbia. Modified after Preto [43].

In the Central Mineral Belt of Labrador the Michelin deposit is associated with rhyolitic rocks exhibiting alkaline affinity (Fig. 21).

Uranium minerals in the Michelin deposit commonly occur in porphyritic zones that are locally metasomatically enriched in Na_2O (7% to 12%) [45]. A typical mineral assemblage consists of pitchblende, a U-Pb-Si phase and titanite [41].

Sediment-hosted deposits

A generalized conceptual genetic model for the sediment-hosted uranium deposits includes postulation that epigenetic mineralization formed from aqueous solutions along redox fronts and within semi-consolidated clastic sedimentary rocks.

Sources of the uranium are commonly granitic rocks or tuffs containing uranium leacheable under supergene conditions. Uranium is transported in surficial or ground waters and deposited due to Eh and pH changes in places where dissolved uranium compounds become reduced and therefore stable. The mineralization is commonly restricted to Phanerozoic clastic sedimentary rocks containing plant-derived carbonaceous material. However, some uranium deposits hosted by Precambrian sedimentary rocks in the Canadian Shield also exhibit genetic features typical of the Phanerozoic deposits. Reducing agents participating in formation of the Precambrian deposits are commonly bitumen, sulphides, and ferromagnesian minerals.

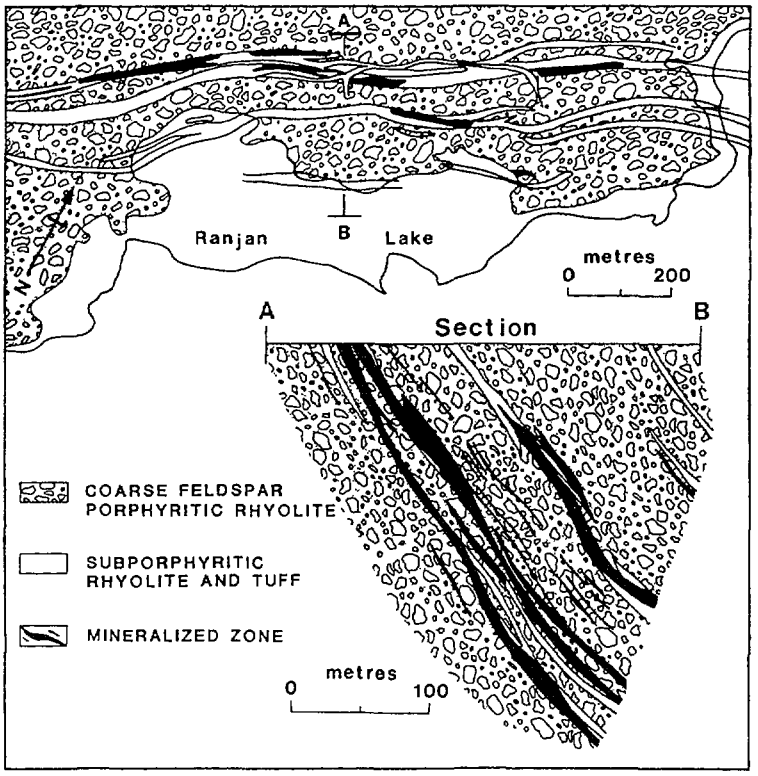


Figure 21: General geology of the Michelin deposit, Labrador Central Mineral Belt. After Gandhi [45].

A conceptual genetic model for Phanerozoic sediment-hosted deposits in Canada can be demonstrated on the Blizzard deposit in the Beaverdell area in the southern part of the Canadian Cordillera.

This deposit occurs in Miocene or possibly Paleocene unconsolidated or poorly consolidated conglomerates and sandstones derived from rocks of the Okanagan metamorphic complex, Marron volcanics or their equivalents (Fig. 22),[46].

Detritus derived from the igneous rocks was deposited in paleo-river channels and the uranium was predominantly epigenetically introduced not only into the detritus, but also into the basement complex and volcanic breccia. The uranium mineralization, which is commonly associated with carbonaceous matter, was apparently preserved by extrusion of capping plateau basalts, which also supplied solutions that participated in the formation and modification of the deposits (Fig. 23).

A representative of the Precambrian sediment-hosted deposits occurs in rocks of the Hornby Bay - Dismal Lakes Group at Mountain Lake, northeast of Great Bear Lake. The host rock of the deposit is mainly impure sandstone, commonly kaolinized, chloritized and containing sulphides. The uranium mineralization is generally restricted to zones near the overlying shales and to faults. Ruzicka [13] interpreted genesis of the deposit to be a result of chemical reactions between uraniferous brines, which were derived from the overlying pelitic rocks, and the matrix of the sandstone, and subsequent redistribution of the uranium minerals along the subvertical faults.

All the uranium resources of the sediment-hosted deposits in Canada are at present dormant.

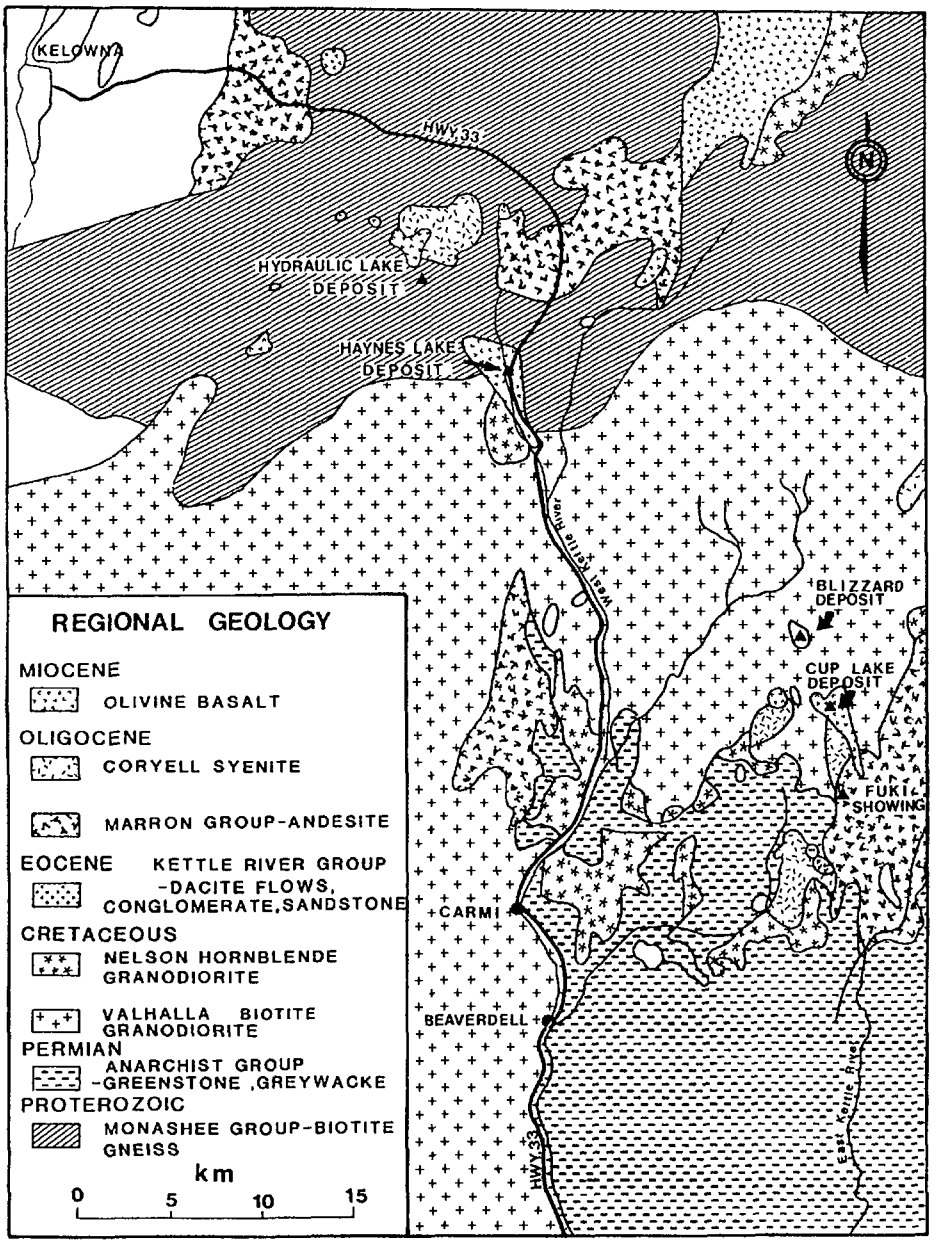


Figure 22: Geology of the Beaverdell area, south-central British Columbia. After Norcen Energy Resources Limited [54].

Surficial deposits

Known occurrences of surficial uranium mineralization in Canada are generally in postglacial, Recent lacustrine and fluviatile environments; several occurrences have been reported by Culbert et al. [47] from the south-central part of Canadian Cordillera. A typical feature of these occurrences is a disequilibrium between uranium and its decay products due to their very young age. Therefore they are also known as concentrations of "young uranium".

Deposits of other types

Uranium occurs in other geological environments, such as in lignite in the Cypress Hills, Saskatchewan [42]; in carbonatites at Crevier and Oka, Quebec, and at Prairie Lake, Nova Beaucage and Nemegosenda Lake, Ontario

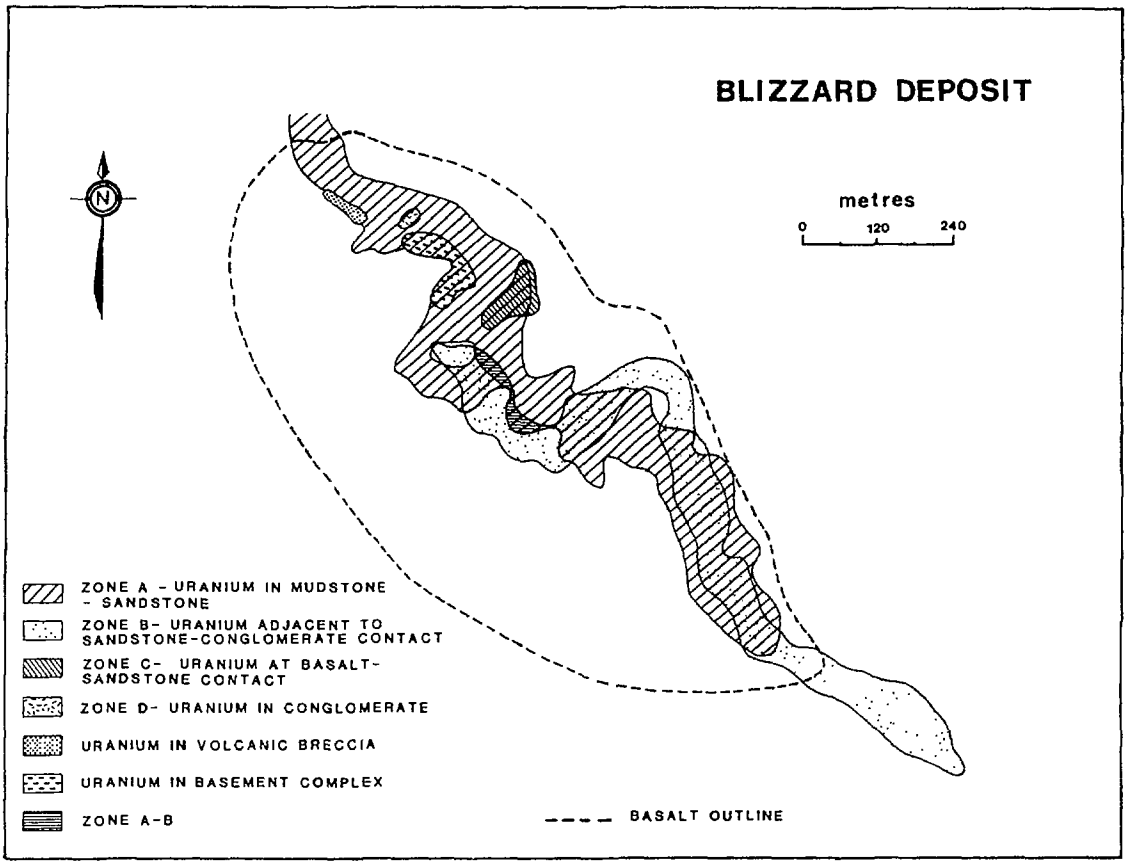


Figure 23: Outline of the Blizzard deposit, Beaverdell area, British Columbia. After Norcen Energy Resources Limited [54].

[42;16;49]; in phosphatic shale in the Alberta Basin [42]; in Wernecke megabreccias in Yukon [48]; and in Holocene placers at Bugaboo Creek, British Columbia [42].

Resources contained in these occurrences are at present uneconomic, but may be recoverable in the distant future.

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A REVIEW OF GENETIC MODELS FOR MAJOR TYPES OF URANIUM DEPOSITS IN THE USA

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Abstract

Nearly all the productive uranium deposits in the United States lie in the western part, including and west of a portion of the High Plains bordering the Rocky Mountains front and extending from the Black Hills of South Dakota to south Texas. This western uranium region contains four major uranium provinces, namely, the Colorado Plateau, the Rocky Mountains and Intermontane Basins, the Basin and Range, and South Texas. The latter two extend into Mexico. The few deposits lying outside the western uranium region are in the Appalachians-Piedmont uranium province.

The major uranium deposits in the United States are of the sandstone, collapse-breccia pipe, classical vein, and volcanogenic types. The sandstone-type, which comprise about 95% of the production and reserves, are of two genetic forms, tabular and roll-front. The most favored source of uranium for both forms was volcaniclastic sediments, either overlying or adjacent laterally to the host sandstone; however, a granite source is also proposed in some areas. A common model for the tabular deposits in the Colorado Plateau uranium province is precipitation of uranium during diagenesis at an interface of two solutions, commonly between brine and freshwater. The solution interface model has been rejected by recent researchers in the San Juan Basin New Mexico, where ore is associated with humate. The basis for their lacustrine-humate model, which is described as a diagenetic event related to early pore fluid evolution, is that overlying volcanic mudstones were the source of humate associated with primary ore. Either the uranium traveled as a urano-organic complex and precipitated directly or later passage of uranium-bearing oxidizing ground water enriched the humate to ore grade. In host rocks characterized by syngenetic detrital organic matter, a single ore-forming fluid rather than a two-solution interface is called upon to precipitate uranium under reducing conditions. The roll-front type in the Intermontane Basins and Texas formed as oxidizing waters entered the host sandstone from recharge areas and moved down the hydrologic gradient toward the center of a basin to form the deposits at the redox interface. The collapse-breccia pipe deposits, which occur only in the Grand Canyon region of Arizona, probably formed by action of downward-percolating uraniferous ground water from overlying Late Triassic volcanic sediments that entered a pipe, and uranium precipitated where the solutions encountered a reducing environment. The widely distributed classical veins formed by hydrothermal processes in faulted and brecciated brittle host rocks. Volcanogenic uranium deposits in the Basin and Range province formed as veins by hydrothermal activity, as roll-front accumulations, and as syngenetic disseminations.

I propose that most of the deposits can be explained by a few large, regionally distributed processes of mineralization occurring at specific intervals or episodes. These processes produced deposits commonly of one type, but in some places two or more, and in a relatively restricted geologic setting, such as a stratigraphic unit, basin, or structural environment. Although local variations in the geologic setting produced single unique deposits, the general genetic concept applies to a large number of deposits in a given uranium mineral belt or district. Four major episodes of mineralization could account for most deposits, namely, Late Triassic, Middle

Jurassic, Early Cretaceous, and Tertiary. The latter is characterized, owing to local conditions and the host-rock age, by pulses in Eocene, Early Oligocene, Miocene, and Pliocene. A widespread fifth episode has been ongoing in surficial environments in recent time in many parts of the country.

The various types of deposits formed for the most part during only one or few episodes. Tabular uranium deposits are generally limited to the Late Triassic, Mid-Jurassic, and Early Cretaceous episodes. Roll-front deposits are limited to the Tertiary episode; one significant event was the redistribution of primary tabular ores in the San Juan Basin into redistributed or roll-front ores. Collapse-breccia deposits are limited to the Late Triassic episode. Classical vein and volcanogenic deposits are related mainly to Tertiary episodes.

THRUST-INDUCED CONSANGUINITY IN DIVERSE GENETIC TYPES OF URANIUM DEPOSITS: NORTH AMERICAN AND OTHER EXAMPLES

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Abstract

In comparison with the genesis of most mineral deposits, the tandem of source, transport, and precipitation has been given particular attention in the study of uranium metallogeny. Of these, transport is the member which has seen perhaps only a one-sided scrutiny. In the past, research has focused on the physico-chemical aspects of the fluids, with the structural environments through which the fluids advance remaining less specified.

It is the tectonics s.l. which provides the link between the metal sources and the eventual area of precipitation. This paper centers on thrusts as a particularly important type of structural deformation.

The combinations of differing permeabilities and varying fluids contents and compositions within the thrust-bound blocks with specific types of thermal gradients have led to increased anisotropy and triggering of the formation of localized hydrothermal cells. Sources of various kinds, variable lithologies, differing stratigraphies and distinct metamorphic grade could all be involved within the thrust domain. Obviously, these diverse environments produce or substantially contribute to the contrasting and numerous "genetic" types of uranium deposits: conglomeratic, albitite, unconformity, intra- and peribatholitic, etc.

The differing genetic types of deposits might be seen as converging to some degree through the involvement of more universal processes, as for example by a unifying metallotect: the thrust. Thrusts therefore represent particular controlling structures and targets (s.l.) in uranium exploration.

1. INTRODUCTION

Motto: "Conventional classification of resources types based on compositional differences may be merely descriptions of the retail package label rather than of the primary generator",
E.S.T. O'Driscoll, 1978.

The illustrative phrase of O'Driscoll [1] seems to be a modern variant of an old sentiment. Previously in 1861, B. Cotta moderated an excitement with a "right rock" approach by declaring"... rather the tin accompanying the granite is an exclusion, while granite association with tin ores is a rule". Regardless of the sophistication added by modern geology, this caution, perhaps surprisingly, to some theoreticians with lesser set-backs in the field experience, applies to "specialized" granites as well.

Some explorationists do not see a guideline in specific rocks alone, nor in empirically-based classifications and conceptual genetic models stripped to the bare skeleton, but in a combination of processes and structures operative during particular periods within an orogenic and/or plate tectonic evolution. This paper's author joins the above trend by emphasizing a particular tectonic control: the thrust. This, of course, includes such varieties characterized by O'Driscoll as "...subtle and elusive discontinuities comouflaged under a facade of more flamboyant features", among them, and importantly, those of "more fundamental kind, predating their associated rocks."

2. THRUSTS AND THEIR METALLOGENIC SPECIFICS

This paper includes thrusts s.s. and reverse faults under the term thrust, i.e. without distinguishing either the angle or the size of propagation. Such a generalization covers the compressional tectonics with an up-dip movement. Although observable, this might not be a predominating and/or unique translocation within such systems. Other styles of movements, particularly the strike-slip, may participate variably within thrusts mentioned in the paper.

Metallogenic specifics of thrust domains rest both with their particular thermal regimes and with the types of structural and lithological domains involved.

2.1 Thermal Regimes Induced by Thrusts

Thrusts generate specific thermal anomalies which are either absent or underdeveloped in other tectonic environments. Sizeable up-dip movements would generate larger displacements of earlier isotherms. Larger strike-slip and transpressional translocations would rather be characterized by frictional heat only.

2.1.1. General Configuration of Thrust-Related Thermal Regimes

Thrusts represent a particular tectonic domain where usually more porous, cooler, more fluid-rich and younger rocks have become suddenly confined beneath a roof of less permeable, warmer and older rocks. In other instances, reversals from normal faulting into thrusting may carry younger rocks above older. Thrusts lead to a sudden re-arrangement of an earlier equilibrated thermal regime and to the formation of a positive thermal anomaly surrounded by a generally cooler

environment. In contrast to a normal fault, the newly established thrust-triggered thermal gradient takes a longer time to dissipate in the downfaulted wedge. These thermal cells are more effective not only by a particularly favourable confined geometry and therefore by a sharper gradient, but also by their prolonged duration.

2.1.2 Thrusts as an Energy Supply

In uranium geology a great emphasis is commonly given to heat released by radioactive decay. Possibly less well known (save by metamorphic geologists) is the elegant proposal by England and Richardson [2]. They demonstrated that even under the normal heat generation, it is particularly the thrust-thickened crust alone which generates "...a convection of heat by uplift and erosion as a potent means of energy supply to the upper lithosphere." Importantly, their model also suggests that the maximum temperature is generated at a time spearated by several tens of Ma (!) from the thrust event, while the pressure decreases during the erosion. Obviously, the tectonically (thrust) thickened continental crust and its specific thermal regime are important not only for the interpretation of metamorphic regimes but should be incorporated as an attractive model for U-metallogeny as well.

Among others, a general configuration of a specific type of metamorphism produced by overthrusting has been demonstrated by Fowler and Nisbet [3]. Within their model of a large overthrust slice, specific phenomena such as the retrograde metamorphism at the base of the upper slab, and prograde high pressure metamorphism of the lower slab and even the local melting at the deeper end of the overthrust wedge may take place if larger amounts of volatiles can be released from the lower block.

2.1.3. Disturbances and Other Specifics of Thermal Regimes

Although it is a generally minor factor in younger porous rocks, frictional heat has been claimed as considerably contributing in thrust domains which encompass the more conductive crystalline basement. Isotopic disturbances observed up to 14 km distance from a major fault have been interpreted by Sibson et al. [4] as thrust-derived heating of tens of degrees and of several Ma of duration, provided that shear stresses within the fault were of the order of 1-1.5 kbar. Similarly, the modelling by Werner [5] of the paleo-heat flow in the Alps, required a substantial heat contribution by friction along the thrust. According to Gretener [6] major thrust sheets result in rapid loading which leads to high pore pressures within the overriden sequence. Fyfe [7] has extended this observation by suggesting that fluids rising from the basement under thrusts would produce hydraulic fractures and that these, in turn, would facilitate the draining of the underplate. In analyzing the importance of strikes, Sibson et al. [4] proposed that the changeover from purely transcurrent movements to oblique compression may generate a major

frictional heat because of the higher stresses needed to induce and maintain reverse slip across "an unsuitably oriented" fault zone.

Observations suggest that the stress (and the frictional heat as well) is not distributed uniformly within the fault plane. Instead, a wavy pattern having a localized maximum stress has been suggested by Tokhtuyev [8] for such locations where, for example, a massive dissolution of quartz has led to a residual enrichment of banded iron formation, while "secondary quartzites" were formed in the pressure shadows. Quartz leaching and oxidation (versus vein formation and reduction) have been ascribed (Fyfe [9]) to the inverted pattern of a thermal gradient triggered by thrusts. Obviously, the leachability of uranium could be enhanced by this particular tectonism.

Another type of disturbance of the thrust-triggered thermal anomaly may be expected in domains which include texturally highly anisotropic lithologies. Among these, perhaps the more laminated mylonites and, of course, the graphite-rich metasediments would be the localized domains of a higher thermal conductivity as compared with their less anisotropic country rocks.

Further on, by using the observations of Fyfe et al. [10], the dehydration of the downfaulted fluid-rich younger sediments would consume some heat, while the retrogressive hydration of the upper slab would positively perturb the thermal gradient.

2.2 Crustal Domains Involved by Thrusts

The geophysical record, if adequate techniques are applied, may distinguish three general categories of thrusts according to the depth of their decoupling.

2.2.1 Thrusts Traversing the Uppermost Mantle

Among the few well-documented cases in North America, the gravity traverse in some sectors of the Appalachian system by Nicolas and Rozendal [11] suggested an approximately 15 km vertical shift of the Moho boundary between the NW block of the Grenvillian (older) block and the SE block of the accreted (newer) basement in the Green Mountains (Vermont, U.S.A.). It is unknown if such a sizeable displacement can be expected along most of such sutures. On the other hand, the above documented case, by its grossly on strike proximity, indicates that such a deep-seated structure may regionally control the Swanson uranium deposit (Virginia, U.S.A.), the albitite type of which (this volume) suits such a broad affinity.

In the Ukrainian Shield (U.S.S.R.), Kaliaev [12] has postulated a minimum of 10 km vertical shift of the Moho along the Krivoy Rog fault zone which is essentially a thrust. This thrust separates the Ingulo-Inguletsk block on the W from the Pridnieprovsk block on the E. Its upper

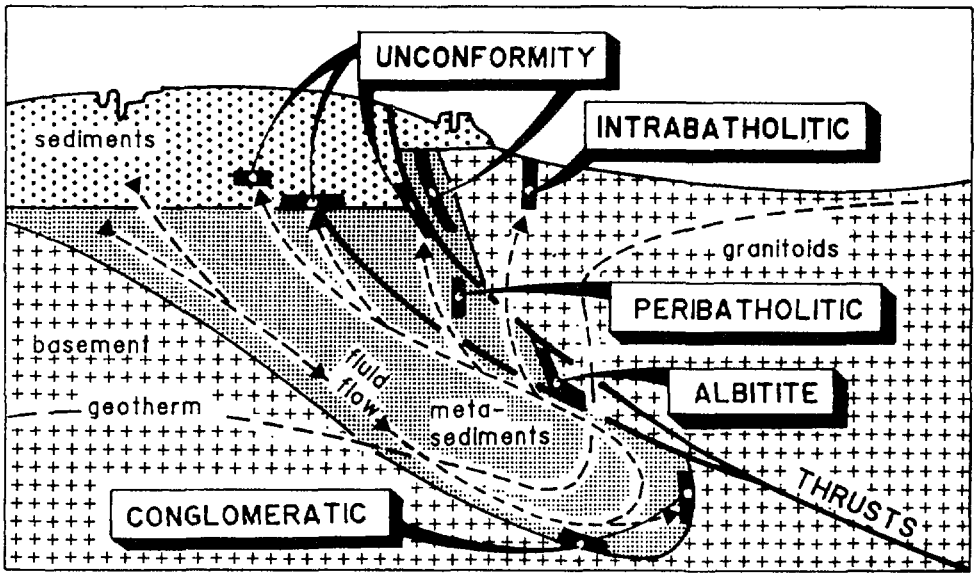

FIGURE-1:

Hypothetical integral diagram of diverse genetic types of uranium deposits bound to thrusts. Three principal units are shown: 1) the early basement with possible younger granitic intrusions (for simplification the boundaries between these subunits are not shown), 2) the infolded metamorphics (mostly metasediments), and 3) the young sedimentary cover. Two types of thrusts disturb the recumbent margin of the metasedimentary synform: 1) the older (flatter) tectonized the basement only, and 2) while the younger (steeper) is rooted in the former one and disturbs both the basement and the sediments. The geotherm is shifted up in the upthrown blocks. Fluids derived from sediments and metasediments are heading towards the warmer ambient within the basement and leave it along their ascendent paths. For simplification, other, more external, fluid sources are not shown.

section controls one of the Proterozoic synforms and a deep-reaching zone of albitization. The Zholtyje Vody deposit can be seen as one of the uranium deposits controlled by this particular fault.

2.2.2 Thrusts Reaching the Upper Mantle

In the past, the Basin and Range arrangement of the topography in Wyoming (U.S.A.) has been traditionally interpreted by steep tectonics. The COCORP deep reflection seismic traverses provided a new interpretation of the fault systems. According to Oldow and Ney [13] the reflections were received from a set of moderately dipping thrusts. These could be traced up to a depth 30 to 40 km, estimated here as the Moho discontinuity. The decoupling of thrusts occurs within an approximately 150 km wide zone beneath the Wind River and Bighorn basins. (A wider extrapolation of this zone of thrusts (to the N) could be postulated as covering the basement units around the Needle Falls Shear Zone (Northern Saskatchewan, Canada). Similar zones of decoupling may be the source for shallower subhorizontal

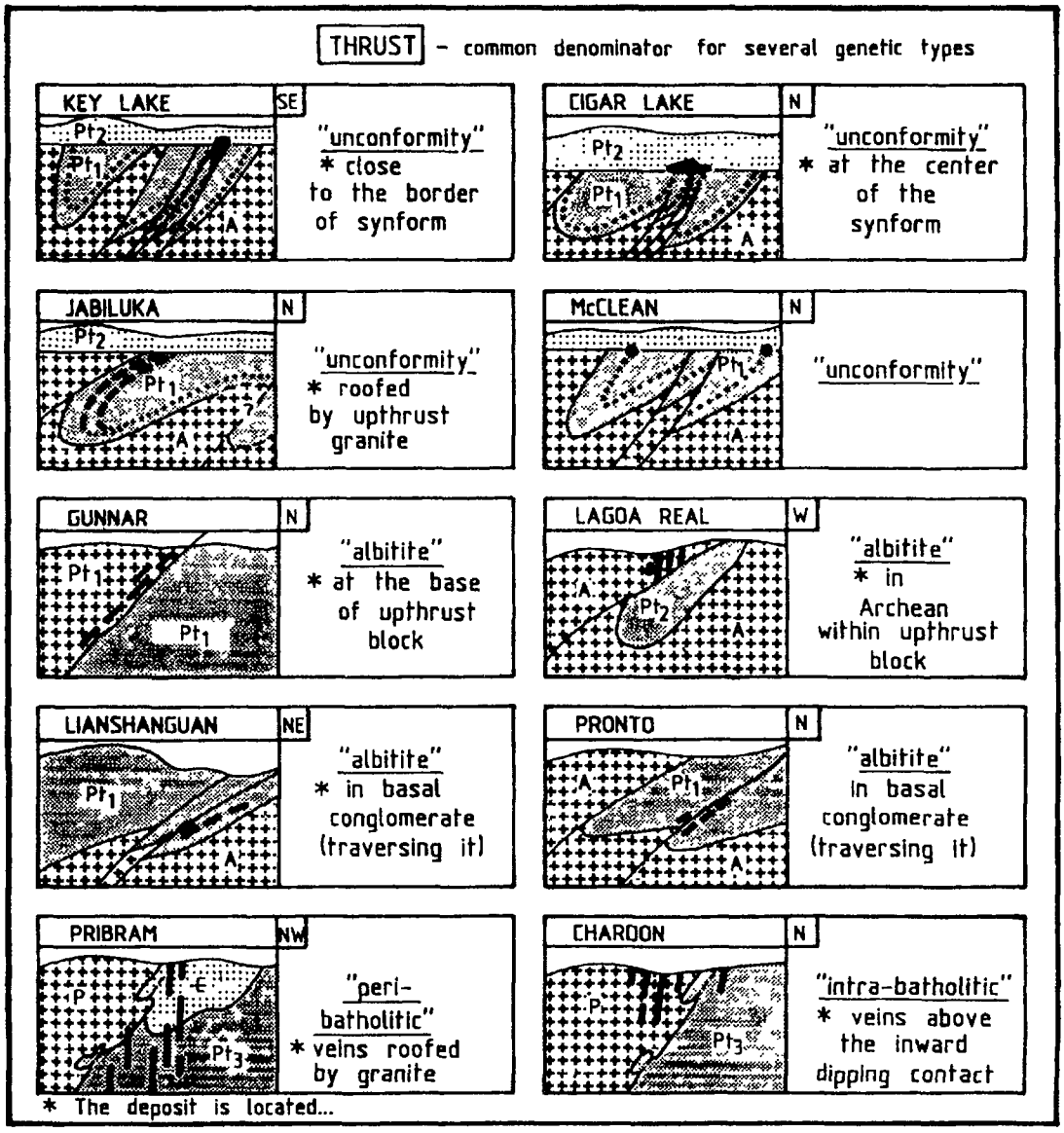

FIGURE-2:

Examples of the principal tectonic (fold and thrust) arrangement at some uranium deposits. All cross- sections are schematic and not to scale. A-Archean, Pt_1-Pt_2-Pt_3 - early, middle and upper Proterozoic respectively, E-Cambrian, P-Paleozoic.

electrical conductivities found on E of the Needle Falls SZ by deep- sounding electromagnetic survey (Handa and Camfield [14]).) Back in Wyoming, the uppermost sections of some principal thrusts (Berg [15]) form gigantic basement overhangs above the overturned basins filled by Paleozoic and Cenozoic sediments. For example, the vertical displacement along the Wind River Thrust attains 14 km. In such a case, at places more than 10 km inward within the basement, we are still virtually above the downfaulted sediments at depth. Obviously, specific thermal regimes and oil-bearing structural traps were generated by such notable thrusts. It is postulated that some sandstone-type uranium deposits could be triggered, complemented or fully generated by such a specific thermal and structural regime.

2.2.3 Thrusts Decoupling Soft Sediments from the Basement

Some shallower-seated thrusts are generated at the basement/overlying sediments boundary. In contrast to those previously discussed, many such thrusts do not involve major basement wedges and propagate along soft horizons (shales, evaporites) re-arranging the stratigraphic sequence within the sedimentary package.

Typical models of such types of thrusting were developed for the Rocky Mountains Foothills belts. One such structural trap has been recognized (Jones [16]) by the discovery of the significant Turner Valley oil-bearing structure in Alberta, (Canada).

2.3 General Minerogenic Implications of Thrusts

Few of the examples already mentioned indicate that thrust domains control in some specific way the formation of mineral deposits.

There is a traditional temptation to relate the epigenetic mineralization with the tensional tectonics alone. Though it is obvious that the structures immediately preceding the mineralization are commonly dilations provided by a tensional regime, the latter are also, and not infrequently, controlled by earlier reverse faulting both in location and grossly in size as well. The normal faults generated by a reversal from the thrusts are those which provide not only a multistage development but likely also a more sizeable tectonism. Specific classes of normal faulting, therefore, in our context, can be viewed as an expected consequence of the relaxation following an earlier compressional system rather than an independent or suddenly appearing event within the evolution of a tectonic regime.

2.3.1 Oil and Coal Deposits

In most environments, thermal regimes were generally recognized as crucial in the formation and concentration of oil. A number of these were found to be associated with specific thermalities and structural settings generated by thrusting. Some were recognized as even being concealed beneath the upthrust wedges of the basement. Obviously, it is not only the presence of optimal source or host rocks but their combination with a particular structural arrangement which is responsible for the accumulation of oil. Among them, increasing numbers of positive sites are controlled by thrusts.

Particularly refined views on thermal regimes associated with folding and thrusting have been presented for the coalification processes. Typically, the post-thrusting coalification runs across the strata and no repetition of the same coal ranks is observed. In similar conditions of a simple folding with post-folding coalification, the vitrinite reflectance of individual seams increases down-dip at the same rate as successively deeper seams increase rank in a vertical drillcore section. Such studies (Pearson and

Grieve [17] and others) in the North American Rocky Mountains were performed in the Jurassic-Cretaceous Kootenay Group, Lower Cretaceous coals, and in the Permian Phosphoria Formation.

2.3.2 Other Non-Uranium Deposits

From numerous examples of thrust-associated mineralization in North America, the Mother Lode and Carlin districts (California and Nevada respectively, U.S.A.) represent two distinct types of gold mineralization. The first is controlled by the Melones reverse (and strike-slip) Fault which is believed to coincide with Jurassic and Triassic subduction zones. The second occurs in the Paleozoic below the Roberts Mountains Thrust, which placed siliceous rocks above the carbonates hosting gold mineralization. The early Proterozoic "greenstone belts" of the Reindeer Zone (western Churchill Province, Canada) includes numerous gold deposits and is dominated by multiple subhorizontal thrusting which might have conditioned the metallogenic specifics of Au-hosting mylonites, metamorphics and intrusives.

Not surprisingly, metals like mercury and antimony, commonly deposited in conditions classically termed as epi- to telethermal carry excellent examples of thrust-bound deposits. Among these, particularly the non-volcanic type belongs to the most significant ones.

In the U.S.S.R., Kuznetsov [18] has emphasized the roofing effect of shales carried by thrusting upon the ore-hosting carbonates. In the significant Khaidarkan and Ak-Tash (Kirgiz S.S.R.) mercury deposits, Silurian slates and Cambrian schists were thrust upon Carboniferous and Cambro-Ordovician limestones respectively. In an analogous arrangement, the thrusts themselves carry mineralization in the Chaganuzun and Chadazyr mercury fields (Gornyi Altai A.O. and Tuva A.S.S.R. respectively). Among the important concentrations of antimony, the Kadamzhai deposit (Kirgiz S.S.R.) is again developed in limestones beneath a thrust roofed by shales.

The world's largest Sb-deposit, Shuikonshan (Hunan, China) contains ore which replaces Devonian limestone under the cover of Devonian black shales carried up by a major thrust. Similarly in the sizeable mercury field at Idriya (Yugoslavia) most of the orebodies are in impervious shales which rest upon a complex thrust zone.

3. THRUSTS AS AN UNIFYING CONTROL IN DIVERSE TYPES OF URANIUM DEPOSITS

The above mentioned examples have demonstrated that numerous mineral deposits and especially those of typically low temperature environments are effectively controlled by the thrust-bound domains.

Similarly, temperature-sensitive uranium, once liberated from resistate forms, refractories, and/or silicates, is expected to behave analogously, i.e. being involved in those

hydrothermal cells triggered by thrusting. Discussed below are examples of diverse types of uranium deposits where thrusts represent not only a commonly perceived structural control s.s. but a variously prominent metallogenic factor as well.

3.1 Conglomerate-hosted Type

The Huronian Elliot Lake conglomerates (Ontario, Canada) containing uraninite, monazite and zircon of 2.45, 2.55 and 2.45 Ga respective ages (Meddaugh et al. [19]) indicate that the heavy minerals have younger provenances if compared with the late Archean culmination of granite ("Algoman") plutonism. Nonetheless, the minimum age of 2.45 Ga for uraninite shows a detrital (although not necessarily a granitic) origin. The basal Huronian was folded around 2.3 Ga and a localized albite-chlorite metasomatism emanated from possibly subvertical structures and penetrated along ancient subhorizontal (thrust) fractures into the basal reef replacing it almost fully. Locally, this often unrecalled metasomatism has been accompanied or followed by a remarkable enrichment of uranium (parts of the Denison Mine). In other areas (Pronto Mine) the albite-microcline-chlorite matasomatism did not lead to a substantial increment of U, even though it dominated the bulk of ore. After the intrusion of the Nippissing diabase (2.2 Ga), which in some cases has used the earlier metasomatic channels, a younger sizeable thrusting has covered at least the southern portions of the basin and thrusts decoupled beneath the conglomerates and above them along the Pecors Formation argillites.

The Lianshanguan deposit (Liaoning, China) within this present paper's context represents an excellent example of a multistage genesis where several earlier stages dominated by diverse processes remained preserved. It is, therefore, difficult to assign a single integral denomination of a genetic type to such a deposit. The complexity has been pointedly emphasized by Qin and Hu [20] who noted some similarities with the Alligator Rivers Region while pointing also at the differing host rocks. In Lianshanguan, a considerable volume of the mineralization is confined within the conglomerates and quartzites of the basal Langzishan Formation, resting above the Archean granites. In contrast to the Elliot Lake camp where the 2.45 Ga age of the uraninite and its detrital nature were suggested, the 2.1 Ga age received on the earliest mineralization at Lianshanguan has led to the postulation by Zhong and Guo [21] that the primary mineralization precipitated on clays, carbonaceous substances and pyrite from syngenetic solutions. Substantial localized upgrading is however definitely younger and thrust-controlled as it will be shown within the description of other genetic types (ref. section 3.2).

3.2 Albitite Type

Among the oldest structures controlling the albitization process is the Destor-Porcupine Fault Zone (Superior Structural Province, Canada). This zone had already during

the late Kenoran attained a reversal into a significant thrust which carried volcanics above the sediments (both Archean). The base of the upper sheet is intruded by trondhjemites with intensive albitization and in variable lithologies it hosts a considerable part of gold mineralization in the famous Kirkland Lake district. The altaite-dated Au-mineralization of 2.5 Ga confirms the epi-Kenoran age of thrust-bound albitization.

In the Beaverlodge district (Canada) the distinctly younger (2.3 Ga) model age of galena at least suggests the early Blezardian foundation of the ore-bearing structures. Nonetheless, it does not prove that thrusting and/or albitization are of this age. However, in the neighbouring Nonacho Basin (this volume) the albitite-hosted U-mineralization has been dated as 2.2 Ga old and thus it occupies the Kenoran-based structures re-activated by the early Blezardian. Grossly contemporaneous [22], i.e. early Blezardian (pre-Nippissing), is the localized thrust-bound albitization and U-enhancement of the Matinenda Formation in the Elliot Lake camp (ref. 3.1). Younger, late Blezardian (and still pre-Hudsonian) events are documented at least by the Gunnar granite (Beaverlodge district). This granite is 2.2 Ga old and since it dips inward, we may only postulate that it has used a thrust for its emplacement above the metasediments. The albitization (as well as the significant albitite-bound U-mineralization) developed within the base of this granite overhang must be younger than 2.2 Ga.

Hudsonian albitization in the Beaverlodge district is well documented. In our interpretation, the St. Louis Fault is a thrust, which after a reversal from a normal fault, carried the older rocks above the younger Tazin Group (early Aphebian?) argillites and left a sliver of earlier downfaulted Martin Group (late Aphebian) 1.5 km beneath the present surface. This Martin block is albitized and the immediate footwall of the fault zone is metasomatized by quartz-feldspar "granite". The albitized hanging- and footwalls carried the substantial U-mineralization mined by the Ace-Fay-Verna mines. In the Nonacho Basin, grossly contemporaneous thrusts placed part of the early Blezardian albitites above the late Aphebian Nonacho Group basin. The intensive wall-rock alteration in Port Radium (Canada) U-veins, commonly described as "jasperoid", was found by UEM (1982), at least locally, to be fully replaced by albitization, thus predating the development of proper veins; the mineralization of the latter, in contrast to the wall-rock alteration, has been meticulously recorded during the time of the mining. Contemporaneous U-bearing albitites at Zholtyje Vody (Ukrainian Shield) were mentioned in 2.2.1. The principal upgrading of the Lianshanguan deposit (China) has been accompanied at 1.9 Ga by an intensive albitization acting along the stratabound thrusts developed within argillite intercalations above the Archean-Proterozoic contact with local slivers of Archean "protruding" into basal Proterozoic (ref. 3.1).

A major break-through was achieved with the discovery of the Lagoa Real deposit (Bahia, Brazil). It is probably the first and certainly the most eloquent example of where the upper amphibolitic to granulitic Archean, otherwise plainly condemned as barren because of its U and/or fluid "dryness", became itself a productive host. Lobato et al. [23] have shown that Archean-hosted albitic orebodies which penetrated the upthrust Archean were generated by fluids derived from downfaulted and concealed Middle Proterozoic rocks.

In our opinion, the downfaulted supracrustals (Série de Poli) provided fluids for the albitization at the Kitongo deposit (Cameroon) [25]. Not unlikely as in the Gunnar deposit, the albitization invaded the base of the inward dipping granite (0.6 Ga old) which has perhaps used an ancient thrust overriding the Poli supracrustals.

Substantially younger albitization at the Swanson deposit (U.S.A.) was possibly controlled by the earlier (mid-Ordovician) deep-seated thrust (ref. 2.2.1). Among many albitite-type mineralizations, studied particularly in China by Du [24] and others, several are also thrust-dominated. In the Xiang-Shan U-camp (Jiangxi province), part of the Heng-Jian deposit is controlled by a granite porphyry penetrative into a thrust which placed Upper Proterozoic (Sinian) above the Jurassic sandstone (personal communication Huang Shijie and Chen Zuyi, 1985).

3.3 Unconformity Type

A further subdivision according to particular phenomena facilitates the orientation within a broad variety of thrusts occurring in this type of deposits.

3.3.1 Mylonites and Associated Structures

The Carswell Structure (Saskatchewan, Canada) includes two subtypes of deposits although both are frequently claimed as being of unconformity type. Both the unconformity-type s.s. (represented by the "D-orebody") and the vein-type (Dominique-Peter deposit) are controlled by a major mylonite zone. This, in our interpretation, is basically an ancient (possibly 2.0 Ga old) tectonic system along which the younger and softer Peter River gneiss slid over the older and more rigid Earl River Complex basement with thrusting becoming more obvious at places where it emplaced slivers of the basement into the base of its overriding metasediments. After the uplift, younger thrusting guided by mylonites controlled the "D-orebody". A few kms to the NW, the same mylonite controls a system of veins forming the Dominique-Peter deposit. These are structurally rather unique among other deposits of the region. Instead of being foliation or stratabound, as nearly elsewhere, the veins cut the foliation and their strike is oblique or normal to the orientation of the mylonite. In some instances the mineralized veins are blind and since they do not reach the present (basement) surface they were also separated by a barren zone from the now eroded superjacent Athabasca.

Obviously, the vein structures were formed after the mylonites were uplifted into the cooler domain which generates the brittle tectonics. Their association with mylonite, while commonly stated, is however left less specified. In this concrete case and in general as well, we see mylonites as a specific structural and textural domain. Structural anisotropy leads to an adjustment of structures generated by younger stress fields along these earlier discontinuities. The enhanced textural anisotropy better conducts the heat and positively disturbs the general isotherm of the country rock. The distinct linear anisotropy of the mylonites within the surrounding lithologies may conduct and/or confine the flow of mineralized fluids. In addition, in some cases, the locales of younger tectonics could have been inherited from earlier systems associated with mylonites since some models [26] show that high-angle antithetic faults could form above the master fault and other secondary faults could form above and below the master thrust that do not strike parallel to the latter.

3.3.2 Inheritance and Propagation of Thrust Systems

In past interpretations of the Athabascan unconformity deposits, the Archean has been commonly admitted as a domal structural feature in the proximity of the deposits and possibly as an ultimate source of uranium. However, in a prevailing atmosphere dominated by the Athabasca itself and by the post-Athabascan ages of the mineralization, the Archean has been seen as an excessively old domain to be considered more seriously. Among the few voices in favour of a substantially broader Archean envolvement, we have shown extensively as early as a decade ago, [27] that both the compositional and structural heterogeneity of the Archean basement may have a major implication in the overall evolution leading to the formation of these deposits. Particularly, the subtle (and commonly unconsidered) EW-oriented structures were proposed as of Kenoran foundation and the deposits were postulated [27] at such places where Hudsonian and Kenoran structures met. The idea has not been particularly adapted by the prolific genetic models. Two years later however, the first deposit comfortably occurring within such a specific orientation and located on one of few EW-striking regional gravity lows [27, 28, 29] was discovered at Cigar Lake. In describing this phenomenal deposit (Fouques et al. [30]) also noted (at least sketchily) that "...larges structures d'orientation est-ouest...pourraient représenter une direction archéen...". Although at this moment we may only postulate that some Archean fault tectonism are thrusts, we are more confident that Archean tectonics either localize the roots or adjust the trajectory of some of the minor Aphebian belts and also thrusts which propagated into these superjacent early Proterozoic metasediments.

Among the oldest are the mylonites also particularly frequent in the principal belt of unconformity deposit i.e. well beyond the Carswell Structure, where these were rather emphasized in connection with the development of U-veins

(ref. also 3.3.1). At many places, mylonites were found as extensive sheets wrapping around the Archean domes. Since in the Carswell Structure mylonites were also documented above the lower limbs of basement domes the mylonites could have been generated as subhorizontal décollement sheets deeper in the crust and mostly prior to both diapiric piercing by lighter basement granites, as well as (?) to principal folding. After the folding, the now steeper mylonites represented a new major structural heterogeneity proximal to Archean domes. In detail, however, the major mechanical gradient instrumental for propagation of mylonites in the NW of the Wollaston Domain, was at the base of the soft graphite-bearing peri-basal sequence, but above the basal (Aphebian) plagioclasic sequence which behaved as rigidly as the subjacent Archean granite. Since the plagioclasic unit is relatively thin at least at the Key Lake deposit, (this volume [31]), mylonites are proximal to (but not exactly and/or necessarily only at) the Archean (or another basement) contact. Later stages of folding which led to the asymmetric to recumbent folds, generated shearing preferently at the overturned limbs and possibly the first major stacking of graphitic lithologies has also occurred.

After the uplift, younger (now only brittle) shears developed as thrusts or reverse faults in many cases in proximity (rather above) of the old mylonites. Possibly of major significance are the less obvious pre-Athabascan thrusts. These led to a repetition of strata, especially of the soft graphite-rich horizons [29], and to a general disturbance of the stratigraphy along such metapelites. Thrusts usually occur in clusters and may extend either above the contacts with Archean antiformal limbs (Key Lake), or beneath the overturned Archean overhangs (Jabiluka).

In other cases, ancient zones of weakness could be located beneath inner portions of Proterozoic synforms and the younger thrusts would then propagate and occupy a portion of a synform considerably away from the Archean contact e.g. Cigar Lake. This strikingly rare and simultaneously most productive case was possibly conditioned by the above specifics of the sub-Aphebian tectonics combined with the broadness of the Aphebian synform. The final position of the uppermost sheet of the graphitic horizon after the multiple thrusting, carried the graphite from its original peri-basal stratigraphic position into the position structurally closer to the center of the synform which simultaneously (?) attained an asymmetric cross-sectional geometry. In our opinion, this explains why the Cigar Lake deposit, together with its associated mylonites and graphite, are all concurring 1.2 km away from the northern Archean contact. Three to four conductive zones [30] filling the northern half of the 3 km broad asymmetric synform with recumbent (?) southern limb may represent a single graphitic sequence multiplied within an imbricate fan of thrusts, where the southern member possibly attains the largest vertical component.

Commonly, the most visible (but not necessarily the most sizeable) is the younger post-Athabascan (Canada) or post-Kombolgie (Australia)) component. In the Athabasca Basin, the vertical displacement of the unconformity at some prospects may reach 300 m, however at most deposits a substantially smaller movement (few tens of metres) has been observed. Since the compressional systems must relax, at later stages a reversal to normal faulting may lead to an apparently smaller (residual) displacement. Therefore, in some cases the present observation of "flatness" at the unconformity may not characterize the position of blocks during the earlier compressional stage. The flatness may have another reason and this (if observed on cross-sections only) does not exclude the possibility of strike-slip post-Athabascan tectonism. For example, if the regional stress-field derived from the NW-oriented diabases is applied to the prevailing EW-orientated basement structure at the Cigar Lake deposit, it would propagate into the sandstone (at the time of the diabases, i.e. at the time of ore emplacement) as a zone of pronounced dextral strike-slip structure without an up-dip component. If the same stress field is applied to the ENE and NNE-oriented basement at the Key Lake and Midwest deposits respectively, their propagation into the sandstone would also require a strike-slip structure, but combined with an up-dip (reverse fault) component. The behaviour of all three sites conforms to the above prediction based on the analysis of this particular stress-field.

Reverse faults (or their combination with strike-slips and younger tensional relaxation) penetrative into the Athabasca channelled the fluids into the basement. The absence of such faults would have left the earlier basement-hosted mineralizations in their low grade and stratabound form. If faults are present, but in the absence of a thermal telescoping, the flow would be constrained broadly within the basement restructuring the stratabound mineralization only mildly (Jabiluka), more obviously (Eagle Point South) or even more intensively (Eldorado Resources Limited [32]) from strata to off-strata steeper [27] structures (Eagle Point North). However, in neither case has a substantial transportation up to the unconformity probably occurred and, in addition, and characteristically, the ore remains monometallic. In the presence of thermal telescoping (which, based on data of [36] and in part on [35], implies the emplacement of specific arsenides in our case), the flow includes a well-channeled up-dip course and the truly unconformity deposits (Cigar Lake, Gaertner orebody and flanks of Deilmann orebody at Key Lake deposit, Midwest deposit etc.) are formed. By this process the earlier stratabound, but volumetrically sizeable and low grade U-orebodies are fully restructurized [27] and transformed up to the unconformity, upgraded (by reducing volume) and become polymetallic.

The deposits in the Alligator Rivers Region (Australia), with some exceptions (Au) generally monometallic, could, then be considered as unoverprinted by a major thermal

telescoping and thus left in an earlier (basement- hosted) configuration with little or no tendency to vertical (up-dip) shrinkage of the mineralized volume and thus without related upgrading at the unconformity [27, 29]. This could have lead to some preservation of the pre-Kombolgie ages as reported recently [33]. In contrast, the strongly enhanced grade at Eagle Point indicative of restructuration makes this site (although hosted by the basement) a less probable candidate for preservation of pre-Athabascan ages. Other high grade (and polymetallic) deposits at the Athabasca unconformity are practically excluded from retaining earlier (pre- Athabascan) ages.

Hence, in looking for higher grade deposits of this general type, the existence of fluid-rich sediments and the sufficient tectonism for the channelling of the fluids into the basement are necessary. On the other hand, the presence of these parameters remains ineffective if the subjacent basement does not include a very specific pre-Athabascan tectonic setting and the variably advanced U-mineralization or orebodies.

Concluding by our earlier observation [27, 28, 29], the geographical (lateral) location of the unconformity deposits is initiated, progressed and governed by processes acting in the basement prior to the deposition of the sedimentary cover. Their vertical position (relative to the unconformity), their grade and composition and an apparent absolute age are conditioned by the processes which include particularly those derived from the sedimentary cover. Essential stages of both pre- and post-Athabascan development were undoubtly associated with thrust-dominated tectonism within various compressional regimes.

3.3.3 Other Examples of the Thrust-Bound Unconformity Type Deposits

Both principal basement domains subjacent to Athabasca Basin include and/or control examples of this kind.

In the Western Craton, the "D-orebody" of the Carswell structure follows a reverse fault between the upthrust basement and the downfaulted sandstone, i.e. in our view, a common setting which does not require an elaborate rotation by the Carswell event. The Fond-du-Lac deposit is located in the basal Athabasca above the Archean rocks which were possibly thrust upon the Aphebian metapelites. The Nisto deposit, hosted within a basement block placed upon the Athabasca may represent a root of an unconformity deposit (Homeniuk and Clark [37]), but, if monometallic (?), in accordance with the thermal telescoping model, it could be of the Eagle Point subtype and here also influenced by fluids from the underplated sandstone. A similar tectonic situation is known to UEM at the opposite side of the basin, at the same structural boundary, where the vertical post-Athabascan displacement achieved the maximum size in the region, about 300 m.

In the Cree Lake Zone most of better known deposits of this type contain various degrees of visible evidence of thrusting. Many of these were discussed in this section (ref. 3.3). Among these, the Eagle Point deposit is unique by its being both sizeable and fully hosted in the basement.

Structural analogons of the Eagle Point-setting are a few important deposits in Australia. The Koongarra deposit also shows, amongst others in the region (Jabiluka), that appreciable amounts of uranium have penetrated neither into the downfaulted nor the superjacent Kombolgie sandstone respectively. (Using both these and the local (Harrigan Zone) examples together with thermal telescoping model which confines (earlier) monometallic (U) mineralization to the basement, we would not expect that the Eagle Point deposit has formed any appreciable U-concentration either at or within the now eroded sandstone cover). The Ranger No. 3 deposit contains a sliver of downfaulted Kombolgie, as does the Hades Flates deposit include a remnant of barren Kombolgie, in a situation similar to that of Eagle Point. A foliation-traversing reverse fault controls the Narbarlek deposit. In the South Alligator Valley U-field, the Koolpin Formation forms the hanging wall above the downfaulted Coronation sandstone in both the Rockhole Mine and the Palette deposits. In the Rum Jungle area, the dragging of shales at the Dyson's deposit and the dip of a shear at the White's deposit, as shown by Paterson et al. [38], infers that the Giant's Reef Fault, beyond its obvious horizontal displacement, might include a thrust component which has partly concealed the Proterozoic of the Embayment beneath the Archean granite. To the south of the same area, the Kylie prospect (similarly to White's East) contains narrow but deeply downfaulted Carpentarian sandstones along the reverse faults. According to Pagel et al. [39], the mineralization is associated with these faults. Though not claimed earlier [39] explicitely, according to our present model, the fluids for this localized upgrading were probably provided from the downfaulted sandstones.

3.3.4 Roofing Effect of Thrusts

In paragraph 2.3.2 we noted that numerous oil and gas, Au, Hg and Sb deposits are roofed by impermeable shales, and that for many of these this arrangement has been traditionally claimed [18] as an important factor. Similarly, Arthru et al. [34] have proposed that the graphite-rich peri-basal sequence of the Wollaston Group in the Wollaston Domain (Canada) functioned as a barrier for the upward advancing granitization which presumably fully consumed the postulated conglomeratic (!) basal units. With only minor exclusions, such an intensive granitization can be confirmed at least at some major uranium deposits (Key Lake, Eagle Point etc.). However, another part of the [34] postulation, i.e. the confinement (roofed by graphite-rich metamorphics) of ore-fluid movement, becomes a valid concept if extended by further addition.

In principle, we will show that shales alone (in this context s.s.) do not represent a major metallotect. The necessary addition in our view implies that it is not the normal stratigraphic superposition of shales, but their emplacement by a thrust which makes them metallogenically operative. If superimposed only stratigraphically, their roofing effect would remain unused because no substantial amount of fluids would penetrate their footwall. It is therefore rather the thrust which collects and guides the sizeable flow of fluids, and thus only then do the superjacent shales become (secondarily) an effective roofing element.

The size of thrust-triggered roofing by shales would be typically large because a thrust would propagate within the shale softness under a very low angle. For most of its development would it follow their footwall, further up it would penetrate the shale package and only in its uppermost trajectory it would abandon the shales and leave these in its footwall. Since the latter segment (in folded and steeper domains) would be commonly eroded, this explains why the thrust-bound roofing by shales is such an abundant metallogenic control.

3.4 Peribatholitic and Intrabatholitic Types

A nearly similar number of thrust-bound examples as were in the unconformity type are counted by this group of deposits.

For practical purposes within this paper, we distinguish three subgroups according to their relative distance from an intrusive body. Note also that some of these deposits and especially those of the "distal" subgroup are either transitional to or hard to distinguish from the basement-hosted unconformity type or some albitite-type deposits.

3.4.1 "Peribatholitic" with Distal or Unknown Intrusives

The Schwartzwalder U-Mine (Colorado, U.S.A.) represents a deep reaching complex system of veins developed within the Precambrian metamorphics. Although 2 miles away on strike from a subjacent Tertiary-aged monzonite body, the hosting block seems to be also upthrust upon the deeply downfaulted Mesozoic sediments. Also in Colorado, a unique (dolomite-hosted) mineralization occurs in the Pitch Mine. Here, the Mississippian dolomite, which was severely broken by late tensional tectonism, rests at the upthrust front of an recumbent antiform composed of Precambrian. Subjacent to both the ore and the thrust are the deeply downfaulted Pennsylvanian sediments. In both mine settings, sizeable amounts of fluids released from downfaulted sediments could have penetrated the overriding blocks and contributed to the formation of ores.

In many complex and large regional tectonic zones it is difficult to describe the relative movement along individual tectonic sheets and thrusting therefore becomes less obvious. Among such regional zones of prime metallogenic

importance is the Singhbhum Copper-Uranium Belt (Bihar, India). This zone is also commonly called the Singhbhum Thrust Belt, although some workers [40] do not see a direct evidence on a local scale for a larger up-dip movement in this moderately dipping zone and therefore favour the noncommittal "ductile shear". However, in general, it seems that the Dalma volcano-sedimentary terrane, together with its subjacent fragmented continental crust, has been thrust upon the Singhbhum Archean granite in the south. The situation is not dissimilar to the Needle Falls Shear Zone (Saskatchewan, Canada), which also separates the ensimatic from ensialic regimes. The Singhbhum Belt itself carries numerous stratabound deposits with commonly overlapping metals such as Cu, U, (Ni, W, Mo etc.). The uranium deposits are stratabound sheet-like orebodies and although of very low grade, they can reach considerable (vertical) depths, generally to 450 m (Naroapahar deposit), but also with some mineralization proven [40] at 800 m (Jaduguda deposit). Emplacement of the stratabound metasomatic "Soda granite" into the zone also gives these deposits an affinity to albitite-type deposits, another factor illustrative of genetic complexity.

In the Czechoslovakian part of the Bohemian Massif, three types of essentially strata- or foliation-bound disjunctive structures are commonly considered prospective: 1) major mylonite zones up to several hundreds meter thick, 2) faults developed along the regional fault zones, and 3) smaller dislocations associated with some larger faults along the contact of Variscan granitoids.

Among the two first categories are U-bearing stratabound shears. This general geometry resembles the basement-hosted unconformity type (Eagle Point), deposits in the Singhbhum Zone and others. The Slavkovice-Petrovice deposit (though not resulting as particularly productive) has been explored for 3 km in length and up to 550 m in depth mostly by underground workings. Individual lensoid and feather structure orebodies (U-Se) extend between the sole fault and the superjacent, 1 km distant, splay fault (which dip 20° - 50° to NE) where they join at 500 m depth. The tectonized wedge between the principal faults (thrusts?) extends along the marbles, calc-silicates and gneisses of the Moldanubian Varied Series. The tectonic hanging wall represents the Moldanubian Monotonous Series. The zone itself is a part of the regional Labe Lineament. The Jasenice deposit occurs at the thrust zone which places katazonal Varied Series of the Moldanubian above the phyllitic Moravian Block. Several individual shears are filled in part with mostly allochtonous graphite. Two subordinate parallel faults in the hanging wall of the master thrust carry U (V) mineralization and some pre-ore albitization.

In the E-portion of the Bohemian Massif the stratabound deposit at Kletno (Poland), follows a thrust between subjacent Upper Proterozoic marbles (together with squeezed-in Carboniferous conglomerates) and the superjacent granitic gneiss.

As mentioned for the Singhbhum Zone, sizeable shears which are comfortably stratabound are difficult to be assigned simply as thrusts. Nonetheless, for example, the renewed debate on the existence of substantial thrusts within the Moldanubian and the Bohemian Massif as a whole has been supported particularly by Vrána [41] who pointed out the thrust-bound stratigraphic complexity of the Moldanubian, and by Pacltová [42] who found early Paleozoic microfossils within crystalline rocks traditionally considered as invariably Proterozoic. It seems, therefore, that many of these younger (now metamorphosed) sequences were concealed within the earlier basement by the most probable mechanism, by thrusting. This and other similar Variscan terranes can be then viewed as thrust-dominated and thus prospective for stratabound (thrust-bound) mineralizations of the Slavkovice-Petrovice setting.

3.4.2 Peribatholitic s.s.

This type is also well developed in the Variscan of Europe. Those in Portugal and Spain are rather shallow-seated accumulations and thus very dissimilar to others in the rest of the Variscides. Therefore, their Iberian-type denomination seems to be unextandable especially to those with larger vertical productivities.

In Massif Armoricain (Britanny, Vendée, France), deposits termed "intrametamorphic" (Poty et al. [43]), are associated with major shear zones along the leucogranites (both indicative of microplate boundaries) and are characteristically polymetallic (Retail, Penaran). For some deposits along the same structure (Chardon) a strike-slip and thrusting have been recognized as principal movements along these shears. An older (340 Ma, Middle Devonian) age has been claimed [43] for those deposits separated from the granites by major shears, and with "no primary connection with these granites".

Such an age and an apparent temporal affinity with other (earlier) granitoids is nonetheless well documented geologically by the intrusion of the Bohutín quartz-diorite (tonalite) in the Příbram district (Bohemian Massif, Czechoslovakia), representing the Acadian disturbance (between late Silurian and early Devonian at approx. 400 Ma), which, in turn, follows the formation of the Upper Proterozoic (late Cadomian, 700-650 Ma) uranium protores and their early Paleozoic (early Caledonian, Taconic, 460 Ma) progression [44]. Here, at Bohutín, a significant thrusting (with a vertical displacement of over 2 km) consisted at least of late Cambrian and post-early Devonian components [44] and roofed the sizeable Pb-Zn-Ag veins hosted by downfaulted Cambrian. Another part (three kms to SE across the tectonic grain) of the same district, yields the world's deepest uranium veins (mineable up to 1,850 m depth) which are hosted by downfaulted Upper Proterozoic (+ Cambrian) sediments beneath an enormous granitic overhang. Hercynian granite has perhaps used an older thrust, which (possibly after a reversal from normal fault) placed ensialic (s.l.)

Moldanubian above the ensimatic Bohemian block, i.e. at the boundary of differing crustal thickness and thermal regimes. The productivity of some veins beneath the granite overhang is sizeable. At the surface, in some places up to 600 m from the contact "inside" the granite we are still above the uranium veins hosted by rocks other than the granite, which, in turn, (though with some localized albitization [44] at some other on-strike locations within this granitic endocontact) remains barren.

At another suture of the Bohemian Massif, one of the principal aims to be followed up by the supra-deep (cca 15 km) drilling located at Erbendorf in West Germany (Bavary), is the observation of fluid movements along the thrusts between the Moldanubian and Saxothuringian [45]. Although not explicitely noted in this short version of the program, in this connection it remains of significance that both the Großschloppen (West Germany) and the Jáchymov (Czechoslovakia) uranium deposits are located on the Saxothuringian side of this major boundary. The monometallic Großschloppen deposit occurs not far away from the proposed drilling in a segment where both general units in contact are mostly ensialic. Only 75 km along structural strike, the polymetallic Jáchymov deposit is also hosted by the ensialic Saxothuringian, but in a contact with an unusually ensimatic sub-unit of the Moldanubian, with the Bohemian Block. The Jáchymov veins extend above the blind portion of granites and principally beneath the (upthrust?) sheet of superjacent phyllites. Possibly except of some structures in the Abertamy field, and some EW structures, major thrusting is not obvious on a local scale.

On the East of the Bohemian Massif the western part of the peribatholitic deposit at Kowary (Poland) is roofed by the granite and extends up to 650 m below the surface together with prevailing magnetite-bearing skarn.

3.4.3 Intrabatholitic Type

In the Massif Armoricain (France), [43] have distinguished intragranitic (Commanderie) and contact deposits (Chardon, Ecarpière). The latter are related to the granitic (Mortagne Massif) block thrusted above the Upper Proterozoic. The Chardon deposit consists of mostly perpendicular veins traversing predominantly within the upthrust sheet of blastomylonitic granite.

On the other hand, on a local scale, most of the two-mica granite ("episyenite") - hosted deposits of the Massif Central are controlled by tensional tectonics. On a regional scale, however, this generally granite-dominated environment may include earlier thrust-bound granitic emplacements. Among these, for example the Brame granite, has been considered as thrust-bound (M. Moreau, personal communication, 1980) and in other places of the Massif Central considerable thrusting has been also postulated [46]. Although not directly obvious, thrust-abundant

essentially granitic terrane may conceal the downfaulted supracrustals, which could have conditioned the granitization processes and the localized enrichment of fluids penetrative into the upthrust sheets and resulting in the formation of veins, now of the "intragranitic" signature.

3.4.4 Volcanogenic Type

In the Kitts-Post Hill Belt, the uranium deposits confined to early Proterozoic Aillik Group (Labrador, Canada), claimed by Gandhi [47] as volcanogenic in a broad sense, also display many features of albitite-type. The hosting belt is generally separated from the Archean by tectonic sliding, while at its E-side, Archean rocks are prominently thrust upon the belt.

An interesting structural variant is represented by the deposits of the Shengyuan volcanic basin (Jiangxi, China). According to Wang et al. [48] these epigenic deposits occur above the base of the shallow nappe structure which placed the Upper Jurassic volcanic host above the pre-Devonian metamorphics.

3.5 Sediment-hosted Type

Section 2.2.2 (which related to thrusts reaching the Moho discontinuity) has shown that some deposits in Wyoming (U.S.A.) could be associated with thermal regimes triggered by sizeable thrusts.

The protores and/or low-grade U-sediments in the Shaba Copper Belt (Zaire) became used at the sites dominated by multiple Upper Proterozoic thrusting during the later epigenetic process (of perhaps enhanced temperatures) and have formed rich vein-type deposits at Shinkolobwe (Kasolo) and few other locations of this predominantly cupriferous province.

The Hamr deposit (Czechoslovakia), a very large accumulation of low grade uranium (and zirconium) ores, spreads through the base of the Upper Cretaceous sediments in the relative proximity of the sizeable Lužická porucha thrust which carries granites and Proterozoic basement above the Upper Cretaceous basin. The overturned Jurassic in the immediate footwall of the thrust is mineralized by Pb-Zn-Cu. At another place (Křižany) along this thrust, the upthrown basement block hosts: 1) in the parallel structure U and Ni-Co sulpharsenides, 2) in the younger oblique veins, mineable fluorite, and 3) in the youngest perpendicular joints with squeezed-in Cretaceous rubble a disseminated U. Inside the basin and only a few km away (across the fault) from Křižany occurs the Hamr U(Zr) deposit right above the sub-Upper Cretaceous unconformity. Although some other young faults displace the Hamr deposit by 500 m vertically (Scharm et al. [49]), its epigenetic emplacement (from the alkaline (?) basement sources) could have been supported by thermal cells triggered by earlier phases of thrusting.

The setting of the Křižany deposit within the upthrust basement block is broadly analogous to the situation at Wölsendorf (Bavary, West Germany) where the fluorite (+U) deposit (and other U-mineralized sites (from Altfalter up to Hauzenberg)) occur off the principal (Bavarian Quartz Lode) fault. The above mentioned Lužická porucha thrust at the Hamr deposit represents one of a wider set of regional reverse faults (NW-striking with downthrust sediments on SW) generated prior and during the Wernigerode disturbance at the end of the Upper Cretaceous. Those with larger vertical movements (most of those in Bavary at the SW periphery of the Bohemian Massif i.e. at Wölsendorf etc.), and especially at the crossings with other earlier (pre-basinal) regional systems, have a potential to generate and/or control transient thrust-bound thermal anomalies within the downfaulted sediments.

4. CONCLUSIONS

We have previously (1980) extended [27] one part of the source-transportation-precipitation tandem (STP) beyond its abstractive form also by using the thrust-bound fluid derivation of Fyfe [10]. We have considered this model to be of significance in uranium exploration for two reasons: first, it connects fluid transportation with an important metallotect critically missing in the STP-the structure; and second, by including this, we have moved one step ahead from the operationally less essential discussion of how the deposits were possibly formed to the more pragmatic question, where the deposits could be found.

Meanwhile, the work of uranium-oriented field geologists and of specialists from other geological disciplines allowed a further substantiation of the metallogenic potential of thrust-bound domains. This present paper yields the following observations:

1) Beyond the commonly perceived structural control, thrusts and their associated particular thermal regimes may be considered as a metallotect having a broader implication. They may tap deeper sources (mostly at the boundaries of differing crustal thickness and thermal signature), and here, or in other settings, guide, confine or collect fluids derived from the downfaulted lithologies. By these processes they are capable of also making productive such sequences which otherwise either were already or would remain barren.

2) In a common "atectonic" reading of maps, the granites are expected to dip away and the basement smoothly dipping under the neighbouring sediments. However, a good portion of an epigenetic mineralization rather avoids such a monotonous, though prevailing, configuration. Instead, inward-dipping granite contacts, basement faulted upon the basins boundaries, the basement slivers inside the basins, and the basinal outliers downfaulted into the basement are the

attractive structural complexities in particular regional tectonic settings, and many of them are initiated and/or dominated by thrusting, not by normal faulting.

3) For example, standing upon a "firm" crystalline basement, without an adequate geophysical survey we would rarely suspect that at depth, other downfaulted units might extend and that these provide fluids for the mineralization of and/or alteration of the upper plate, or that the downfaulted units themselves might even host the bulk of ore (Příbram). For example, among such situations the inward-dipping granite contacts constitute an important setting controlling deposits of differing classes: 1) albitite (Lagoa Real, Gunnar, Kitongo), 2) unconformity (Jabiluka, McClean), and 3) peribatholitic (Příbram, Chardon, Kowary). If the fluids further penetrate the granitic upper plate, the deposits may attain an intrabatholitic-type signature.

4) Our examples have also shown that thrusts and their associated processes are, if not a common, an abundant and operative factor in the formation and the location of uranium deposits, usually classified by other criteria in differing categories. We see in this a kinship in which distinct domains resulting in various types of deposits are unified by processes dominated by an important tectonic common control.

5) In a number of epigenetic deposits of other metals, classified (similarly as in uranium) by the traditional systems into various genetic types, thrusting attains an obviously unifying role among other metallotects participating in their formation.

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THE BLIND RIVER (ELLIOT LAKE) URANIUM DEPOSITS*

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Abstract

In the Blind River area Proterozoic sedimentary and minor volcanic rocks (Huronian Supergroup) uncomformably overlie and trangress northwards over dominantly granitic Archean terrane (2500 + Ma) and are intruded by Nipissing Diabase (2115 Ma). Later deformation and metamorphic events are recognized. The developing depositional basin was controlled by the incipient Great Lakes Tectonic Zone marginal to the Algoman Craton.

The Matinenda Formation (basal Huronian) comprises northwards-derived fluvial arkose, quartzite, and pyritic, uraniferous oligomictic conglomerate containing half of Canada's recoverable uranium resources. Production to December 1986 comprises 123,000 tonnes U (average recovered grade 0.093% U) and minor amounts of Th and Y. An additional 752 tonnes U were produced by leaching at Agnew Lake.

The conglomerate beds lie in southeasterly-striking zones controlled by basement topography down sedimentation from uraniferous Archean granite. Uraninite textures, monazite distribution, and local reworking indicate placer deposition. "Brannerite" formed by solution of uranium from uraninite grains and redeposition on titaniferous minerals. Some pyrite may be detrital, some authigenic and some introduced during mafic volcanic and intrusive activity. Kerogen in layers locally present at the top of conglomerate beds may represent algal mats which entrapped uraninite grains. Similar uraniferous deposits occur at Agnew Lake and in the basal Huronian north of Sudbury, where trace gold values reflect the local source area.

Drab-coloured rocks, uranium-sulphide mineralization, kerogen (thucholite) and a post-Archean regolith formed under reducing conditions suggest a reducing or low-oxygen atmosphere. In the upper Huronian, red beds, including monazite - iron oxide assemblages and local copper mineralization indicate oxidizing conditions.

Provenance, lack of complete oxidation, water transportation and deposition, diagenetic redistribution, and the lack of post-depositional

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destructive processes are the dominant factors in the formation and preservation of the ores. The modified placer theory of genesis for the deposits is widely accepted.

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1. INTRODUCTION

The Blind River uraniferous pyritic quartz pebble conglomerates were identified in 1949. Their commercial importance was realized in 1953. Between 1955 and December 1986, 123,000 tonnes U (average recovered grade 0.093% U) were produced.

The paper addresses the present knowledge of the deposits and draws on earlier papers, particularly Card et al [1], Frarey [2], Robertson, J.A. [3], Roscoe [4], which provide extensive references.

Robertson [3] was originally released in 1983 as open file report 5430 of the Ontario Geological Survey prior to publication 1986 in special volume 33 of the Canadian Institute of Mining and Metallurgy. The writer is endebted to both organizations for permission to use that material, in particular Figs. 1-14 and Tables I-IV in preparation of this review paper. These figures and Figs. 15 and 17 were prepared under the supervision of R. Balgalvis of the Ontario Geological Survey; the Manuscript and Fig. 16 were typed by Miss K Ryan of the Mineral Development and Lands Branch Ontario, Ministry of Northern Development and Mines.

The author is grateful to the many students, academics, staff of exploration and mining companies, federal and provincial government geologists who have contributed to the understanding and knowledge of the Blind River deposits since there discovery.

2. REGIONAL GEOLOGY

Blind River (Fig.1) lies on the North Shore of Lake Huron, halfway between Sudbury and Sault Ste. Marie. The town of Elliot Lake, built to service the uranium mines, lies 20 miles (32 kilometres) northeast of Blind River. Both names are used for the deposits.

The region lies on the boundary between the Southern and Superior Provinces of the Canadian Shield (Fig.2). The Superior Province (Goodwin et al [5]) comprises Archean rocks that were affected by the Kenoran Orogeny (2,600 Ma) and the Southern Province (Card et al [1]) includes Proterozoic rocks, the Huronian Supergroup affected by the Blezardian Oregeny with a metamorphic culmination at 1,920 Ma and the Penokean (?) orogeny with late orogenic granitic rocks at 1,750 Ma).

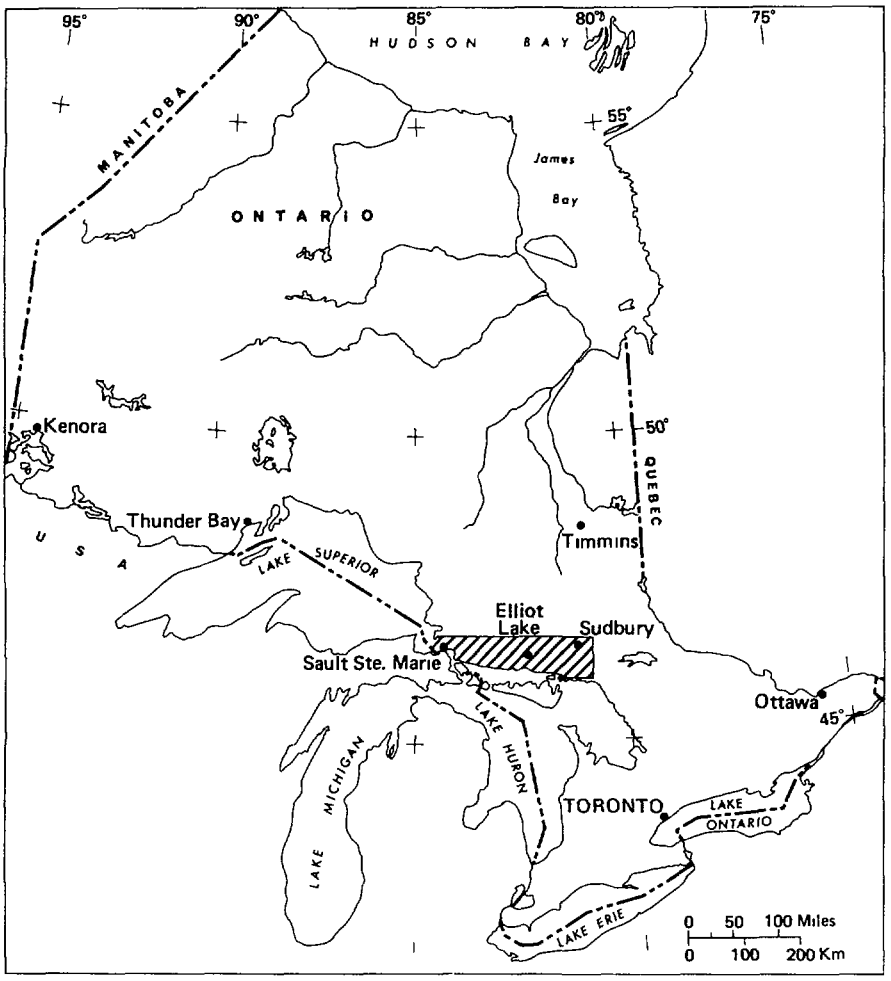

FIG. 1 Location of Blind River - Elliot Lake Area.

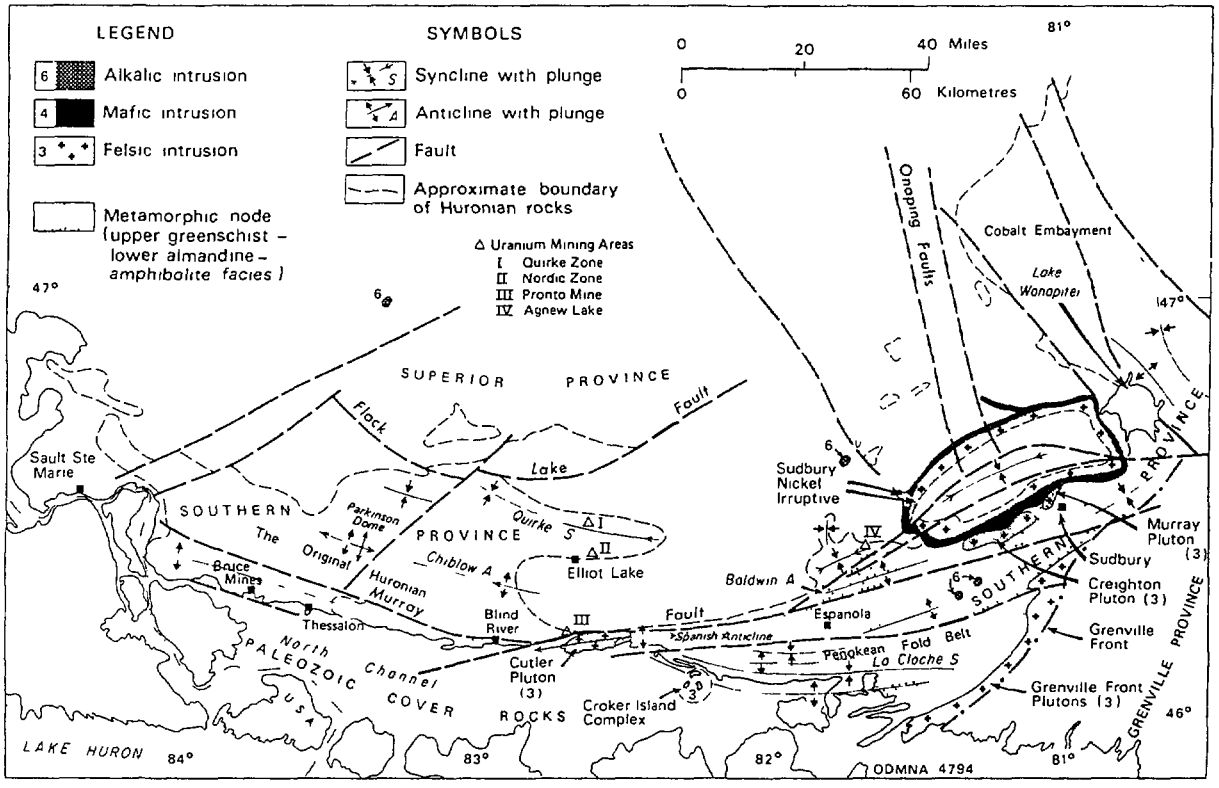

FIG. 2 Eastern Southern Province - Structural Elements and Uranium Mining Areas.

To the west, equivalents of the Huronian Supergroup have been recognized in Michigan (Cannon [6]) and in scattered areas of the Wyoming Province (Houston and Karlstrom [7]) (Fig. 8). To the east, the Huronian has been traced to Sudbury and Killarney (Card [8], Frarey [9]) and northeast to the Cobalt-Noranda area (Fig. 2) with possible equivalent in the Otish Mountains (Fig. 8). While uranium mineralization is known at several localities production has only been achieved in the Blind River-Elliot Lake camp including Agnew Lake.

Table I is a Table of Formations using the nomenclature recommended by the Federal-Provincial Committee on Huronian Stratigraphy (Robertson J.A., et al, [10]) and indicates the approximate ages of the rock units.

Table II provides a synopsis of stratigraphy and its relation to mineralization: uranium ore only occurs in the Matinenda Formation.

The bedrock of the area falls into three broad units. These are:

(1) the Archean basement, consisting of Keewatin-type greenstone, Algoman granite, and minor mafic intrusives,

(2) The Huronian Supergroup comprising meta-sedimentary rocks, with local mafic volcanics, and

(3) Post-Huronian intrusive rocks, comprising the Nipissing Diabase sills, post-Nipissing Diabase dykes, the Cutler Granite, the Croker Island Complex, and Late Precambrian olivine diabase.

In the Blind River area, the Huronian Supergroup has been gently folded into westward-plunging folds, and the metamorphic grade is low. To the southeast folding is severe and the metamorphic grade reaches the amphibolite facies; post-Huronian granite occurs locally (Card [8], Card et al [1], Robertson, J.A. [11]).

2.1 Archean (Early Precambrian)

The Archean of the Blind River area has been subdivided into: Keewatin-type metavolcanics and meta-sediments, including minor cherty iron formations; pink to grey gneissic granitic rocks with abundant inclusions of Keewatin-type rocks; and massive, moderately radioactive, red quartz-monzonite see (Fig.3). Airborne spectrometry has confirmed that much of the quartz-monzonite north and northwest of the Elliot Lake area contains anomalous amounts of uranium (Fig.4) (Richardson et al [12]). Charbonneau [13] has shown that these rocks actually contain about 4 times

TABLE I FORMATIONS FOR THE BLIND RIVER-ELLIOT LAKE AREA

Unit	Dominant lithology	Age (million years)
Phanerozoic		
Cenozoic		
Pleistocene and Recent	Sand, gravel, till	
	Unconformity	
Paleozoic		
Ordovician (20)[4]	Limestone	
Precambrian		
Proterozoic		
Keweenawan Supergroup		
Sudbury dikes (19)	Olivine diabase	1 225
	Intrusive contact	
Mount Lake Dike[1]	Quartz diabase	
Lamprophyre	Lamprophyre	1 385
Croker Island Complex (18)	Gabbro, granite	1 460
	Intrusive contact with Nipissing Diabase	
Hudsonian = Penokean		
Cutler Batholith	Granite	1 750
	Intrusive contact	
Blezardian		
Nipissing (17)	Quartz diabase, diorite	2 115
	Intrusive Contact	
Murray-Creighton[2]	Granite	2 165
	Intrusive contact	
Huronian Supergroup		
Cobalt Group		
Bar River (16)	Quartzite	
Gordon Lake (15)	Siltstone, sandstone	
Lorrain (14)	Quartzite, conglomerate arkose	
Gowganda (13)	Conglomerate, greywacke, quartzite	
	Unconformity-disconformity	
Quirke Lake Group		
Serpent (12)	Quartzite	
Espanola (11)	Limestone, siltstone	
Bruce (11)	Conglomerate	
	Local disconformity	
Hough Lake Group		
Mississagi (10)	Quartzite	
Pecors (9)	Argillite	
Ramsay Lake (8)	Conglomerate	
	Local disconformity	
Elliot Lake Group[3]		
McKim (7)	Argillite	
Matinenda (5)	Quartzite, with or without uranium-conglomerate Conglomerate Arkose, with or without uranium-conglomerate	
Thessalon-Dollyberry Lake[3]	Mafic volcanics, minor felsic volcanics, sedimentary rocks	
Livingstone Creek	Quartzite, minor conglomerate	
	Unconformity	
Archean	Regolith	
Late Archean intrusives	Diabase, gabbro-anorthosite	2 500 (?)
	Intrusive contact	
Kenoran (Algoman) (3)	Granite	2 600+
	Intrusive contact	
Early Archean intrusives	Gabbro	
	Intrusive contact	
Keewatin (1)	Volcanic and sedimentary	

1 Mount Lake Dike may be 1795 m.y. old, relationship to lamprophyre not known.

2 There are no Murray-Creighton Granitic Rocks represented in the Elliot Lake area, however, age determinations provide a closer upper limit on the Huronian Supergroup than those from the Nipissing Diabase.

3 Volcanic rocks are found locally in the Elliot Lake Group (6); each occurrence has been given its own name; age about 2400 m.y. Units to south and east may be distinct from the Thessalon-Dollyberry Formations, and related to gabbro-anorthosite intrusions.

4 Codes keyed to fig. 2 are in parentheses, Geologic ages given are from a variety of sources, recalculated Stockwell [22]

TABLE II SUMMARY OF HURONIAN STRATIGRAPHY IN THE BLIND RIVER-ELLIOT LAKE AREA.[1]

Group	Formation	Lithology	Thickness (in feet)[2,3]	Depositional Environment[3]	Source	Mineralization
Cobalt	Bar River	Quartzite	At least 1 000 — Flack Lake; at least 4 000 — Willisville	Coastal—beach	Source north but currents variable	
	Gordon Lake	Siltstone, sandstone	1 000 — Flack Lake; 3 000 — Willisville	Tidal flat		
	Lorrain	Quartzite, conglomerate, arkose	2 000 — 6 000	Fluvial to near shore	North-northwest	Th (U)[4] in north Cu
	Gowganda	Conglomerate, greywacke, quartzite, siltstone	500 — 4 200	Glacial in north; glacial-marine in south	North-northwest	
Quirke Lake	Serpent	Quartzite	0 — 1 100	Fluvial	Northwest	
	Espanola	Limestone, dolostone, siltstone	0 — 1500	Fluvial, lagoonal—marine	Northwest	U trace in Victoria Tp. Cu in limestone against diabase
	Bruce	Conglomerate	0 — 200	Glacial, glacial-marine	North?	
Hough Lake	Mississagi	Quartzite	0 — 3 000+	Fluvial—shallow marine	West-northwest in west; north in southeast	U-Th near basement highs
	Pecors	Argillite	40 — 1 000+	Shallow water—turbidite	North-northwest	Traces U near basement highs
	Ramsay Lake	Conglomerate	5 — 200	Glacial—glacial-marine	Northwest?	Traces U where unconformable on Matinenda Formation
Elliot Lake	McKim	Argillite—greywacke	0 — 2 500+	Shallow water, turbidite to S.E.	Northwest	Traces U near basement highs
	Matinenda	Quartzite, arkose, conglomerate	0 — 700+	Fluvial—deltaic	Northwest	U-Th-Rare Earths in conglomerate in basement lows [5]
	Volcanic rocks	Andesite—basalt (felsic volcanic rocks)	Local piles	Subaerial	Flack Lake F. Murray F.	U-Th in conglomerate interbeds
	Livingstone Creek	Subarkose, conglomerate	0 — 1 000+	Fluvial	Unknown?	

[1] Table from Robertson [3]

[2] To convert to metres, multiply by 0.3048

[3] Deeper water facies are found in the Espanola wedge to the S.E.

[4] Abbreviations: Cu — Copper, Th — Thorium, U — Uranium, F — Fault

[5] All U-deposits of commercial importance in the Blind River-Elliot Lake area are in the Matinenda Formation.

the ground equivalent uranium content as derived from the airborne data. Rb-Sr isotope studies show that these red granitic rocks are little contaminated by pre-existing crustal rocks.

The Montreal River-Lake Superior area some 300 km northwest of Blind River is characterized by low-grade uraniferous Archean pegmatites and by Late Precambrian pitchblende occurrences, typically adjacent to northwest-trending diabase dykes.

After the Early Precambrian (Kenoran) orogeny, the area was peneplaned and local topography was controlled by basement lithology and structure.

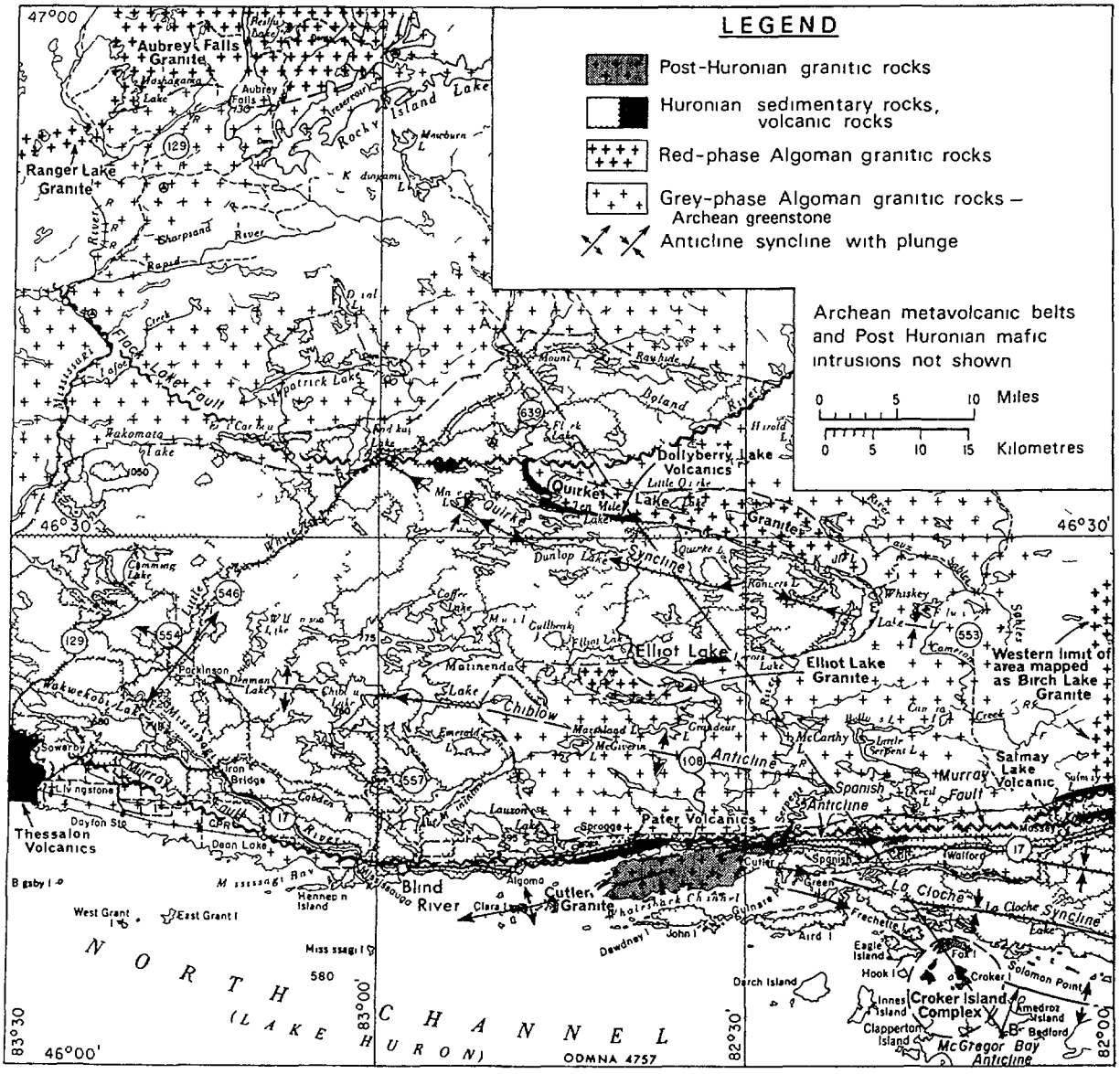

FIG. 3 Generalized Geologic Map of the Blind River-Elliot Lake Area, with Schematic Cross-Section.

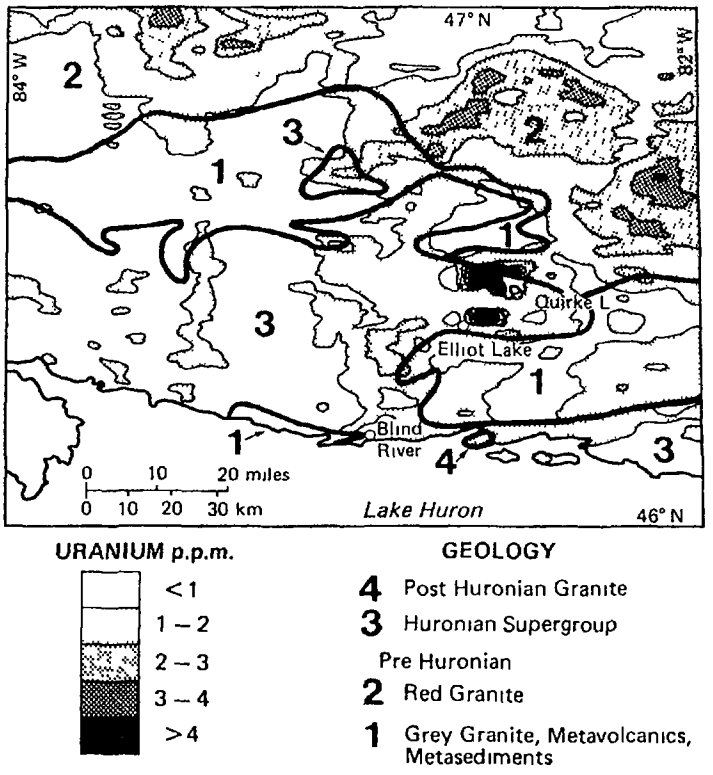

FIG. 4 Uranium Distribution in the Blind River Area (Airborne Gamma-ray Spectrometry after Richardson, Killeen and Charbonneau, [12]). The two areas with anomalies >4ppm are the areas in which tailings from the mining operations are stored.

Throughout the Blind River area partially weathered zones (regolith or palaeosol)[1] have been preserved under the Huronian-Archean unconformity and, particularly, over the granitic rocks, but also volcanic rocks. The granitic regolith comprises quartz, microcline, and sericite with a preserved granitic texture gradational to unweathered granite.

The salient features are (1) the destruction of the plagioclase and the removal of the soluble constituents, (2) the stability of the potassic feldspars (microcline), and (3) the formation of hydrated clay minerals represented by sericite. Chemically Ca and Na have been removed, total Fe has been reduced with ferric in preference to ferrous. Uranium has been slightly reduced. Thorium and Zirconium are slightly increased (Pienaar [14], Robertson, J. [15].

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[1] Grandstaff et al gave a useful list of criteria for identification of Paleosols in "Chemistry and Mineralogy of Precambrian Paleosols at the base of the Dominion and Pongola Groups (Transvaal South Africa)" Grandstaff, E.E., Edelman, M.J., Foster, R.W., Zbinden, E., and Kimberley, M.M., Precambrian Research 32 (1986) 97-131.

As regolithic material contributed to the formation of the uraniferous, pyritiferous, oligomictic conglomerates of the basal Lower Huronian, the presence in the regolith of FeO (ferrous iron) and the persistence of uranium normally soluble in an oxidizing environment are of interest, whatever the cause of reduction.

2.2 Proterozoic (Middle and Upper Precambrian)

2.2.1 Huronian Supergroup (Tables I, II, Figs. 3, 5)

The Huronian Supergroup unconformably overlies the Archean rocks and comprises thick sequences of clastic sediments and minor tholeiitic basalts. The sediments were derived from the Archean Craton to the northwest and were deposited as migrating diachronous facies with cyclical rejuvenation. The Huronian is subdivided into four groups, an initial eugeosynclinal group , the Elliot Lake Group, with volcanics and turbidites as well as the uranium bearing quartz-pebble conglomerate - arkose sequences, at the margin of the developing Great Lakes Tectonic Zone (Sims et al [16]); two groups , the Hough Lake Group and the Quirke Lake Group, each representing a cycle initiated by tillite and followed by coarsening upward sequences; and a fourth group , the Cobalt Group, which represents a third cycle followed by an upper sequence of beach and tidal fluvial deposits. In the Cobalt Group characterised by red beds there is evidence of post-depositional solution and migration of iron and trace amounts of uranium.

The depositional basin extended east-west and deepened towards the southeast. The distribution of volcanic rocks and marked changes in thickness and facies of sedimentary units were controlled by hinge zones, which later became regional fault zones. Minor changes in composition of similar rock types are due to shifts in provenance and to the efficacy of weathering and winnowing processes. Radioactivity and heavy minerals are characteristic of quartz-pebble conglomerates in the fluviatile near-shore facies. In the lower Huronian the association is of uranium and sulphides, predominantly pyrite, and in the upper Huronian it is of thorium and iron oxides.

Glacial deposits are characteristic of the lower and middle Huronian (Robertson [17] , Young [18], Miall [19]) while the uppermost Huronian comprising beach, tidal flat and fluvial deposits was apparently deposited in a dry and hot environment. Figure 6 shows the variation in maturity of the paraconglomerate matrices, which decreases towards the Gowganda Formation, the marked increase in soda, and in the lower part of the

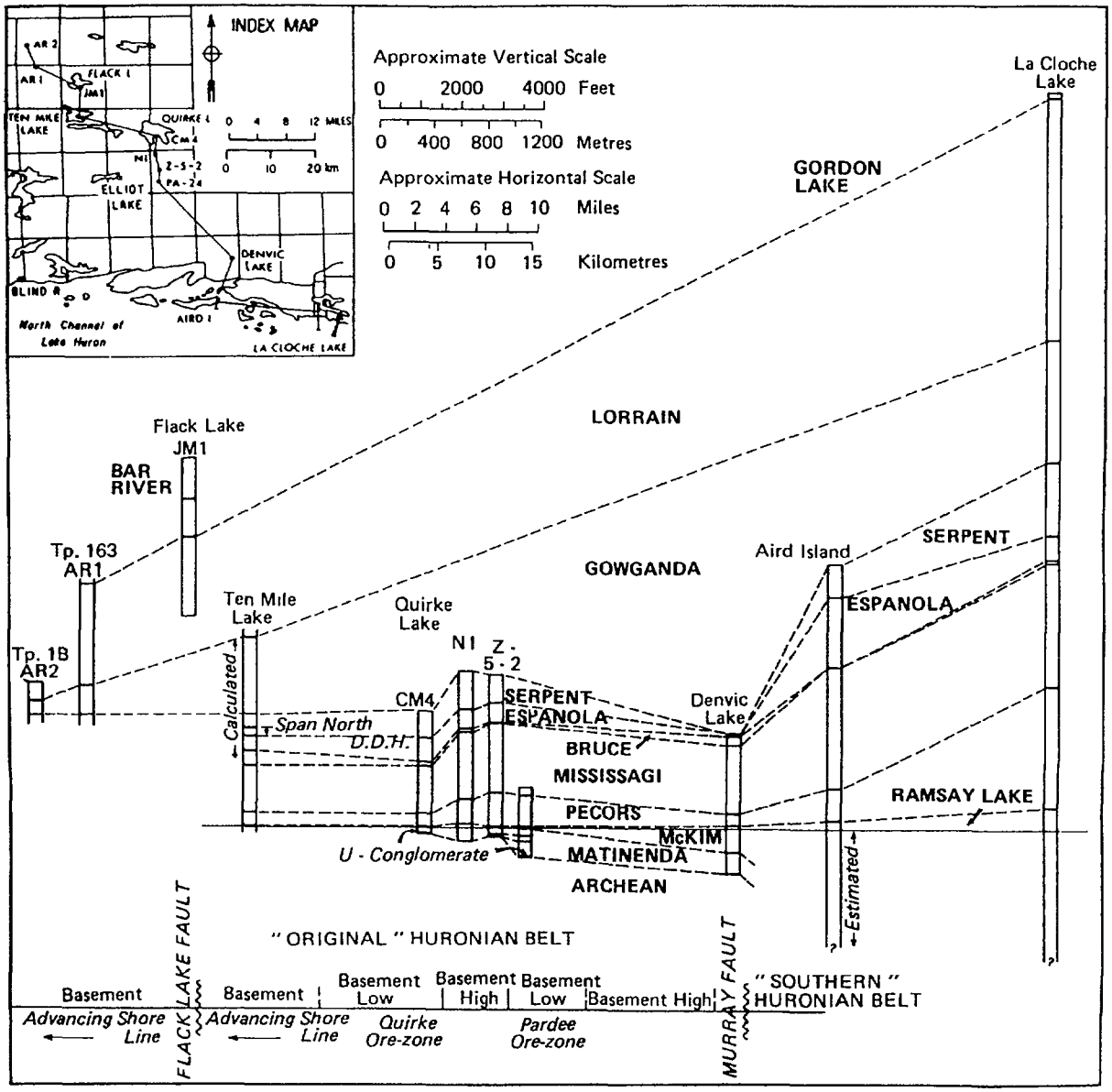

FIG. 5 Lateral Variation of the Huronian Supergroup, Elliot Lake Area.

paraconglomerate sequences, the incorporation of potassic material from the underlying arenite. Figure 7 shows an increase up stratigraphy in ferric/ferrous iron ratio in the argillaceous rocks, reflecting change in general oxidation conditions; an increase in the SiO_2/Al_2O_3 ratio, reflecting increased efficacy of chemical weathering in the upper Huronian; and variations in the Na_2O/K_2O ratio, reflecting changes in provenance from a granitic to a granodioritic-greenstone terrane. The arenaceous rocks show similar changes in provenance and efficacy of chemical weathering. The role of oxidation is apparent in the frequency of red beds from the Gowganda Formation upwards contrasted to the total lack of red beds in the lower formations the preservation of iron oxides and of red granite clasts.

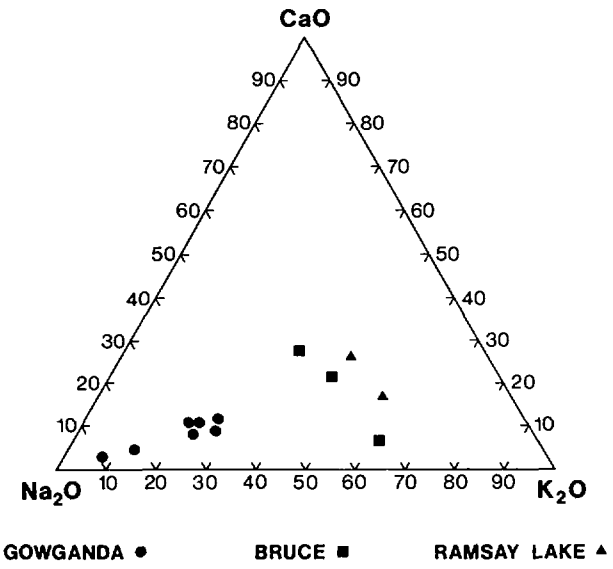

FIG. 6 Alkali Content, Huronian Polymictic Conglomerates.

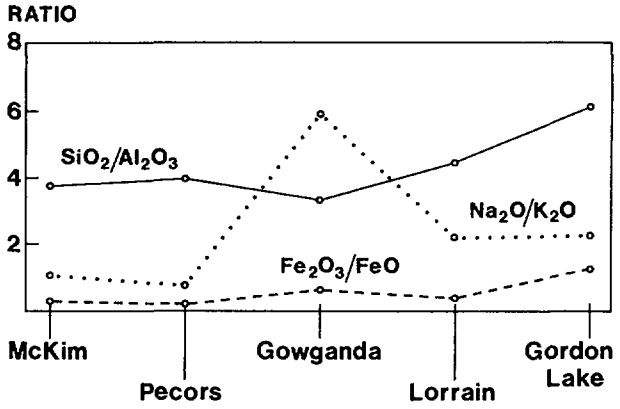

FIG. 7 Silica/Alumina, Ferric Iron/Ferrous Iron and Soda/Potash Ratios for Huronian Argillaceous Rocks.

Roscoe [20] placed the oxyatmoversion point within the Gowganda Formation. J. A. Robertson [17] pointed out that the Huronian bears evidence of free oxygen at least as early as the Espanola Formation and Dimroth and Kimberley [21] would place free oxygen (at very low levels) at least as far back as the Archean.

2.2.2 Post Huronian Events

The North Shore of Lake Huron has been subjected to a long history of Middle and Late Precambrian structural deformation, igneous and metamorphic events. These are summarized below and the principal elements are shown on Fig. 2:

1) Vulcanism and early tectonism accompanied the deposition of the Huronian;

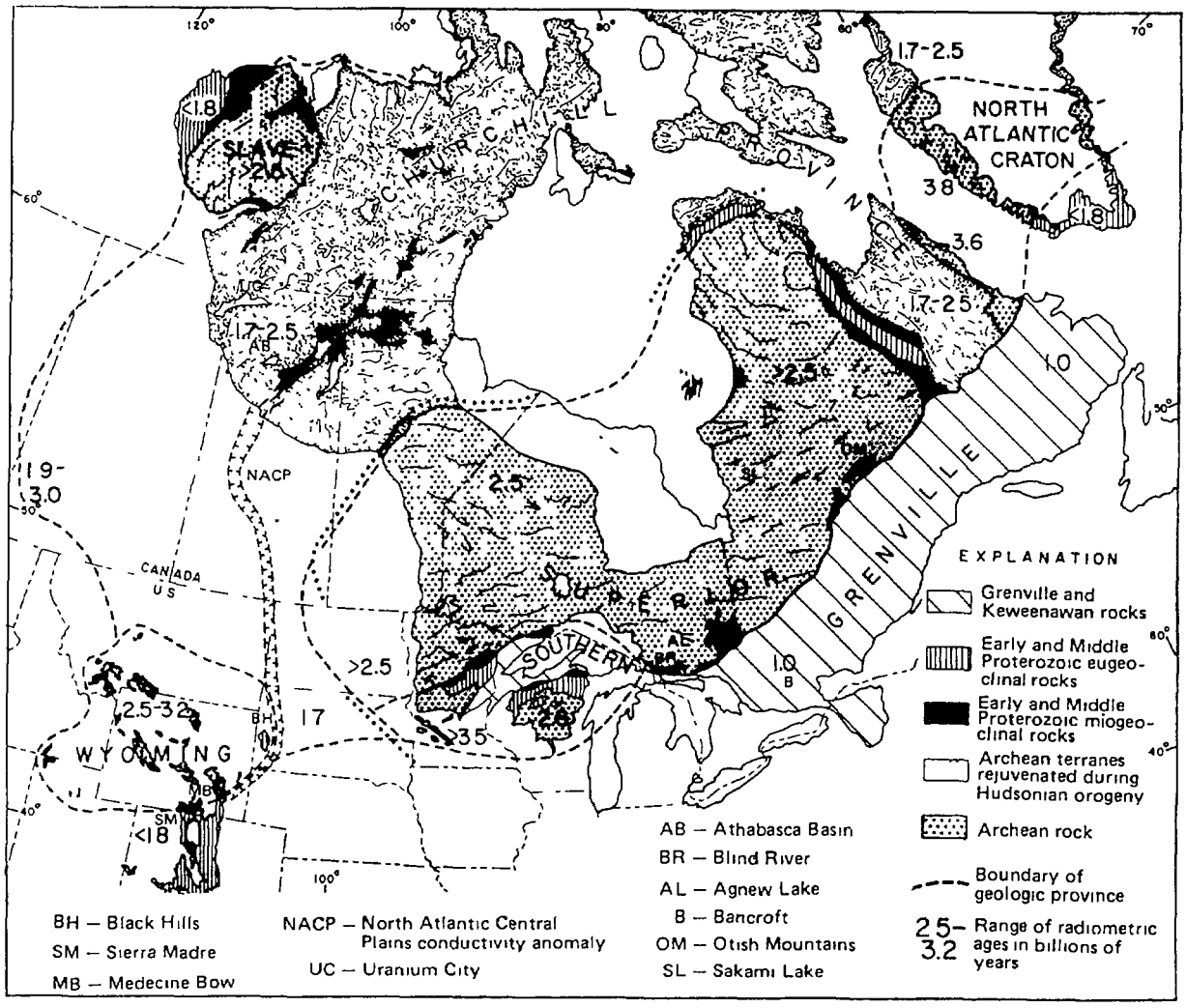

FIG. 8 Geology of the Archean Nucleus of North America (After Houston and Karlstrom [7]).

2) A period of mild metamorphism and deformation and intrusion of granitic rocks near Sudbury preceded the Nipissing diabase (Robertson, J.A. [11] and constitutes Stockwell's [22] Blezardian event;

3) Intrusion of the Nipissing Diabase 2115 Ma;

4) The Sudbury event - intrusion of the Sudbury nickel irruptive possible triggered by meteorite impact; (Pye et al [23]).

5) Deformation and metamorphism locally attaining amphibolite facies, of the Penokean (Hudsonian) Orogeny peaking at about 1900 Ma; followed by

6) Late orogenic granite intrusion (the Cutler 1750 Ma and Grenville Front granites)

7) Various post orogenic felsic and mafic intrusions.

Late Precambrian diabase dykes intruded radioactive Archean granite remobilized uranium resulting in small pitchblende deposits particularly in the Theano Pt.-Montreal River area north of Sault Ste. Marie (Robertson, J.A. [24]) approximating to the source area for the Huronian as postulated by McDowell [25].

These post-Huronian events had no genetic relationship to the Blind River uranium deposits. Dating of the Murray-Creighton granite at Sudbury further defines a minimum age of the Huronian as 2165 Ma (Stockwell [22].

Alteration (albitization, chloritization, and carbonatization) associated with Nipissing diabase dykes or sills has locally affected the pre-existing uranium deposits, (Robertson, J.A. [26, 27]. Deformation and metamorphism of that part of the Blind River area in which uranium ores are found have been minimal and this has been a factor in the preservation of the ore bodies. Age data on minerals, reflects some resetting of the decay clocks at times corresponding to known peaks of regional metamorphism or thermal events rather than episodic introduction of more uranium (Roscoe [4].

3. THE URANIUM DEPOSITS

Uranium and thorium-uranium deposits are found in conglomerates at a number of localities in the Blind River-Elliot Lake and Agnew Lake areas, as well as throughout the Huronian belt (Robertson, J.A. and Gould [28, 29]). Similar mineralization has been discovered (Fig. 9) in the Black Hills of South Dakota and in the Medicine Bow and Sierra Madre Mountains of Wyoming (Houston and Karlstrom [7], Roscoe [30]). In Canada deposits at Sakami Lake, Otish Mountains and Montgomery Lake, (Robertson, D. [31], Roscoe [30]) also bear similarities in style and setting to the Blind River deposits. The studies on the Rand, Blind River and Jacobina (Brazil) have formed the basis for definition of the uranium (gold) bearing quartz-pebble conglomerate class of ore deposits. The most significant recent publications with extensive bibliographies are: Armstrong [32], Button and Adams [33], Houston and Karlstrom [7], Pretorius [34] and Robertson, J. A. [3].

3.1 Distribution of Uranium Ore Deposits

3.1.1 Blind River - Elliot Lake

The workable uranium deposits of the Blind River camp are found as uraniferous quartz-pebble pyritic conglomerate interbedded with conglomeratic to barren arkosic quartzite beds in zones controlled by basement

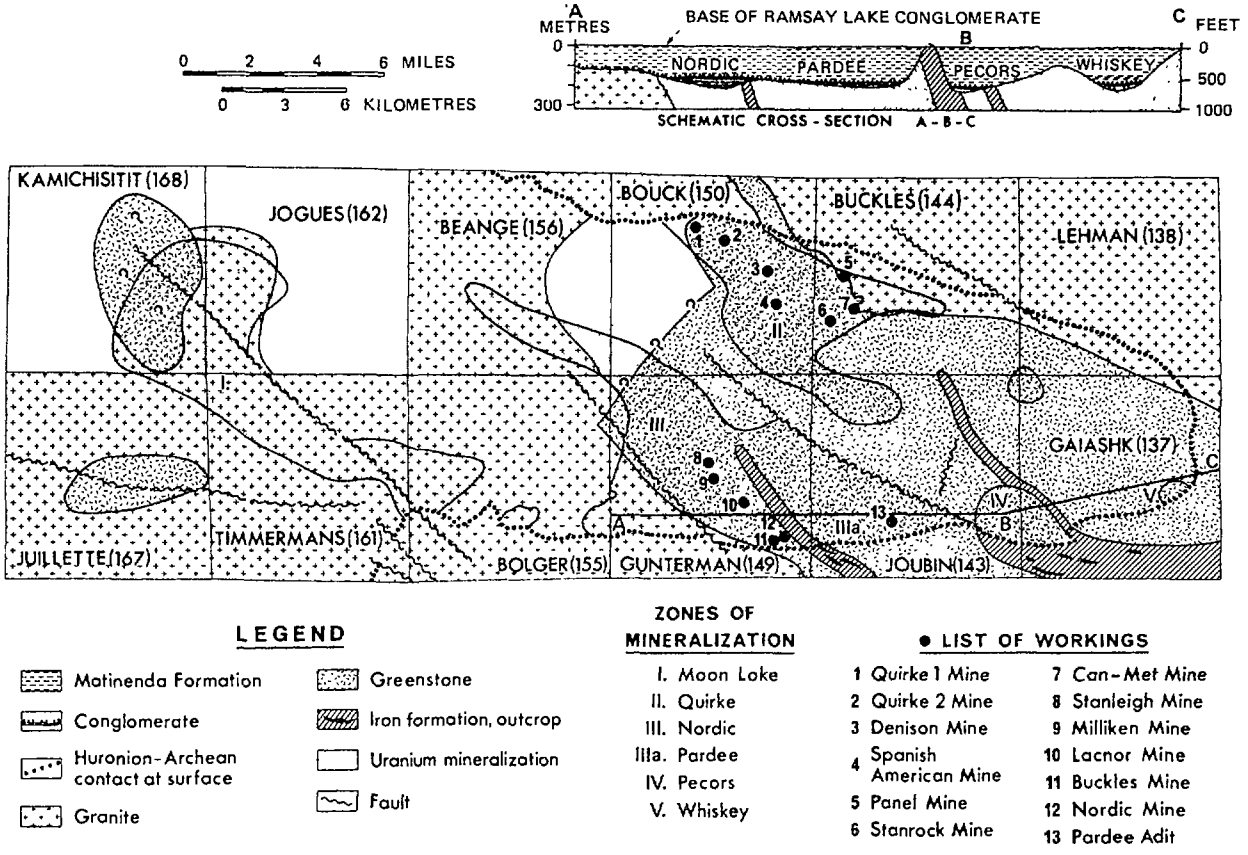

FIG. 9 Uranium Deposits in Quirke Syncline - Elliot Lake Area. In the blank areas the presence of Huronian Volcanics obscures the Pre-Huronian.

topography (Figs. 4,9,15). Such zones are characterized by thicker and coarser yellow green weathering arkose, often showing scour and fill structures, cross-bedding and fining upward cycles. Pyritic quartz-pebble bands and lenses are present in the lower part of the sequence. These arkosic sequences have enhanced U, Th, and K as well as U:Th ratio as compared to the Matinenda Formation in less favourable areas and can be identified by reconnaissance scale airborne radiometric surveys.

Sedimentation studies have further documented the fluvial features of the conglomerates, arkoses and sandstones of the Huronian, particularly the lower part of the Matinenda Formation (Fralick & Miall [35]). In the Quirke Syncline the relation of the uraniferous conglomerates to granite-greenstone contact areas and valleys over softer zones in the greenstone belt is clearly demonstrated (Fig. 9) The Pronto deposit is located on granitic basement on the flank of a regional basement high.

The ore zones strike northwest-southeast and are controlled by basement topography. The Quirke zone (the largest in the area) is 32,000 ft. (9,600 m) long and from 6,000 ft. (1,800 m) to 9,000 ft.(5,700 m) long and

from 4,400 ft. (1,320 m) to 6,000 ft. (1,800 m) wide (Robertson, J.A. [26]). The Pronto deposit (Robertson, J.A. [27]) and the unworked zones are of smaller dimensions.

At Quirke No. 1 the main ore reef is approximately 30 m (100 ft.) above basement and is approximately 3.5 m (12 ft.) thick. Toward the east the ore zone is truncated by an unconformity at the base of the Ramsay Lake conglomerate. At Quirke No. 2 (Fig. 10) the Dension (Fig. 11), the best ore development is in the Denison Reef some 30m (100 ft.) below the Quirke Reef. The Denison Reef normally comprises two conglomerate zones each 1.8 to 3.6 m (6 to 12 ft.) thick separated by barren arkose 0.6 to 2.4 m (2 to 8 ft.) thick. Other conglomerate beds 0.6 to 3 m (2 to 10 ft.) thick separated by quartzite beds 3.6 to 6 m (12 to 20 ft.) thick are known on both the Quirke and Denison properties. At Stanrock Mine another reef was found under the Denison Reef in the southeastern part of the mine. The en-echelon pattern with the oldest reef to the southeast conforms to the regional overlap pattern. Table III shows the reef nomenclatures used in the mines of the Quirke zone.

Table IV shows the nomenclatures used for the reefs on the South Limb. At the Nordic Mine the main ore bed comprised conglomerate or conglomerate with quartzite over a width of 3 m (10 ft.) with a grade of 2.5 lbs U_3O_8 per short ton (1.25 kg per tonne). Locally another reef lower in the sequence, the Lacnor Reef, was mined where grade attained 2.0 lbs U_3O_8 per short ton (1 kg per tonne). In the eastern part of the mine a third reef, the Pardee Reef, attains ore grade, 2.3 lbs U_3O_8 per short ton (1.15 kg per tonne) over 5 ft. (1.5 m).

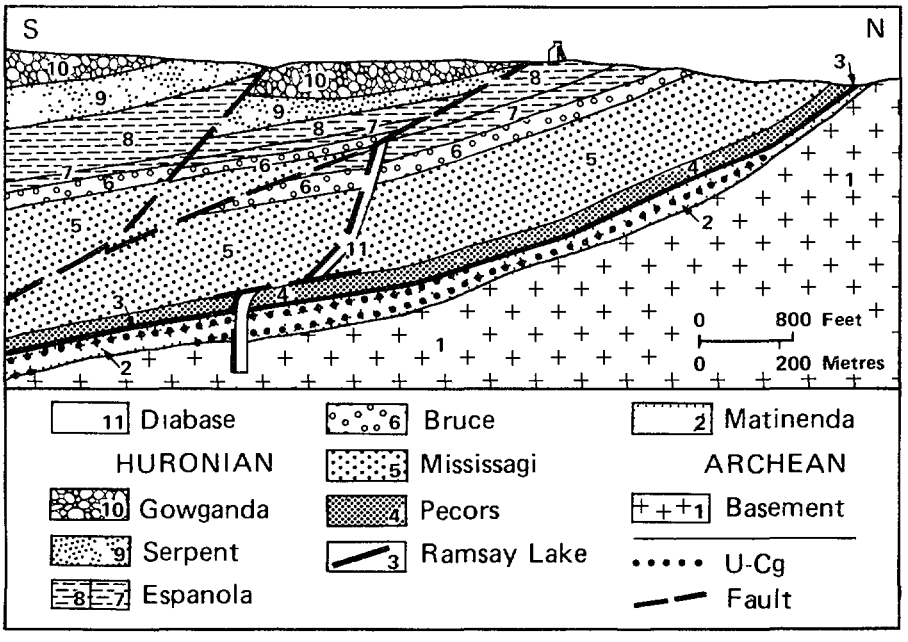

FIG. 10 Cross-section - New Quirke Mine (After Rio Algom Ltd.).

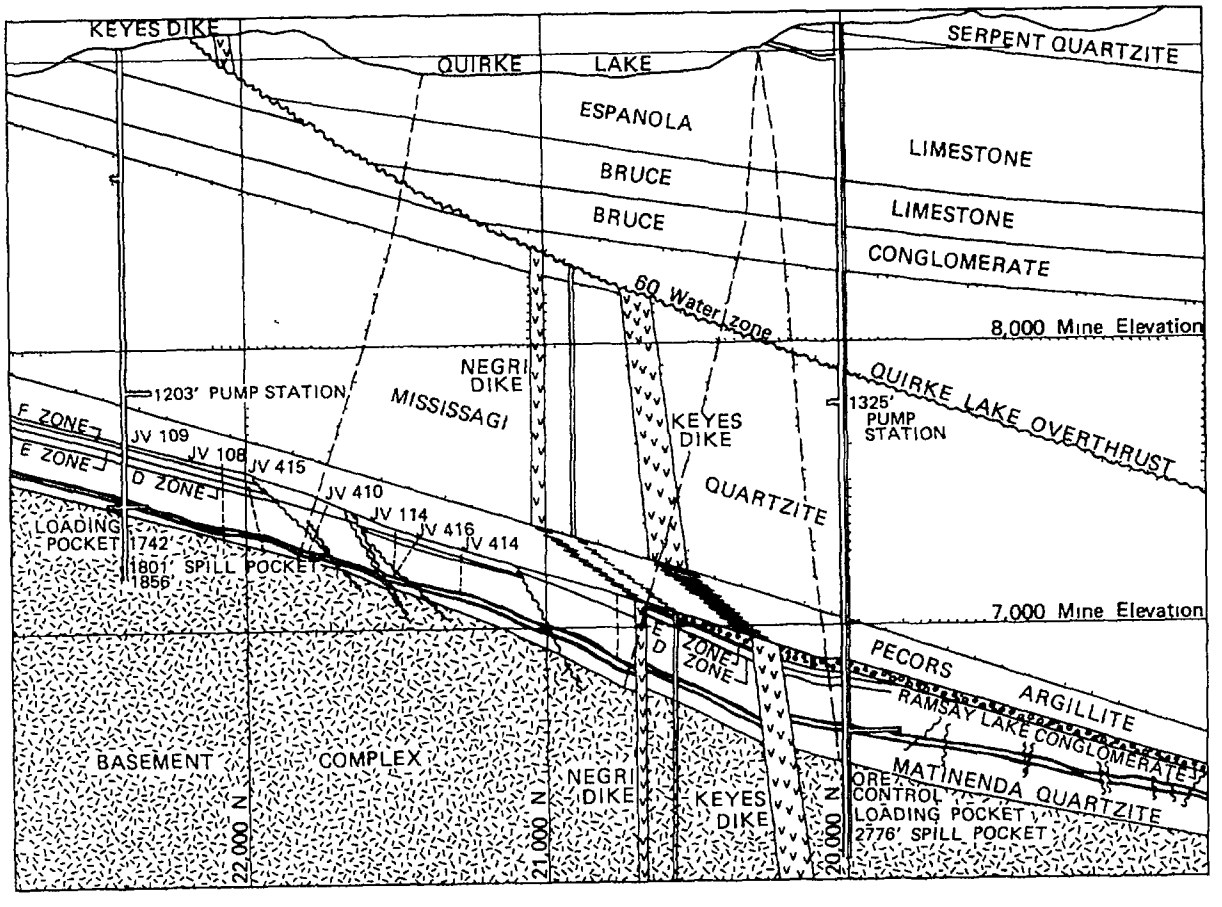

FIG. 11 Cross-section - Denison Mine (After Denison Mines Ltd.).

TABLE III CORRELATION OF QUARTZ PEBBLE CONGLOMERATE REEFS, QUIRKE ZONE [1]

QUIRKE 1 & 2 Rio Algom Ltd	DENISON Denison Mines Ltd	STANROCK Denison Mines Ltd
Ramsay Lake Formation	Ramsay Lake Formation	
Quartzite	Quartzite	
Upper[2]	F	
Quartzite	Quartzite	
A(Quirke 1)	E	
Quartzite	Quartzite	
B	D	
Quartzite	Quartzite	
C L	Floater reef(s) ----?	
Quartzite	Quartzite	
C(Quirke 2)	A	A_1 / Quartzite / A_2
		A_1 / Quartzite
		St_1
	I Q (Interbedded quartzite)	Quartzite
	B	St_2 / Quartzite
		St_3 / Quartzite
Quartzite	Quartzite	
FWC (Scraps)	Scraps	
Quartzite	Quartzite	
Basement	Basement	Basement

[1] Modified from Robertson [3]

[2] Underlined beds have given rise to production

TABLE IV CORRELATION OF SOUTH LIMB REEF TERMINOLOGY (RIO ALGOM LTD)

Stanleigh	Stanleigh	Milliken	Lacnor	Nordic
1961-present	1955-1961			
Upper	Upper	Pardee	Pardee	Pardee
Main	Lower	Upper	Upper	Nordic
Lower	Upper Footwall	Lower	Lower	Lower[2]

[1] Modified from Robertson [3]

[2] The names Basal Reef and Lacnor Reef have also been used for this reef.

This reef extends eastward over a basement ridge into the Pardee and Pecors mineralized zones (Fig. 9). These reefs extend down rake to the Stanleigh Mine where original operations were largely carried out over the Lacnor and Nordic Reefs.

Ore reefs at Stanleigh are currently named lower, middle and upper, (Table IV) (Fig. 12). Resources are primarily in the middle and upper reefs whereas original mining operations were carried out in the middle and lower reefs. As with the Quirke zone, other reefs of conglomerate of submarginal grade (which locally may average 1 lb U_3O_8/5.0 feet) or minor extent are known.

Five types of boundary (Figs. 9,10,11,15) to the ore beds are known:

1. Outcrop of the conglomerate bed.
2. Wedging due to contact with either regional local basement "highs". To the west of Quirke No. 1 the "basement" may be the edge of a pile of Huronian volcanics rather than Archean.
3. Lateral thinning of conglomerate and thickening of the intervening quartzite beds accompanied by drop in grade of the radioactive units. This is probably the typical boundary and the definition is arbitrary.
4. Removal by erosion subsequent to deposition, as for example in Quirke, Denison, and Panel, where there is an unconformity at the base of the Ramsay Lake Conglomerate. Where the Matinenda Formation has been incorporated into the Ramsay Lake conglomerate, the latter contains anomalous but minor amounts of uranium mineralization.
5. Fault contact. Locally, areas were not mined either because of unfavourable mining conditions caused by faults, extensive fracturing, or diabase dykes or because of unfavourable milling conditions caused by albite, chlorite, or carbonate alteration.

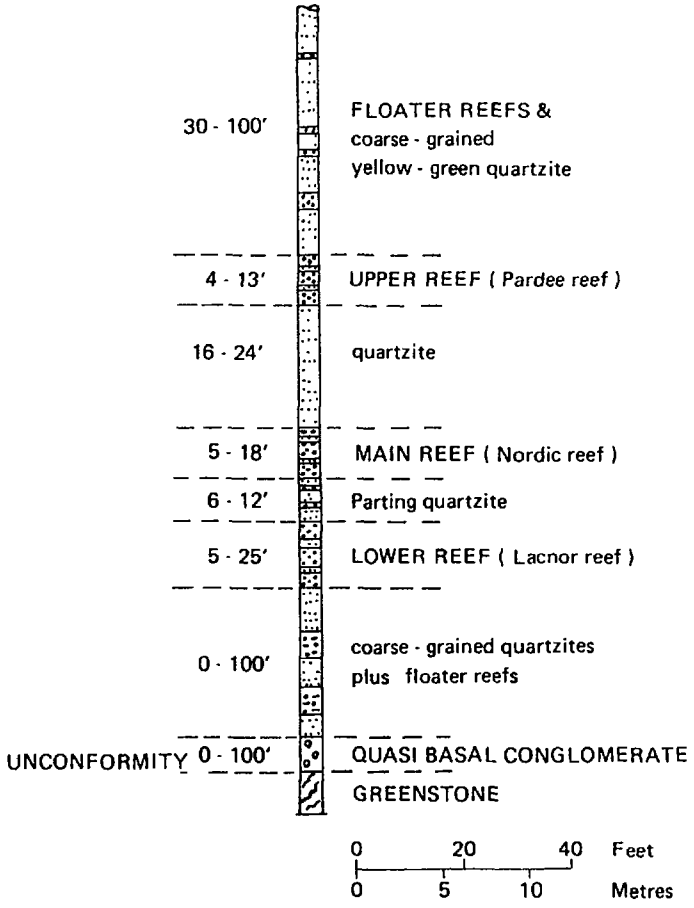

FIG. 12 Diagramatic Section of Ore Zone South Limb (Rio Algom Ltd.).

3.1.2 Agnew Lake Area

Stratiform uranium deposits in basal Huronian rocks also occur at Agnew Lake (see Figs. 2, 13, 14). At the Agnew Lake deposit (Wilton, [36]) the ore comprises gritty oligomictic conglomerate interbedded with arkose in a metamorphosed quartzite-argillite-conglomerate sequence which is probably equivalent to the Matinenda Formation of the Elliot Lake area. Pebbles at Agnew Lake are smaller and sparser, and pyrite is less conspicuous. The ratio of thorium to uranium is generally higher than at Elliot Lake reflecting the presence of substantial uranothorite and monazite. Post-Huronian deformation has been considerably greater, resulting in steeper dips, more pronounced cleavage, and stretching of pebbles.

3.1.3 Cobalt Embayment

That part of the Southern Province lying north of Sudbury is known as the Cobalt Embayment (Figs. 2, 14) Lower Huronian rocks are intermittently exposed in the southern portion of the Cobalt Embayment but are largely concealed by Nipissing Diabase and upper Huronian rocks. The regional geology has been discussed by Meyn

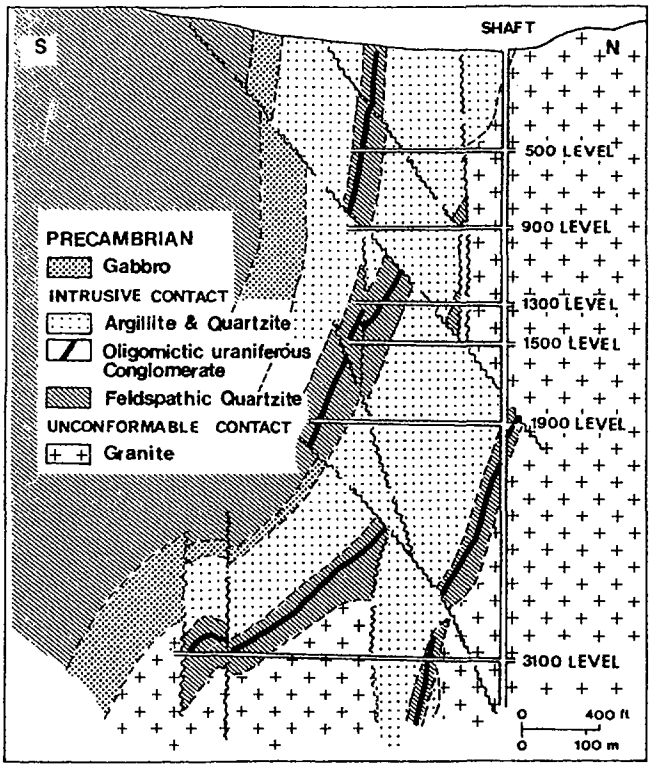

FIG. 13 Cross-section - Agnew Lake Mines Limited (After D. S. Robertson [31]).

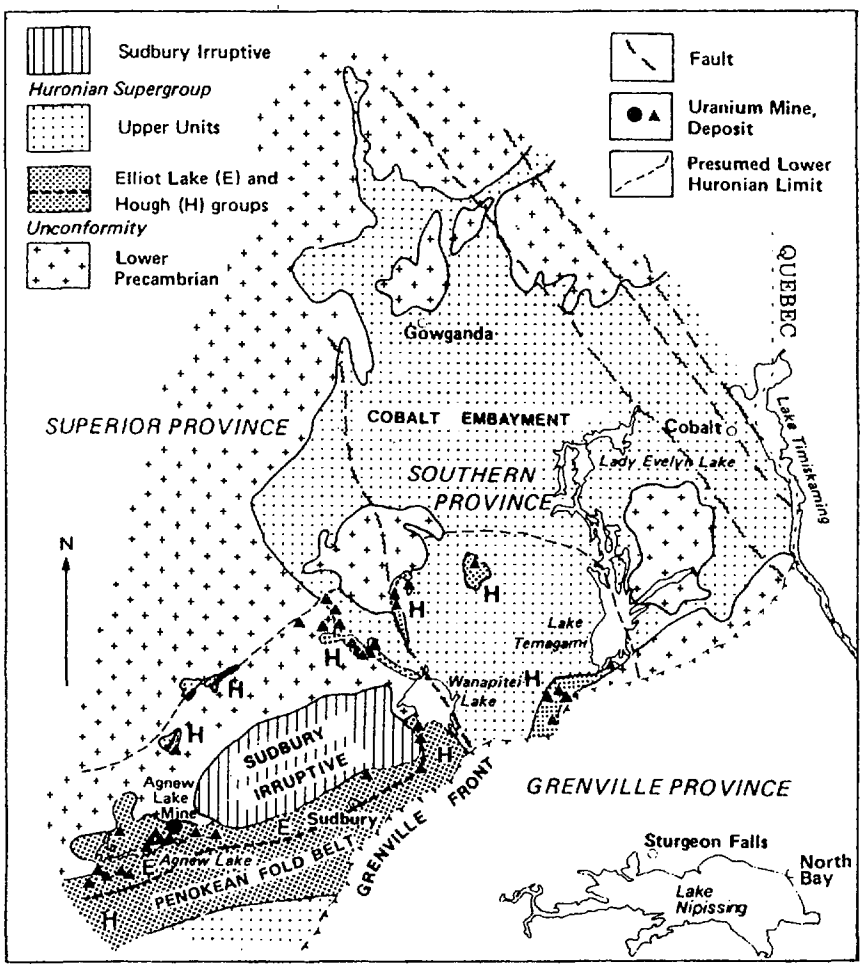

FIG. 14 Uranium Deposits - Cobalt Embayment and Agnew Lake Areas.

[37] and Meyn and Matthews [38]. Precise stratigraphic correlation of the lowermost stratigraphic units with Blind River is unclear, but rocks equivalent to the Mississagi and younger formations are present. In the lowermost units, wherever exposed, there are anomalous concentrations of uranium (Fig.14) and, at some localities, gold and uranium in conglomerates and uranium in argillaceous quartzites. Meyn and Matthews reported the uraniferous minerals as "brannerite", uraninite and coffinite. They suggested a fluviatile environment (braided stream) but indicated some of the uranium could have been transported in solution. The deposits were modified by later events.

Traces of gold have also been found in upper Huronian fluvial sandstones (Long and Colvine [39]). The provenance for the eastern Huronian includes the auriferous greenstone belts of the Abitibi sub-province.

3.2 Lithology and Mineralogy of Uranium Ore Deposits

The typical ore-bearing conglomerates of the Matinenda Formation consist of well-rounded, well-sorted quartz pebbles or cobbles in a matrix of quartz, feldspar, and sericite and have a pyrite content of 6-10 per cent. Monazite and ziron are characteristic heavy minerals. "Brannerite" and uraninite are found in the matrix. Thucholite (kerogen) is found as disseminations and locally as thin beds and thucholite may occur in fissures in the ore beds. The ore minerals are "brannerite", uraninite, and monazite.

Thucholite (kerogen) is present in the ore but is also in fractures as a post-ore secondary mineral. The interest in hydrocarbon at the Rand (Hallbauer [40, 41], Pretorius [42, 43, 34]) prompted Ruzicka (Ruzicka and Steacy [44], Ruzicka [45]) to initiate comparative studies on Blind River material.

Gummites (soddyite and uranophane) are rare. Uranothorite has also been identified (Roscoe [4], and Patchett [46]) identified coffinite in altered material from the Nordic Mine.

Pyrite is the commonest sulphide mineral; it usually constitutes some 6 to 10 per cent of the ore, is concentrated in the matrix, and only rarely is there indication of replacement or fracture filling in the quartz pebbles. Individual grains may be rounded ("buckshot" pyrite) or subhedral to massive, although spongy varieties are also present. Arnold, R.G. [47] suggested that the pyrite formed by sulphidization of detrital magnetite, and he described grains showing cores rich in leucoxene that he considered to have developed from ilmenite exsolved from the original magnetite. The post depositional replacement of titaniferous magnetite has been confirmed by the studies

of Theis, [48] and Robinson and Spooner [49, 50, 51] effectively countering the argument of Davidson [52], Simpson and Bowles [53] and Clemmey [54] that the lack of magnetite in the ore was a serious difficulty for the placer theory. Theis [48] considered that the greater part of the pyrite was detrital and noted shapes and textures similar to those illustrated by authors such as Hallbauer, and Saager papers in Armstrong [32], Minter [56] from the Rand. Bottrill [55] and Robertson, J.A. [57] have suggested that the sulphur required was derived from the lower Huronian volcanic rocks. Pienaar [14], in a trace-element study, could not distinguish between the pyrite of the ore beds and the pyrite found in other rocks of the district. Kimberley et al [58] have indicted that Co/Ni ratios are characteristic of volcanic rocks. Ross [59] suggested that the gold present in the ores was confined to the pyrite and was probably introduced in fluids derived from volcanism. Most authors have followed Roscoe [4] who suggested that pyrite was polygenetic with detrital, authigenic and introduced pyrite all being present. Robinson and Spooner [49, 50, 51] consider the bulk to be authigenic with some detrital also present.

As distinct from the Rand (Pretorius [42, 43, 34]) and Jacobina (Gross [60]), gold is a very minor component of the Blind River ores. Mining companies do not routinely assay for gold. However, Boyle [61] indicated that in the samples available to him gold was typically 0.09 ppm largely contained in pyrite bearing 0.64 ppm. Ross [59] obtained values in the range 5 to 987 ppb with individual reefs averaging 73 to 117 ppb with reworked reef at the base of the Ramsay Lake conglomerate attaining 400 ppb. A wide variety of other sulphides and heavy minerals has been identified, but these occur in very small quantities (Roscoe [4]). Mossman and Harron [62] have listed the known gold occurences in the Huronian.

The description of the main minerals in the ore, has been mainly from polished-section work but more recently electron microscopy studies have been undertaken.

The predominant ore mineral at the Pronto Mine and in the Quirke Mine A Reef (Theis [48]) is "brannerite", first described from the area by Nuffield [63]. "Brannerite" is typically found in the metamict state showing bladed rutile and quartz surrounded by a uranium oxide and rare-earth oxides; the two-phase uranium-titanium compound of Piennar [14]. Ramdohr [64] suggested the "Brannerite" formed by the "Pronto-reaction":

$$UO_2+2-3TIO_2=UTiO_2-3O_{6-8}$$

which he held took place during metamorphism.

Ferris and Ruud [65] and Theis [48] have concluded that Blind River "brannerite", and the brannerite or uraniferous leucoxene of the Rand, formed at low termperatures during diagenesis as a result of uranium migrating from uraninite to decomposing ilmenite.

Uraninite is the second most important mineral at Pronto and apparently the most important in the Nordic zone and in the C Reef at Quirke Mine (Theis, [48]). Generally it occurs as black rounded to subhedral grains approximately 1 mm across. The uraninite typically has 6.5% ThO_2 and a Uranium/Thorium ratio approximating 10. This corresponds to the composition of pegmatitic rather than hydrothermal uraninite (Roscoe [4] and Theiss [48]; Robertsonm J.A. [17]. The rounding and thorium content indicate a detrital origin confirmed by isotopic age-determinations. Davidson [52] used the general lack of uraninite in modern placers and geochemical principles along with the Lyellian concept of uniformitarianism (actualism) as argument against the detrital origin of uraninite.

Early descriptions of Thucholite from Blind River ore were given by Robertson, J.A. [26, 27]. Two types were recognized - dissemenations within ore beds and in post ore fractures along with post ore sulphides and rarely palygorskite (described as pilolite by Kaiman and Horwood [66]).

In the mid 1970's, as mining progressed scattered at localities particularly towards more peripheral areas of the reefs, thin-layered units comprising uraninite and thucholite were found at the top of reefs. This coincided with publications of Pretorius [43] and Hallbauer [40] emphasizing the role of hydrocarbon in the Rand. Hallbauer (personal communication and [67] illustrated a sample from Nordic mine with the same filamentous structure he had documented from the Rand. Ruzicka has since collected and documented (Ruzicka and Steacy [44], Ruzicka [45]) the banded thucholite (hydrocarbon) from the Elliot Lake area and has endorsed a biogenic origin - probably algal mats which also trapped the uraninite. Nagy has identified in material collected by Ruzicka kerogens confirming the biogenic origin (Willingham et al [68]).

Hydrocarbon has been identified by Ruzicka and Robertson in some surface showings e.g., Alexander occurrence near Massey (Ruzicka [69]) and Spine Road in Elliot Lake (Ruzicka and Le Cheminant [70]). At the latter locality as well as in material from the mines (Mossman & Dyer [71]) there is some indication of gold enrichment up to 2000 ppb (Mossman to Ruzicka in Ruzicka and Le Cheminant [70]) see also Willingham et al [68]. Kaiman and Horwood [66] concentrated on the globular variety of thucholite in fractures and suggested that

such material formed by polymerisation of diesel fumes, however most mine geologists now discount a post-mining formation of such thucholite.

Roscoe [72] has described the monazites from the Blind River ores and has pointed out that monazite can contain considerable uranium and is, therefore, one of the ore minerals. Grains are normally rounded to subangular and less than 0.3 mm in diameter. Grey varieties of monazite are strongly radioactive, may contain uranothorite or thorite, and have pyrite inclusions. Roscoe has shown that the uranium-thorium ratios in monazite are comparable to that of the basement. The lateral variation in the ore-mineral and uranium-thorium ratios, as studied by Roscoe [73]; Robertson, D.S. [74]; Robertson, J.A. [26], are best explained by the relative stability of monazite during transportation (elaborated on with respect to Denison and Quirke mines by Theis [48]). Monazite is the chief radioactive mineral in the occurrences in the Lorrain Formation.

3.3 Production

By December 1986 the Blind River-Elliot Lake camp produced 132 thousand tonnes of uranium from 123 million tonnes of ore milled for average recovered grade of .093% uranium with an additional 752 tonnes U recovered by leaching of broken ore, both underground and on surface, at Agnew Lake. (Derived from Company Annual Reports.)

Minor amounts of thorium and yttrium, details of which are not in the public realm, have also been produced. In mid 1968, a consortium started producing yttrium at a plant adjacent to the Denison Mill.

Maximum mineral production from the camp was obtained in 1959 when some 9345 tonnes of uranium were produced.

In the Elliot Lake mines as mining progresses grade of the ore will continue to drop although this effect is being partially offset by underground leaching of broken low grade ore or altered ores unsuitable for normal milling. Part of the recent expansions undertaken at Elliot Lake were to maintain output in face of declining ore grades and part to enable the companies to meet their long term contracts with Ontario Hydro.

3.4 Reserves and Resources

Given the bedded nature of the deposits and the extent of diamond drilling, the resources of the camp have been known since the late 1950's and were generally quoted as approximately 400,000 to 500,000 tonnes uranium e.g. Griffith and Roscoe [75]. Changes have

been made in resource data reflecting exploration, production, mine development, and economic factors influencing the classification of known mineralization.

The most detailed published breakdown on Ontario Resources (predominantly the Elliot Lake camp) is that given to the Porter Commission [76]: measured 49,000 tonnes U; indicated 75,000 tonnes; inferred 246,000 tonnes U; and prognosticated 182,000 tonnes U at prices >$156/kgU(1978). These resources also contained 100,000 tonnes of recoverable ThO_2.

Current estimates of uranium recoverable at prices up to $300/kgU(1986) from rocks are in the 250,000 - 300,000 ton range. Most of the prognosticated mineralization is no longer considered economically accessible and only a limited portion of Elliot Lake mineralization would be viable at current spot price (US$18.00/lb U_3O_8). Foreign contracts signed under the influence of high prices and perceived shortages expire by 1994. After that date, there are continuing contracts with Ontario Hydro, which will ensure continuity of production until 2020.

4. ORIGIN OF THE URANIUM DEPOSITS OF BLIND RIVER TYPE

Uranium and thorium mineralization occurs at a number of localities throughout the world in quartz-pebble conglomerates bearing appreciable pyrite and, especially at the Witwatersrand in South Africa, gold in the matrix. The origin of these conglomerates has been much debated. The similarity of the deposits at Blind River to one or another of several of the well-known deposits at Witwatersrand, South Africa; and Jacobina and the Quadrilatero Ferrifero Brazil, have been pointed out by Armstrong [32], Button and Adams [33], Davidson [52], Derry [77, 78, 79], Joubin [80], Gross [60], Villaca and Moura [81], and Robertson, D.S. [31].

Davidson also mentions similar deposits in Australia and Russia. This characteristic assemblage and its distribution is the major theme of Armstrong [32] the papers from a 1965 workshop on Genesis of Uranium - and Gold-Bearing Precambrian Quartz-Pebble Conglomerates", sponsored by the U.S. Geological Survey. This workshop sparked development of the quartz-pebble conglomerate model and intensified exploration of the Wyoming Precambrian (Button and Adams [33], Karlstrom et al [82], Houston and Karlstrom [7]. The relation to major unconformities, particularly those marking the Proterozoic-Archean boundary, has been emphasized (Derry [78]).

In the Blind River camp this unconformity can be placed at 2,500 Ma;it is clear that suitable conditions for the deposition of uranium did not persist beyond a

minimum of 2,165 Ma and that the period 2,500 to 2,300 Ma seems the most favourable. Early workers such as Joubin [80], Davidson [52], and Heinrich [83] proposed a hydrothermal origin for the ores but Pienaar [14], Roscoe [4, 30], Robertson, D. [74], Robertson, J.A. [3, 26],and Ruzicka [45] have strongly supported a placer origin with modification by later events, as originally proposed by Holmes [84].

Many authors, for example Pienaar [14], Roscoe [4, 20, 30] and Robertson, D.S. [31], have suggested that the regolith and/or other features of the uraniferous sequences implies a reducing atmosphere. Robertson, J. A. has pointed out that even if limited oxygen were available the rapid transportation and deposition of the uranium bearing detritus under conditions in which glaciation was frequent would severely limit the efficacy of oxidation and consequent solution of uranium. Similar conditions elsewhere in the world during the later Archean or at the Archean-Proterozoic boundary have been considered to suggest a reducing (anoxygenic) or oxygen deficient atmosphere which presumably provided a chronological control on the Blind River type of uranium deposits (Robertson, D.S. et al [85, 20]; Smith [86]). However, Dimroth and Kimberley [21] have concluded from a study of the distribution of sedimentary carbon, sulphur, uranium and iron that is is not necessary to invoke an oxygen-deficient atmosphere and further postdated low level oxygen in even the Archean atmosphere. Grandstaff [87], [88], and Gay and Grandstaff [89] as part of studies on uraninite kinetics analysed serial samples from regolith profiles and noted that in the uppermost portion of the regolith Fe_2O_3 was enriched relative to FeO indicating that minor amounts of oxygen were available at the regolith surface.

More recently Kimberley et al [90] have studied palaeosols as now accessed in the Denison workings and have shown that the degree of oxidation in these correlates with the palaeoelevation. They also suggested that the climate was warm and humid, which runs counter to those who suggest a near glacial environment. More detailed descriptions of the Denison Palaeosols have been given by Goddard [91]. Goddard has also illustrated and briefly described the relationship of ore grade to basement highs with a marked increase in uraninite in embayments on the leeside of local kidney-shaped highs Fig. 15 is a composite based on the descriptions given by Theis [48], Goddard [91] and observations on underground trips with Denison mine gological staff, particularly A. Schappert, on whose beat these features are best observed.

Roscoe [4] compiled the available isotopic data on various minerals in the Blind River ores and concluded that the data are compatible with the primary age of 2500 Ma and modification (resetting) reflecting

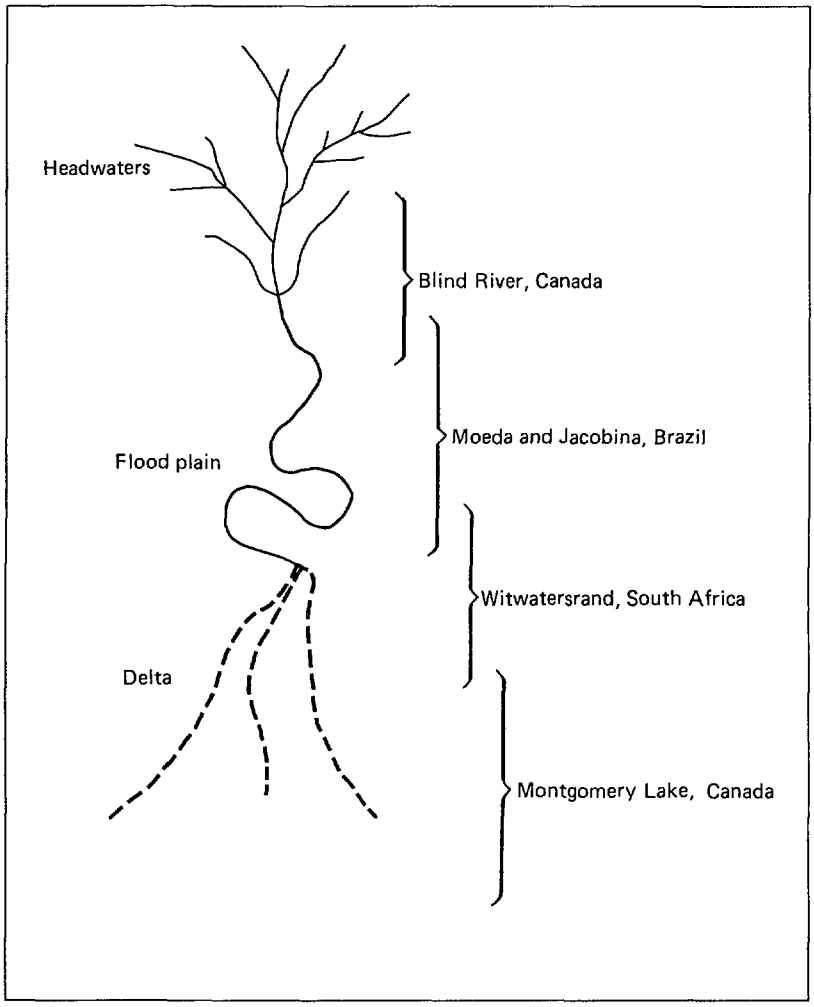

FIG. 15 Stratigraphic relationships vicinity of local basement high - Denison Mine, based on Theis [48], Goddard [91], and personal observation.

the later tectonic, metamorphic and thermal events, the effects of which increase from north to south as the Penokean Fold Belt is approached. Episodic introduction of uranium mineralization was not indicated. Subsequent detailed studies have confirmed an Archean age for the uraninite grains 2550 + 50 Ma, Meddaugh and Holland [92], Robinson and Spooner [51].

The over-all distribution of beds and the behaviour of thickness and grades are more consistently explained by the modified placer hypothesis, first enunciated by Holmes [84] which the author has supported (Robertson, J.A. [26, 3]). Mineragraphic studies of Ferris and Ruud [65] and Theis [48] and the electron microscope studies of Robinson and Spooner [49, 50, 51], have added cogent additional support to the modified placer hypothesis. Robinson and Spooner have also pointed to the lack of apatite in the ores although it is ubiquitous in the source granites and to partial solution of monazite grain margins and have suggested that phosphate complexing may have played a major role in the solution of the uraninite.

The modified placer hypothesis proposes that the Blind River deposits were derived from a cratonized Archean terrain to the north and northwest which included uraniferous grantitc rocks with or without uraninite-bearing pegmatites, transported by rapidly moving water, and deposited in a near shore fluviatile environment under (cold?), oxygen deficient conditions (but not necessarily an atmosphere devoid of oxygen) about 2500 Ma ago. Mafic volcanic rocks were simultaneously accumulating in the basin and may have provided a sulphur source to convert magnetite to pyrite. The basin location was controlled by the incipient Great Lakes Tectonic Zone (Sims et el [16]). The equivalent units in Wyoming bear a similar relationship to the McMullen-Nash Creek shear zone which, like the Great Lakes Tectonic Zone, marks an Archean plate boundary (Houston and Karlstrom [7]; Karlstrom et al [82]; Button and Adams [33]). The uranium deposits were later subjected to diagenesis and to minor alteration during subsequent intrusive, metamorphic, and tectonic events, but were not subjected to either erosion or leaching The modified placer hypothesis has been recently endorsed by Robinson and Spooner [49, 50, 51] but with doubts expressed on the evidence for a reducing atmosphere.

The foregoing genetic hypothesis has led to a systems-analysis approach to resource-potential and exploration-potential assessment. The geological factors (parameters) inherent in source, transportation, deposition, modification, and preservation have been identified (Fig. 16) and their efficacy assessed. This systems approach has been further developed and expanded as part of the work of the Federal-Provincial Uranium Resource Appraisal Group (Ruzicka [93, 94, 95]). A similar approach was used for the National Uranium Resource Evaluation (NURE) studies conducted under the auspices of the US Department of Energy. The modified placer hypothesis is generally accepted and provides the model for genesis, exploration, and resource evaluation of the Proterozoic uraniferous pyritic quartz pebble conglomerate deposits. Skinner [96] has provided a conceptualisation relating the known uranium bearing pyritic quartz pebble conglomerates to the fluvial system (Fig. 17) in which he places the Blind River deposits straddling the upstream margin of the flood plain.

1. SOURCE	
Uraniferous Granitic Rocks + pegmatite 2600 Ma	Radioactive anomalies U showings in pegmatite and near diabase dykes.
2. WEATHERING	
Disintegration & Weathering, Formation of uraninite-bearing detritus, little or no oxidation or solution	Regolith at Archean-Proterozoic contact.
3. TRANSPORTATION	
Rapid transportation by SE-flowing streams and rivers of quartz pebbles, feldspar uraninite and resistates, little or no oxidation or solution	Huronian Sedimentation directions (SE), no red beds.
4. DEPOSITION	
Rapid deposition and burial of quartz-pebble conglomerate with uraninite, iron oxide (?) pyrite, monazite and zircon in shallow fluvial/littoral environment. Little or no exposure to oxygen. Algol mats in quiescent areas trap uraninite grains.	Scour and fill structures, Cross-bedding, thick arkose sequences, fining upwards cycles, basement valleys (magnetic expression). Embayments in Archean contact. Radiometric anomalies. QPC lenses and beds + radioactivity, pyrite, kerogen.
5. DIAGENESIS AND MODIFICTION	
Compaction and consolidation migration of pore fluids. Clay minerals form from feldspar debris, "brannerite" by migration of U from uraninite to titaniferous aggregates, authegenic pyrite S possibly derived from volcanism.	Yellow green colour, No magnetite.
Hydrothermal alteration near Nipissing diabase (2115 Ma) little U remobilization	Albite (red), chlorite (green), carbonate near diabase contacts. Post-ore veins and joint coatings sulphides,
6. PRESERVATION	
Lack of exposure to oxygen, little or no post-depositional solution, no erosion of un-consolidated materials no destruction by later metamorphism, erosion.	

FIG. 16 Deposit model Uraniferous Pyritic Quartz-Pebble Conglomerate, Blind River based on Ruzicka [93, 94, 95].

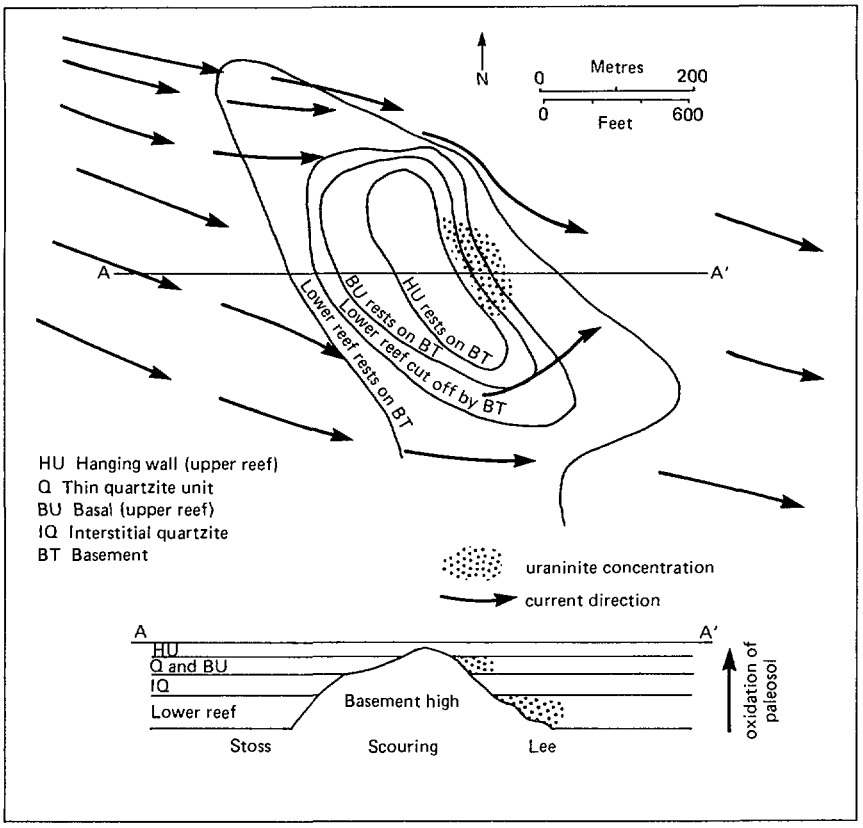

FIG. 17 Idealised Fluviatile System and Possible Setting of Five Detrital Uranium Deposits Skinner [96].

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A CONCEPTUAL MODEL FOR DEVELOPMENT OF MEGABRECCIAS AND ASSOCIATED MINERAL DEPOSITS IN WERNECKE MOUNTAINS, CANADA, COPPERBELT, ZAIRE, AND FLINDERS RANGE, AUSTRALIA

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Abstract

The Wernecke Mountains in Canada, compare with the Copperbelt in Zaire and with the Flinders Range in Australia in having areas of megabreccias with horizontal extent in the tens of kilometres and with clasts predominantly of sedimentary rocks, some greater than kilometre-size. Mineral deposits occur as older stratiform sedimentary or diagenetic mineralizations within the blocks, as veins and alteration zones associated with emplacement of the breccias and as supergene veins and crusts. The strong elemental signatures are: Cu, Co, U, Fe and Ba with weaker signatures including Pb-Zn, Au, Ag, Mo, REE, or Pt-Pd.

For the above mineral deposits a general conceptual model proposed is:

(a) sedimentary/diagenetic concentration in closed basins in association with marine or lacustrine evaporite facies;

(b) after burial these sediments and earlier stratiform deposits were mechanically and chemically transported upwards during diapiric action; and

(c) breaching, exposure and later weathering permitted removal of the evaporite minerals, some slumping and development of supergene crusts.

The amount and degree of study and attendant economic mineral development in these areas vary considerably.

The Copperbelt has very significant past production and resources in Cu, Co and U. The Flinders Range has widespread Cu + Co and relative to Zaire minor production, but nonetheless provided incentives that led to discovery of significant source rocks (which predate stage 'a' above) in the Olympic Dam deposit. In both these areas supergene enrichment was significant. The Werneckes have excellent indicators in U, Cu, Co and Au but lack significant supergene development and more importantly have neither been explored thoroughly nor yet have been developed, mainly because so far the deposit discoveries and the development of the geological framework is less than two decades old. The questions whether the Werneckes should prove to have deposits of the grade and tonnage of Zaire or of the Flinders Range or targets for significant source rocks of the Olympic Dam type are addressed. In any case features in one area that apparently are lacking or appear weak might be sought by analogy with another, for example Pt-Pd associated with U as at Shinkolobwe could be sought in the Werneckes.

1. INTRODUCTION

The purposes of this paper are two fold: 1) to describe and discuss salient features of the geology shared by these three areas and 2) to propose a unified conceptual model for these shared features and for the formation of their uranium and other deposits. Descriptions and discussions of uranium and other deposits are given in other papers for Zaire [1-13], for Australia [14-21] and for Yukon [22- 28]. The reader is directed to these for further information. All three areas are established copper provinces with common Fe, Co, U, Pb-Zn, and Ba. Ni, Mo, Au, Ag, REE, Pt-Pd, and Se are also locally significant. The gross aspects of similarity among the three are the late middle to latest Proterozoic stratigraphy and the presence of megabrecias. Most of the important mineral deposits occur in association with these megabreccias.

Data sets are not equal in these three areas. Various deposits have been exploited in Zaire and Australia for more than 80 years and consequently they have been better described and interpreted. In contrast, deposits of any kind were discovered in the Proterozoic rocks of the Wernecke Mountains less than 20 years ago, and uranium deposits were discovered only 10 years ago. The Precambrian part of the Wernecke Mountains has only been mapped on a regional scale and is not under active study.

The regional geology and stratigraphy of South Australia are very well defined, especially through the series of 1:250 000 maps available for the entire area. This is not the case for the other two areas, although excellent local maps and stratigraphic studies or transect maps of geology have been published for Zaire [4,5 and especially 6 and 29]. Most of the geological syntheses of Wernecke Mountains date from about 1980 [24, 25, 30-33].

Inferences from a superior aspect of the data bases from one area should be useful to predict mineral occurrences in other less known areas.

2. STRATIGRAPHY

Figure 1 generalizes the stratigraphic columns of the three areas. The upper parts (Heysen, Windermere, Kundelungu) are strikingly similar in containing, not only similar shale-sandstone dominated sequences, but also two cycles of glacial and/or periglacial sediments with capping dolomites. These similarities have often been noted [14, 16, 24, 28, 30, 33, 34]. The older limit for the base of these successions is about 750 to 800 Ma and they are capped in Australia and Canada by lowermost Cambrian strata [28, 33]. The succession in Zaire is insufficiently studied and may yet reveal Ediacaran to lowest Cambrian strata at the top. These successions contain stratabound Cu deposits, iron-formation, and Mississippi Valley type Pb-Zn deposits in carbonates, at the top especially in both Australia and Canada.

The lower parts of the columns are only grossly similar [28]. They are commonly carbonates, orthoquartzites and shales with evidence for evaporites especially abundant in Australia and in Zaire [11, 16, 28, 35-38]. In the Curdimurka Subgroup and "Mines" Group the strata in general report as

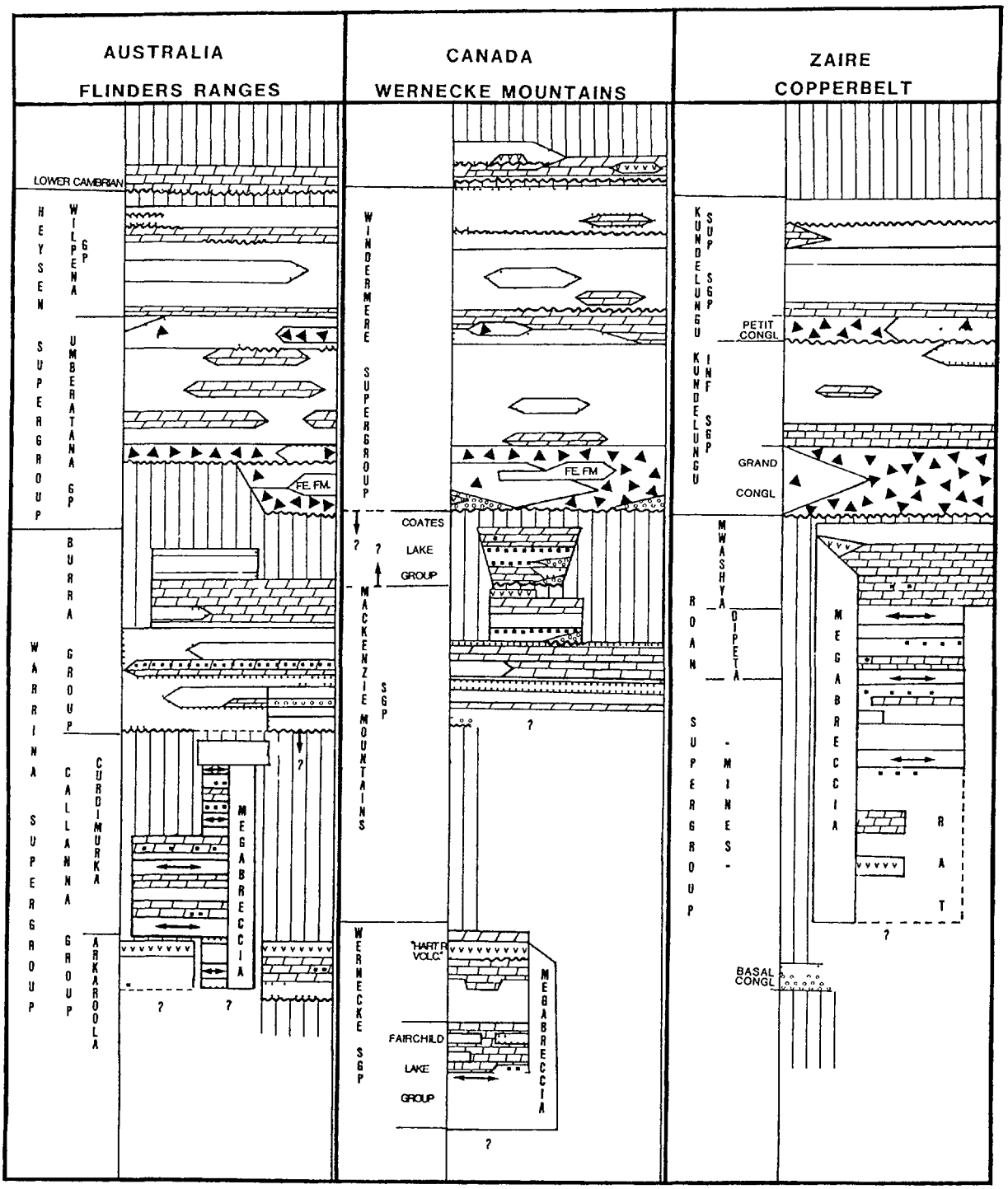

Figure 1: Schematic stratigraphy in Flinders Ranges, Wernecke Mountains, and Copperbelt [after 6, 7, 16, 28, 30, 47]. Symbols, vertical lines gaps, dots-sandstones, brick-carbonates, blank-shales, triangles-tilloides, V's- mafic volcanics, squares-evaporite facies, horizontal arrows-possible vanished evaporites.

huge rafted blocks in megabreccias in domal (salt dome intrusion type where diapirs cause folds) or anticlinal and decollement diapirs (tectonic diapirs where folds cause diapirs). Reorganization of these strata into coherent packages has led to the suggestions that gaps and apparent

discordances are the sites of vanished evaporites. By contrast, in Canada much of the evaporites in Coates Lake and underlying Little Dal groups [26] is still in coherent units but the older lower part of the Fairchild Lake Group may have had thick evaporite beds now lost in breached diapirs [25] in much the same fashion as in Australia and Zaire. The Warrina Supergroup, Mackenzie Mountains Supergroup (including Coates Lake Group) and Roan Supergroup contain evidence for stratiform Cu, Co, U, Ni mainly in fine grained rocks, (often at least weakly carbonaceous) [1-13, 16, 18, 26-28] although the evidence for stratiform U is still debated [13]. The Burra Group, perhaps most of the Curdimurka Subgroup, and the Mackenzie Mountains Supergroup are younger than 1200 Ma, but perhaps not much older than 800 Ma. The Arkaroola Subgroup is most likely at least 1100 Ma and the Wernecke Supergroup at least 1200 Ma years old [28]. No clear cut ages for the Roan Supergroup are defined although it may not be much older than 1200 Ma.

Volcanic rocks are minor throughout the column. Mafic flows and associated dolerite intrusions have been documented in the lowest parts of the Heysen, Windermere [28] and Kundelungu supergroups as well as in the Mwashya Group [29]. Mafic flows and dolerites occuring as rafts in the breccias are likely from the Arkaroola Subgroup (i.e. Wooltana flows) in Australia, and from undefined levels in the Roan in Zaire. In Canada, some if not all of the mafic rafts in the Wernecke breccias come from below and hence predate the approximately 1200 Ma old Hart River volcanics [28].

Analyses of the copper and associated deposits suggest that there is vertical (stratigraphic) as well as lateral zonation. For example in Zaire lateral zonation from north to south is Cu, to Cu + Co, to Ni + U, to Fe [4-6]. This lateral zonation is not apparent in Australia. It may be the case in the Wernecke Mountains where U is almost totally restricted to the easternmost part although Cu and Co are still common within the individual deposits [23].

There is room for considerable research in all areas to determine the nature of the evaporite facies. The presence of silica replacements (some may be of magadiites) and various Na carbonate pseudomorphs in Australia [38, 39] along with other features strongly suggest lacustrine rather than marine evaporites. Data from Canada and Zaire are comparable with lacustrine environments and several authors have proposed lacustrine models [26, 28] for some successions. Parallels may be drawn with the Damara belt further south and west of the Copperbelt where detailed studies [40, 41] document the lacustrine playa model as well as the behavior of the evaporites and associated rock during structural and metamorphic modification. More such studies could be applied to the Adelaidean, Wernecke and Copperbelt strata.

3. MEGABRECCIAS

The principal features that drew my attention to these areas were the outstanding megabreccias. Figures 2, 3 & 4 at about the same scale indicate the size and distribution of these breccia "fields". Some are fairly well documented to be <u>not</u> intrusive. These are in the zone of klippes between

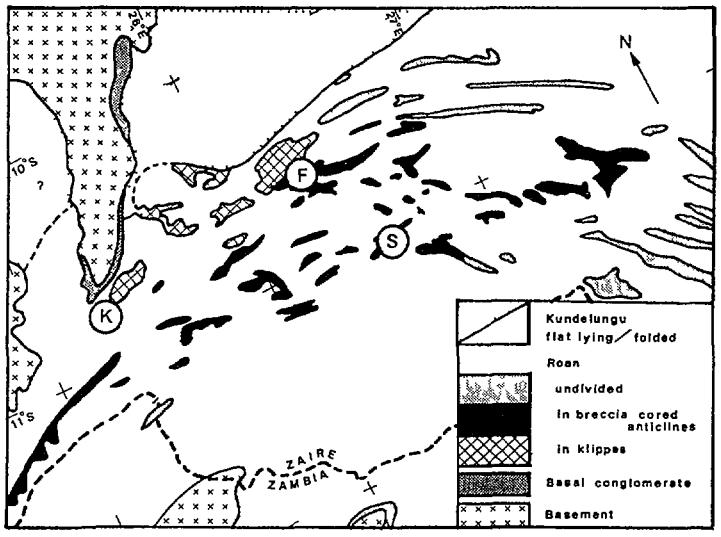

Figure 2: Copperbelt in Zaire [after 4, 6, 8, 9]. K = Kolwezi, F = Fungurume, S = Shinkolobwe.

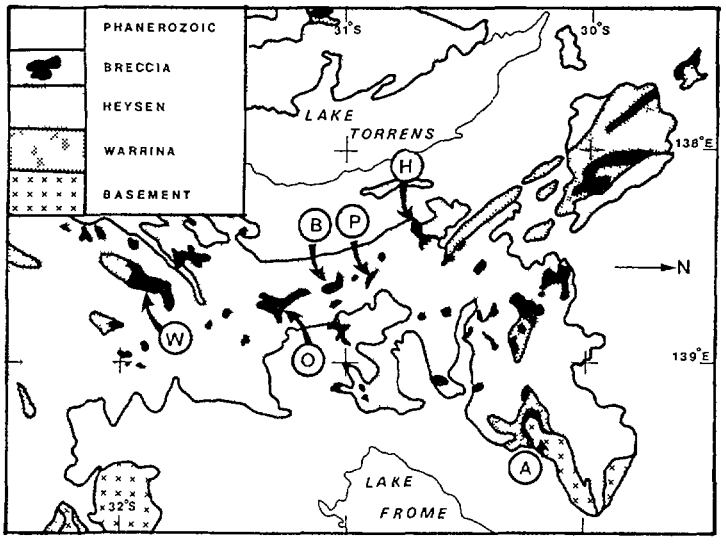

Figure 3: Flinders Ranges in South Australia [after 46, 47]. A - Arkaroola and Mount Painter, B - Blinman diapir, H - Beltana diapir, O - Oraparina diapir, P - Palawarta diapir, W - Warumba diapir.

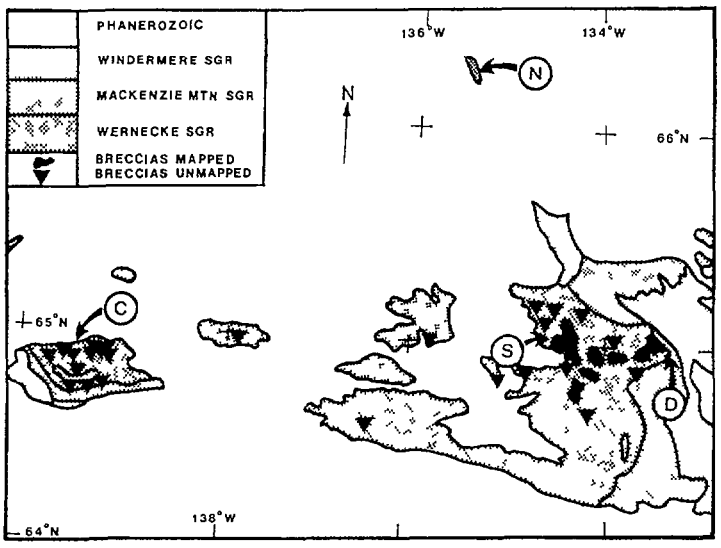

Figure 4: Wernecke (east half) and Ogilvie Mountains (west half) [after 22, 23, 25]. C - Coal Creek Dome, D - Dolores Creek, S - Slats Creek, N - Nor breccia.

Kolwezi and Fungurume in the northwestern corner of the Zaire Copperbelt. The others include some [42, 43] in the Ogilvie Mountains, west of the Werneckes which may relate to sedimentation along possible transcurrent fault zones but not all are sedimentary (compare [29, 42]). Some in Australia have been interpreted as olistostromes [35] but this interpretation has been discounted [44]. Most Australian Adelaidean breccias have been clearly demonstrated [44-48] to have been intrusive in the fashion of salt domes (for minority views see [47, 49]) although intrusive anticlinal, tectonically driven, decollement breccias may have been present locally and in part were superposed on the earlier domal breccias. In the Wernecke Mountains the intrusive nature of the breccias is established [25] but to what degree these "diapirs" are antecedent to and causing folding (i.e. as "salt" domes) or are consequent to folding during the Rackla orogeny as anticlinal diapirs is not yet unequivocally established [22-25]. In all three areas there is local to extensive alteration including silica, hematite, carbonate, chlorite and alkaline metasomatism in various degrees and combinations [25, 27]. That evaporites were present is clearly established in the Adelaidean (e.g. [35, 46]), fairly well identified in Zaire [8, 10, 11] and clearly identified in Mackenzie Mountain Supergroup [22, 26] but weakly identifed, so far in the Wernecke Supergroup [25, 28] in Yukon.

Figures 5, 6 (Zaire), 7, 8 (South Australia), and 9, 10 and 11 (Wernecke Mountains) show the nature of these breccias. The Fungurume breccia (Figure 5) may be part of a klippe. The others illustrated here are intrusive: in Australia commonly through to the Umberatana - Wilpena contact but often to and including Lower Cambrian strata; in Canada only through the Wernecke Group; and in Zaire at least to the upper half of the Kundelungu superior. The fragments range to kilometre size. Most large fragments (rafts, "écailles", blocks) and virtually all the matrix breccias are from lower levels (Callanna Group in Australia, lower Fairchild Lake Group in Canada, Roan Supergroup in Zaire) although occasional huge foundered blocks of upper strata have been identified in Australia (e.g. Beltana) and in Zaire (Kundelungu inferior at Shinkolobwe). Commonly the fragments are overturned or subvertical and "jumbled", although streaming of smaller fragments parallel with the discordant contacts are identified in Australia [44] and in Canada (Figure 11). Very minor amounts of basement gneiss and granite have been identified in the breccias in Australia and tentatively so in Canada. The matrix in the breccias in Australia and the nature of the RAT ("roche argilo-talqueuse") in Zaire appears to resemble that described by Kent [50] for presently inactive diapirs in Iran. Figure 8 illustrates the degree to which locally brecciated and semi-coherent blocks of breccia can be mapped. More of this sort of detail is necessary in all three areas.

Views contrary to the diapiric origin [47, 49] of all or parts of the Australian breccias as diapirs, as a salt dome type of diapir have been largely discounted [44] and the eloquent analysis by Dalgarno and Johnson [46] has been almost universally accepted. For Zaire the various interpretations

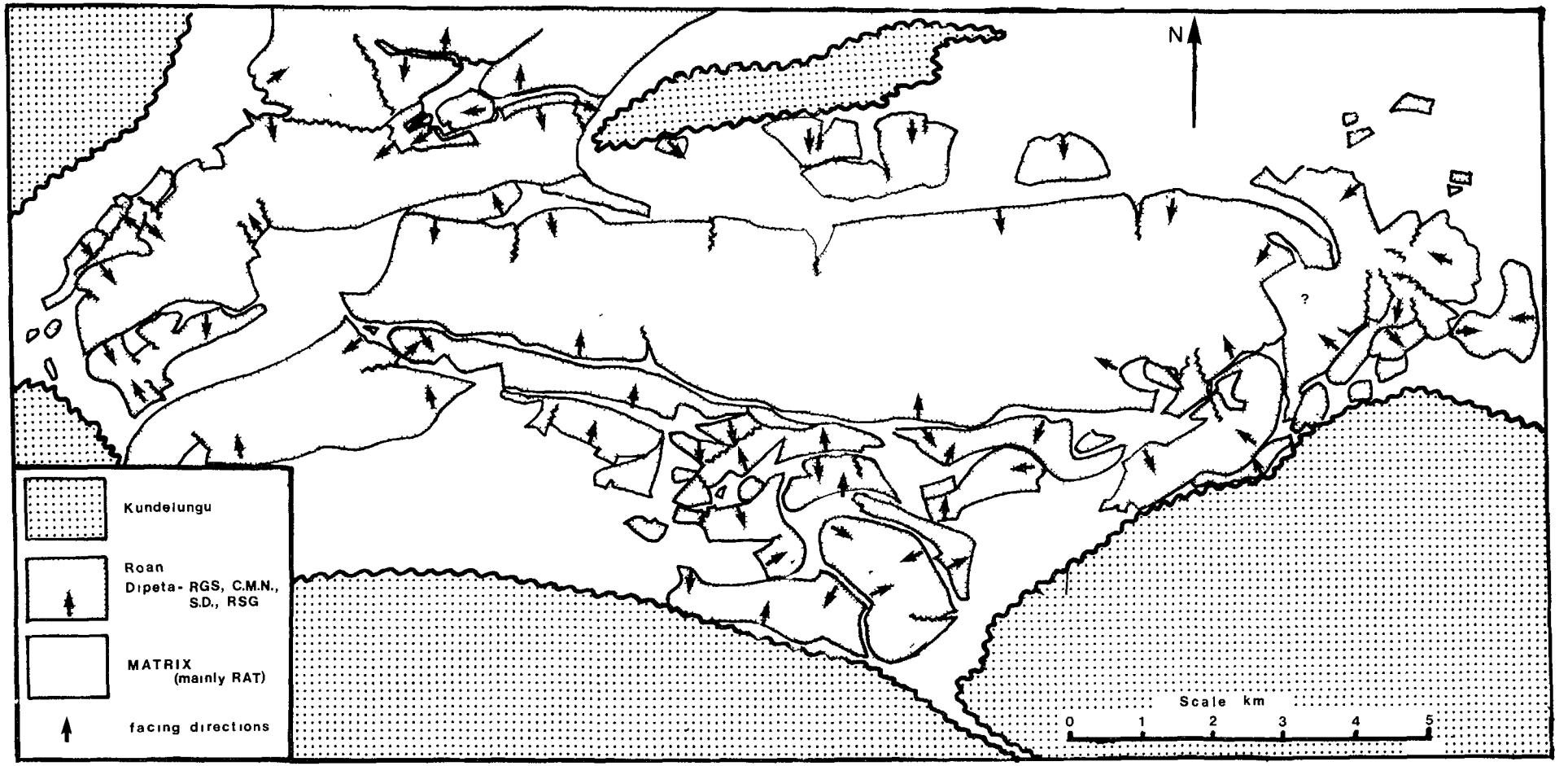

Figure 5: Fungurume breccia in Zaire shown mainly to illustrate maximum size of raft blocks [after 5].

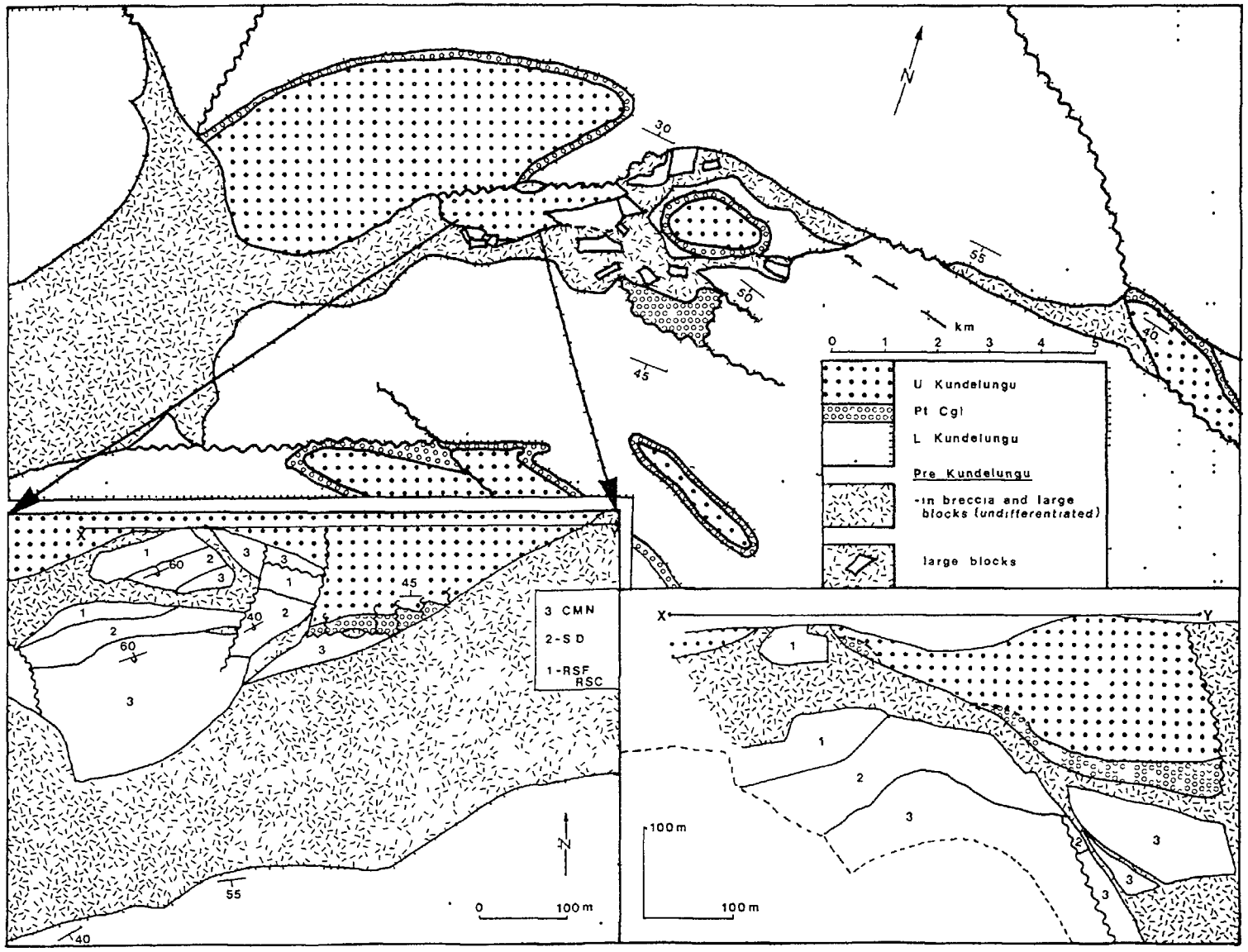

Figure 6: Shinkolobwe area with enlarged inset (b) and cross section (c) (after [1, 7,] see also [29]).

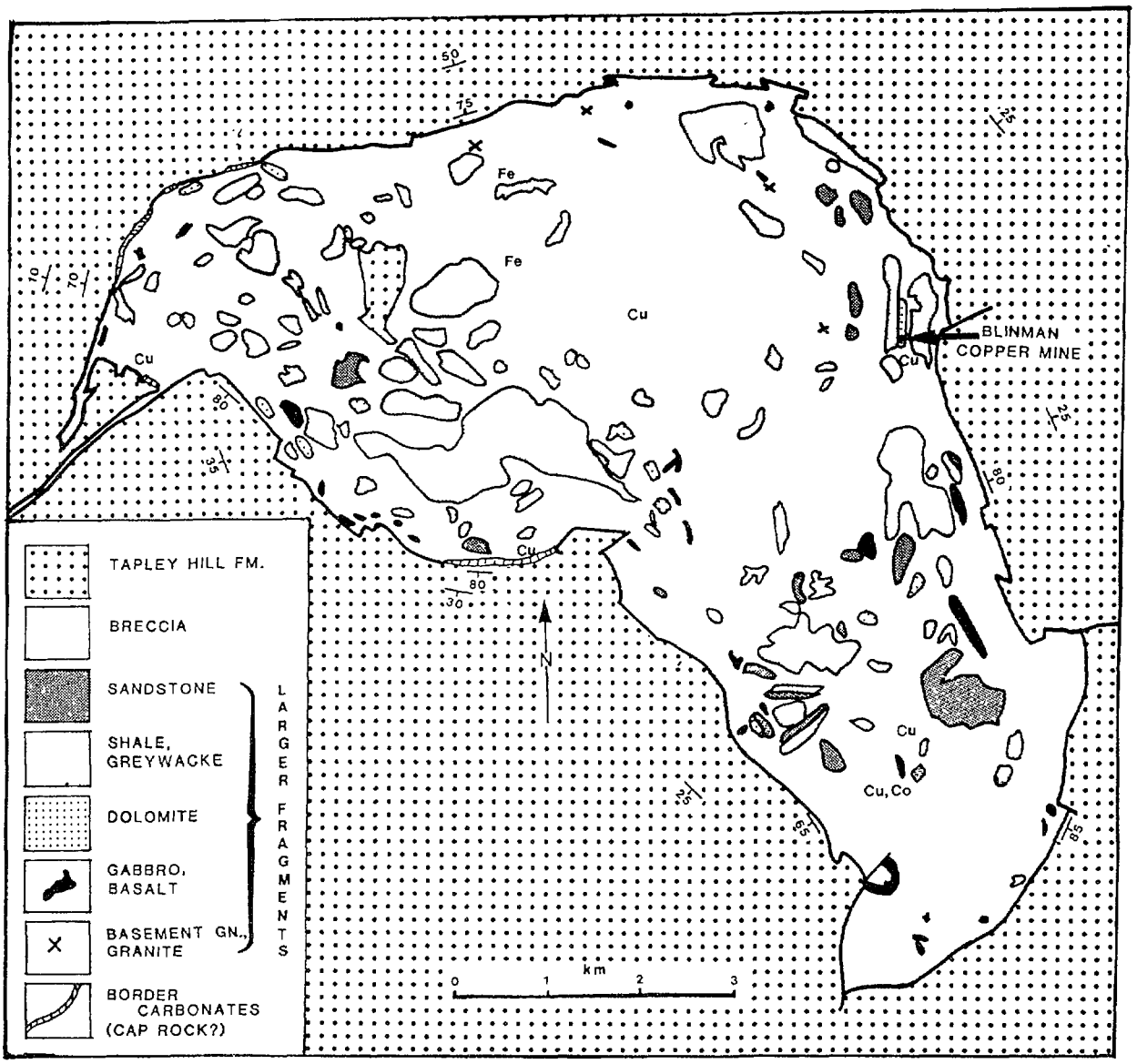

Figure 7: Blinman dome, South Australia showing the larger fragments and mineral deposits (after [45]).

were summarized by Francois [6] who interpreted the breccias in the western part to be klippes and elsewhere as anticlinally cored intrusions (truly diapirs but not salt domes) and later suggested [11] that some, including Shinkolobwe, are salt-driven diapirs. The sedimentary tectonic origin for Zaire megabreccias proposed by Grujenschi [51] was largely disproven by Lefebvre [34]. The various origins for the Wernecke breccias [22-25, 27] still need some clarification, the diatreme aspects have now been largely discounted [22, 23, 25]. Models invoking faulting and a sort of hydrothermal stoping [22, 23, 25, 27] are not, in my view, inconsistent with salt-driven diapirism. Indeed the local knots of intense alkali metasomatism, are most likely caused by endogenous, sedimentary derived brines rather than by being associated with igneous intrusions which appear to predate diapirism.

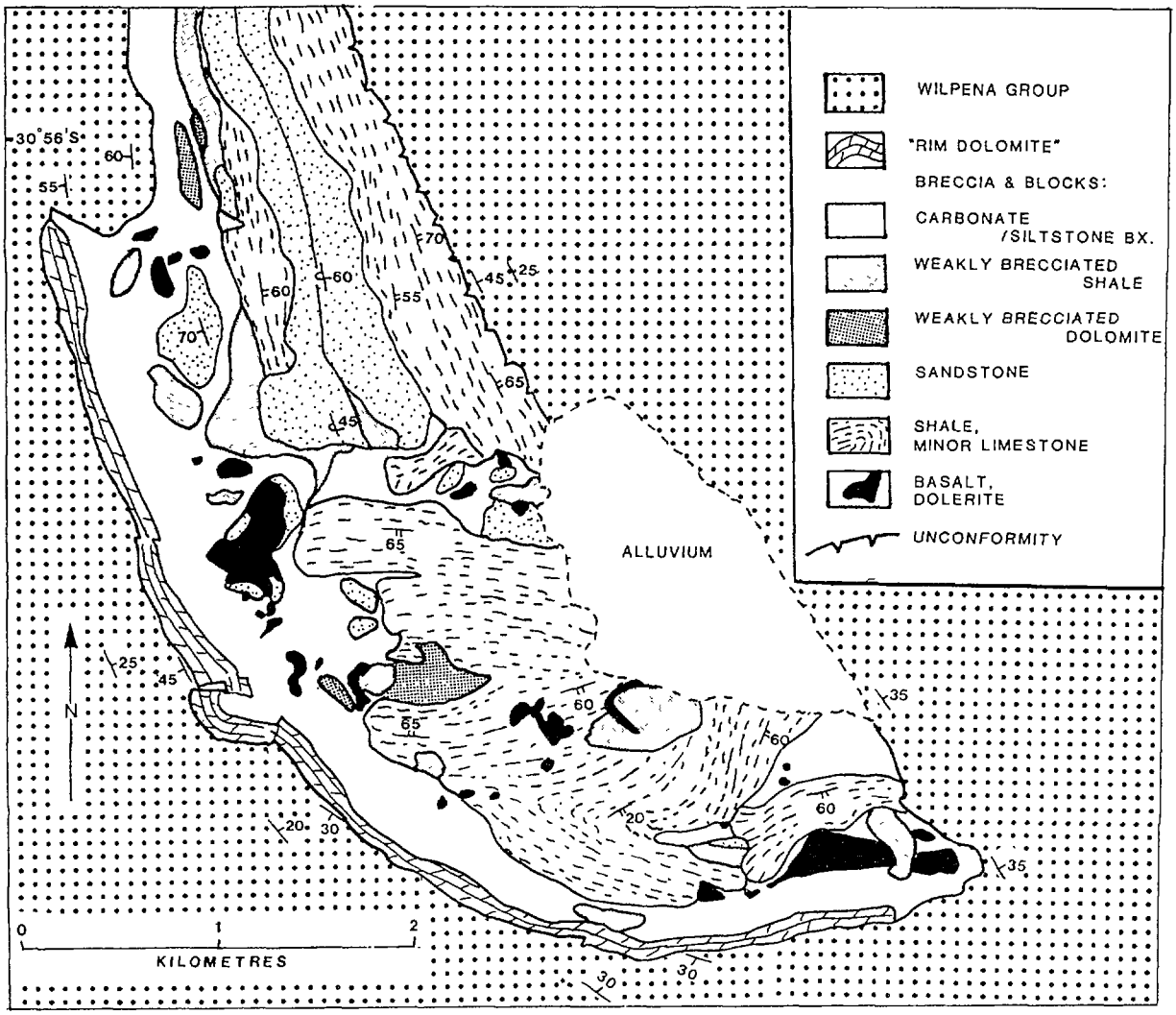

Figure 8: Palawarta diapir, South Australia showing the larger fragments including weakly brecciated rafts (after [21]).

The above suggests that studies like those on north African base metal deposits associated with salt driven diapirs [52] could be fruitfully applied to these megabreccias. Some of this type of research was done at Palawarta [21] in Australia. The temperatures determined even for the earliest stages of mineralization are well within the range encountered during salt diapirism. Temperatures close to 300°C have been identified in diapiric fields [53]. In addition the location of closed, intracratonic, evaporite basins in extensional crustal regimes as well as the very high thermal conductivity of salt would be more than adequate for such temperatures, certainly to at least 300°C, without a direct or indirect igneous input.

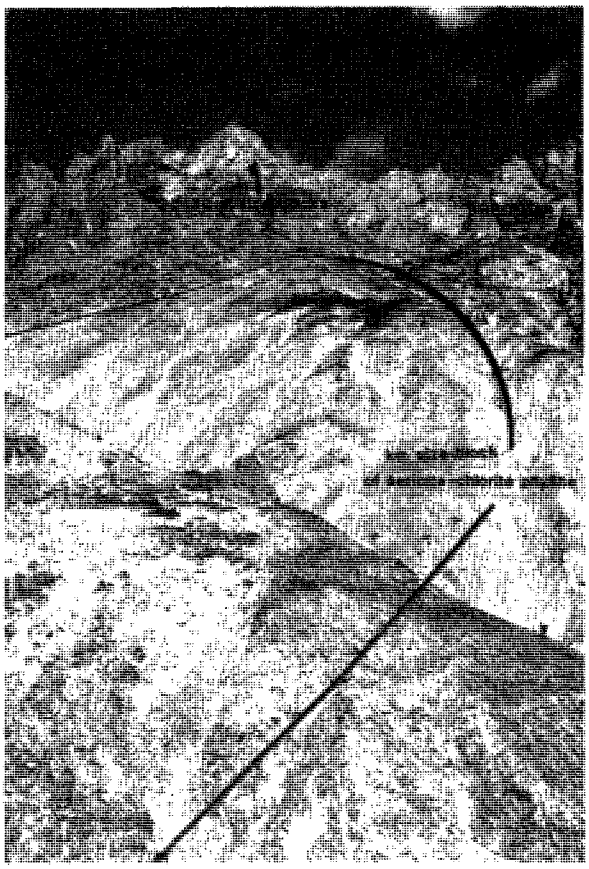

Figure 9: Slab breccia in Wernecke Mountains. Note figure for scale in lower right foreground (GSC Photo 203111D).

4. THE MODEL

Figures 12 and 13 illustrate schematically a general model for megabreccia-hosted deposits. Figure 12 is most applicable to the Australian area (4 superimposed basins gradually becoming more connected to the World Ocean, diapirism active throughout). Modification of Figure 12 for the Werneckes would invoke diapirism only in the earliest succession and modification for Zaire might use only three superimposed basins. Figure 13 shows salt dome diapirism as well as decollement and fold dominated diapirism and abortive as well as final erosional collapse events.

These considerations above lead to proposal of a general model for the deposits in these three areas. Three phases are important for this model.

(a) The first phase is development of sedimentary and diagenetic mineral deposits in closed, intracratonic basins or troughs in association with evaporite facies. The source of the metals would be the cratonic hinterland. In these basins the metals would be initially concentrated in evaporating systems [8, 10, 16, 28, 37-39, 54-57] and precipitated in associated reducing, fine-grained facies. Metal-rich brines expelled during compaction and lithification, would deposit ore minerals during the process of diagenesis of the adjacent coarser grained facies.

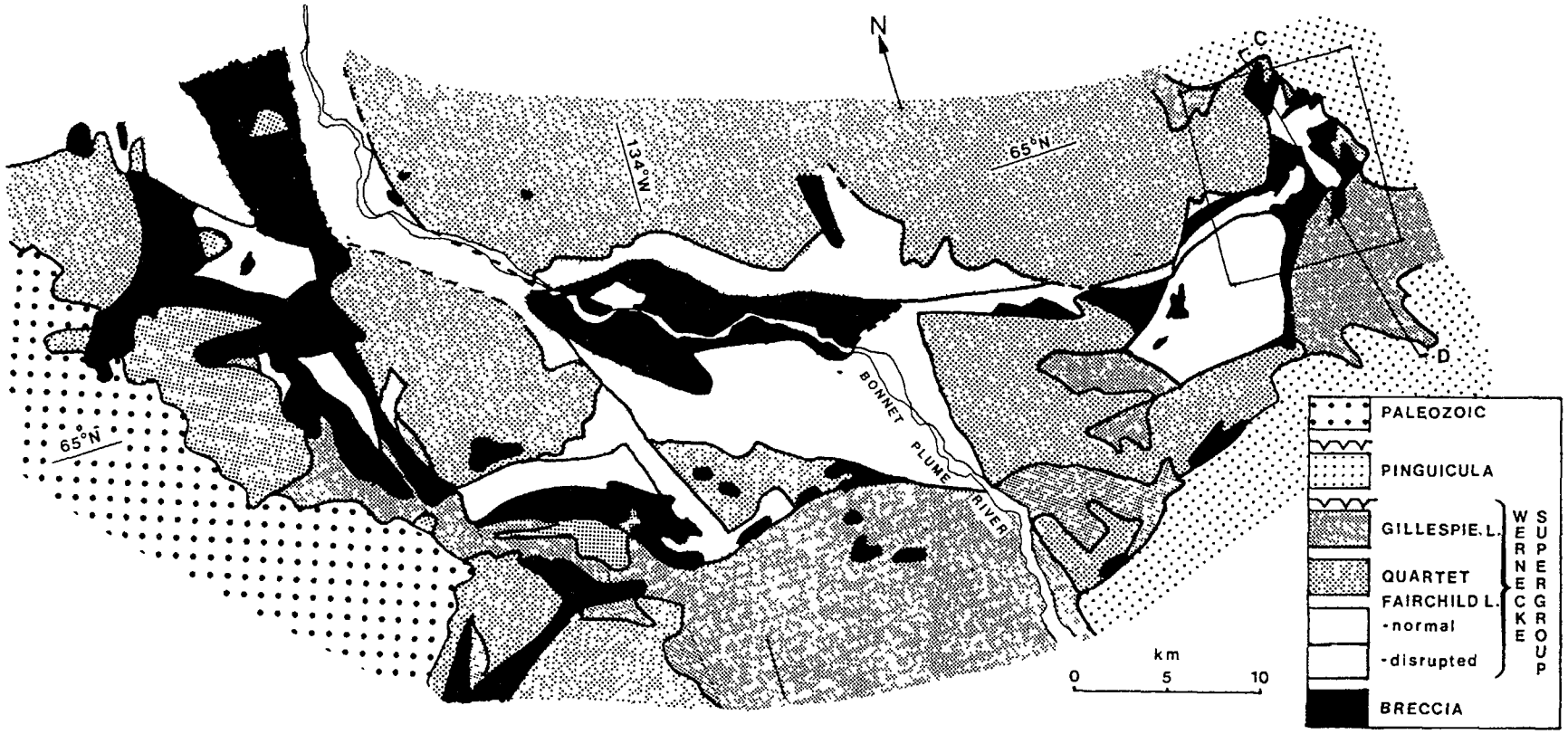

Figure 10: The region between Slats Creek and Dolores Creek of Figure 4 in more detail showing breccia and descripted phases of the complex [25]. See Figure 11 for enlarged inset and cross section.

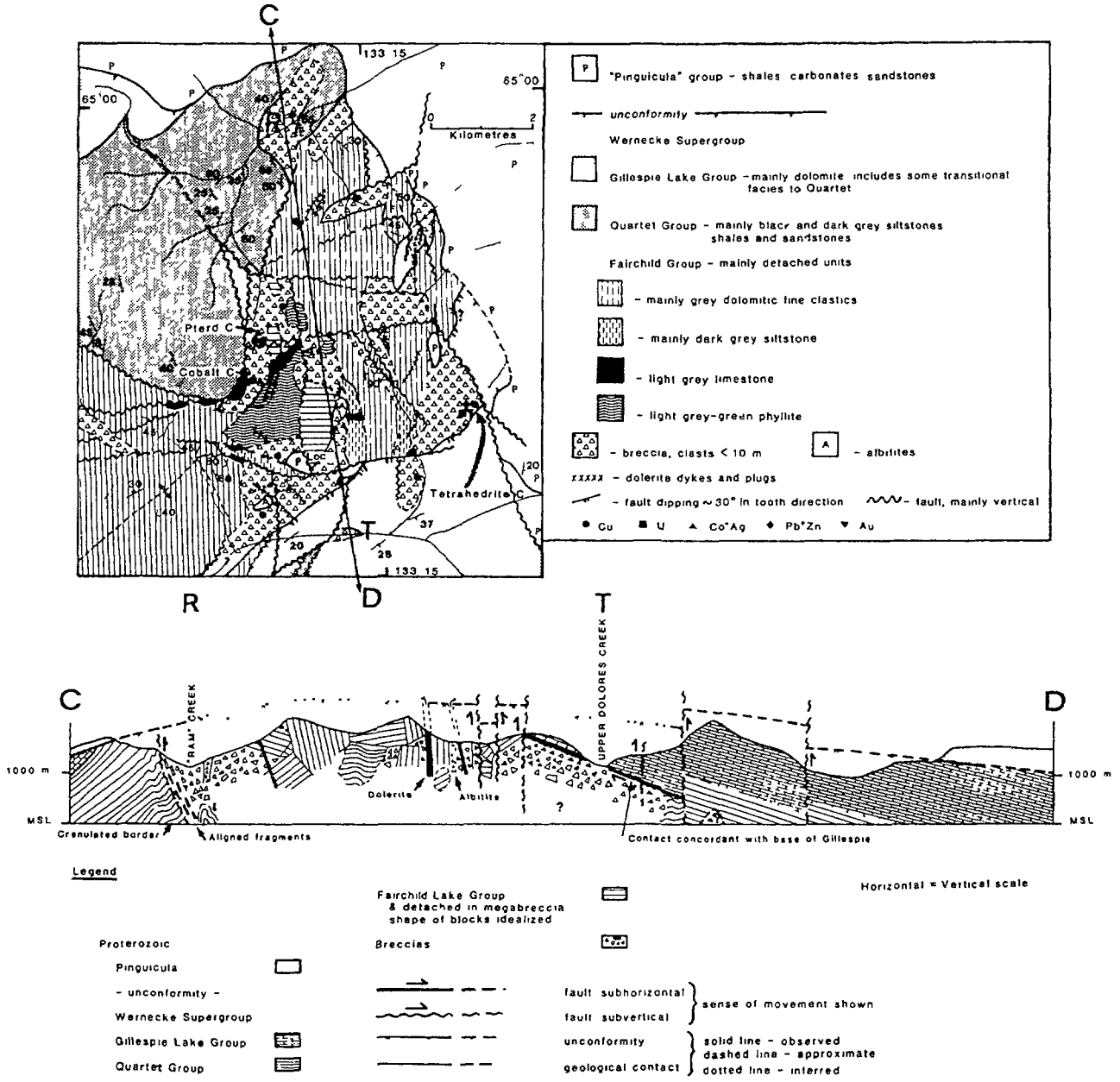

Figure 11: Detail and cross section of breccia in Dolores Creek area (after [25]).

(b) After burial these sedimentary rocks within and adjacent to the evaporite facies would be mechanically transported upward as blocks and rafts during diapirism, whether in passive salt dome diapirs or in tectonic anticlinal diapirs. During this process adjacent basinal as well as internal brines, would also scavenge and carry some of the metals upward to be deposited as replacement and vein minerals in the upper reaches of the diapirs, in the cap rocks and in the surrounding fractured host rock [see 52]. The resultant hydrothermal cells could even have penetrated to the upper parts of the basement to scavenge metals as suggested long ago by Davidson [57].

An interesting variation could occur if the diapir system were breached, allowing escape of these metal-rich fluids to form sedimentary exhalative systems. I would suggest that

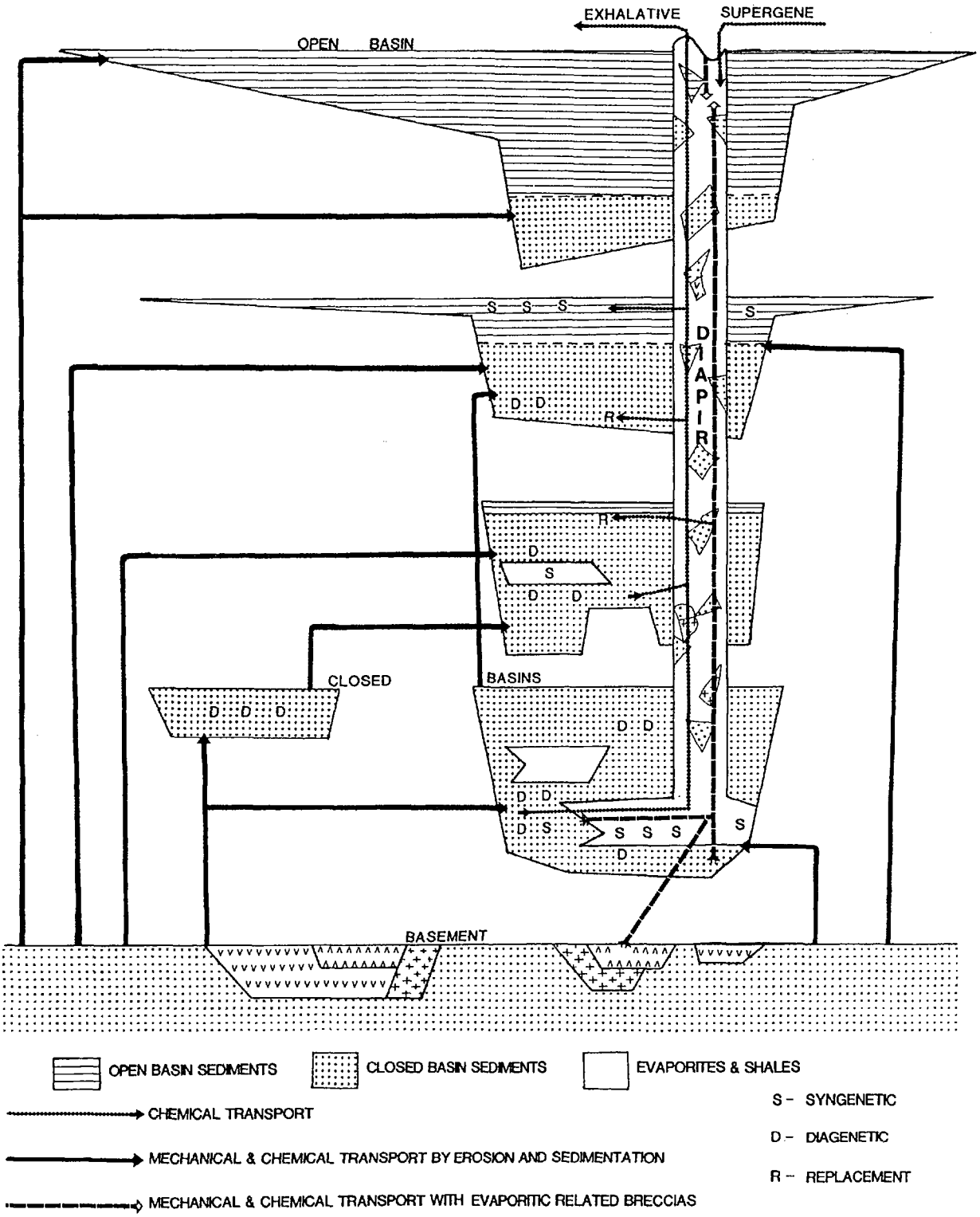

Figure 12: Schematic model for evolution of mineral deposits both in sediments and breccias largely based on Flinders Range model showing transport paths of mineralizing fluids.

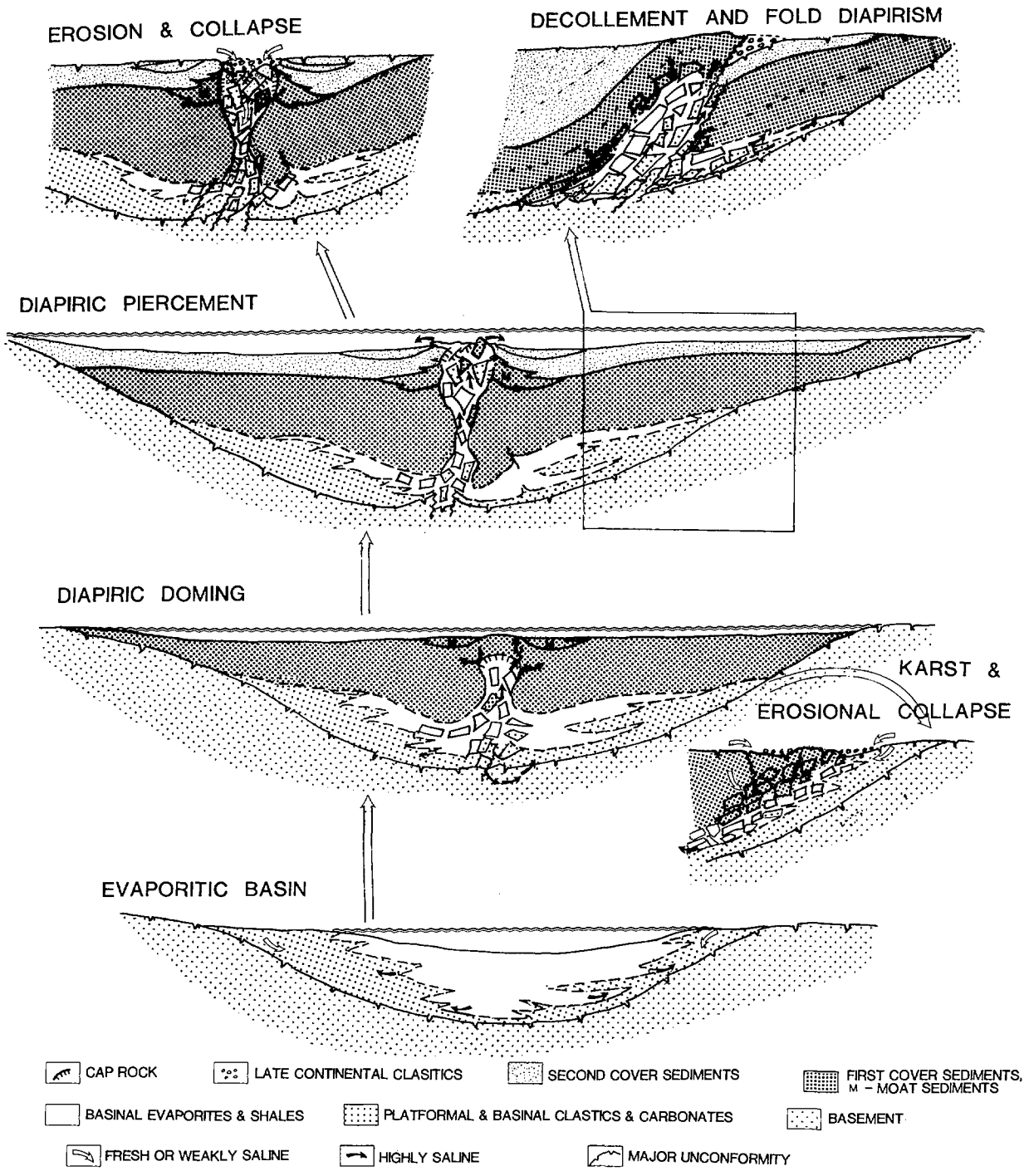

Figure 13: Schematic model for evolution of diapiric megabreccias and variations.

banded iron formation such as at Snake River [23-25, 28] in Canada and Braemar in Australia and the thin stratiform copper concentrations as in the Bunyroo in Australia may be a consequence of breached diapirs rather than contemporaneous volcanism or erosion of mafic piles yet unidentified.

(c) In any case, breaching, either during diapirism or by later erosion should ultimately permit weathering and removal of the most soluble of the evaporites and

slumping and clastic infilling of the upper parts of the original diapirs (these latter would impose sedimentary features tending to confound diapiric interpretations). Continued weathering would enhance development of supergene crust as well as secretionary deposits where deeper brine-rich and more reducing fluids would interact with descending meteoric waters. These later phenomena certainly have been important in Zaire and in Australia but may have been minimal in Yukon.

Two variants of this model could be expected. The first would have occurred during an intermediate stage of erosion and weathering wherein all or limited parts of the evaporite basin collapsed due to removal by meteoric waters of the saline components and thus produce a stratabound karsted and solution-breccia zone. This may have been applicable to parts of the Adelaide breccias [35]. The second variant would have occurred where the evaporite zones behaved as decollements and in overthrusting resulting in thick brecciated klippes. Such may be the case for the Kolwezie "dome" in Zaire. In both variants diapirism might have occurred further out in the basin (for another variant on this scheme see [40, 41]). In all cases the initial phase of syngenetic and diagenetic mineralization as well as variation in the mechanical and chemical aspects of evaporites would have influenced later mineralization.

5. DEPOSITS AND THEIR PREDICTION

The only truly economic deposit of uranium in megabreccia in these areas was (is?) Shinkolobwe in Zaire. In Australia uranium deposits appear to be trivial except at Mount Painter [19, 20] where breccias are unlikely to be directly related to diapirism but are more likely attributable to later (even post-Delamerian orogeny) seepage of iron-rich hydrothermal solutions [19], which might still relate to this model. In Werneckes exploration of these deposits is at present dormant and further work must be done.

An important indirect aspect is that of the highly successful grassroots search by Western Mines for sources that resulted in the discovery in the mid 1970s, of the huge Fe-Cu-U-Au Olympic Dam deposit and other similar indices on the Stuart Shelf in Australia [17, 18, 58]. These deposits lie in the basement and were likely developed at the close of or immediately after craton (basement) stabilization. Undoubtedly these types of deposits contributed to the types of deposits seen in the Adelaidean megabreccias through erosion and redeposition into closed basins or later by deep scavenging by brines (perhaps as envisioned by Davidson [57]). Thus in this context the same sort of grassroots search can and should be made near the Copperbelt and near the Werneckes for similar source deposits.

A final aspect is that of the little appreciated fact that Shinkolobwe also produced Pt-Pd [3]. Perhaps we could look closer at these three areas for platinum group elements. If discovered, such deposits would gain greater economic viability through greater diversity of recoverable metals in addition to uranium.

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THE FORMATION OF INFILTRATION-TYPE URANIUM DEPOSITS ASSOCIATED WITH GRANITIC AND METAMORPHIC BASEMENT COMPLEXES — EXPLORATION GUIDELINES

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Abstract

Granitic and metamorphic basement complexes are commonly the source areas for a wide variety of groundwater infiltration type uranium deposits. Deposits associated with these complexes may be classed as a) proximal (basal-type); b) distal (channel, basal, roll-front types); c) supergene in-situ and d) surficial 'young' deposits. Such deposits have generally formed during Tertiary and Quaternary times. Fertile basement complexes have undergone a multiphase history of intrusion and an important period of extensional tectonism which has led to optimum hydrological development. The high density of micro, macro and mega fracture zones and their high degree of interconnectivity ensures maximum groundwater -- rock interaction within these complexes. Sediment hosted uranium deposits on, or adjacent to, these basement complexes occur over or along the extensions of major structural zones which appear to be the loci for regional groundwater flow.

An examination of present day groundwaters draining fertile basement complexes can often explain the composition of associated uranium deposits. The availability of such elements as Ca, Mg, K, Ba, Pb, P, and V for groundwater leaching has resulted in economic concentrations of unusual primary uranium minerals such as ningyoite, francevillite, saleeite, uranocircite, autunite and carnotite.

Most of the proximal and distal infiltration-type uranium deposits found to date are exposed at surface or occur under very shallow cover. The incorporation, in an exploration program, of the genetic, geochemical and geological features just described is, therefore, paramount if deposits under thicker and more extensive cover rocks are to be found. The association of these deposits with basement structures, such as fault zones and small grabens, is so universally consistent that geophysical and photogeological techniques of detecting or extending such structures under regions of extensive cover rocks (e.g., tertiary volcanic fields) should be mandatory in any exploration program. Detection of surficial uranium deposits is dependant upon recognition of potential source lithologies, suitable climatic conditions for formation, and geomorphic features capable of trapping uranium.

Regions with the greatest potential for the above mentioned types of uranium deposits are generally characterized by uplifted segments of felsic intrusions or metamorphic biotite-gneiss, mica-schist basement rocks that have undergone extensive fracturing and block faulting and that have experienced at least one period of tertiary erosion followed in some cases by continental volcanism.

THE GREEN MOUNTAIN URANIUM DISTRICT, CENTRAL WYOMING: TYPE LOCALITY OF SOLUTION FRONT LIMB DEPOSITS

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Abstract

The Green Mountain uranium district, an up to 24 Km (15 miles) long and 4 Km (2.5 miles) wide area contains known mining-diluted reserves in excess of 70 million pounds U308, ranging in grade from 0.20% to 0.23% U308. As of yet, undefined resources could approach an additional equal amount. The host rock for these reserves is the Eocene Battle Springs formation, an over 1,500m (5,000 feet) thick sequence of continental fluvial deposits consisting of arkosic sandstones, conglomeratic sandstones, and siltstones. The Granite Mountains, an ancient crystalline high, supplied the detritus for both the Battle Springs formation to the south and the Wind River formation of the same age to the north. The latter area contains the Gas Hills uranium district. Despite source rock and age similarities, remarkable differences exist between the districts in respect to the morphological habit of uranium concentrations. Significant uranium mineralization in the Green Mountain district occur at the interface between carbonaceous trash-rich siltstone lenses, acting as reducers, and the more permeable arkosic sandstone and/or the conglomerates. Where a high frequency of these interfaces exist and oxidizing waters penetrated these reducing siltstones, economically significant deposits can occur. Based on drill log data, it is postulated here that the uranium of Battle Springs formation was originally introduced into the sediments during deposition or very shortly thereafter. A regional redox cell known to extend over a stratigraphic thickness in excess of 1,200m (4,000 feet), concentrated the intraformational uranium when surface water during a later erosional cycle could penetrate the Battle Springs formation. Locally, these redox cells with high grade limb deposits are very complex because aquicludes are absent.

1. Introduction

Since the inception of the concept of chemical fronts related to uranium deposits in arkosic sandstone in the Gas Hills over 30 years ago, numerous papers have been published on the form and mechanism of roll front, also referred to as solution front, or Wyoming sandstone uranium deposits [1,2]. Ideally, these deposits are depicted as C-shaped concentrations in cross-section with the highest grade and most abundant ore occurring in the frontal or C-shaped zone.

Paramount to this concept is the redox boundary, the zone between the reduced (fresh, unaltered) and oxidized (altered) host rock. This concept has been used so successfully world-wide for the exploration and delineation of sandstone-hosted uranium deposits.

The morphological aspect of uranium mineralization of the Green Mountain district differs significantly from other roll front uranium districts. These differences are directly the results to the depositional environment of the Green Mountain host rock and have important implication in the exploration, delineation and evaluation of these types of uranium deposits [3].

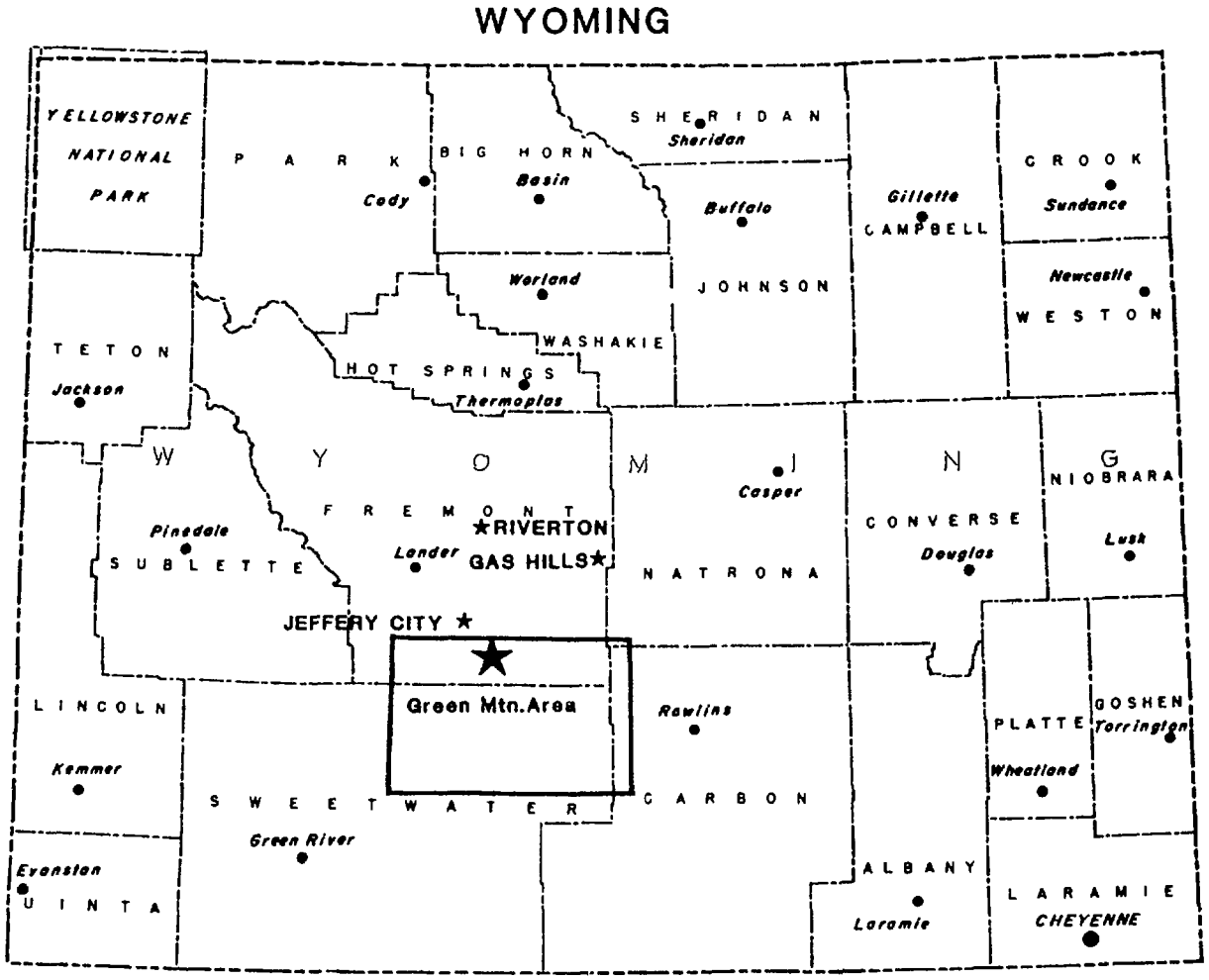
There are many uranium deposits and occurrences in the Great Divide (Red Desert) Basin besides the Green Mountain (Crooks Gap and Sheep Mountain) deposits. However, the difference in morphology (e.g. Sweetwater deposit), host rock associated (e.g. lignite or sub-bituminous coal) and age (e.g. Lost Creek schroeckingerite, a caliche-type occurrence) are unlike the Green Mountain-type limb deposits present in the ancient sedimentary basin inlet area, i.e. the Green Mountain.

Geological description of the Crooks Gap area, which has produced uranium since February 1957, do not mention the morphological difference between classical roll fronts vs. limb deposits described here. However, Bailey was the first and only author to mention that uranium occurs over a thick stratigraphic range (450m [1,500 feet]) in the Crooks Gap area and that it was difficult to follow individual rolls as ore trends tend to be erratic [4]. Besides, the depositional host rock environment of the early Crooks Gap mines were in a lower stratigraphic level when compared to other Green Mountain trends so that the uranium concentrations are of different form for part of the district.

Limb-type deposits have been mined by open pit and underground methods at the Big Eagle Mine. Observation from this area and data from hundreds of exploration and development holes which have defined underground mining-thickness diluted reserves of 70 million pounds U308 in the 0.20 to 0.23% range does warrant to designate this area as an uranium district.

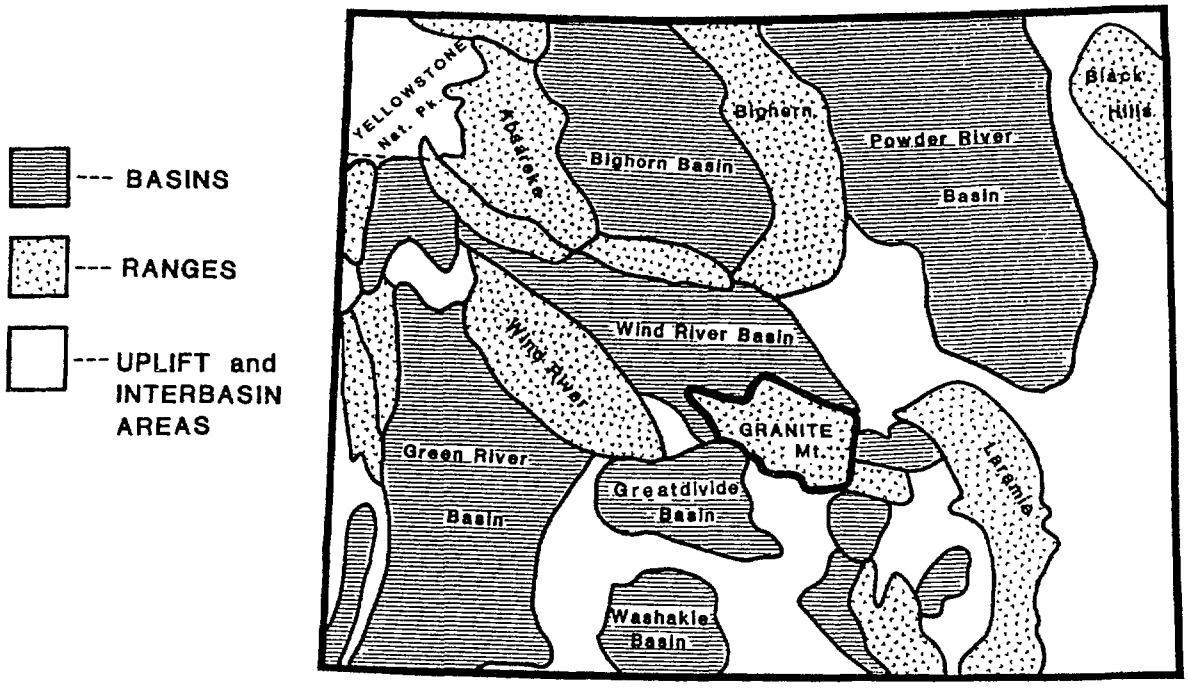
2. Regional Setting

The Green Mountain uranium district is located in southern Fremont County, Central Wyoming. Green Mountain forms a prominent topographic high rising 750m (2,500 feet) from the surrounding terrain to an elevation of 2,750m (9,000 feet) (Fig. 1). It is part and forms the northern fringe of the Great Divide basin, a structural and topographic depression, except for Green Mountain, encompassing approximately 9,300 km^2 (3,600 square miles) (Fig. 2). This basin borders to the north for the Granite Mountain Province, an Archean (approximately 2.8 to 2.5 b.y.) granitic and metamorphic complex. The Gas Hills uranium district is on the northern fringes of this ancient crystalline complex in the Wind River Basin. The two districts are about 15.6 km (25 miles) apart (Figs. 3 and 4).



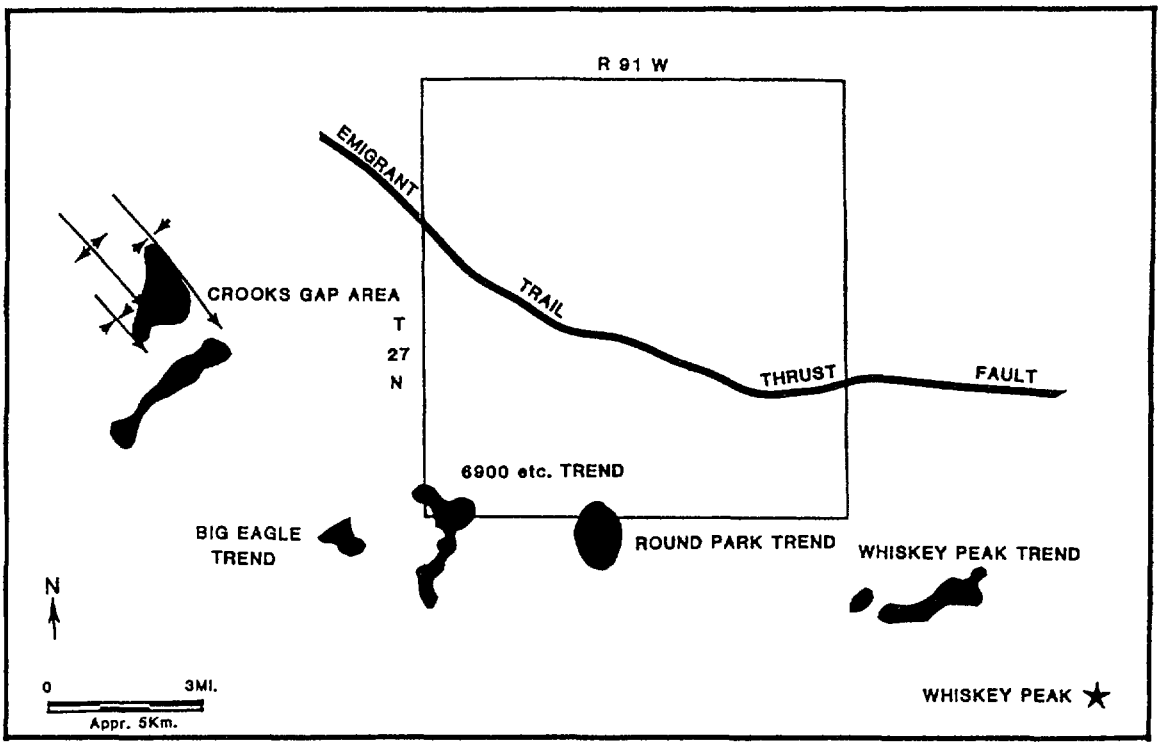
INDEX MAP

FIG. 1.



MAJOR WYOMING BASINS and RANGES

FIG. 2.



GREEN MOUNTAIN URANIUM DISTRICT MAIN ORE TRENDS

FIG. 3.

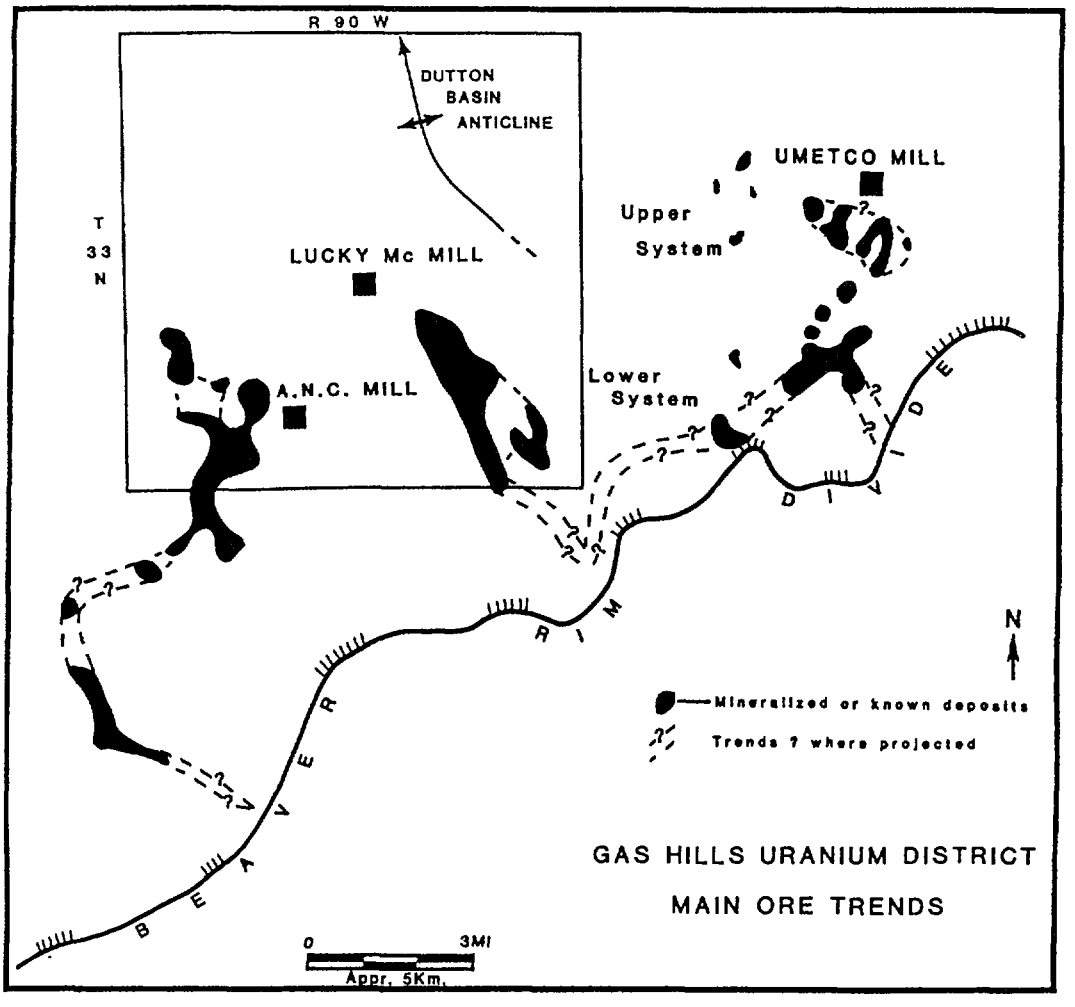
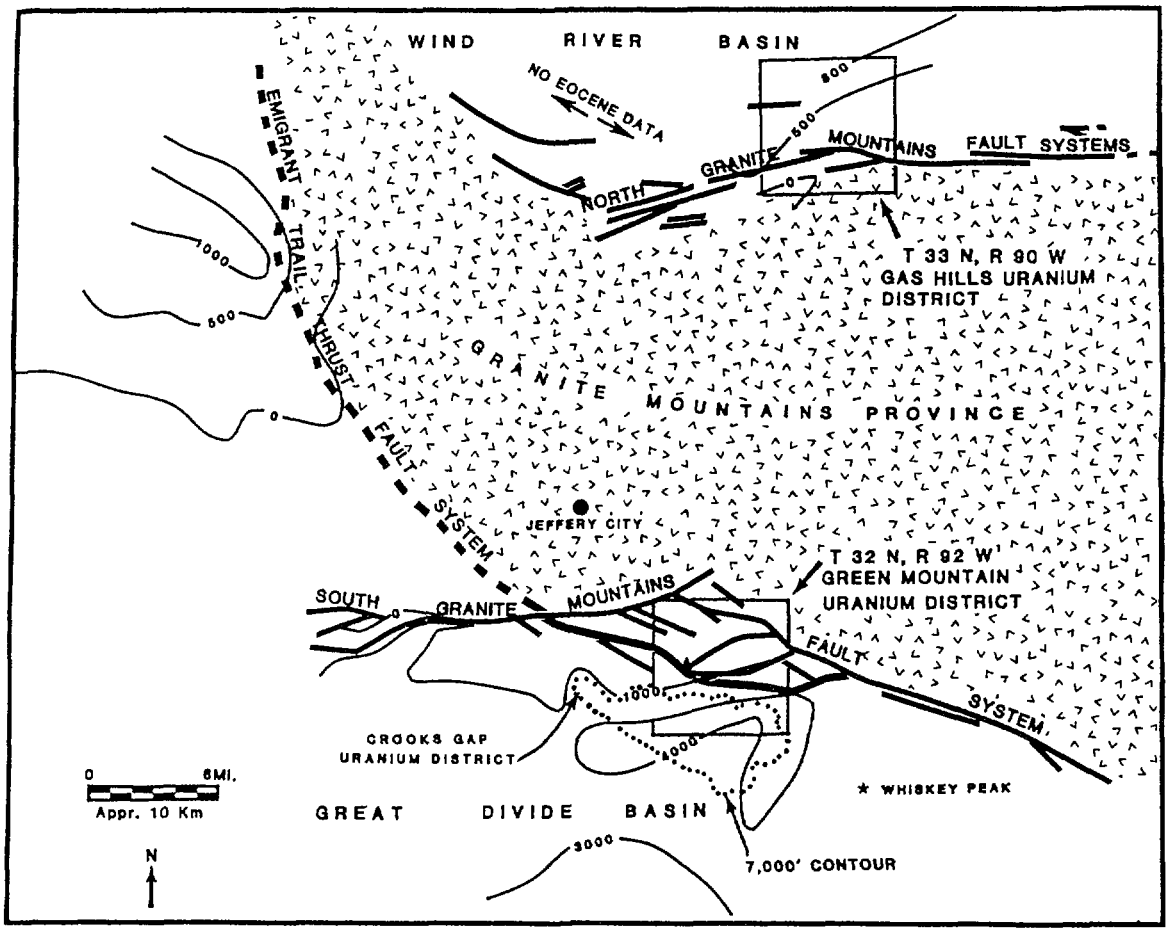


FIG. 4.

The Crooks Gap (Sheep Mountain) uranium deposits are to the west and interfingers with the 24 Km (15 miles) long and up to 4 Km (2.5 miles) wide Green Mountain district. Both areas are truncated to the north by the Imigrant Trail Thrust and South Granite Mountain faults. The Whiskey Peak area, a topographic high, is the eastern extension of the district.

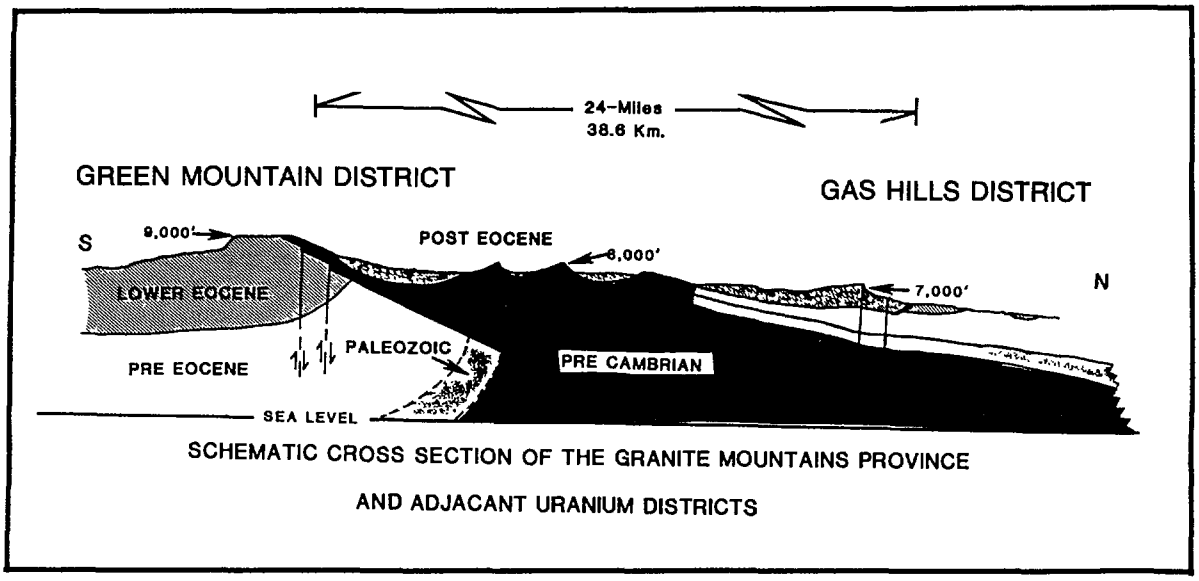
During early Eocene times, the western part of the Granite Mountains Province was a topographic high supplying detritus to the Great Divide and Wind River basins (Fig. 5). Near the source, the Eocene sediments are coarse decreasing in grain-size towards the basin interiors. Judging by the large amounts of conglomerates and



ISOPACH OF LOWER EOCENE FORMATIONS AND GEOLOGICAL FRAME

FIG. 5.

the greater stratigraphic thickness, the Green Mountain area was at or near the basin inlet area, particularly when up to 520m (1,700 feet) of lower Eocene Crooks Gap Conglomerate, containing some garage-size granite boulders, is added to the 1,220m (4,000 feet) Battle Springs formation. Post Eocene thrust and reverse faulting has elevated the Green Mountain lower Eocene rocks at least 300m (1,000 feet) above the present erosional surface of the Precambrian crystalline terrain (Fig. 6).



SCHEMATIC CROSS SECTION OF THE GRANITE MOUNTAINS PROVINCE AND ADJACANT URANIUM DISTRICTS

FIG. 6.

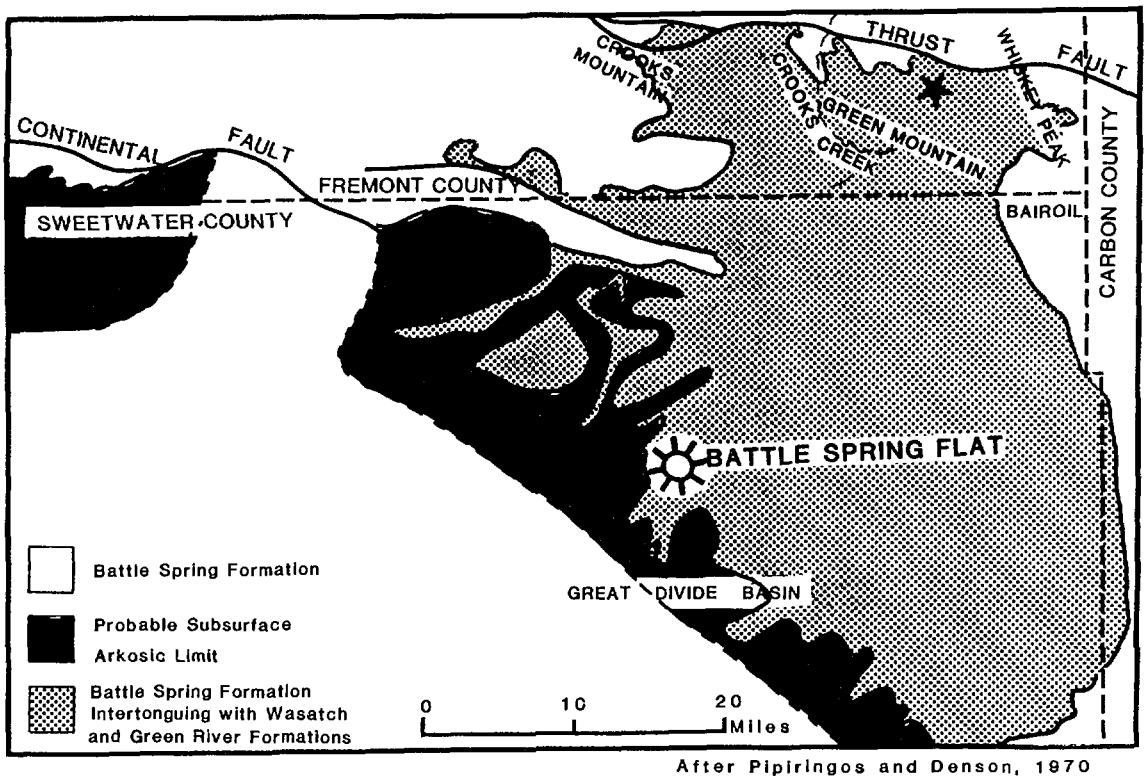
3. Stratigraphy and Lithology

The host rock of the Green Mountain District is the Battle Springs formation of lower Eocene age which is known to contain uranium between at least 900 m (3,000 feet) of stratigraphic thickness.

Early workers correctly recognized that the rocks outcropping at and around Green Mountain are time-equivalent to the wide-spread Eocene Wasatch formation consisting of loosely consolidated continental fluvial deposits. A separate formation name was proposed by Pipiringos in 1955 after the outcrops located at the Battle Spring Flat in the central area of the Great Divide Basin [5,6] (Fig. 7).

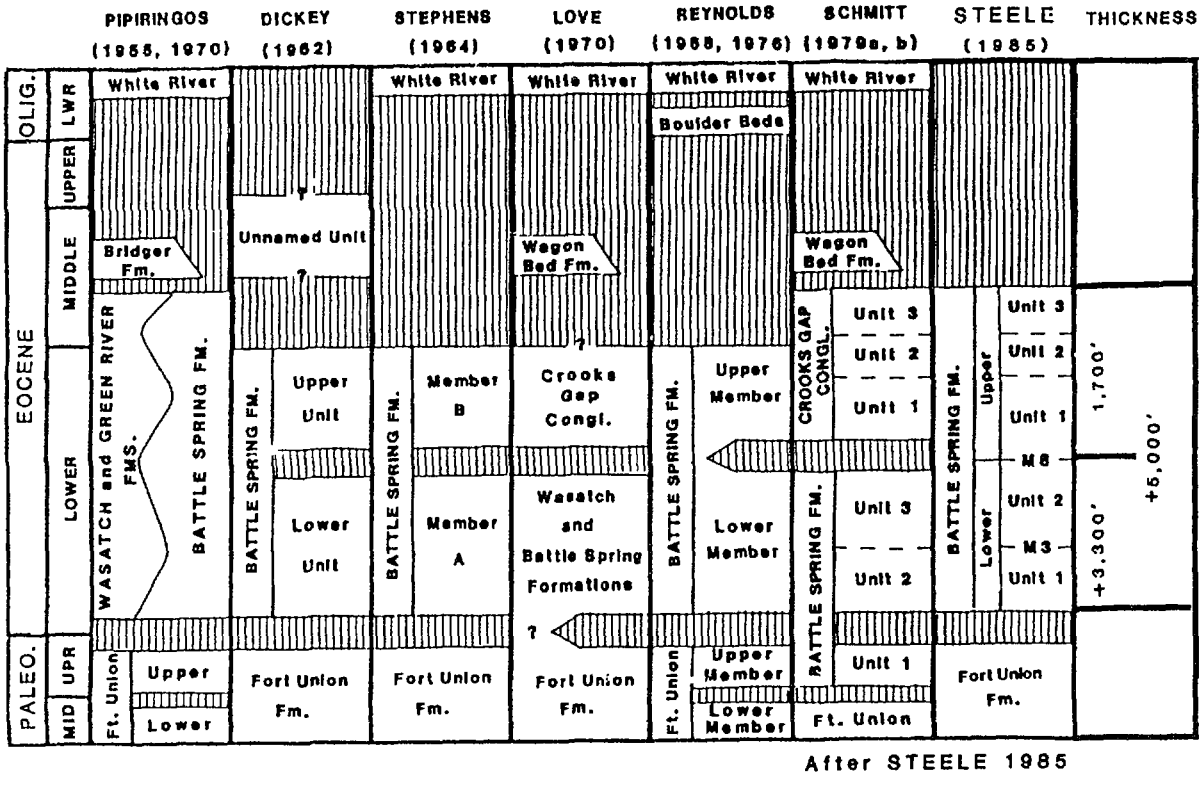
The existence of an up to 15^{o} angular unconformity in the Crooks Gap area is the reason by USGS authors to elevate the upper 520m (1,700 feet) section of Battle Springs formation into a separate unit, e.g. Crooks Gap Conglomerate [7,8]. Based on drill cuttings, cores, and electrical logs, our work does not justify this subdivision as the lithologic character and the interpreted depositional regime are essentially identical with the lower section of the formation. The conglomeratic fraction is more abundant in the upper section while arkosic sands increase in frequency in the lower Battle Spring formation. It is interesting to note here, that drill penetration rates increase with depth to correspond with the decreasing conglomerates and increased sands. Using a Markov analysis for one 3,150 feet deep core hole started in the top of Green Mountain, Steele recently also retained Pipiringos' original nomenclature [9] (Fig. 8).

The lower contact of the Battle Springs is possibly gradational with the upper Paleocene Fort Union formation, which contains on the top very fine-grained sands. Based on oil well data, the Battle Springs is at the thickest section approximately 1,750 m (5,700 feet) thick where the Crooks Gap Conglomerate is included in the formation.



Extend of Battle Spring Formation

FIG. 7.



After STEELE 1985

Battle Springs Nomenclature and Thickness

FIG. 8.

The regional dip of the formation is one to three degrees to the northeast, or reversed from the original depositional gradient. At the extremes of Green Mountain, e.g. Crooks Gap to the west and Whiskey Peak to the east, beds dip locally as much as 65^{o} to the southwest and 15^{o} to the west, respectively. The steep dips in the Crooks Gap area are due to the Sheep Mountain and Crooks Gap folds.

The three principle rock types are conglomerates, arkosic sandstones, and siltstones. The first two rock types make up most of the formation and are in excess of 90% of the entire lithologies. Pure end members are uncommon and intermixing of the end members is a rule rather than an exception, especially between the conglomerate-sandstone and sandstone-siltstone association. Sedimentary features such as large-scale cross bedding, channel fills, and sandstone or silt intercalation in conglomerate are common and point to a high energy depositional environment. Other features observed include frame work (clast) support which predominates rather than matrix support in the conglomerates and sandstones and the existence of reverse graded bedding or upward fining.

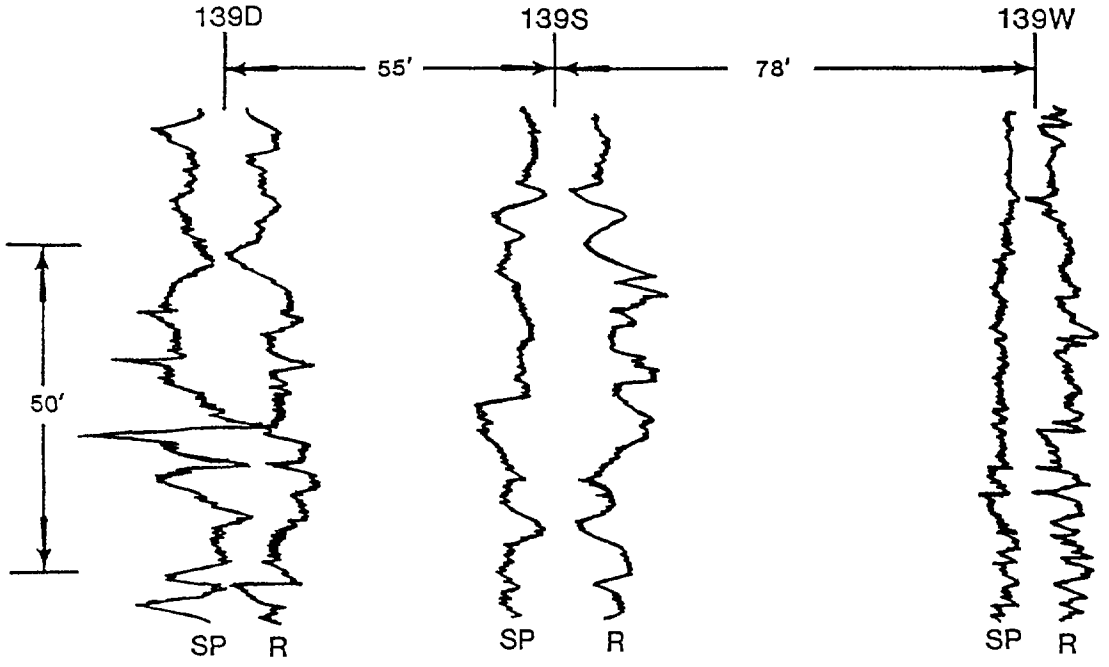
By far the most predominant clasts of the conglomerates are a light colored to pinkish, coarse to medium-grained alkaline granite containing biotite as a pervasive accessory mineral. Altered mafic clasts of diabasic composition are present, but are uncommon.

The sandstone fraction consists of quartz (50%), feldspar (35%) and granitic rock fragments (15%) with minor micas (greenish biotite, muscovite - some altered to sericite), chlorite, glauconite and traces of heavy minerals (zircon, tourmaline). The grains are angular to sub rounded while coarse to very coarse size ranges are most common. Most sandstones are friable and lack cementation except(?) near areas of uranium mineralization where calcite, pyrite or iron oxides may be present.

Siltstones are essentially of the same composition as the sand-size fraction with the exception that organic trash has been preserved predominantly in this size range and minor amounts of volcanic glass fragments or its alteration products have been noticed [10]. The organics consist most commonly of discrete fragments of leaves, twigs and other plant material having been subject to physical disintergration so that organic particles are common. Some tree trunks, branches, and hand-size leaves (sycamore?) have been found in the Big Eagle Mine where tree trunks in growth position, slanted and parallel to bedding have been excavated.

Examples of the SP (self potential) and R (resistivity) response is shown in Fig. 9 representing data from a wedged hole 17m (55 feet) and 24m (78 feet) apart at a depth of 625m (2,050 feet). From the electrical log it should be noticed that there is a general lack of correlation of "shale breaks" representing thin siltstones and the inability, as confirmed by coring, to differentiate between conglomerates and sandstones. As observed from cuttings and electrical logs, better defined sandstone beds predominate the lower (+770m [2,500 feet]) tested section of the Battle Springs formation.

To date no persistent coarse or fine-grained marker beds have been identified from the Big Eagle open pit mine, cored sections, or

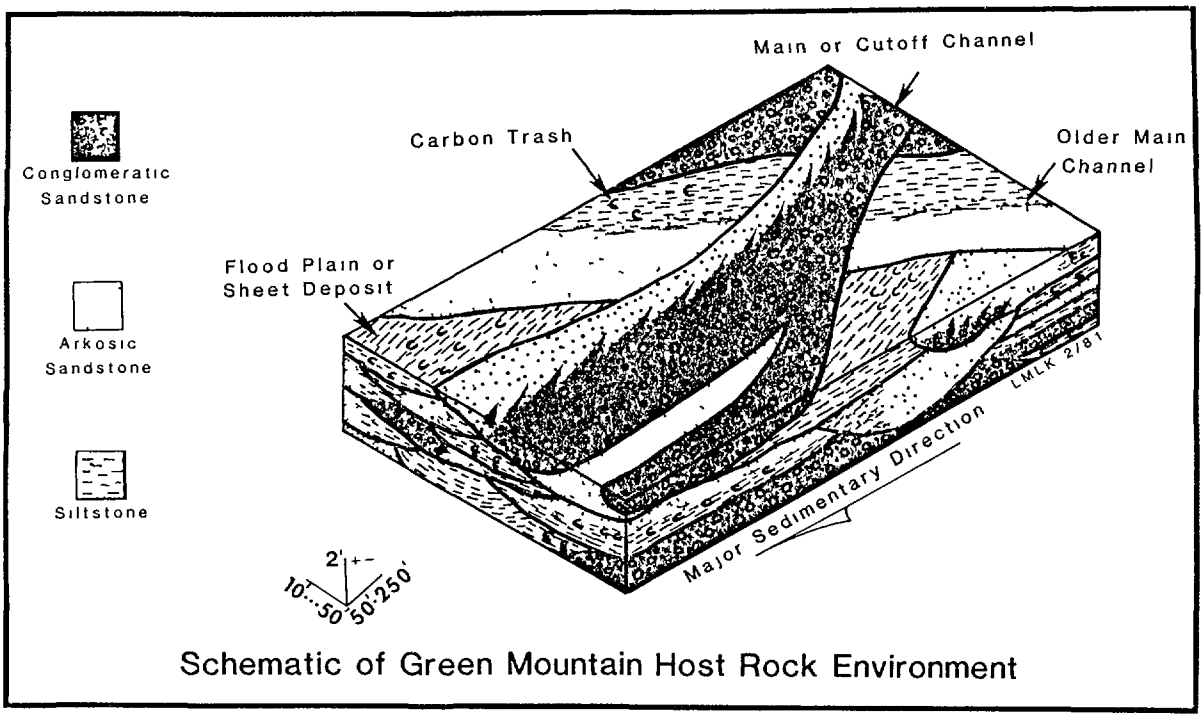


Example of Electric Logs
Lower Battle Springs Formation

FIG. 9.

numerous up to 4,000 feet deep plug drill holes. In fact, correlation between drill holes as close as 17m (55 feet) is mostly impossible from either drill cutting or electrical logs.

From the foregoing descriptions, the depositional environment is envisioned as depicted in Fig. 10. It is interpreted to be the proximate reaches of a Piedmont terrain where neighboring mountain streams coaless.



Schematic of Green Mountain Host Rock Environment

FIG. 10.

4. Mineralization and Alteration

Secondary uranium concentration or epigenetic mineralization are known in the Battle Springs formation from Crooks Gap (Sheep Mountain) to Whiskey Peak, a distance of 24 km (15 miles). The stratigraphic thickness between the highest and lowest mineralization is known to be in excess of 900m (3,000 feet). Untested ground of the district could possibly increase the stratigraphic interval containing solution front uranium deposits.

Uranium mineralization occurs as uncolored (host rock color), dark gray to black amorphous interstitial fillings and impregnations. The principle uranium minerals is a mixture of coffinite and uraninite [11]. Economically important uranium mineralization is related but not restricted to organic fragment-rich siltstone lenses, especially those which are adjacent (stratigraphically below and above) to altered arkosic sandstone and conglomerate beds. Not all siltstones are mineralized even though evidence of alteration and organic trash is present. Some mineralization is present in the arkosic sands and conglomerates but the grades tend to be lower than the adjacent siltstones. All rock types devoid of visible organics can contain mineralization and sandstones without siltstone can contain high grade mineralization (+1.0% U308).

Characteristically the mineralization is thin (less than 0.6m [two feet]) and relatively high grade. Using a 0.05% radiometric cutoff, 85% of a part of Pathfinder's 6,900 trend, intercepts are two feet or less thick. For these same intercepts, 25% contain 1.0% or better radiometric U308. The existence of these thin high grades zones has been confirmed with deep coring. As is common with solution front uranium deposits, the higher grades tend to be in positive while the lower grades tend to be in negative disequilibrium state for cores tested.

The alteration colors and products are similar to those observed in other sandstone-type deposits containing iron sulfides. Reddish, pinkish and orange hues (10YR8/2, 10R7/4, 5R4/6, 5Y8/4, 5YR8/1 etc. -- GSA rock color chart) are common in the oxidized (altered) zone which has been observed to attain a stratigraphic thickness of over 1,200m (4,000 feet). Under ideal conditions, such as clear drilling fluids (aeriated water or light foam) a slight difference in color hues can be observed between the altered and weathered zones which extends over the 6,900 feet trend to a depth of 200 feet. Reduced (unaltered, fresh) colors are in the gray range (N-5 to N-7).

Pyrite and/or marcasite is present in the reduced (unaltered) section as very fine to microscopic-size grains which tend to have both euhedral and reniform crystal faces. Based essentially on megascopic observations of drill cuttings with all of the inherent limitations, sulfides are most common in the carbonaceous siltstones and related rocks, although not all carbonaceous silts contain iron sulfides. Fist-size, elongated pyrite-cemented concretions have been observed in the Big Eagle Mine area in very coarse arkosic sands. Megascopic evidence shows that the center of these concretions contain remnants of organic fragments like broken-off twigs. Calcite cement is not pervasive and is related and appears to be restricted to the redox system.

Peculiar to the Green Mountain district is the fact that redox boundaries and also mineralization occurs over a thick stratigraphic thickness which, in plan view, may be overlapping, sloping, or interfingering. Interfingering of oxidized-reduced strata is a rule rather than an exception so that it becomes misleading to think of a redox boundary in the common sense. Instead, the redox boundary should be visualized in three dimension or as a ratio of reduced to oxidized strata in relation to a certain stratigraphic thickness.

The background gamma count for oxidized strata is between 50 and 70 cps (2.4 to 3.3 ppm eU308) and from 70 to +250 cps (3.3 to 12.0 ppm eU308) or a median value of 100 cps (4.8 ppm or twice background) for reduced ground (Fig. 11). Incipient oxidation is usually not detectable from the color changes of the drill cuttings. Spikey or thin mineralization with high background (+100 cps) are interpreted to be the characteristics for this oxidation stage.

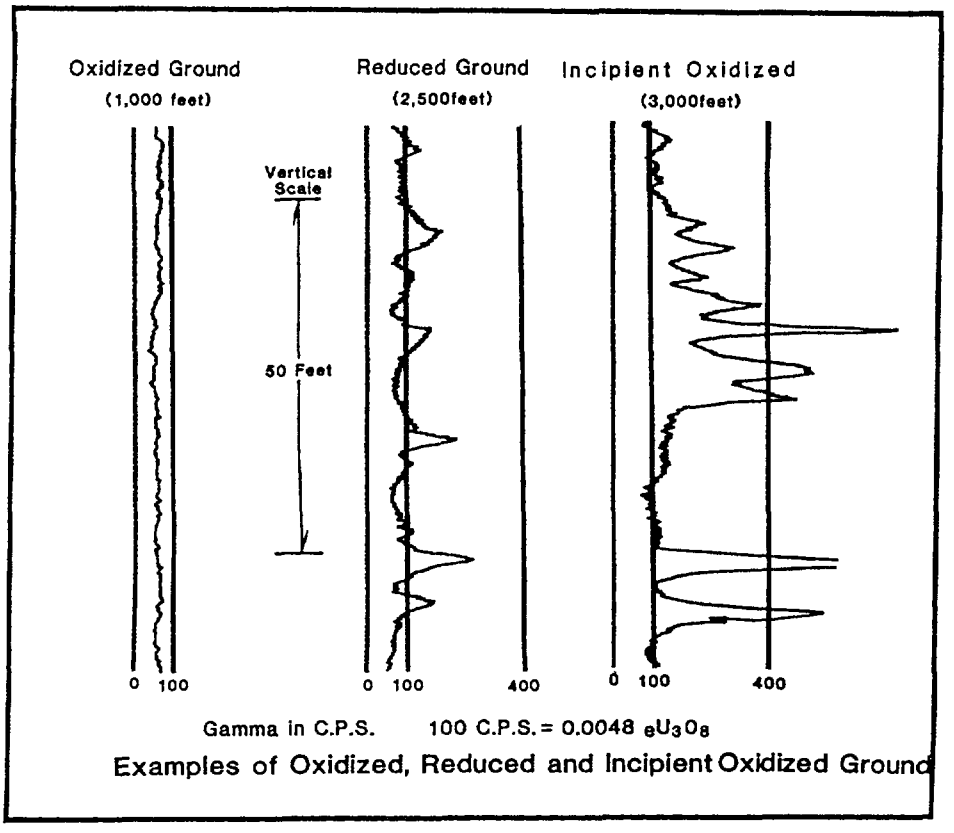
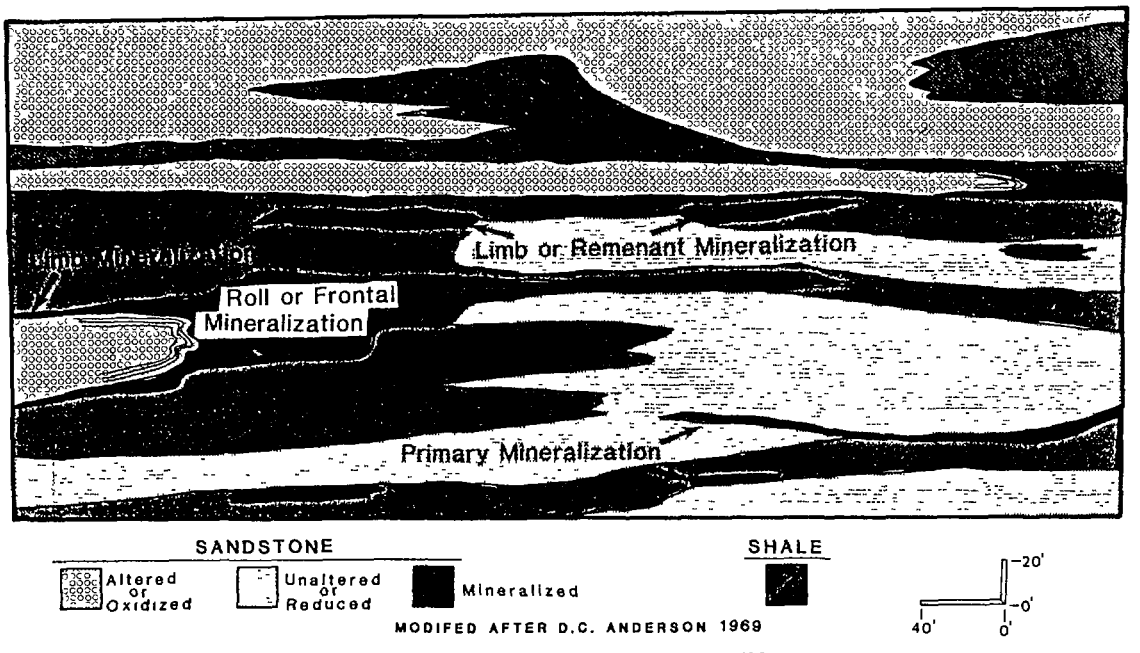


FIG. 11.

5. Review and Morphology of Roll Front or Solution Front Uranium Deposits

The concept of solution front uranium deposits was developed in the early fifties in the then young Gas Hills uranium district [1,2]. This concept was based on acute field observations such as trenches and drill hole data. Later, as the first uranium ore was mined by open pit method, the boundary of ore vs. no ore, e.g. the concave side of the C or roll front could be depicted with knife-edge accuracy the term roll front was used to describe this phenomena.

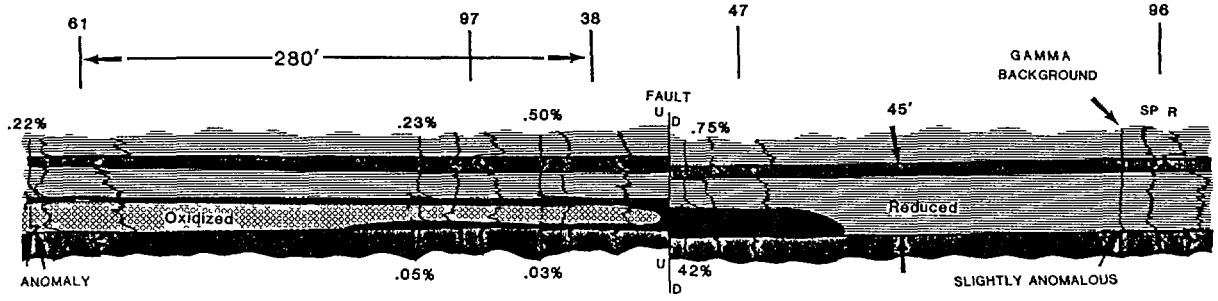
One of the best actual cross-section based on detailed data rather than idealized imaginations in the literature depicting the morphological character of a roll front is a cross-section produced by Anderson which is shown with modifications in Fig. 12 [12]. This picture is quite different from the idealized sketches seen in almost all published articles depicting roll fronts. Although Anderson does not elaborate on the morphology of uranium concentrations, three different types are recognized here, namely, roll or frontal, limb or remnant, and primary mineralization. Miners working in the Gas Hills and other Wyoming districts definitely know the difference between roll and limb ore! The former type is of higher grade and thicker and is and was the desirable target in most of Wyoming's uranium mines. As depicted in Fig. 12, the limb ore is relatively thin (less than 0.6m (2 feet)) and tapers off to nothing. This mineralization commonly extends for not more than 12m (40 feet) from the front or roll. Remnant mineralization is detached from the roll front and appears to be isolated. Essentially it is uranium mineralization left behind. Primary mineralization is interpreted by this author to be of original origin and has not been subjected to concentrating or mineralizing fluids.



Morphology of Uranium Rollfront
Gas Hills District - Actual

FIG. 12.

An interpreted roll front model of the Grants District is shown in Fig. 13. Although there are some similarities, the obvious difference is not only the relatively simple morphology but also lateral extend of the upper limb mineralization. From a miner's standpoint, the upper limb can be mined for a distance of over 280 feet behind the frontal ore. In this case there is no economic significance of the lower limb. Also, notice that the oxidation "follows" the bottom of the lower sandstone unit. At a large distance behind the frontal zone, the entire sandstone unit will be oxidized.



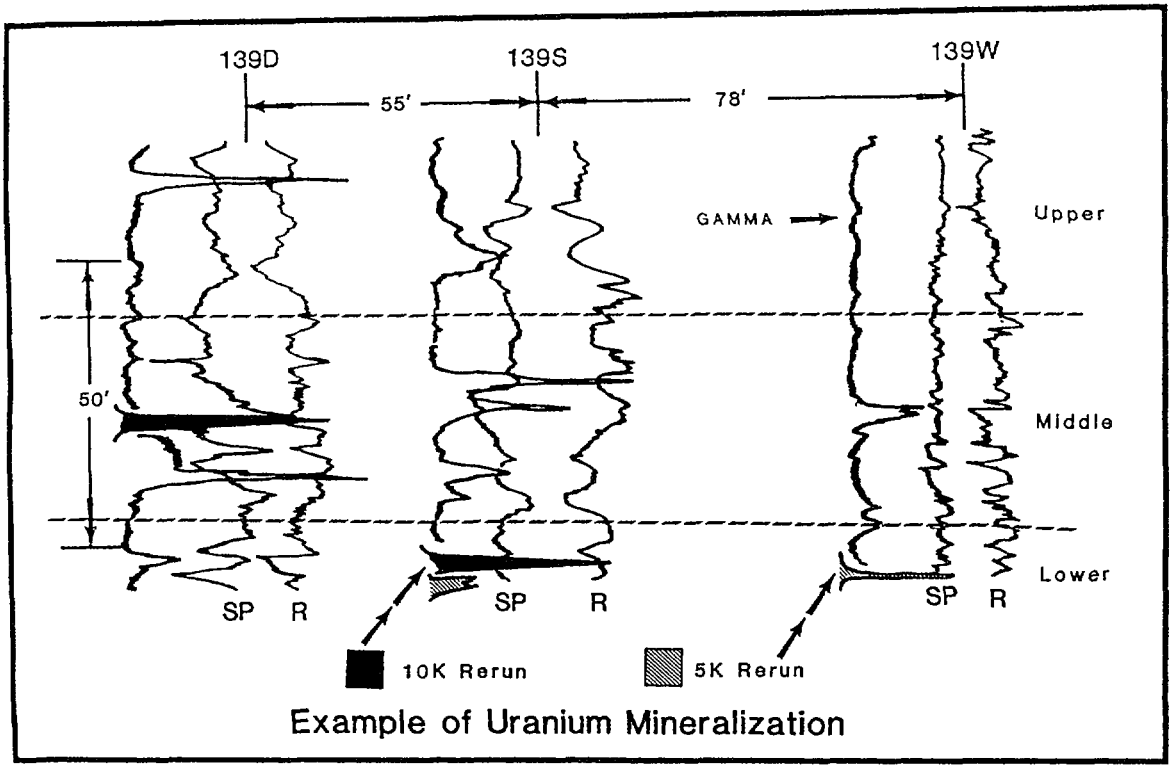
Rollfront Uranium Mineralization, Grants District - Projected

FIG. 13.

In summary, the morphology of uranium roll front deposits is a reflection of the confining clay beds or aquiludes and the porous strata between these clays. Multiple aquiludes and aquifers will host a morphological more complex roll front system than a single aquifer sandwiched between two continuous aquiludes.

6. Model of Green Mountain Type Limb Deposits

The thin nature of the mineralization is shown in Fig. 14 and Tables I and II. This data demonstrates two important criteria which need to be incorporated into any model for the Green Mountain area. These criteria are: 1) the absence of thick mineralization or thick anomalous zones and, 2) the apparent lack of correlation between mineralized zones although the strata is essentially horizontal (0.5 to 2^{o} dip). This pattern is present throughout the district, not only for anomalous but also for mineralized zones (+0.05% eU308). An increased frequency of individual mineralized zones and stronger



Example of Uranium Mineralization

FIG. 14.

Table 1

Grade (eU308) and Thickness (Feet) of Wedged Hole No. 139*

Lower Battle Spring Formation

Possible Correlative Zones	139D	139S	139W
Upper	1.4' at .05	---	---
Middle	0.7' at .67	1.6' at .04	---
	1.9' at .06	1.7' at .07	1.5' at .03
Lower	---	1.2' at .46	---
	Anomalous	2.5' at .06	1.4' at .11

* Refer to Fig. 14.

Table II

Examples of Limb Type Mineralization
Green Mountain District

Zone*	Thickness (Feet) Barren	Thickness (Feet) Mineralized	Grade (%eU308)	GT (%eU308xft)
4.6	3.2	1.4	0.469	0.657
3.5	2.6	0.9	0.559	0.503
3.0	1.6	1.4	0.870	1.217
N.A.	N.A.	1.4	0.119	0.166
2.5	0.2	2.3	1.214	2.792
3.5	2.0	1.5	2.012	3.018
N.A.	N.A.	1.5	1.423	2.134
27.0	25.3	1.7	0.201	0.341
2.0	0.8	1.2	0.039	0.047
2.2	1.3	0.9	1.058	0.952
4.8	3.9	0.9	0.786	0.700
1.9	0.9	1.0	1.577	1.577
2.2	--	2.2	0.052	0.115
2.6	0.5	2.1	0.057	0.121
7.2	5.8	1.4	0.058	0.081
2.9	1.9	1.0	0.078	0.078
8.9	7.6	1.3	0.038	0.049
3.0	1.2	1.8	0.041	0.074
2.3	0.5	1.8	0.327	0.589
7.9	5.0	2.9	0.095	0.276
3.5	2.6	0.9	0.173	0.156
11.2	10.4	0.8	3.039	2.431
N.A.	N.A.	4.3	0.043	0.185

* From top of intercept to top of next lower intercept.

mineralization does occur in known ore trends. Although not all intercepts are as thin as those shown in the attached tables, there is definitely a lack of thick mineralization. It should be remembered here, that the 6,900 and Round Park ore trends have been defined with surface drilling. Ore trends occurring at depths in excess of 915m (3,000 feet) can not be drilled out economically on a 15.7m (50 feet) grid commonly used in open pit areas! Returning to the model, it is envisioned that the main mineralization is associated to sheet-type strata, e.g. carbonaceous siltstones, representing the smallest size fraction of the formation. When the mineralization and alteration are superimposed on the lithologic model, it can be visualized that because of the braided nature of the host rock, continuous sheets of mineralization in senso stricto is lacking (Fig. 15). Part of the individual sheet deposits, representing flood banks and/or temporary shallow depressions, were disected by later stream channels as shown in the top view of the model. Mineralized lenses in specific areas and restricted stratigraphic thickness can occur as shown

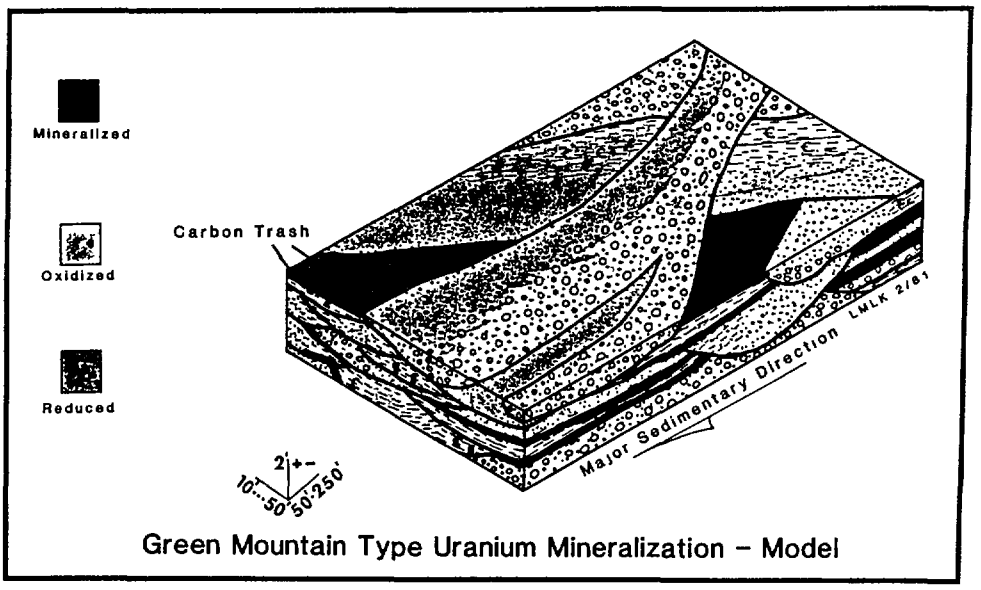


FIG. 15.

schematically in Fig. 16. Three hypothetical individual lenses are partially superimposed. From a geological standpoint, they represent three different events of silt deposition and subsequent mineralization. From an economic standpoint these lenses may be mineable underground only if 1) an individual lens contains sufficient mineralization like Lens I in the hypothetical example (Fig. 16), or 2) if two or more lenses are overlapping and combined with the intermittent unmineralized ground become economic.

This pattern of overlapping, sheet-like mineralization envisioned in the model is repeated for the central ore trends of the Green Mountain district. At the Round Park trend four major overlapping trends have been defined with a 122m (400 feet) drill grid containing in-between confirmation drilling. These major trends are separated by 91, 46, and 152m (300, 150, and 500 feet) or a total of 290m (950 feet) stratigraphic thickness! In this area the mineralization is stacked. In other areas, an en echolon or sloping pattern is present.

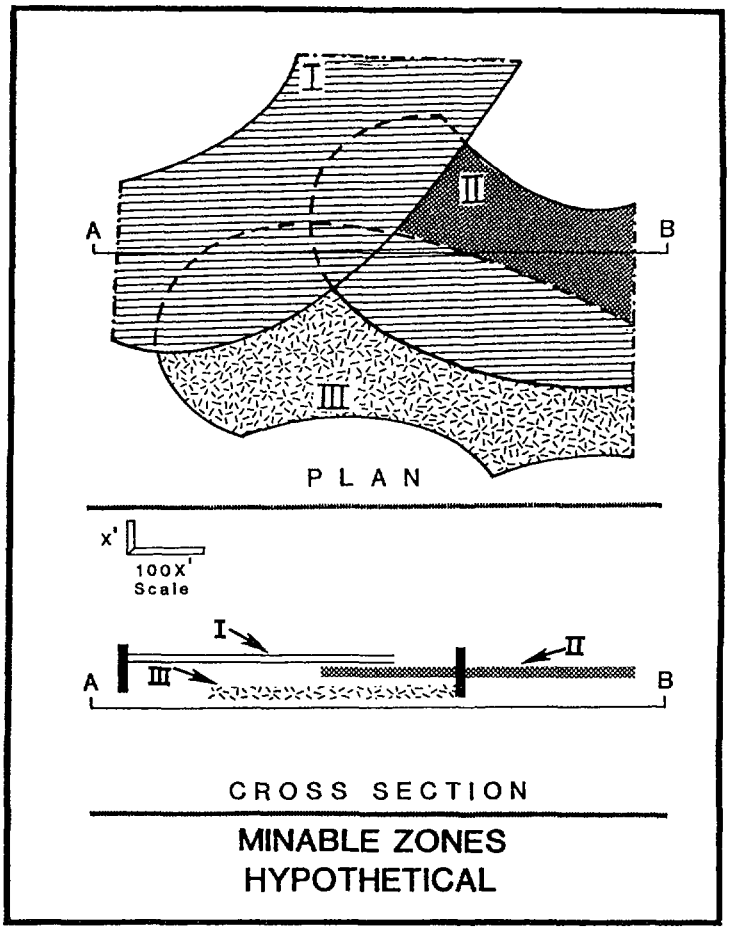

I
II
III
A
B
PLAN
X'
100X'
Scale
I
II
III
A
B
CROSS SECTION
MINABLE ZONES
HYPOTHETICAL

FIG. 16.

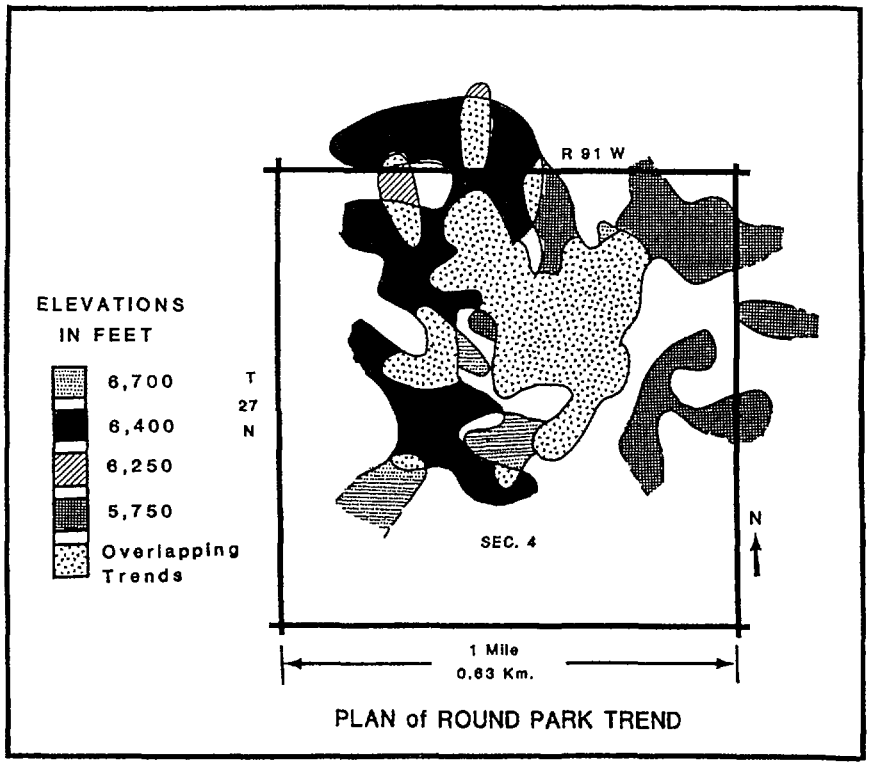

ELEVATIONS
IN FEET
6,700
6,400
6,250
5,750
Overlapping
Trends
T
27
N
R 91 W
SEC. 4
N
1 Mile
0.63 Km.
PLAN of ROUND PARK TREND

FIG. 17.

7. Conclusions

The western end of the Granite Mountains crystalline complex is bordered to the south by the Green Mountain and to the north by the Gas Hills uranium districts. Similarity between these districts include:

1) source and age of host rock,
2) uranium source,
3) age of uranium concentrations [13],
4) mechanism of uranium concentration.

Despite these same paramount criteria, a significant difference exists in morphological habit between the two districts. In fact, this difference exists even between the extreme northwestern end and the center of the Green Mountain district. This difference is contributed to the absence of continuous aquicludes in the Green Mountain area. The host rock here is a leaky aquifer, an uncommon host for solution front uranium deposits. Confining shales or even continuous semi-confining siltstone units are lacking because of sediments accumulating near a rapidly subsiding area adjacent to a rising source terrain. Under these conditions silts and grit-size sediments and particulate organic fragments deposited in temporary, perhaps seasonal, depressions. The depositional energy environment was too high to deposit appreciable amounts of clay-size particles even when these were deposited from airborne ashes.

It is postulated here, that the organic-rich depressions or puddles collected economically unimportant uranium during or shortly after sedimentation, definitely prior to compaction, when the system was exposed to original or depositional surface waters. The mechanism is visualized to be similar to the presently accumulating organic-rich surficial deposits in the western United States. At a later time, possibly with the beginning of the Oligocene and during the middle of the upper Oligocene (25 m.y.) the hydraulic gradient of the basin was such, that oxygenated surface waters penetrated the Battle Springs formation and formed a huge, complex redox front dissolving uranium from the Battle Springs host and concentrating it along the least permeable, discontinuous reducing barriers to form economically important uranium concentration or limb deposits.

ACKNOWLEDGEMENTS

The author is grateful to Pathfinder Mines Corporation for permission to present this paper and publish propriety data. U. S. Energy gave permission to use some of their drill logs and ore trend data. I also would like to acknowledge the discussions I have had over the years with my colleagues, specifically with D. C. Anderson, who were exposed to "buttered pancakes", "flattened plum puddings", "anti-swiss cheese", and "peanut butter sandwich" trends and other culinary ideas.

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URANIUM ROLL-FRONT DEPOSITS IN THE SOUTHERN BLACK HILLS, SOUTH DAKOTA

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Abstract

In the southern Black Hills of South Dakota, uranium roll-type deposits are present in early Cretaceous Lakota Formation sandstone. Analysis of a 45-foot drill core, representing a vertical section through the nose of the roll-front, by scanning X-ray fluorescence (XRF), standard XRF, X-ray diffraction (XRD), organic petrography, electron microprobe, and scanning electron microscopy (SEM) is underway.

The core is lithologically composed of an orthoquartzite with varying amounts of chert and consists of an oxidized zone, four reduced zones, and three ore zones. The oxidized zone is characterized by medium- to fine-grained, well-sorted, well-rounded orthoquartzite with minor hematitic kaolinite weakly cementing and coating quartz grains. Reduced zones have angular to rounded, medium- to fine-grained gray to black quartz grains; coarse-grained, angular, white to black chert; thin laminae and small isolated fragments of carbonaceous material with pyrite. Ore zones are composed of trough cross-bedded, poorly-cemented, well-sorted mixtures of rounded quartz grains and angular to rounded chert with yellow to olive-green uranium- and vanadium-rich clays, and carbonaceous material with pyrite.

The chemistry of the entire core was determined by scanning X-ray fluorescence for 46 elements. In the oxidized, reduced, and ore zones, uranium and vanadium averaged 40 ppm U and 3300 ppm V, 800 ppm U and 3000 ppm V, and 3800 ppm U and 5000 ppm V, respectively.

No uranium or vanadium minerals have been found by XRD or microprobe analysis. However, certain segments of the core are enriched in U and V, including those with high clay content. Preliminary SEM analyses have shown smectite, kaolinite, and possibly illite as coatings on quartz grains. U and V are present in some of the clay coatings, and probable carnotite and an authigenic vanadium mineral were found. Carbonaceous laminae are present in the reduced and ore zones and commonly contain pyrite with associated uranium.

1.1. Introduction

Although the uranium roll-front deposits of the southern Black Hills of South Dakota were mined successfully for a number of years, some fundamental questions remain concerning 1) how and in what minerals or other constituents the uranium is present, 2) what the source(s) of the uranium is(are), and 3) what is the relationship of these deposits to the regional geology of the Black Hills. Uranium roll-front deposits in other parts of the United States (Rackley, 1976) have been subjected to detailed and thorough study, and their origin and development is well understood. However, those in South Dakota have been relatively neglected. In a general way, they appear very much like other deposits, but in detail, there are significant differences in sedimentology, in age, in mineralization, and in relationship to the regional geologic setting. In the southern Black Hills, uranium roll-front deposits are in braided channel sandstones of Cretaceous age with only a minor feldspar component. Clay minerals appear to have been a favored site of uranium precipitation, and vanadium is a significant component.

1.2. Geologic background of area

The early Cretaceous Inyan Kara Group, which is divided into the older Lakota Formation and the younger Fall River Formation, is host to these deposits. The Lakota Formation makes up the lower two-thirds of the group and is 200-500 feet thick. The Lakota Formation is composed mainly of orthoquartzites and feldspathic orthoquartzites which were derived from preexisting sedimentary rocks. The Fall River Formation contains a significantly higher proportion of angular detrital material from igneous and metamorphic rocks. The Inyan Kara Group was deposited in a variety of continental environments, with the dominant environment being a fluvial system characterized by northwesterly-flowing streams (Gott and others, 1974; Chisholm, 1963).

During the late Cretaceous, the Black Hills area was uplifted into a domal structure and subsequently eroded to expose a Precambrian igneous and metamorphic core (Fig.1). As a result of this uplift, fractures developed and groundwater moved through them and into aquifers of several formations. According to Gott and others (1974), this moving groundwater dissolved evaporites in the Permian Minnelusa Formation, and breccia pipes resulted from subsidence within the Minnelusa Formation. These breccia pipes extend upwards into the Inyan Kara Group and form part of a complex "plumbing" system through which fluids circulate. These fluids carry low concentrations of uranium. Uranium precipitates under reducing conditions, and roll-front type deposits are present in channel sandstones of the Inyan Kara Group at the interface between oxidizing and reducing environments. This system of channel sandstones changed course along its length and through time and produced deposits of complex geometry.

1.3. Research to date

1.3.1. Core and sample selection

A 45.5-foot drill core from the Lakota Formation (PT-152; Fig. 2) was selected for detailed study. This particular core was selected because 1) it is complete, 2) it exhibits a variety of facies, and 3) it

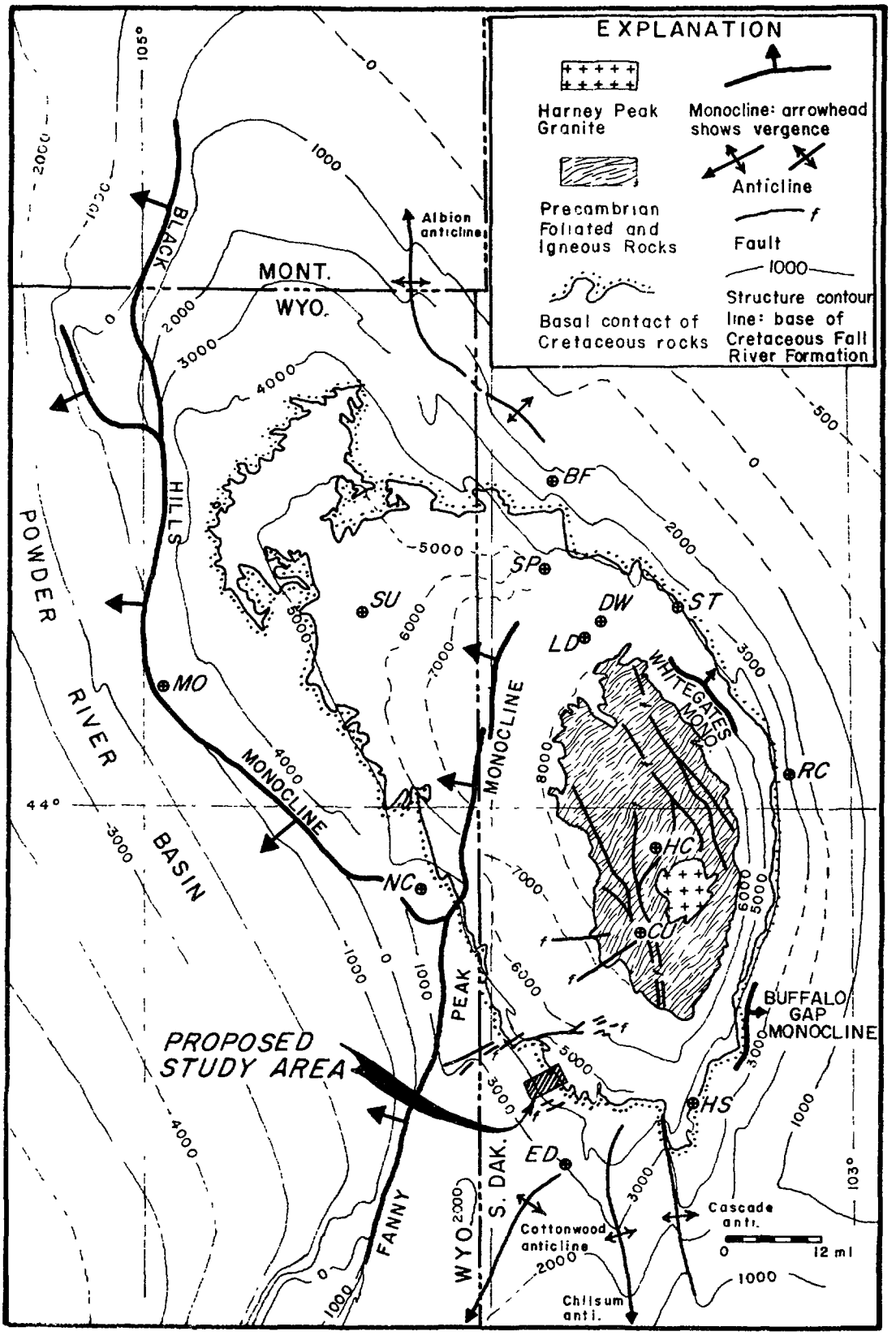

Figure 1. Tectonic map of the Black Hills, South Dakota, Wyoming and Montana (from Rich, 1981).

is from the approximate roll-front. A diagram of the core is shown in Figure 3 and indicates the methods of analysis used at various core intervals and lithofacies or zones within the core.

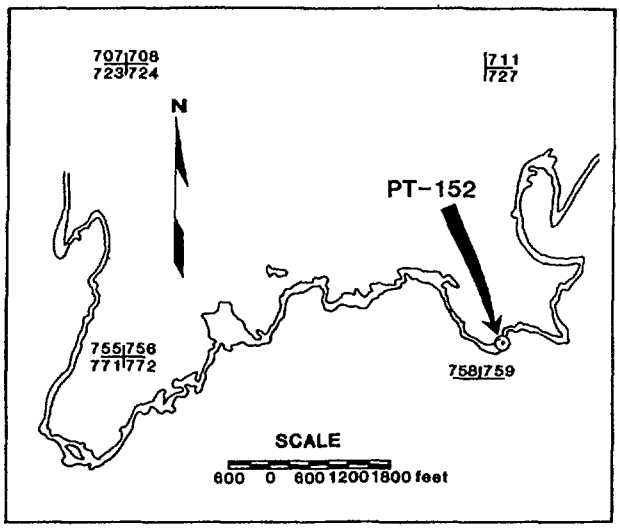

Figure 2. Location of uranium roll-front deposits, southern Black Hills, South Dakota.

1.3.2. Petrographic description

The 45-foot long core is composed predominantly of orthoquartzitic sandstone that has undergone various stages of alteration. The sandstone is underlain and capped by an impermeable fine-grained unit at the base and top. Three principle lithofacies units have been recognized along the length of the core (Fig. 3). These have been classified as reduced, oxidized, and ore zones. Because of the complex geometry of the channel deposits and the fluctuations in the roll-front, the core repeatedly passes through the oxidized, mineralized, and reduced lithofacies or zones.

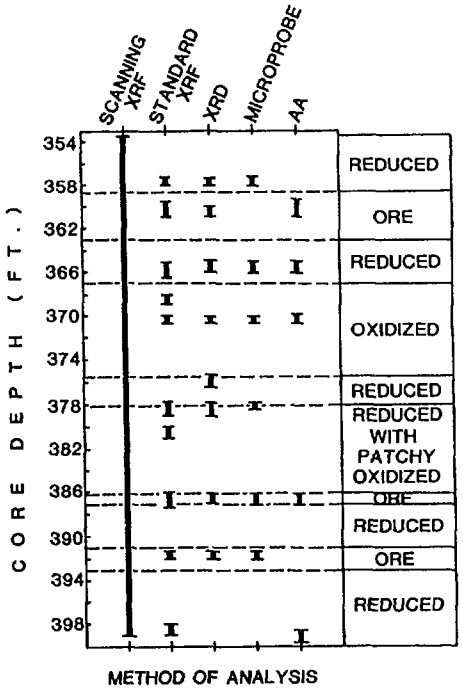

Figure 3. Diagram of 45-foot core, showing lithofacies zones, types of analyses, and location of samples analyzed.

1. Reduced zones

The reduced sandstones consist of over 95 percent fine- to medium-grained subrounded to subangular quartz with minor proportions of clay and chert as matrix. All the sandstone along the core is clast-supported. Also present are minor amounts of coaliferous material plus epigenetic pyrite.

2. Oxidized zones

The oxidized sandstones are composed of barren orthoquartzite with no discernible organic material or pyrite. The oxidized core has a reddish tinge to it due to a hematitic coating on quartz grains. Less chert is present than in the other two zones.

3. Ore zones

The ore zones of the core, which contain most of the trace and minor elements, also consist of orthoquartzite but with a substantial and varied amount of clay, chert, pyrite and organic matter. The ore zones are easily recognizable by their yellow-green coloration due to uranium oxidation.

1.3.3. X-ray fluorescence (XRF)

Core PT-152 was transported to Battelle Pacific Northwest Laboratories, where the entire core was subjected to scanning X-ray fluorescence (XRF) for more than 40 elements. These continuous chemical analyses of the core were followed by standard XRF analyses of selected samples. Sample selection for standard XRF was based on the scanning XRF data.

Elemental concentrations are given in terms of ranges and means for selected elements from this core in Figure 4. Figure 5 is a schematic diagram of part of the core showing the correlation between uranium and vanadium. It can be seen that, in general, uranium and vanadium vary sympathetically although not uniformly.

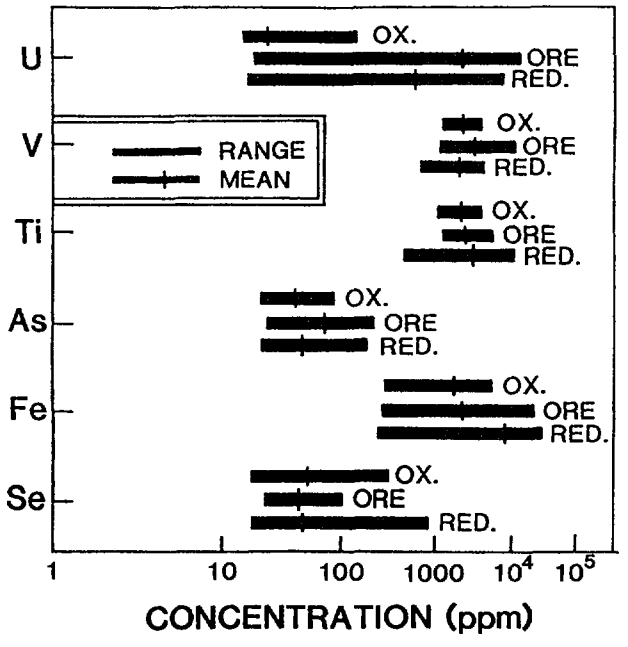

Figure 4. Diagram of overall ranges and means of concentration of uranium and related elements, in ppm, for oxidized (OX), reduced (RED), and ore zones.

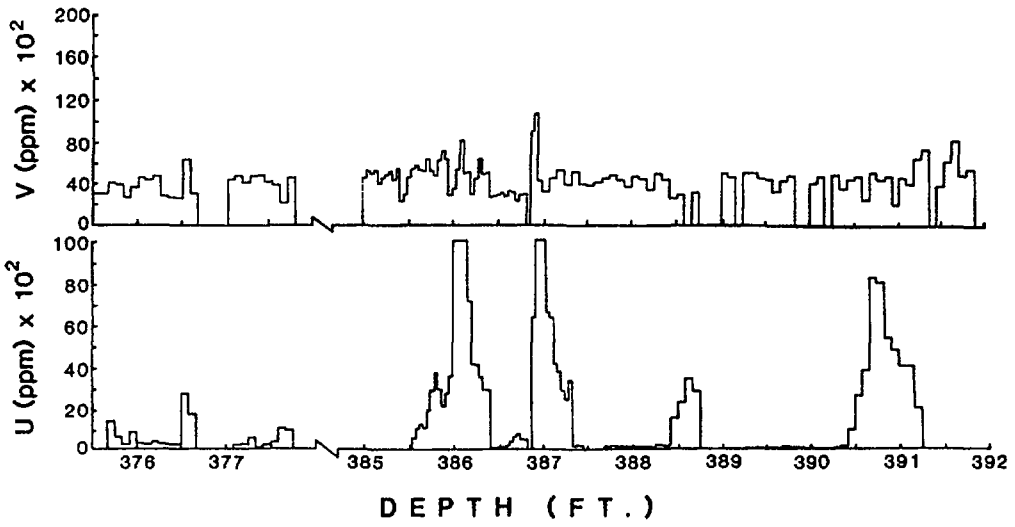

Figure 5. Diagram of XRF scan of PT-152 for uranium and vanadium.

1.3.4. X-ray diffraction (XRD)

X-ray diffraction (XRD) shows interstitial material that consists predominantly of kaolinite plus montmorillonite, illite, quartz, gypsum, pyrite, and orthoclase. Diffraction patterns from powdered samples of two ore zones show the principal minerals to be montmorillonite, kaolinite, quartz, pyrite, gypsum and, possibly, jarosite. Uranium minerals are conspicuous by their absence.

1.3.5. Organic petrography

Several polished pellets containing coaliferous sandstone were point-counted with a reflecting Zeiss photometer. The most abundant maceral was vitrinite with lesser amounts of semi-fusinite and resins. This reflected light microscopy also illustrated the abundance of framboidal and matrix-forming epigenetic pyrite within the organic material. Electron microprobe analyses of pyrite showed significant concentrations of uranium and/or titanium.

1.3.6. Scanning electron microscopy (SEM)

Several fragments of sandstone from the ore zones were examined by SEM. Results showed:

A. A mineral between the layers of kaolinite that apparently contains uranium. The overall spectrum contains uranium, but its presence in the interlayer mineral could not be absolutely confirmed (Fig. 7). The kaolinite appears "chewed up", consistent with radiation damage.

B. The presence of clay films on detrital quartz grains. Figure 6 shows a quartz grain with multiple coatings representing the paragenetic sequence of a smectite, partially covered by kaolinite, with remnants of possible illite on the kaolinite. Uranium and/or vanadium is concentrated in scattered sites, especially in the kaolinite.

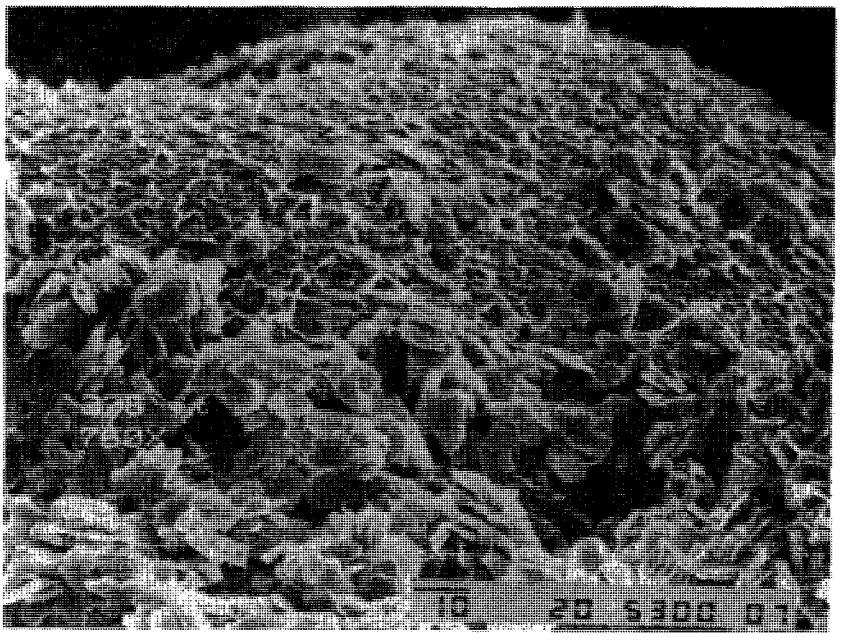

Figure 6. SEM micrograph, bar scale = 10 microns. Quartz grain with coating of smectite (upper part), partially covered by kaolinite (lower part).

C. The presence of uranium in carbonaceous bands in the sediments. A uranium distribution map from within a coaliferous band indicates an organic structure with the uranium concentrated preferentially in certain parts of the cell structure.
D. An authigenic vanadium mineral surrounded by authigenic potassium feldspar.
E. An authigenic U-V-Th-Ti mineral on a smectite coating on a quartz grain.
F. Some detrital clay with a major potassium and a minor calcium peak.
G. Considerable authigenic potassium feldspar in several samples.

2.1. Synthesis

Despite a wealth of chemical data, finding where and how the uranium and related elements are present in these deposits has been elusive. This was due largely to the absence of uranium-bearing minerals in the XRD patterns, the difficulties in the preparation of polished thin section which removed a good deal of the material interstitial to quartz grains, and the complex geometry of the roll front. That no uranium-bearing phases were detected by XRD suggests that uranium is present 1) in the carboniferous component as in other roll front deposits, 2) in amorphous or very fine or poorly crystalline phases, and/or 3) in or adsorbed onto some of the clay material that was detected. It is important to note that only a small fraction of one percent of uranium-bearing mineral would be detectable by XRD due to the high absorption of uranium.

However, with the addition of the very small amount of SEM analysis performed, a picture of these deposits is beginning to emerge. The major cementing material in these sandstones is clay. Several clay minerals--smectite, kaolinite, and illite are present and may represent

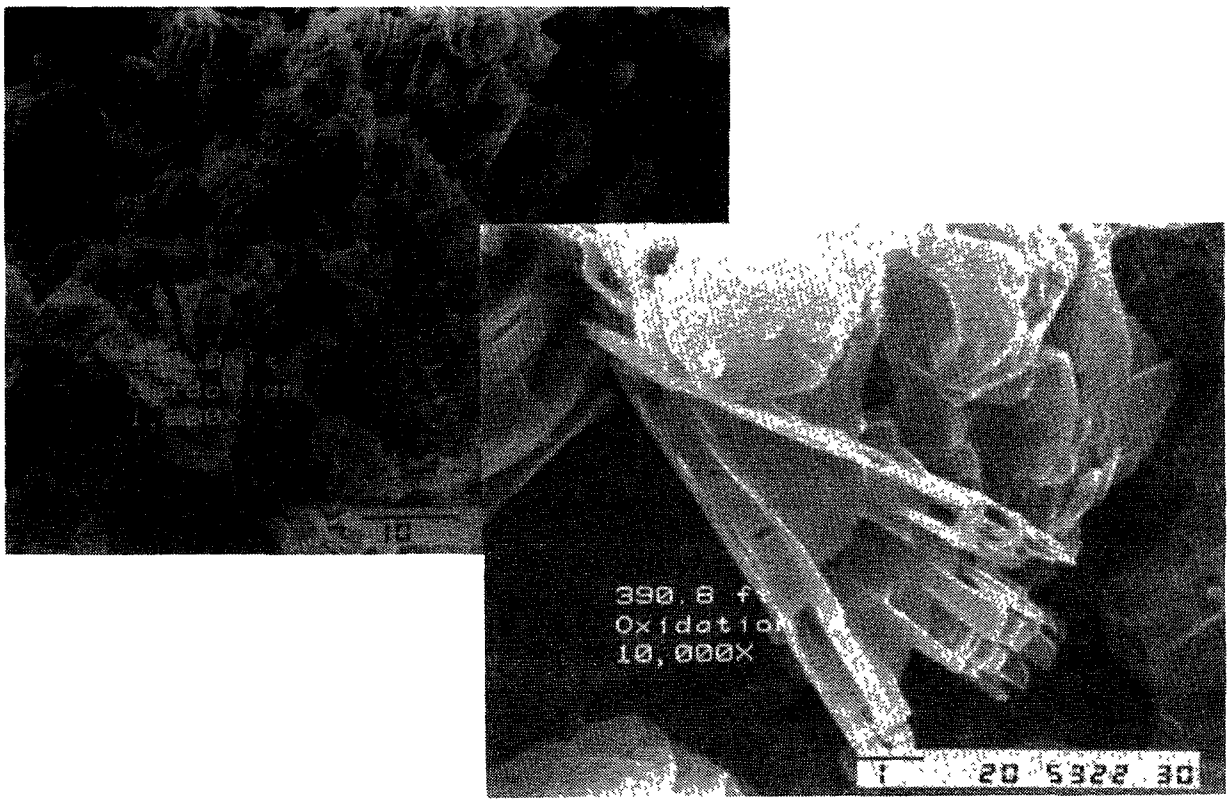

Figure 7A and 7B. SEM micrographs, bar scales = 10, 1 microns in A and B respectively. Uranium-vanadium mineral sandwiched between kaolinite layers.

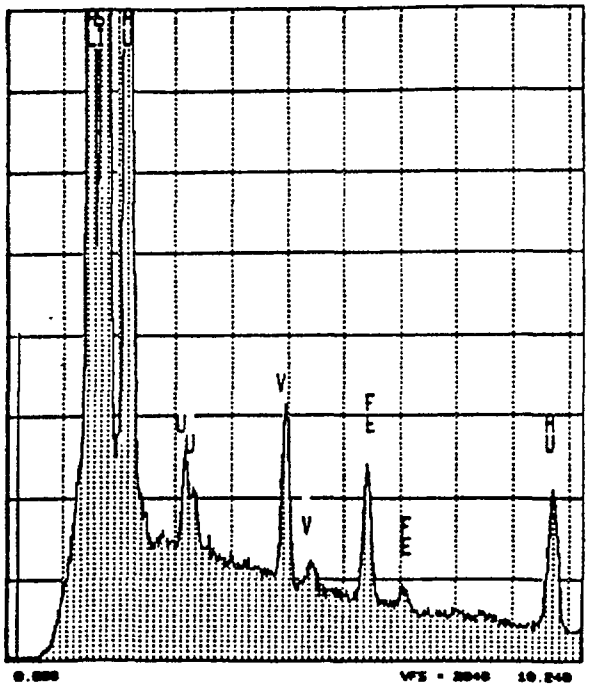

Figure 7C. Overall EDS spectrum of area shown in 7A and 7B.

different paragenetic intervals. The layers of different clay minerals are evidence of radically different pore waters. Clay phases were identified by their morphology and composition on the SEM. Kaolinite, montmorillonite (smectite), and illite were confirmed by XRD.

Uranium is associated with these clays. Because no uranium-bearing phases were found by XRD, uranium as an interlayer cation in clay is a possibility. However, the apparent preferential association of uranium with kaolinite (Fig. 6) makes it unlikely. The crystal structure of kaolinite, including the lack of an unbalanced site charge, probably cannot accommodate uranium as an interlayer cation. The morphology of the kaolinite, as observed in the secondary electron image (Fig. 7) is not typical of kaolinite and suggests interlayering with another mineral. The overall spectrum supports the probability that this other mineral is uranium-bearing. If this is true, the latter mineral should be detectable in an XRD powder pattern. This needs to be investigated along with how the uranium affects the XRD pattern of the clay with which it is associated.

In many roll-type uranium deposits, carbonaceous material and/or pyrite have facilitated reduction and precipitation of uranium. In this deposit, pyrite was observed megascopically within pieces of charcoal in coarse-grained layers in the core. Uranium was consistently detected when analyzing authigenic pyrite by microprobe. The uranium distribution map within a coaliferous lamina shows a preference for uranium to be deposited in certain parts of a cellular structure. The association of the uranium with the pyrite within the carbonaceous material suggests that the precipitation of uranium was associated with the sulfidization of the coaliferous material.

Authigenic uranium and vanadium minerals were also detected by SEM analysis. They are very fine-grained, and the difficulty in finding them suggests that they are rare components of the ore zones. These factors could account for the lack of detection by XRD.

Drastic changes in the chemistry of the pore waters suggested by the different clay layers on quartz (Fig. 6) are also indicated by the presence of detrital potassium feldspar showing partial dissolution and by the presence of authigenic potassium feldspar.

In summary, these deposits have undergone a complex history which produced radical changes in pore waters, presumably in phase with the migration and fluctuation of the roll-front and its ore zone. Uranium was precipitated when and where conditions were favorable, and this apparently was during the deposition of kaolinite and the sulfidization of carbonaceous material. Authigenic uranium and vanadium minerals formed but make up only an extremely minor proportion of the existing ore zones.

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From June through September, 1985, Bonnie Blake was on a fellowship with the Northwest College and University Association for Science (NORCUS)/Department of Energy at Battelle Laboratories in Richland, Washington. The Battelle facilities are state-of-the-art and have a unique capability in the area of scanning X-ray fluorescence. To J.C. Laul and to Richard Arthur, she is particularly grateful for help in all aspects of this work.

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HEMATITE-ENRICHED SANDSTONES AND CHROMIUM-RICH CLAYS — CLUES TO THE ORIGIN OF VANADIUM-URANIUM DEPOSITS IN THE MORRISON FORMATION, SOUTHWESTERN COLORADO AND SOUTHEASTERN UTAH, USA

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Abstract

Fluvial sandstones of the Salt Wash Member, Upper Jurassic Morrison Formation, southwestern Colorado and southeastern Utah, host tabular, epigenetic vanadium-uranium (V-U) deposits. Laterally within a few tens of meters of some of the V-U deposits are two distinct accumulations -- one enriched in iron (hematite), and the other chromium (Cr-rich mixed-layer clays). The iron-enriched sandstones commonly occur at the contact between red and gray (buff in outcrop) sandstones, are dark red and generally color banded. Between the iron and V-U deposits, chromium accumulated in gray argillaceous sandstones that contain small coalified plant fragments.

Variations in Eh, oriented parallel to facies changes but perpendicular to regional ground-water flow, controlled the spatial distribution of iron, chromium, and V-U deposits. Depositional facies within the Salt Wash Member are characterized by fluvial axes containing thick sandstones, and by well-drained floodplains marginal to the fluvial axes. Laterally continuous sandstones contained an organic acid-bearing solution that mobilized iron as Fe(II). This reducing solution mixed with alkaline U-, Cr-, and V-bearing, oxygenated pore waters from floodplain sediments. Due to mixing, dissolved iron in the reducing solution was oxidized and precipitated as ferric hydroxide. Chromium, as chromate (CrO_4^{2-}), was chemically reduced by organic compounds in the vicinity of minor accumulations of detrital plant fragments and was incorporated into authigenic clay minerals. Dissolved U and V were not reduced by the organic compounds; instead, reduction and precipitation occurred by reaction with localized strongly reducing (sulfidic) pore waters. The tabular geometry of V-U deposits was a product of the hydrologic characteristics of the host rock or a brine-freshwater interface. Similar redox processes may explain the association of Cr, V, and U in the Mecsek deposits, Hungary, and deposits hosted by the Jurassic Entrada Sandstone, southwestern United States.

INTRODUCTION

Sandstone-hosted vanadium-uranium (V-U) deposits in the Salt Wash Member, Upper Jurassic Morrison Formation in southwestern Colorado and southeastern Utah are epigenetic, black, tabular layers that are peneconcordant with sedimentary structures. These deposits are distinguished from roll-type uranium deposits because they occur completely within gray sandstones, rather

than at the interface between oxidized and reduced rocks [1]. Descriptions of the Salt Wash deposits, including their physical and compositional attributes, as well as characteristics of the host rocks, have been subjects of a voluminous literature (see review in [2]). Nevertheless, the origin of these deposits is incompletely understood.

Most explanations of the origin of Salt Wash V-U deposits invoke epigenetic transport of vanadium (V) and uranium (U) by relatively low-temperature (<100°C) meteoric or modified ground waters [2]. These metals were chemically reduced, and precipitated in the vicinity of detrital plant fragments. Most models note the absence of structural or lithologic controls on the position of the V-U layers, indicating that aspects of formation were controlled by a transient condition within the host sandstone.

At variable distances (as much as several tens of meters) from some Salt Wash-hosted V-U deposits are sandstones enriched in hematite (Fe deposits) and sandstones containing Cr-rich clays (Cr deposits)(Fig. 1). Characterization of these iron (Fe) and chromium (Cr) deposits previously has been limited to brief descriptions, and thus their relationship to the origin of the V-U deposits has not been thoroughly investigated. In this study, we evaluated the physical and chemical characteristics of the iron and chromium deposits, and contrasted them with those of the V-U deposits. The resulting data are most consistent with formation of all three deposit-types by a geochemical system characterized by systematic variations in Eh.

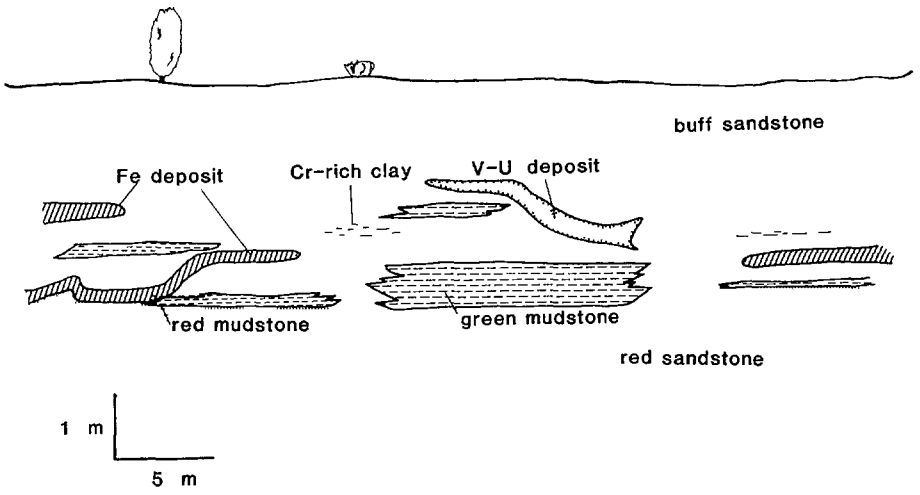


Fig. 1: Schematic diagram of an outcrop within the Slick Rock district containing iron deposits, chromium-rich clay accumulations, and a vanadium-uranium deposit.

Rocks within a few meters of sandstone-hosted U deposits commonly are enriched in As, Mo, Se, and V [3,4]. The distribution and geochemical characteristics of these metals can help to evaluate the origin of U deposits [3,5]. Similarly, aspects of hematite-enriched sandstones and Cr-rich clays associated with Salt Wash-hosted V-U deposits can be applied to understanding the origin of all three deposits. The association of Cr-rich clays and hematite accumulations with U deposits is not unique to the Salt Wash-hosted deposits, and characteristics of similar associations are reviewed below.

Hematite enrichment is associated with a variety of U deposits including sandstone-hosted roll-type deposits [6] and unconformity-type deposits [7]. In both deposit types, the association is attributed to variations in redox potential of pore fluids. Epigenetic redistribution of Fe and its accumulation in ferric oxide minerals near roll-type U deposits is the result of oxidation of Fe(II) in sulfide and carbonate minerals by an advancing, oxygenated water. In contrast, the hematite "cap" overlying unconformity deposits in the Athabasca basin is attributed to upward movement of a reducing solution, which bleached red beds, and transported dissolved Fe until mixing with oxidizing solutions [7]. The V-U deposits in the Salt Wash Member of the Morrison Formation are not considered roll-type deposits, yet hematite-enriched sandstones occur within 10 m of some deposits [8,9].

Uranium deposits associated with Cr-rich clays are uncommon. In addition to the Salt Wash deposits, these clays have been noted in U deposits hosted by the Permian sandstones of the Mecsek Mountains, Hungary [10] and those hosted by the Jurassic Entrada Sandstone in the Rifle and Placerville districts, Colorado, U.S.A. [11,12]. The Mecsek, Entrada, and Salt Wash deposits are distinguished also by high vanadium contents, suggesting a genetic link between chromium and vanadium. Chromium-rich clay minerals in the Morrison Formation are reported by McConnel [13], Vogel [14], and Wier and Puffet [15]. Vogel [14] and Wier and Puffet [15] noted that these clays occur along bedding planes that are marked by relatively abundant detrital plant fragments. Neither investigator offered an explanation relating the Cr-clays to V-U deposits.

Geology

Most of this investigation was conducted in the Slick Rock V-U mining district in southwestern Colorado (Fig. 2) with additional reconnaissance data collected from adjacent areas of southwestern Colorado and southeastern Utah. Deep canyons within the study area expose a thick sequence of upper Paleozoic and Mesozoic sedimentary rocks most of which are red beds of fluvial, lacustrine, and eolian origin [16].

The Morrison Formation was deposited by an aggrading alluvial system. Constituent sandstones, mudstones, and siltstones were deposited by fluvial and lacustrine (and eolian?) processes. During sedimentation, the climate was semi-arid with seasonal flooding [17].

The Morrison Formation in western Colorado is subdivided in ascending order into the Tidwell, Salt Wash, and Brushy Basin Members [17]. Most V-U deposits are hosted by the uppermost Salt Wash Member. This member is approximately 100 m thick and consists of interbedded sandstones and mudstones. The upper Salt Wash is composed of a thick (as much as 30 m), laterally continuous sandstone composed of stacked channels, and thin interbedded mudstones.

Systematic variations in the proportion of sandstone (50 to 70 percent) and bedforms in the Salt Wash Member across the Slick Rock district are related to paleogeography and the depositional system [18]. Sandstone

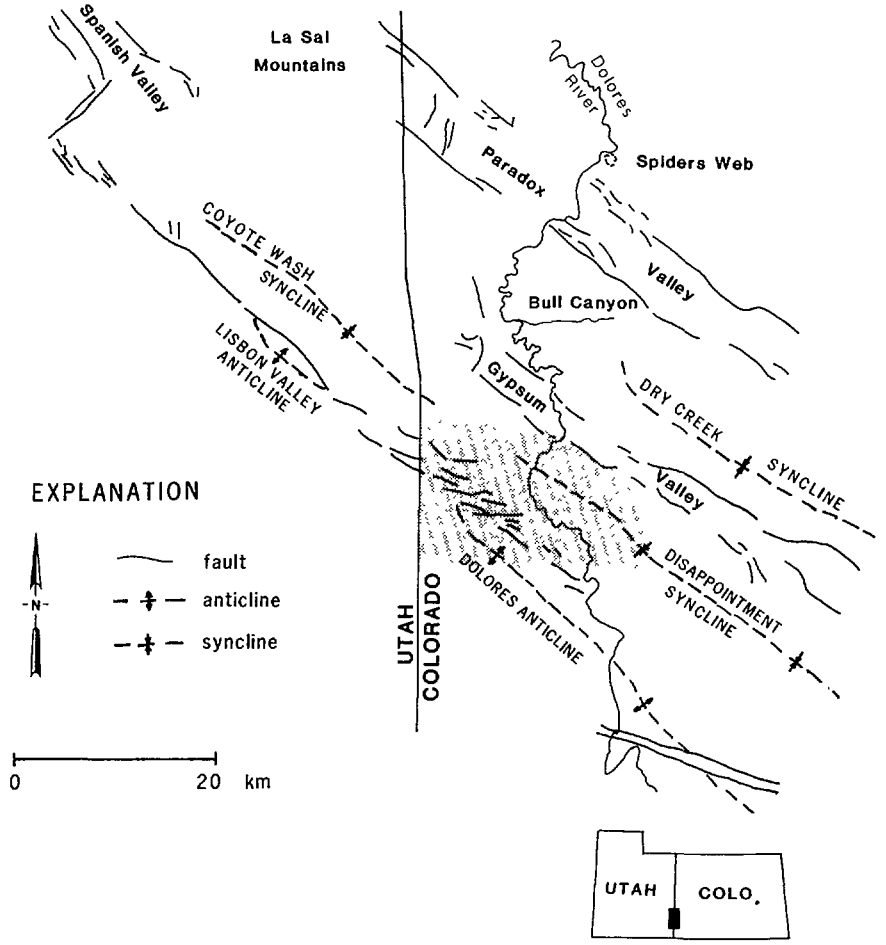


Fig. 2: Location of the study area. Stippled area defines the portion of the Slick Rock V-U district examined in detail.

accumulated preferentially along east trending fluvial axes. Floodplain deposits, characterized by greater amounts of mudstone, siltstone, and low-energy sandstone were deposited in well-drained areas marginal to fluvial axes.

Pervasive iron oxide (red pigment) characteristic of the floodplain deposits is consistent with deposition in a relatively well-drained, subaerial environment. In contrast, the sediments along the fluvial axes (and locally within the floodplain) were mostly water saturated, and more likely to retain reducing conditions, hence the prominent gray color of most laterally continuous sandstones in the Morrison Formation within the Disappointment syncline. (This pattern is also partly due to late diagenetic bleaching [19].) The contrast between red and gray rocks reflects the redox variations which later controlled mobility of iron, chromium, vanadium, and uranium.

The lower third of the Brushy Basin Member, deposited directly over the upper sequence in the Salt Wash sandstone, is composed mainly of red siltstone and mudstone with minor channel sandstone. Lithologically and compositionally these rocks are similar to the floodplain deposits in the Salt Wash Member. For purposes of discussion, the two are grouped as floodplain deposits.

In the Salt Wash Member, clastic components were mostly eroded from pre-existing sedimentary rocks [20]. Volcanic ash was a minor component of the Salt Wash, but it increased in abundance in the Brushy Basin Member. The Salt Wash sandstones are very fine to medium grained and moderately sorted. The detrital constituents are dominated by monocrystalline quartz (as much as 90 vol. percent) with the remainder composed of rock fragments, potassium feldspars, illite-smectite, and plagioclase. Authigenic minerals in the sandstones include albite, barite, calcite, chalcedony, chlorite, dolomite, hematite, illite-smectite, kaolinite, and quartz, as well as the mineral constituents of the V-U deposits [19].

Sedimentary rocks in the study area are deformed by northwest trending folds (Fig. 2). Diapiric movement of bedded evaporites in the Pennsylvanian Hermosa Formation initiated by basement faulting caused the folding. Periodic uplift and collapse of the anticlines has occurred since the Permian [21]. Therefore, the folds affected deposition and preservation of most Mesozoic units, including the Morrison Formation. The uplift and collapse of the folds also resulted in faulting subparallel to the fold axes [22].

RESULTS OF EVALUATIVE STUDY

Iron deposits

Sandstones containing unusually abundant hematite (up to 10 vol. percent) occur near contacts between overlying gray/buff sandstones and underlying red-brown sandstones or mudstones. The iron-rich layers range from tabular, peneconcordant with bedding, to complex "rolls", which locally cross bedding at steep angles. Layers concordant with bedding generally are confined to thin, flat-bedded sandstones; the roll shapes are more common in massive, crossbedded sandstones. The red to purple cement is banded on the scale of centimeters because of variable amounts of limonite and hematite (Fig. 3a). The color alternation resembles Liesegang bands and is particularly well developed in the roll shapes. Because red sandstones are uncommon near the V-U deposits, iron deposits were not detected close to most V-U deposits.

A well-exposed iron deposit crops out on the north rim of Bull Canyon (Fig. 2). It extends for 100 m along a horizontal surface, and is truncated by the canyon so its original extent is unknown. Collectively, the iron-rich bands are about 1.5 m wide and have a thickness of about 2 m. Along the sinuous trend of the hematite-enriched sandstone are two small V-U prospects. The prospects were recognized by secondary V-U minerals and scintillometer readings. Rocks underlying the Fe and V-U deposits are distinguished by their colors. The V-U deposits are underlain by green mudstone whereas the iron layers are underlain by red sandstone or mudstone.

Hematite in the iron-enriched sandstones is present as microscopic hexagonal plates projecting radially from detrital grains (Fig. 3b). The plates commonly encircle quartz grains beneath syntaxial quartz overgrowths (Fig. 3c). Locally, hematite fills pores and cements the sandstone. Barite, calcite, and dolomite cements fill pores lined by hematite. In summary, the textural relationships of the hematite plates suggest formation during early diagenesis. Submicroscopic iron oxides that color "average" red sandstones in the Salt Wash have similar paragenetic relationships; thus the two types of

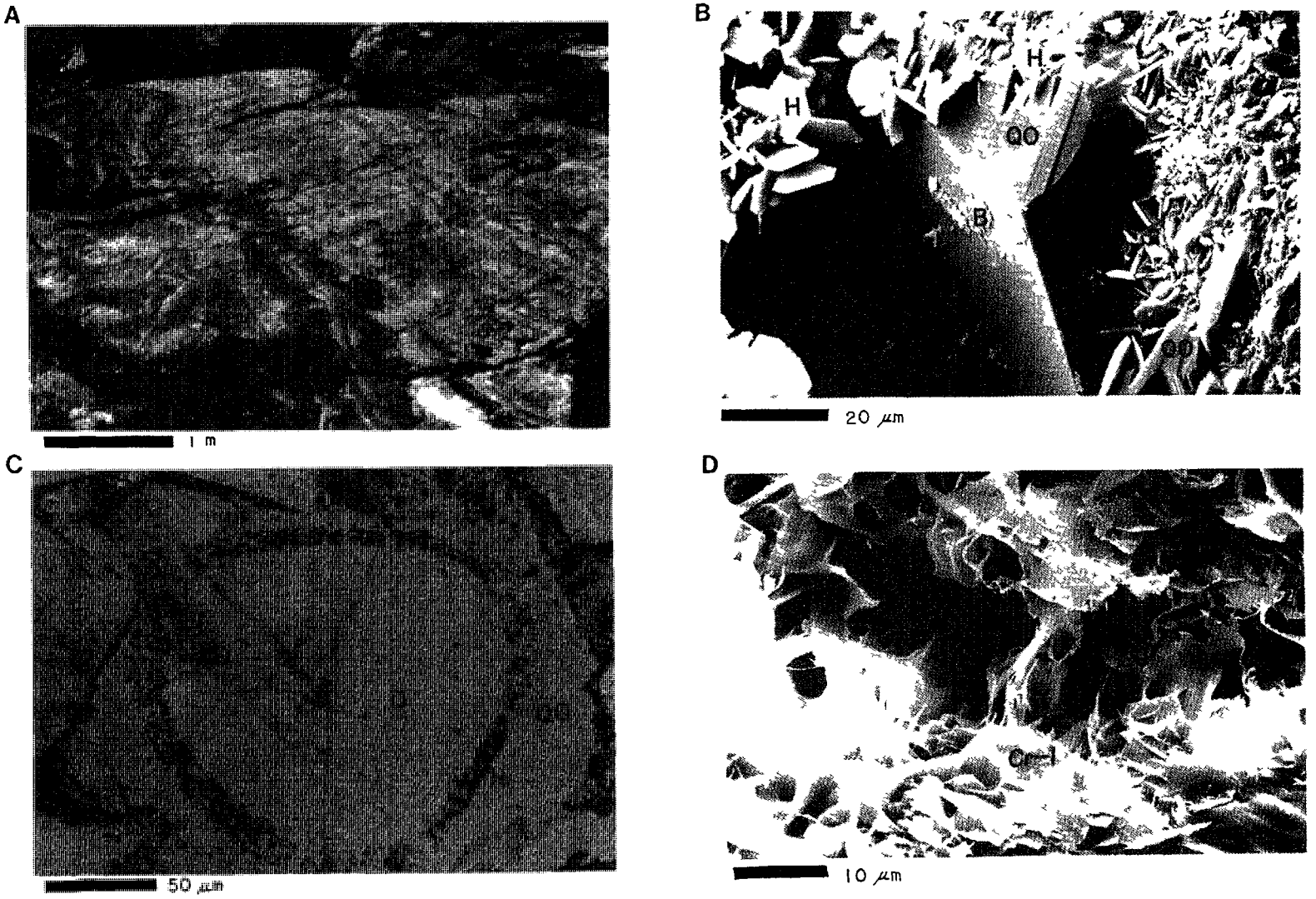


Fig. 3: a) Photograph of contact between hematite-enriched sandstone (dark) and buff sandstone. Note the banding of the dark layers. Notebook in the foreground is 13x21 cm. b) SEM micrograph of hexagonal hematite plates (H), quartz overgrowths (QO) and barite (B), c) photomicrograph of coarse hematite (H) beneath a quartz overgrowth (QO) that is optically continuous with the rimmed grain, d) SEM micrograph of Cr-rich illite-smectite (Cr-I).

hematite may have formed simultaneously. The amounts of detrital iron-titanium (Fe-Ti) oxides in the iron deposits are similar to those in the adjacent red sandstones.

The hematite-enriched sandstones contain as much as 10 wt. percent Fe, about 20x the mean abundance of iron in red sandstones (0.5 wt. percent, [19]). Chemical analyses of the hematite detected 0.8 wt. percent V. The high vanadium content is consistent with analyses of iron-enriched sandstones in Lisbon Valley [8]. Chromium content of the hematite is < 0.02 wt. percent; the U content is close to the background value of the host sandstone (2 ppm).

Limonite in the iron deposits forms disseminated spots (1-3 mm diameter) independent of banding, as well as discrete thin (<1 cm) bands that parallel the hematite layers. Limonite bands occur dominantly on the gray/buff sandstone side of the iron deposits; however, they also were observed between and crossing some hematite layers. The co-occurrence of hematite and limonite suggests two generations of iron oxide, one related to early diagenetic formation of hematite and the other due to more recent oxidation.

Another notable feature of the iron deposits is their association with pebble to granule sized intraclasts of mudstone and micritic calcite. These clasts occur scattered along scour surfaces. The micritic calcite has not been corroded, suggesting that diagenetic pore waters remained in equilibrium with calcite. Mudstones near some iron deposits contain large (up to 8 cm diameter) calcite nodules, presumably formed by soil processes during deposition of the Morrison [18].

Chromium deposits

Within a few meters of all iron deposits are accumulations of authigenic clay minerals containing >2 wt. percent chromium. The clays are distinctively bright green and readily distinguishable from locally abundant green mudstones, although they have been confused with secondary copper minerals. These bright-green clays occur as matrix within thin (<10 cm), horizontally bedded, gray to buff, fine to very fine-grained argillaceous sandstones. In most occurrences, the Cr-clays form thin layers marking beds containing small (<5mm), disseminated, coalified plant fragments. The intensity of green color, and presumably chromium content, decreases markedly away from the woody fragments. Beds marked by green clay extend discontinuously for as much as 10 m; most occurrences are visible for <1 to 2 m. Sandstones hosting the Cr-clays generally lack sulfide minerals and limonite pseudomorphs after pyrite.

Within sandstones hosting the Cr-clays, the dominant clay mineral is illite-smectite (Fig. 3d). Less than 1 μm separates, containing 5 percent Cr_2O_3, are composed of dioctahedral illite-smectite with 15 to 30 percent smectite interlayers. Other authigenic phases are rare within these samples; therefore, the paragenesis of the Cr-rich illite-smectite is poorly defined.

Chemical analyses of <2 μm separates containing >2 wt. percent Cr (7 samples) detected anomalous amounts of V (about 1000 ppm). The Cr-rich clays also contain less iron and more aluminum than detrital illite-smectites within the Salt Wash mudstones [19]. Uranium contents of rocks hosting the Cr-clays were near background, 2 ppm.

Vanadium-Uranium deposits

Primary (unoxidized) Salt Wash-hosted V-U deposits consist of sandstones impregnated with chemically reduced V and U oxides and silicates. Ore averaged 0.2 percent U_3O_8 and 1.4 percent V_2O_5; production has amounted to 37,000 t U_3O_8 and 217,000 t V_2O_5. Rocks hosting the V-U deposits commonly contain abundant coalified plant fragments and pyrite (up to 1 wt. percent S). Sulfur isotope compositions ($\delta^{34}S$ = -20 to -40 $^{o}/oo$ CDT) of pyrite are consistent with the formation of sulfide by bacterial sulfate reduction [23].

The long axes of the V-U tabular layers parallel the depositional fabric of the host sandstone. Mined layers extend as much as 700 m, although a trend of discontinuous ore layers may extend for several kilometers [2]. Perpendicular to the depositional trend the layers may be 70 m wide and as much as 3 m thick. Locally, the V-U layers are convoluted and they cross bedding at steep angles [24].

Most uranium in primary V-U deposits occurs as coffinite ($USiO_4$) [25,26]. This silicate formed during early diagenesis based on its paragenetic relationships. Minor amounts of uraninite also are reported in some orebodies [25].

Vanadium in the primary ores is contained in chlorite, illite (hydromica), and montroseite (VOOH). Vanadium-rich samples contain as much as 20 vol. percent chlorite (Fig. 4a). Chlorite occurs between adjacent quartz grains, beneath and on quartz overgrowths, and locally replaces detrital grains (Fig. 4a,b). The chlorites within the V-U deposits are consistently larger (as large as 20 μm) than those in barren sandstones; however, the chemical compositions of ore and non-ore chlorites, aside from the V contents, are very similar -- high magnesium and aluminum, low iron. The relatively constant chemical compositions suggest that chlorites in barren and mineralized sandstones formed from similar solutions.

Vanadiferous illite (illite-smectite) (Fig. 4c), which formed after the chlorite, was identified in several V-U deposits. In some ore samples, where the ore was altered by post-U mineralization processes, chlorite was removed and vanadiferous illite-smectite is the only preserved V-clay [19]. Similar illite-smectite (hydromica) is reported in several other Salt Wash V-U deposits [27,28].

Elongate prisms of vanadium oxide, presumably montroseite (VOOH), radiate from the boundaries of detrital grains (Fig. 4d). In thin section, these oxides commonly appear to "float" within quartz overgrowths. Contact relationships between the chlorite and oxides suggest that they formed simultaneously, most likely during early diagenesis.

Other authigenic minerals

Several authigenic minerals in the Salt Wash formed shortly before or contemporaneous with constituents of the Fe, Cr, and V-U deposits. These include chalcedony, quartz overgrowths, smectite, calcite, chlorite, hematite and pyrite [19]. The presence of minerals such as calcite, smectite, and

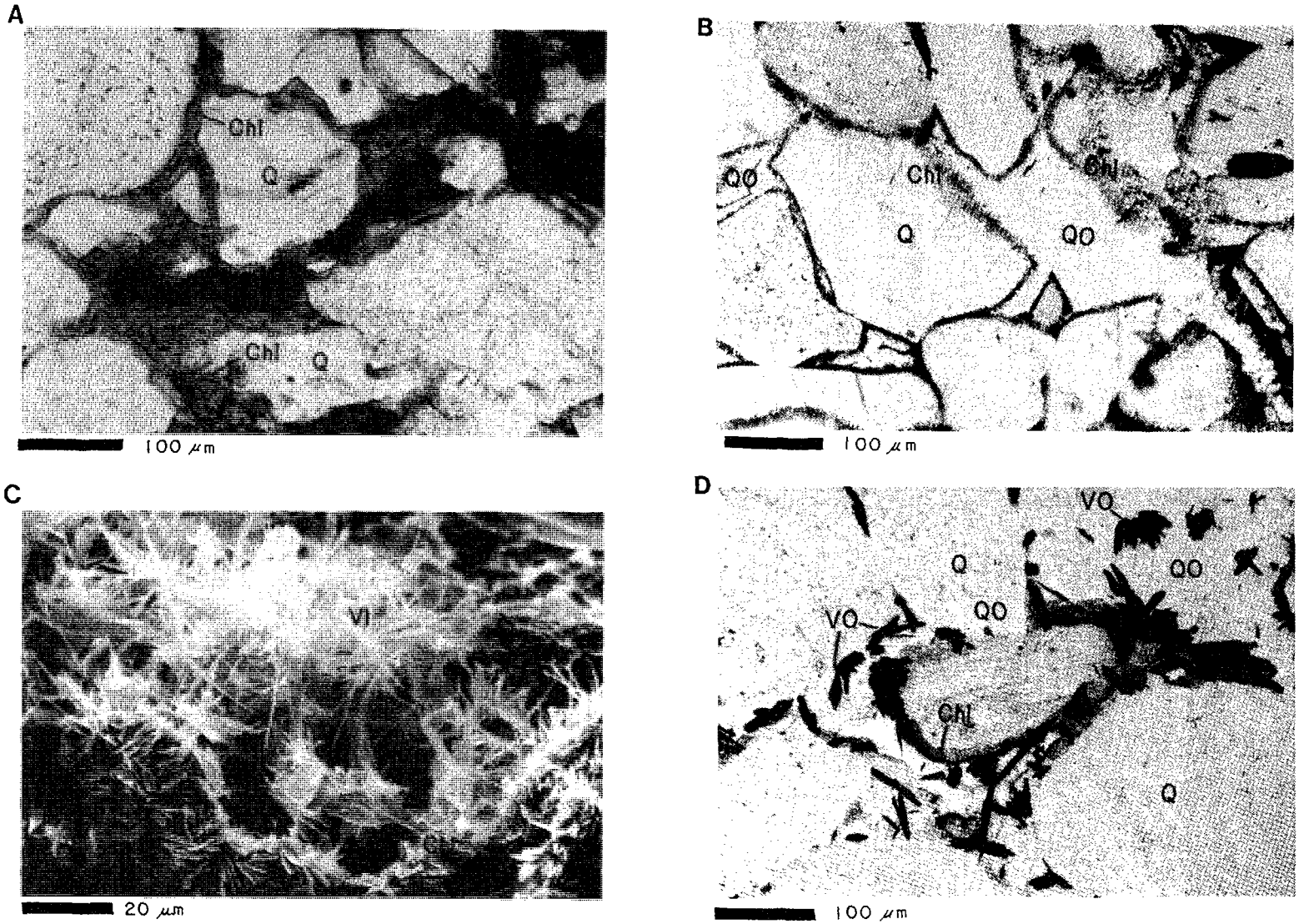


Fig. 4: a) Photomicrograph of V-rich chlorite (Chl) along boundaries of quartz grains (Q), b) photomicrograph V-rich chlorite (Chl) rimming detrital quartz (Q) beneath quartz overgrowth (QO), c) SEM micrograph of V-rich illite (VI) and chlorite (Chl), d) photomicrograph of V-oxides (montroseite) (VO) intergrown with quartz overgrowths (QO) and chlorite (Chl).

chlorite suggests that the Morrison pore waters had a basic pH and contained sufficiently high dissolved solids contents to stabilize the clay minerals. Cogenetic formation of pyrite and hematite is consistent with drastically different Eh conditions within Morrison sediments.

CHEMICAL CONSTRAINTS

Prior to discussing the origin of the Fe, Cr, and V-U deposits, geochemical characteristics of each of these elements are reviewed.

Iron

Iron, in natural conditions, is present in Fe(III) and Fe(II) oxidation states. Within the Morrison Formation, Fe(III) is contained mostly in insoluble iron oxides, including hematite; Fe(II) is present in carbonates, clays, and pyrite. In general, Fe(II) is relatively soluble in aqueous solution, but reaches appreciable concentrations only at low pH and Eh (Fig. 5). Thus, the moderately basic pH of pore waters, indicated by the assemblage of early diagenetic minerals, is compatible with the limited mobility of iron in the absence of a chemical reductant. Natural reductants, which can reduce Fe(III) to Fe(II), include organic compounds and H_2S.

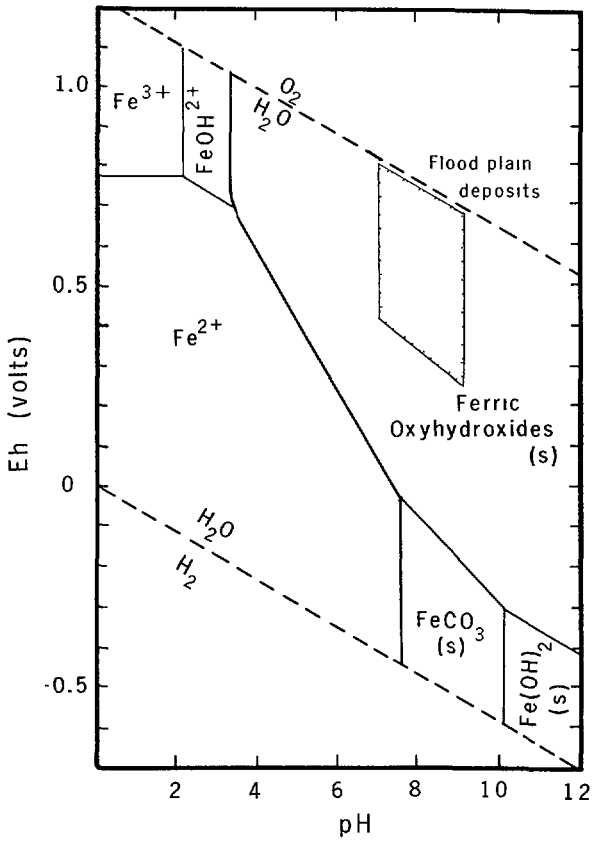


Fig. 5: Eh-pH diagram of the system $Fe\text{-}O_2\text{-}CO_2\text{-}H_2O$ at 25°C and 1 atm. Total carbonate species = 1×10^{-3}M, Boundary between solids (s) and ions at total activity of dissolved species of 1×10^{-5}M. Diagram calculated from thermodynamic data used in Whittemore and Langmuir [76]. Ferric oxyhydroxides log K_{sp} = -37.1. Stippled area depicts composition of proposed floodplain pore waters.

Chromium

In natural systems, Cr is stable in two oxidation states Cr(III) and Cr(VI) (Fig. 6). Chromium contained in clay minerals is exclusively the trivalent form [29]. Chromium(III) is relatively immobile in low-temperature aqueous solutions because of its tendency to hydrolyze and adsorb on mineral surfaces. However, organic complexes can greatly increase Cr(III) solubility [30,31]. The Cr(VI) species (chromate, CrO_4^{2-}), in contrast to Cr(III), is relatively soluble [32], but is the dominant species only under oxidizing conditions. Reductants capable of reducing Cr(VI) to Cr(III) include H_2S, Fe(II), and organic compounds [33,34,35].

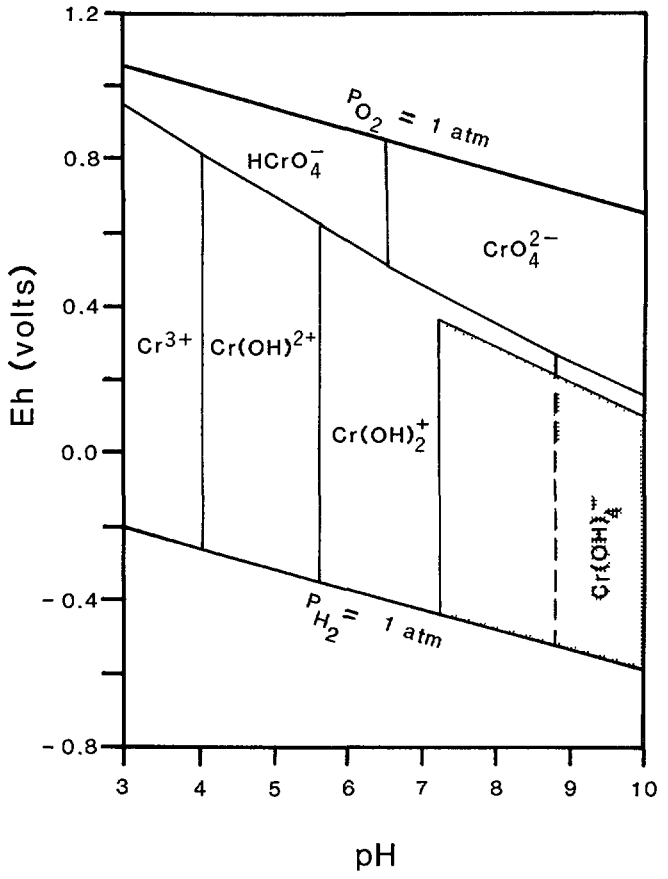


Fig. 6: Eh-pH diagram of the system Cr-O_2-H_2O at 25°C and 1 atm. Stippled area defines the stability of $Cr(OH)_3$ (solid) at 1.9 x 10^{-5}M dissolved Cr. Diagram calculated from data used in Hem [77].

Uranium

In natural systems, uranium may have formal oxidation states of (IV), (V), and (VI) [36]. Uranium minerals in the V-U deposits contain the most reduced form, U(IV). Transport of uranium in solution to V-U deposits was most likely as complexed uranyl ion (UO_2^{2+}) (U(VI)) (Fig. 7). Uranyl ion is stable under oxidizing conditions and is particularly soluble in the presence of carbonate ion. The reduction of uranyl ion to U(IV) at ambient temperature by H_2S [37] and at higher temperatures (120°C) by natural organic compounds [38] has been demonstrated.

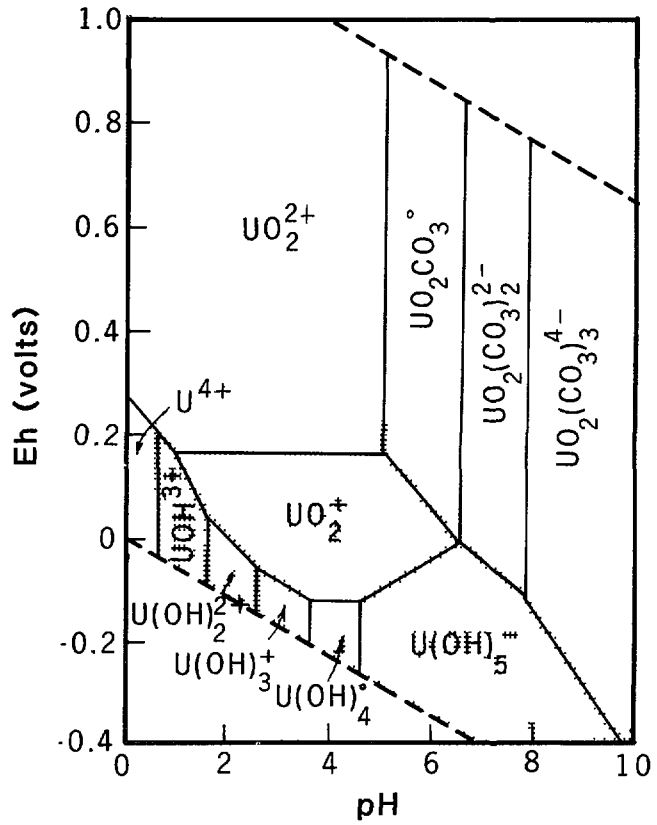


Fig. 7: Eh-pH diagram of $U-O_2-H_2O-CO_2$ at 25°C and 1 atm calculated from thermodynamic data in Langmuir [36]. Stippled area indicates the stability of uraninite at 1 x 10^{-6}M total dissolved uranium. CO_2 pressure of 0.01 atm.

Vanadium

Three oxidation states of V are stable in natural systems, V(III), V(IV), and V(V) (Fig. 8). Vanadium in chlorite and oxides within the V-U deposits is dominantly V(III) [39]. Like Cr(III), V(III) species are relatively insoluble because they rapidly hydrolyze and precipitate. Most likely, V was transported to the V-U deposits as soluble V(IV) or V(V) species [36]. Vanadium(V) species are stable in aerated surface waters over a wide range of pH values [40]. Vanadium(IV) is stable in slightly reducing, low pH solutions. Organic compounds, Fe(II), and H_2S are capable of reducing V(V) to V(IV). The only demonstrated reductant of V(IV) to V(III) at ambient temperature is H_2S [39].

DISCUSSION

Geochemical characteristics of metals that formed the iron, chromium, and V-U deposits are most consistent with an origin related to local variations in redox conditions. These variations are reflected by differences in the components of the rocks hosting each of the deposits, notably coalified plant fragments and pyrite. To demonstrate the relationship between Eh and deposit origins, each deposit is evaluated separately.

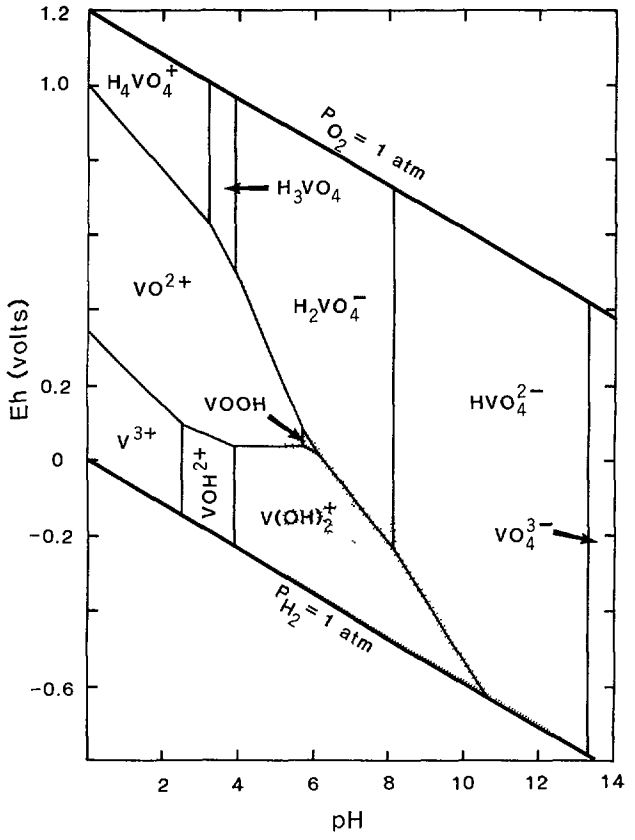


Fig. 8: Eh-pH diagram of the system V-O_2-H_2O at 25°C and 1 atm calculated from thermodynamic data of Wanty [39]. Stippled area outlines the stability of VOOH at 1.96 x 10^{-8}M dissolved V.

Iron deposits

Characteristics of the iron deposits suggest that they formed because of the oxidation of dissolved Fe(II). Red sandstones contacting the iron deposits contain abundant, early diagenetic, micritic calcite clasts, clays and detrital Fe-Ti oxides. These components are consistent with oxidizing or relatively "inert", basic-pH pore waters. Oxidizing solutions would oxidize Fe(II), forming poorly crystalline Fe(III) oxyhydroxides (Fig. 5), which later recrystallized to form hematite in the iron deposits.

Characteristics of the iron mobilizing solution are less obvious than those of the Fe-precipitating solution. Mobilization of iron within now gray sandstones most likely required reductive dissolution. Because of the limited distribution and abundance of preserved sulfide minerals, the most likely reductants were dissolved organic compounds. The presence of dissolved fulvic and humic acid anions within the Morrison Formation seems likely, even though the Morrison, except for local accumulations, lacks preserved solid organic matter [2]. The lack of preservation is the result of rapid degradation of plant fragments in the semi-arid climate ambient during deposition of the host rocks [41]. As part of the degradation of plant-derived organic matter, soluble organic acids form [42].

The best record of soluble organic compounds in the Morrison is the removal of iron from detrital iron-titanium (Fe-Ti) oxides in gray (bleached) sandstones [43]. The red Morrison sandstones contain about 0.15 wt. percent black opaque minerals, composed mostly of hematite after magnetite and ilmenite (Fe-Ti oxides). The average abundance of Fe-Ti oxides in the gray sandstones is about 0.001 wt. percent (D.R. Shawe, unpublished data). Based on experimental and observational data, dissolved organic acids are the natural reagents most capable of extracting iron from these minerals [44,45]. Although H_2S can result in similar dissolution [46], the low abundance of sulfide minerals in most gray Salt Wash sandstones (<0.002 wt. percent) suggests a low activity of H_2S away from the large accumulations of coalified plant fragments.

Based on the previous discussion, iron deposits represent the reaction of two solutions with different Eh values. The reductive dissolution of detrital and authigenic iron oxides by organic acids in a mildly reducing, H_2S-poor solution, redistributed Fe in the now gray sandstones. Upon encountering oxidizing pore waters released during compaction(?) of the floodplain sediments, Fe(II) in the mildly reducing solution oxidized and precipitated as Fe(III) oxyhydroxides (Fig. 9). The banding of hematite layers is consistent with interaction of the two solutions by diffusion, but because of the slow rates of diffusion, the banding more likely is the result of self-organization of ferric oxyhydroxides as they recrystallized into hematite [47].

The high vanadium content of hematite in the iron deposits is consistent with the proposed origin. Vanadium accumulates in iron oxides precipitated from surface waters [48,49,50] by coprecipitation and adsorption [51,52,53]. However, the V content (0.8 percent) of hematite is greater than the content in Fe-Ti oxides (0.15 percent) [9,19], suggesting either an additional source of V, or that the mixing process was more effective at trapping V than Fe.

The abundance and distribution of Fe-Ti oxides distinguish iron accumulations associated with tabular V-U Salt Wash ores and those associated with roll-type U deposits. In some roll-type uranium deposits, detrital Fe-Ti oxides are absent updip from the uranium deposits in the oxidized rock and within iron deposits, and are preserved in reduced rocks within and down dip from the U deposits [6]. In contrast within the Salt Wash, Fe-Ti oxides are preserved in hematitic bands and nearby red sandstones, and were leached from reduced, gray sandstone. Thus, the pattern of Fe-Ti oxide preservation in the Salt Wash suggests that the Fe deposits formed when an advancing, reducing solution moved through oxidized rock.

Cr deposits

The association of Cr-clays with small accumulations of detrital plant fragments strongly suggests that reduction of chromate by organic compounds caused chromium to accumulate. The source of Cr, however, is poorly constrained. Chromium may have originated in detrital Fe-Ti oxides [54]. During reductive dissolution of detrital Fe-Ti oxides by organic acids, Cr may have entered solution in the form of organic-Cr(III) complexes. The association of Cr-clays and iron deposits suggests that the solutions containing organic-Cr mixed with the oxidizing solutions that precipitated iron. Chromium may have been displaced from the complexes, and oxidized to

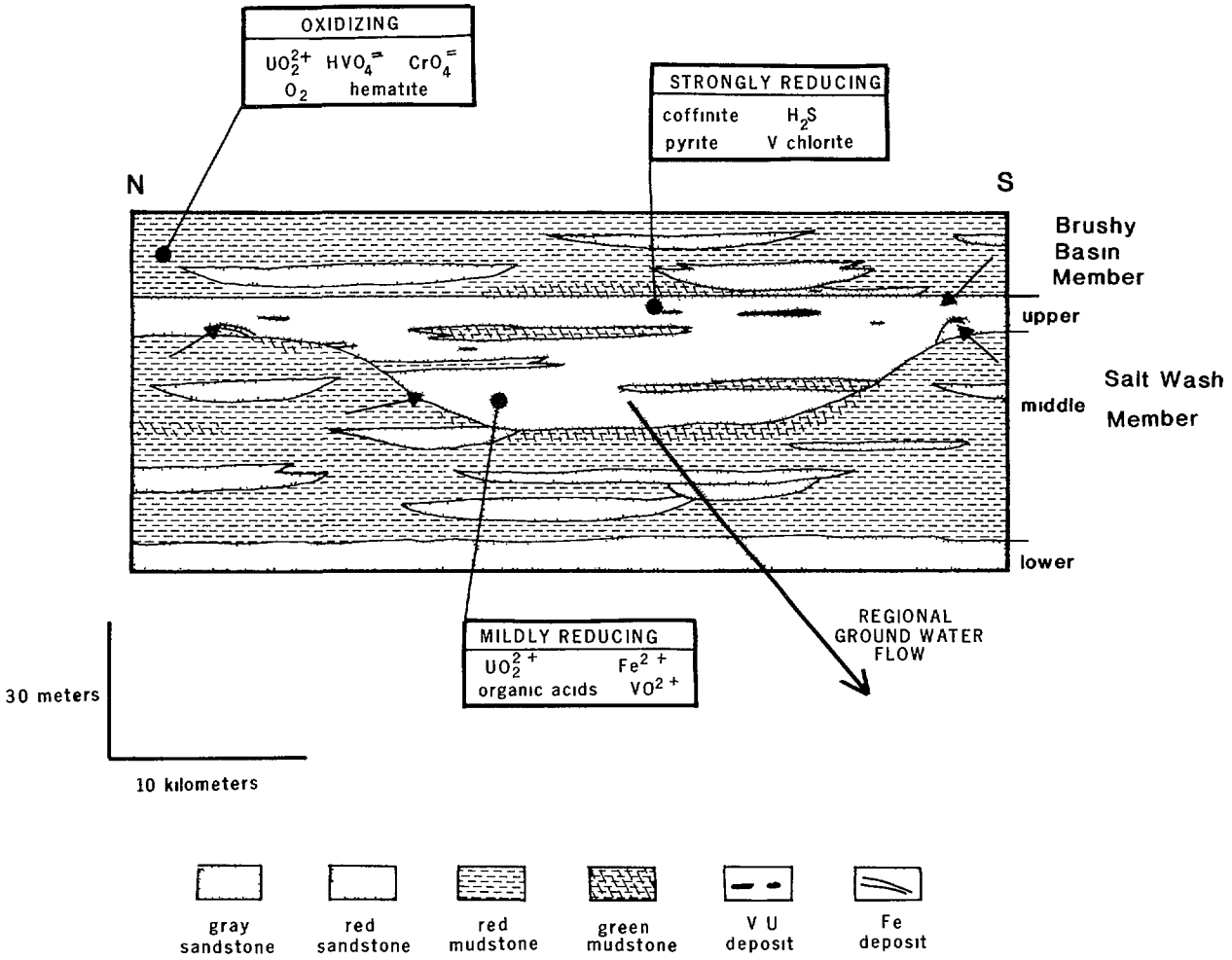
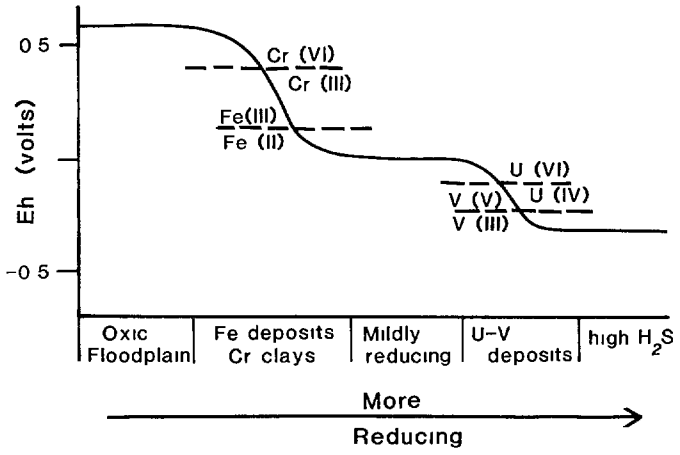


Fig. 9: A) Schematic diagram depicting the movement of solutions in the formation of Fe, Cr, and V-U deposits. Oxidizing solutions containing Cr, V, and U from the foodplain deposits enter the channel sandstones, mix with anoxic, Fe(II)-containing ground waters, causing ferric oxyhydroxides to precipitate. Cr(VI) in the mixing zone is reduced near small accumulations of detrital plant fragments forming Cr-rich clays. V(IV) and U(VI) are transported in the anoxic waters until encountering sandstones with H_2S-rich pore waters where they are reduced and precipitate.



B) Schematic diagram at pH 8 illustrating the Eh conditions characteristic of the proposed pore waters. Eh boundaries for oxidation/reduction of dissolved Fe, Cr, V, and U species are derived from thermodynamic data used in Figs. 5, 6, 7, and 8.

chromate. Chromate was then transported in the oxidizing solution until reacting with the detrital organic fragments, whereupon chromate was reduced and precipitated. This model favors a reduced-oxidized-reduced scenario that requires complex solution movement to concentrate the chromium. An alternative explanation favors the transport of chromate from the floodplain sediments. The pore waters in the floodplain sediments may have been sufficiently oxidizing to stabilize chromate. Chromate is mobile and thus could remain in solution until encountering detrital plant fragments, whereupon it was reduced and incorporated into a forming smectite.

Authigenic, smectitic clay (altered volcanic ash) and detrital clays dominate the matrix of fine-grained sandstones hosting the Cr-clays. The bed forms and composition of these sandstones suggests deposition in a low-energy environment, such as a crevasse splay. Such an environment would favor the accumulation of fine-grained material-- volcanic ash and detrital plant fragments -- which provided the building blocks and the necessary reductant for the Cr-clays.

V-U deposits

Like chromium, vanadium and uranium are mobile in oxidizing waters; therefore floodplain pore waters were a likely medium for their transport. Uranium most likely originated from volcanic ash in the Morrison sediments [55]. Redistribution of uranium from the floodplain deposits is supported by the contrasting Th/U ratios of samples representative of red (floodplain) and gray (fluvial channel) sandstones within the Salt Wash Member. The Th/U ratios of red sandstones are similar to average sandstone ratios (Fig. 10). However, gray sandstones collected away from recognized V-U deposits have much lower ratios. Because of the immobility of thorium in low-temperature systems [56], the lower ratios could be interpreted as an enrichment of uranium. Alternatively, the higher Th/U ratios of red sandstones may also indicate removal of U from red sandstones. Consistent with this analysis, Walton and others [57] noted a preferential loss of U from ash-rich fluvial sediments deposited in subaerial environments (floodplain?), as compared to the conservative behavior of U in sediments deposited in an open hydrologic system (channel sandstone).

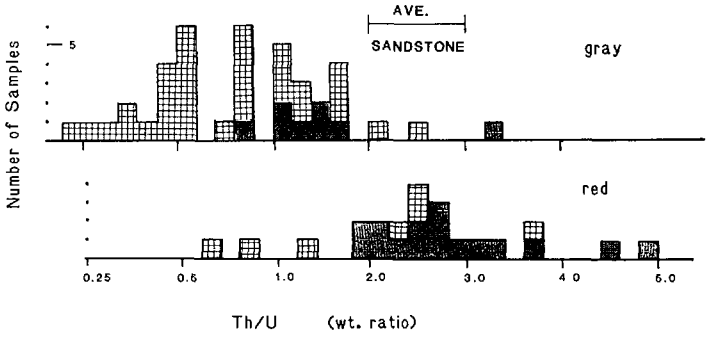


Fig. 10: Histograms of the Th/U ratios of samples from the Morrison Formation collected within the Slick Rock district. Average sandstone from Rogers and Adams [78]. (# - indicates samples in which Th was below the detection limit; hence true values would be less than indicated).

A likely source of vanadium in the deposits are the altered detrital Fe-Ti oxides [43, 54]. These oxides contain 1500 ppm V which could have been leached with the iron. Solutions dissolving the iron oxides were only mildly reducing, favoring the stability of V(IV) or V(V) species, depending on pH (Fig. 8).

The plausibility of detrital Fe-Ti oxides as a source of vanadium was evaluated by a mass balance calculation. A group of deposits within the Slick Rock district contains about 1500 tons of V_2O_5 [58]. This amount of vanadium could be derived from dissolution of Fe-Ti oxides in a reasonable volume of sandstone, 1.5 km wide, 6 km long, and 20 m thick. This redistribution would amount to a loss of 2 ppm vanadium from the gray sandstone. However, no difference in the V content of the red and gray sandstones was detected, possibly because of high variability within each population.

As shown above, Fe-Ti oxides are a likely source of V; however, previous arguments favored oxidizing floodplain pore waters as the medium transporting Cr and U. Because of their geochemical similarity, it is likely that chromium and vanadium originated from the same source. We favor the floodplain sediments. Transport of vanadate and chromate by the floodplain pore waters is compatible with the abundance of Cr and V in hematite within the iron deposits. Conditions within these sediments -- relatively high pH and Eh -- favored V(V) (vanadate) species (Fig. 9). The pH of water in the Fe deposits, estimated from the assemblage of authigenic minerals, was near 8. Such basic pH favors the adsorption of vanadate onto freshly precipitated iron oxyhydroxides [53](Fig. 11), hence, the high content of V in hematite within the Fe deposits. In contrast, chromate did not adsorb at these conditions, and thus remained in solution until contacting the scattered minor accumulations of organic fragments. Because the pore waters near these organic fragments were not H_2S-rich, they were insufficiently reducing to precipitate much vanadium or uranium.

While some of the vanadate adsorbed onto the ferric oxyhydroxides, most entered the mildly reducing solution. In this solution, vanadate was chemically reduced to V(IV) by soluble organic compounds [59] and the oxidizing capablity of the floodplain pore waters was consumed. Uranium was not adsorbed to the iron oxyhydroxides and did not form insoluble phases with

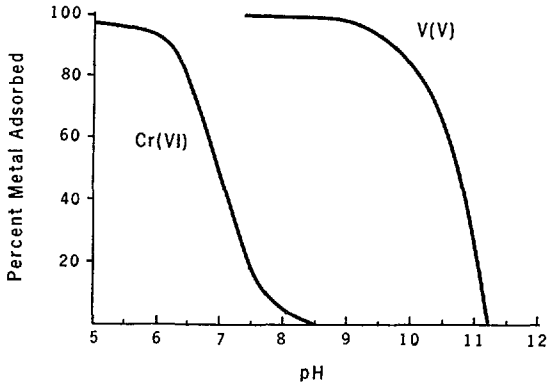


Fig. 11: pH vs. percent of Cr(VI) and V(V) species adsorbed onto amorphous $Fe_2O_3 \cdot H_2O$ using data of Honeyman [53]. Total Cr(VI) 1 x 10^{-6}M; total V(V) 1 x 10^{-7}M ; total available sites 8.8 x 10^{-4}M.

the vanadate because of strong carbonate complexes [60,36]. Therefore, uranyl also entered the mildly reducing solutions but was not reduced by the organic compounds. Both metals remained in solution until contacting H_2S-rich pore waters near large accumulations of organic detritus (Fig. 9).

We have suggested that chromium, vanadium, and uranium were mobilized from fine-grained, aerated sediments deposited in a floodplain environment. Uranium was released during the alteration of volcanic ash and may have been adsorbed to mineral surfaces prior to mobilization. Although the reductive dissolution of Fe-Ti oxides satisfies mass balance constraints for V, and may have supplied some V and Cr, the association of Cr-deposits with detrital plant material strongly favors the floodplain deposits as a source.

A possible sink for the metals dispersed in the floodplain sediments may have been authigenic ferric oxyhydroxides which coat detrital grains. The mobilization of metals from aging authigenic ferric hydroxides has been demonstrated by Zielinski and others [61] who showed that a portion of metals in authigenic iron oxides is released during conversion of poorly crystalline ferric oxyhydroxides to hematite. The ultimate source of V and Cr which accumulated in the early oxides during sediment deposition can only be speculated. Young [62] proposed that the metals enriched in the V-U deposits were derived from black shales in the sediment source area. Smith and others [63] noted that greater amounts of vanadium than uranium are leached from altering volcanic ash.

Age of the deposits

The characteristics of the deposits and the geochemical behavior of the constituent metals are consistent with an early diagenetic age (<2 km of burial) of the deposits. The presence of pore waters in the floodplain sediments capable of transporting chromate species requires minimal burial -- oxidizing conditions (Fig. 6). In contrast, sulfate-reducing bacteria which formed the H_2S in the V-U deposits require anoxic conditions. Granger and Warren [64] showed that free oxygen could be removed by reaction of ground waters with Fe(II)-bearing detrital minerals and fossil wood along a long flow path. Such solutions are only weakly reducing, and therefore were capable of transporting uranyl and vanadyl ions. The anoxic requirement suggests that 1) sandstones hosting the V-U deposits were isolated from the atmosphere, most likely after deposition of the Brushy Basin Member, and 2) deposits formed at a substantial distance from the recharge area.

Preliminary U-Pb age determinations of the Salt Wash deposits suggest an age of about 115 m.y. (Ludwig, K., 1986, written communication). This age is apparently inconsistent with the redox model described above because the rocks hosting the deposits were deposited at roughly 145 m.y. This discrepancy fades when we considered that the host sandstones were buried beneath only 200 m at 115 m.y. (estimated from data in [16]). The shallow depth and slow rate of burial allowed the rock to maintain much of its original permeability, ground-water flow, and chemical characteristics of the pore waters.

Origin of the tabular geometry

The origin of the tabular, peneconcordant shape of V-U deposits is not constrained by the redox conditions considered above. Yet, this characteristic is critical in the development of a model for the origin of the deposits. The brine-freshwater interface documented by the geochemical study of Northrop [65] on Salt Wash V-U ores in central Utah accounts for the tabular geometry of the ore layers. However, isotopic and mineral variations indicative of an interface in the Henry basin were not detected in the Slick Rock district [19]. Sandstones in the Slick Rock district and vicinity, however, were subjected to more intense post-mineralization diagenesis than those in the Henry Mountains mining district. Therefore, any record of a brine-freshwater interface may have been masked by later diagenetic changes. Some of the diagenetic events may have recrystallized or altered the mineralogy of the deposits, but the initial accumulation of metals occurred during early diagenesis.

Hydrologic characteristics within the host rock also may have had a substantial influence on the geometry of the V-U layers [66]. This is reflected in the trend of the layers parallel to the depositional axes of the host rocks and presumably the direction of regional ground-water flow. This flow was approximately perpendicular to the redox gradient described above (Fig. 9). The depositional fabric of the sandstones further influenced this flow as indicated by the abundant ore boundaries that coincide with diastems [67,68]. Aggrading channel sandstones such as those in the Salt Wash Member have complex permeability characteristics. The relative permeability differences between sand units caused by clay drapes and differing orientation of sand grains may have "isolated" solutions containing H_2S from the flow of mildly reducing solutions through the channels. Such phenomena explain the isolation of V-U deposits in selected festoon crossbeds while adjacent identical beds remain barren [69]. This separation of mildly and strongly reducing solutions, distinguished mostly by their H_2S content, may have been further enhanced by preferential growth of clays in the V-U layers.

Comparison with other sandstone-hosted deposits containing Cr, V, and U

The model described above is similar to the one proposed by Barabash and Virag [70] for the uranium deposits in the Mecsek Mountains, Hungary. Their model suggests that metals in the deposits originated in red overbank sediments and they accumulated in the vicinity of carbonaceous fragments. Metal mobilization occurred during early diagenesis, along a redox gradient more or less perpendicular to the direction of regional ground-water flow.

The V-U deposits in the Placerville district, Colorado can also be explained by a similar model. The extent of the V-U layer conforms closely with the depositional limits of an overlying fetid limestone. A Cr-clay layer subparallel to and beneath the V-U layer extends beyond the depositional limit of the carbonate. Oxidizing pore waters containing uranium, vanadium, and chromium from subaerial, eolian sands in the Entrada Sandstone mixed with reducing (sulfidic?) waters from an overlying limestone. The reductants in these pore waters became less abundant away from the limestone and caused the successive precipitation of V-U and Cr.

The model proposed for the origin of the V-U deposits is simple and the result of conditions that exist to varying extents in most red beds. This being the case, why are the deposits not more abundant? Some features of the V-U deposits are common in many red bed units in the form of bleached spots or "fish eyes" [71,72,73,74]. These spots usually contain a core of low-valent U and V minerals that are encompassed by a bleached volume a few centimeters in diameter. Associated with minerals in the cores is a small amount of organic carbon or a sulfide mineral that presumably served as a locus of reduction. Anomalous amounts of Cr have been detected in some of these spots and Mykura and Hampton [75] noted an enrichment of Fe along the contact between red and bleached sandstones. Thus, these spots have many of the characteristics of the V-U deposits, only on a smaller scale. The contrasting size of the Salt Wash, Mecsek, and Entrada deposits with the bleached spots may reflect differences in the depositional system, diagenetic history, and permeability.

CONCLUSIONS

A sequence of progressively stronger reducing conditions from oxidizing in the floodplain deposits to strongly reducing near large accumulations of detrital plant fragments within fluvial sandstones favored the separate accumulation of iron, chromium, and vanadium-uranium. Unlike roll-type uranium deposits, the redox gradient was oriented nearly perpendicular to the regional ground-water flow. This geometry controlled the spatial association of the deposits and affected their morphology. The redistribution of these metals into discrete deposits was favored by the depositional environment, slow rate of burial, availablity of metals, and chemical composition of detrital components. Combination of these factors enhanced the concentration of vanadium and uranium by redox processes, resulting in the large and extensive deposits hosted by the Salt Wash Member of the Morrison Formation.

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DIAGENESIS AND ORE DEPOSITION IN SANDSTONE-HOSTED URANIUM-VANADIUM DEPOSITS IN THE COLORADO PLATEAU: EVIDENCE FROM FLUID INCLUSIONS

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Abstract

In order to better understand the diagenetic history of the U-V mineralization in the Morrison Formation of the Colorado Plateau, fluid inclusions trapped in authigenic calcites have been investigated.

In the Cottonwood Wash district, Lisbon Valley area, Slick Rock district and Grants uranium Region, fluid inclusion data indicate that temperatures near 100°C have been reached. These temperatures correspond to maximum diagenesis of the host rocks. In the Lisbon Valley fault, fluid inclusions in calcite co-genetic with copper deposits contain solutions of variable salinities. Similar solutions were also present in the Slick Rock district. These solutions may have precipitated the vanadium chlorite, or influenced chlorite formation by recrystallization. In the Grants uranium region, fluid inclusion data support the model of Hansley (1) on the alteration of primary ore deposits during maximum diagenesis and formation of altered ore.

I-INTRODUCTION

Most researchers assume that epigenetic sandstone-hosted uranium deposits are not favorable for a productive study of fluid inclusions (2,3). In large part, fluid inclusions have not been investigated in these deposits because of the lack of suitable materials. This paper describes the results of a study of fluids trapped in calcite within and near rocks hosting uranium deposits in the Colorado Plateau region of the United States.

Uranium deposits on the Colorado Plateau have been studied extensively since the 1940's by methods including petrography and geochemistry (4) but the origin of the deposits is still controversial. In general, the models of deposit formation suggest that U^{6+}-bearing solutions precipitated pitchblende or coffinite in organic-rich environments because of redox processes. Two general types of deposits occur in the Upper Jurassic Morrison Formation on the Colorado Plateau including: 1)those associated with detrital plant fragments which contain less uranium than vanadium and, 2) deposits characterized by an intimate association of uranium and epigenetic organic matter and low vanadium contents. The first type of deposit occurs in southeastern Utah and southwestern Colorado. In these deposits, vanadium is generally considered to be cogenetic with uranium. The deposits containing epigenetic organic matter are the major-type in New Mexico.

This paper is a synthesis of fluid inclusion studies from the Cottonwood Wash district (5), the Lisbon Valley area, Utah, the Slick Rock district, Colorado (6), and the Grants region, New Mexico (Fig.1). Samples from the Slick Rock and Cottonwood

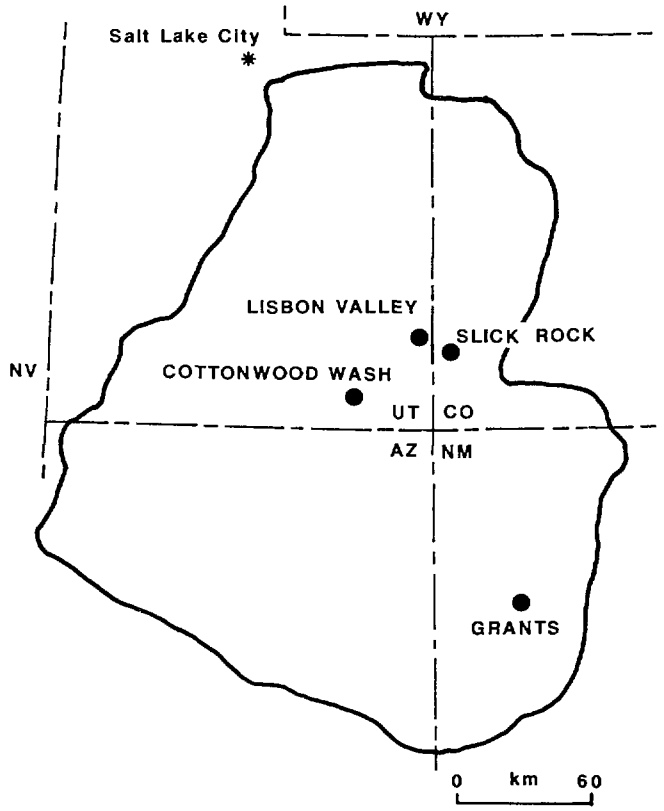

Fig. 1: Location of the study areas in the Colorado Plateau.

Wash U-V mining districts were collected from the Morrison Formation. Samples from the Grants uranium Region were collected from the Middle Jurassic Todilto Limestone Member of the Wanakah Formation. Calcite from Lisbon Valley and some from the Slick Rock district were collected along faults which had wall rocks varying in age between Upper Pennsylvanian and Upper Cretaceous.

2-METHODS

Prior to evaluating the microthermometry of the fluid inclusions (FI), the FI were characterized petrographically to evaluate the importance of shape, size, abundance, and the probable origin.

FI in all samples examined were aqueous and mono or two phased . Size of these inclusions varies between 5 and 20μm.

The inclusions were evaluated to determine whether they were primary (formed during crystal growth) or secondary (formed after crystal growth along healing fractures). Secondary FI occur as planar groups that outline healed fractures. These planar groups come to the crystal surface and were recognized in samples from the Todilto Limestone and the Lisbon Valley area. The isolated and flat groups of FI are interpreted to be primary. Most of the FI occur in planar groups which are oblique or parallel to cleavage plans and do not come to the surface. These inclusions include irregular, tubular, and negative crystal shapes. Within the planar groups, single phase inclusions next to two phase inclusions suggest that they formed by necking down, probably along a healed fracture. Therefore, FI within this group could not be easily classified as primary or secondary.

Microthermometry of FI were conducted using a Chaixmeca heating-cooling stage (7). FI were characterized by their homogenization temperature (Th) which determine the minimum temperature of trapping and by the temperature of melting of the last ice crystal (Tm) which is a function of salinity of the fluid trapped.

3- RESULTS AND DISCUSSION

3-1: COTTONWOOD-WASH DISTRICT

Calcite examined from the Cottonwood Wash district is coarse grained and replaces fossil wood or fills fractures in coalified logs (5). The histogram of Th indicates a main thermal event near 85-90°C (fig 2). Higher values are probably due to leakage. Melting temperatures were not observed but the vapor phase sometimes reappears above 0°C indicating metastabily and suggesting that salinity is low (8).

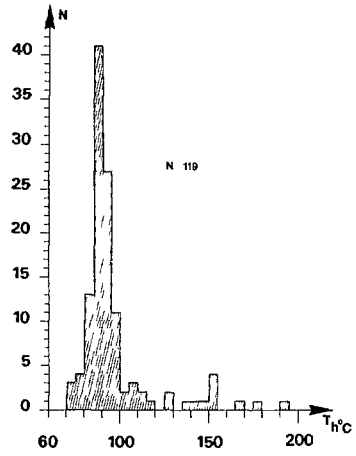

Fig. 2: Th of fluid inclusions in calcite replacing wood, Cottonwood Wash district (5).

Estimates of the depth of burial of the Morrison in SW Colorado and SE Utah range from 2000 to 3000m (9). A depth of 3000m would suggest hydrostatic pressure of approximately 300 bars . This pressure would indicate a correction of pressure of 10°C for Th. Therefore, the calcite did not formed above 100°C. This temperature is consistent with the results of geochemical analyses of detrital coalified plant fragments in the Morrison Formation in Cottonwood Wash (5,10). The composition of this organic matter corresponds to the beginning of the oil window, i.e. a maximum of 120°C. Therefore,the temperatures of 90 -100°C obtained from the FI in the Cottonwood Wash district correspond to the maximum of diagenesis.

Petrographic observations of the ore material indicate that U and V mineralization are authigenic and postdates some compaction. In addition, no radiometric age determinations have been conducted on these ore deposits so their absolute age is unknown. One of the major ore minerals is vanadium chlorite (11). They are characterized by a di-tri octahedral structure and a IIb layer type. IIb chlorite is generally the most stable polytype (12) where sufficient thermal energy or pressure are available. Then, the genesis of vanadium chlorite may have been influenced by the maximum of diagenesis.

3-2: LISBON VALLEY AND SLICK ROCK DISTRICT

Samples of calcite from the Slick Rock U-V district and adjacent Lisbon Valley area were collected near and within faults (table 1). Along these faults in Lisbon Valley are copper deposits which occur mainly in coal - bearing beds in the Cretaceous Dakota Sandstone. Copper is also enriched in U-V deposits near the Dolores zone of faults in the Slick Rock district (13). The copper minerals formed when copper bearing-brines which moved along the faults replaced pre-existing iron sulfides or mixed with an H_2S-bearing

Table 1: Location and description of calcites studied in Lisbon Valley and Slick Rock (6).

SAMPLE	LOCATION AND DESCRIPTION
LISBON VALLEY:	
7004	large crystals(>1cm) of transparent calcite with minor intergrown copper minerals; collected from a fracture crossing the Hermosa Formation.
A29	Large crystals of milky calcite filling a fracture of the Lisbon Valley fault; calcite veins cross-cut by veins of barite; wall rock is Triassic Kayenta Formation.
SLICK ROCK:	
A 8,10	Small crystals (<0.5 cm) of fracture-filling calcite within the Morrison Formation. Sample A10 and A8 collected 20m apart.
7005	Small crystals (<0.5 cm) of moderately transparent calcite replacing wood in the Morrison Formation.

solution (14, 15). Geologic, isotopic and petrographic data (16) suggest that the copper mineralization post-dates the formation of the main U-V deposits, and is cogenetic with calcite along the faults.

Samples from the Lisbon Valley fault (fig. 3) have a range of Th from 40 to 105°C with a mode between 75 and 95 °C. Tm values range from 0 to -6.5°C. This range in Tm corresponds to salinities between 0 to 9 wt.% eq NaCl. Typically secondary FI are characterized by a 90-95°C Th range and high salinities while primary ones exhibit variable Th and Tm. These results indicate changes of fluid composition with time as the calcites grew.

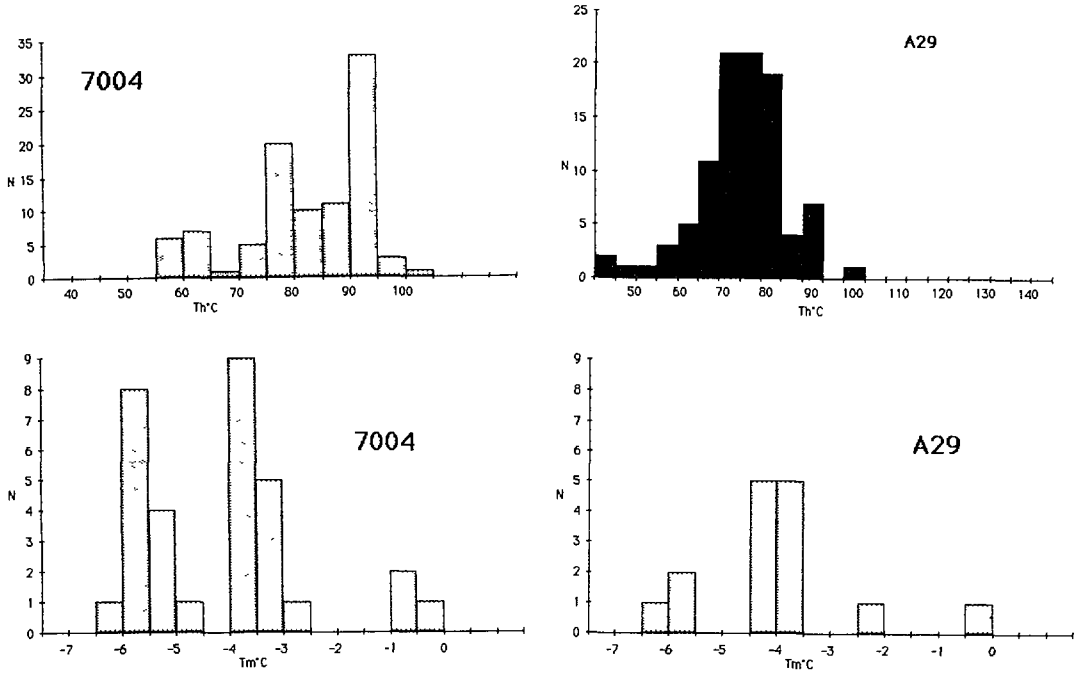

Fig. 3: Th and Tm of fluid inclusions in calcites from the Lisbon Valley fault.See table for description

FI studies of calcites (Fig.4) in the Slick Rock District reveal that the calcite from the Dolores zone of fault is distinct from the calcite replacing wood in the Morrison Formation. Samples from the Dolores zone of faults (Fig. 4) record a thermal event at about 50°C but higher temperatures up to 80°C are also present. Only four values of Tm close to 0°C were obtained from these samples, consistent with a dilute water. Sample 7005 (calcite replacing wood) contains FI similar to those from the Lisbon Valley fault. The major mode of Th is 80-85°C and the range of Tm is from 0 to -5.5 °C.

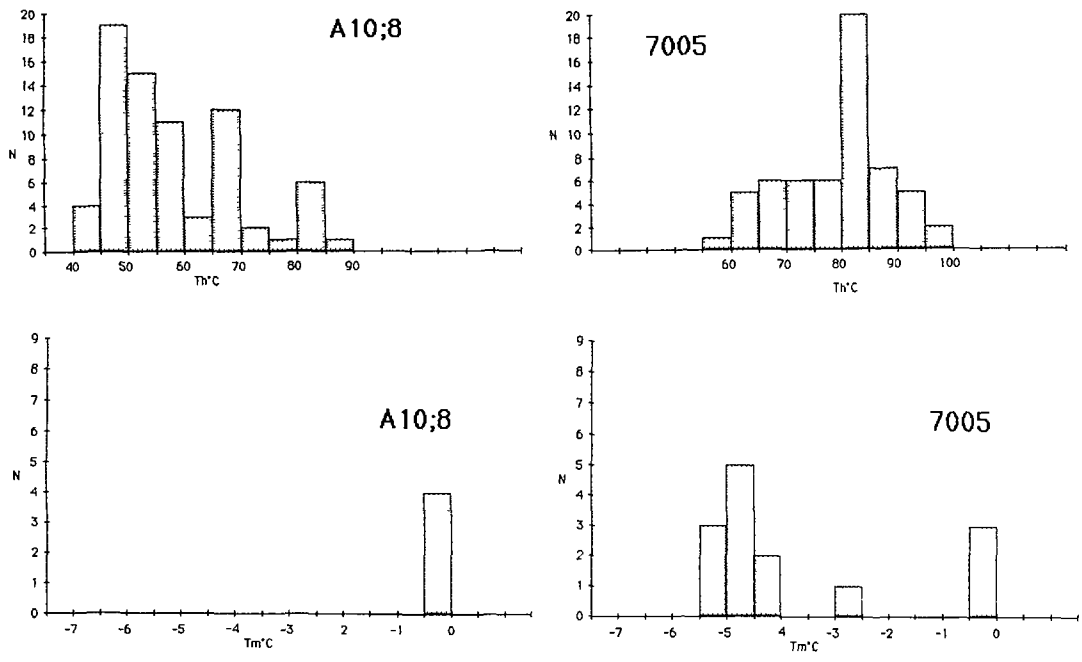

Fig. 4: Th and Tm of fluid inclusions in calcite from the Slick Rock district.See table for description

The calcites are also isotopically distinct. Calcites in the Lisbon Valley fault and in the Slick Rock district have oxygen isotope values ($\partial^{18}O$) between +16 and +18 per mil (SMOW) (16). At a temperature of 90°C these calcites precipitated from a water close to -1 per mil (SMOW). In contrast, the calcites from the Dolores zone of fault have $\partial^{18}O$ values ranging from +7.5 to +11 per mil (SMOW). Therefore, this calcite formed from a water of -15 per mil at 50°C, which is the composition of modern meteoric groundwater near the study area (16).

FI and isotopic data suggest that the same solutions moved through the Lisbon Valley fault and the Slick Rock district at temperature close to 90°C. These solutions of variable salinities were responsible for the copper mineralization during late diagenesis. Sometime after the copper mineralization, a distinct solution, probably meteoric water, moved through the Dolores zone of faults and precipitated a second generation of calcite.

In order to evaluate the importance of these fluids for the uranium deposits, it is noted that similar temperatures of 90-100°C have been reached during diagenesis in the Slick Rock district and Cottonwood Wash district.The vanadium chlorite exhibits similar XRD patterns to those in the Cottonwood Wash district. In addition, data of Breit (16)

indicate that the $\partial^{18}O$ values of chlorites are +6.5 per mil (SMOW). Application of the fractionation factor of Wenner and Taylor (17) assuming a temperature of about 90°C, indicates that this chlorite formed from a water with $\partial^{18}O$ near -1 per mil (SMOW) identical to the composition of the waters which formed calcite co-genetic with copper. Then, vanadium chlorite may have formed either contemporaneously with copper mineralization or from the re-crystallization of previous vanadium minerals during late diagenesis.

3-3: THE GRANTS URANIUM REGION

Large crystals of calcite filling vugs in the Todilto limestone were collected and examined although the relationships between uranium ore and the calcite are unknown. Results of the FI studies indicate the presence of an aqueous, dilute solution with temperatures between 80° and 100°C (Fig. 5).

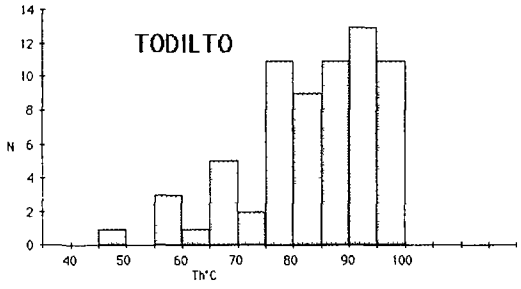

Fig. 5: Th of fluid inclusions in calcite filling vug from the Todilto limestone (Grants region).

Most of the uranium deposits in the Grants uranium region occur in fluvial sandstones of the Morrison Formation while only minor deposits are located in the underlying Todilto limestone (4,18).

The primary uranium deposits in the Morrison Formation are tabular and uranium occurs intimately associated with epigenetic organic material. Some of this ore has been altered resulting in the destruction of organic matter, and the redistribution of uranium as microscopic coffinite. Associated with this altered ore are etched garnets (1).

Hansley (1) demonstrated experimentaly that the etching of garnets similar to those observed in the altered ore can be the

result of alteration by organic acids. The coincidence of the garnet etch zone with organic-poor secondary uranium ore is interpreted to be a direct result of organic acid generation during burial diagenesis of the organic-rich ore zones. Etching of the garnets during early diagenesis is unlikely because sulfate-reducing micro-organisms and fermentation would have consumed available organic acids. Therefore, the organic acids most likely formed during thermal breakdown of the epigenetic organic as a result of heating with increased burial.

According to stratigraphical reconstructions, the Morrison Formation in the Grants region was never buried beneath more than 2000m (19), which is too low to attain 100°C, assuming the present geothermal gradient. In contrast, analysis of the fluid inclusions indicates that such temperatures were reached. Therefore, the model of production of organic acids by thermal alteration is consistent with the temperatures from FI. In addition, FI are consistent with the temperatures of 130°C ± 40 obtained from the isotopic composition of clays in the Morrison Formation (20).

4-CONCLUSION

FI data from calcite can be very useful in constraining conditions of diagenesis in the rocks hosting uranium deposits within the Colorado Plateau. All areas examined indicate the presence of solutions close to 100°C at some time during the diagenetic history, most likely during maximum burial. In Cottonwood Wash, the temperatures can be related to the formation of the vanadium chlorite. Calcites from the Slick Rock and Lisbon Valley districts indicate that solutions of different composition moved successively through the faults reactivated during and after the Laramide. Some of these fluids are directly connected with the copper ore deposits, but they may also have precipitated the vanadium chlorite or influenced its formation by recrystallisation of pre-existing phases. Lastly, in the Grants uranium Region, FI data support the model of Hansley (1) on the alteration of primary ore deposits during the

maximum of diagenesis. Thus, this FI study shows that the importance of diagenesis has to be reconsidered for a better understanding of these uranium ore deposits.

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GEOTHERMAL ANALYSES OF THE BRECCIA PIPES (ARIZONA) — ORGANIC MATTER, FLUID INCLUSIONS, FISSION TRACKS AND COMPUTERIZED MODELING

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Abstract

Geothermal characterization of sedimentary uranium deposits has frequently been carried out using geological data (burial, erosion, faulting...).

Organic matter has also been used as a geothermometer but, considering its involvement in oxidation, the chemical composition of oils, coals or kerogens is not always representative of the thermal maturation. More recently fluid inclusions have been analyzed by microthermometry in several sedimentary deposits. Nevertheless, problems concerning leakage, necking or reequilibration phenomena can disturb the geothermal diagnosis.

Furthermore organic matter gives an integration of the time-temperature effects while fluid inclusions represent temperature peaks. This is why a complete geothermal study including the analyses of fission tracks in apatite has been carried out on the Arizona pipes of the Grand Canyon region (Arizona). Results have been compared to geological data and computerized on two thermal modeling programs at the Insitut Français du Pétrole (organic matter) and at the C.R.E.G.U. (fission track).

Brecciated rocks inside the pipe throat and samples from undisturbed formations have been analyzed. Interpretations give important data on the maximum temperatures, thermal history, time of erosion in this uraniferous area.

THE FLODELLE CREEK SURFICIAL URANIUM DEPOSIT, STEVENS COUNTY, WASHINGTON, USA

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Abstract

A recently discovered uranium deposit occurs in surficial, organic-rich, low radioactivity sediments of late Pleistocene to Holocene age. Its study provides a geologic model for locating other young, and therefore daughter-poor, uranium deposits. The uranium is concentrated in valley-fill sediments that are as much as 4 m thick along the north fork of Flodelle Creek in Stevens County, Washington. These sediments range from mucky peat (50 to 60 wt. percent organic matter) to clay, silt, and sand of lesser organic content. They were deposited in shallow ponds, on flood plains, or in stream channels along the valley floor of the drainage. Uranium content of the sediments ranges from <0.01 to 0.9 percent by dry weight and is positively correlated with content of organic matter. Local bedrock is Cretaceous two-mica quartz monzonite that is anomalously uraniferous; 28 outcrop samples average 5.9 ± 4.2 ppm U and 13 core samples average 15.8 ± 2.7 ppm U. The bedrock is locally fractured and faulted and is mostly covered on hillslopes by as much as 2 m of sandy glacial till. Transport of uranium from this local source rock to nearby organic-rich sediments is via anomalously uraniferous (17-320 ppb U) surface and ground waters, and via springs that issue from till-covered slopes or that dishcarge into valley bottom sediments from below. Recent glaciation appears to have been critical to the establishment of this mineralizing system because it simultaneously provided (1) renewed exposure and comminution of a favorable source rock and (2) formation of environments suitable for water ponding and plant growth so organic-rich sediments could accumulate and act as traps for dissolved uranium.

Introduction

Uranium deposits in soils and surficial sediments only recently have been discovered and classified [1,2,3,4,5]. The deposits are typically young (Holocene-Tertiary), form under varying climatic regimes, and develop when uranium is extracted or precipitated from shallow ground or surface waters. Settings include desert valleys and playas, wetlands, tropical lateritic soils, and alkaline lakes. The best known and most thoroughly documented surficial uranium deposits are the arid land deposits (calcrete, gypcrete) of which Yeelirrie, Australia is the best example. Surficial uranium deposits that form in wetlands are typically rich in organic matter, small in size (usually <500 tonnes of uranium), variable in average grade (100-1500 ppm U by dry weight), close to granitic or other uranium source terrains, and low in radioactivity (U >> daughters). The latter characteristic is of particular importance because daughter-poor deposits of this type yield very little gamma activity and can be overlooked or underestimated by conventional radiometric measurements [6,7]. Clearly, the successful exploration for these low-radioactivity uranium deposits must rely heavily on the recognition of favorable geologic settings and on the direct measurement of uranium. Such deposits may contribute significantly to the low-cost uranium resource base in the U.S. and elsewhere.

This paper summarizes the geologic environment of an unusually uraniferous, organic-rich, surficial uranium deposit. The low-radioactivity deposit is located in northeastern Washington and was inadvertently "discovered" during a stream sediment sampling program designed to search for vein-type uranium deposits in the local bedrock. Because this occurrence represents a new class of uranium deposit, the U.S. Geological Survey is conducting multidisciplinary studies to understand better the conditions leading to its formation and preservation [8,9,10,11,12,13,14]. To the extent that this deposit is considered to be the type example, the resultant geologic model may be useful in the search for additional deposits in similar geologic

settings. Studies of other wetland-hosted uranium deposits in the Sierra Nevada of California and Nevada [15], the Basin and Range of Nevada [16], and the Rocky Mountains of Colorado [17] are in progress.

Regional Geology

About 50 percent of northeastern Washington and northern Idaho is underlain by granitic rocks that range in age from Jurassic through early Tertiary [Fig. 1][18]. These granites intrude older metamorphosed sedimentary rocks of Precambrian and Paleozoic age. The youngest granites of this group intruded during a period of early Tertiary crustal extension that saw the formation of extensional basins and domal metamorphic core complexes flanked by low-angle normal faults [Fig. 1][19, 20].

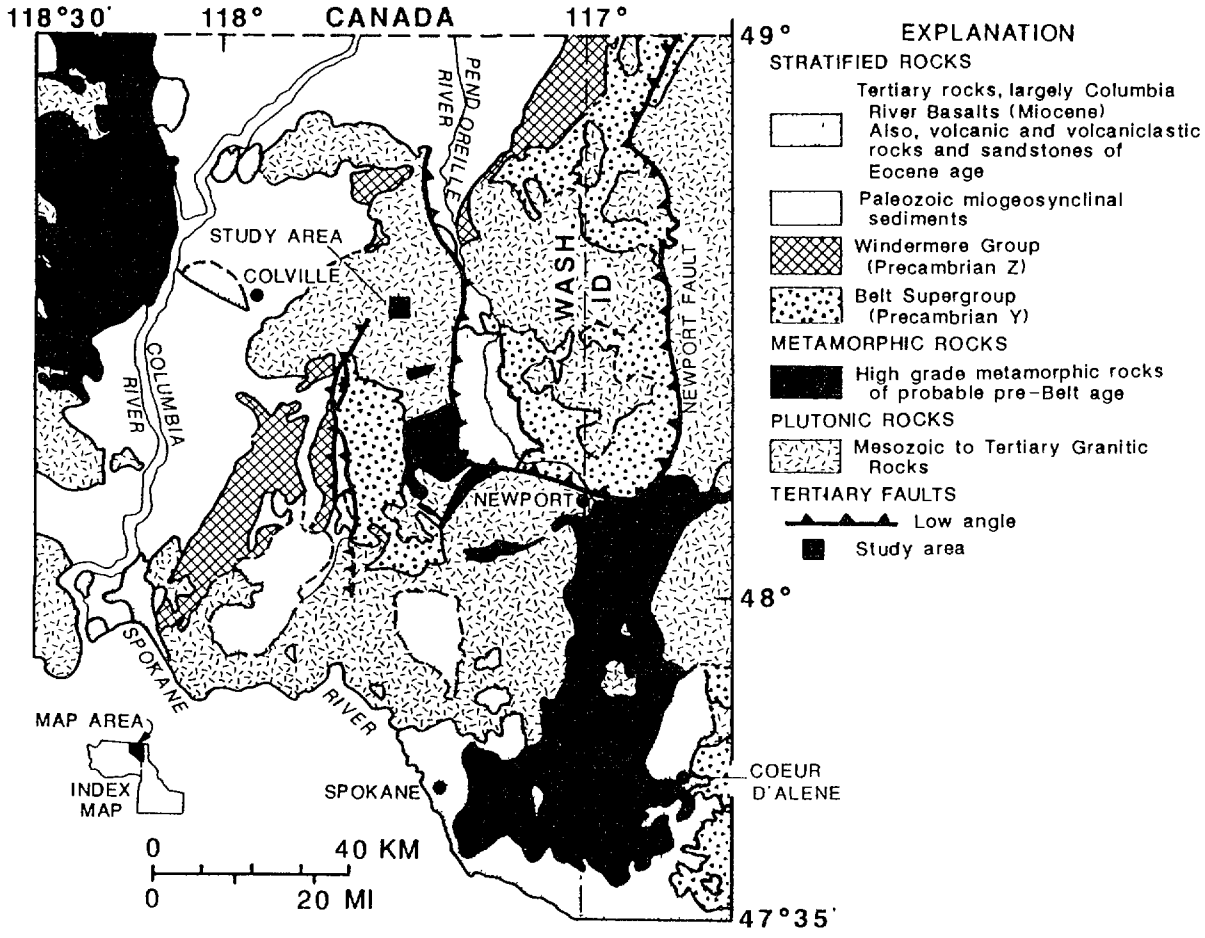

Figure 1. Generalized geologic map of northeastern Washington and adjacent Idaho, modified from [19, fig. 3, eastern part]. Note location of the Flodelle Creek drainage near the center of the figure.

During the Pleistocene, northeastern Washington was periodically covered by glaciers that left behind extensive glacial drift and glacio-fluvial and glacio-lacustrine deposits. The last glacial episode to affect the area ended about 10,000-15,000 years B.P. [Fig. 2][21], after which, erosion and sedimentation have further modified the topography.

Site Description

The surficial uranium deposit occurs in organic-rich valley-fill sediments of the north fork of Flodelle Creek, Stevens County, Washington (Fig. 1, 2). This first-order stream drains a samll watershed (4.1 km^2) that is underlain entirely by granitic bedrock. Topographic relief in the basin is about 180 m. The stream rises in a small marsh near the drainage divide (site labeled "government rock" in Fig. 2). It drops approximately 50 m in elevation along the first 1.6 km of its run and is confined to a narrow valley flanked by steep (30-65 percent) slopes. The valley is typically swampy and flat-bottomed and ranges from 20 to 70 m wide. The stream follows a channel that meanders across the width of the valley floor. Several abandoned beaver ponds occur between government rock and the spring pool (Fig. 2). Grasses, tall shrubs, riparian deciduous trees, and various conifers grow in the flat valley bottom. Two steep, narrow, V-shaped sections occur; one, between government rock and the spring pool, and the second, between the spring pool and the meadow mine. Little or no organic-rich sediment and very little uranium has accumulated in these sections.

The stream then enters a broad, relatively flat, gently sloping meadow (meadow mine of Fig. 2) flanked by an older valley terrace to the east. The modern channel is cut about 1 m into the surface of the upper end of the meadow. Older abandoned channels parallel the modern channel. The upper end of the meadow is dominated by grasses whereas the lower end is locally marshy and has reeds and sedges. The stream exits the southwestern corner of the meadow and flows through a narrower valley constricted by a collapsed terrace

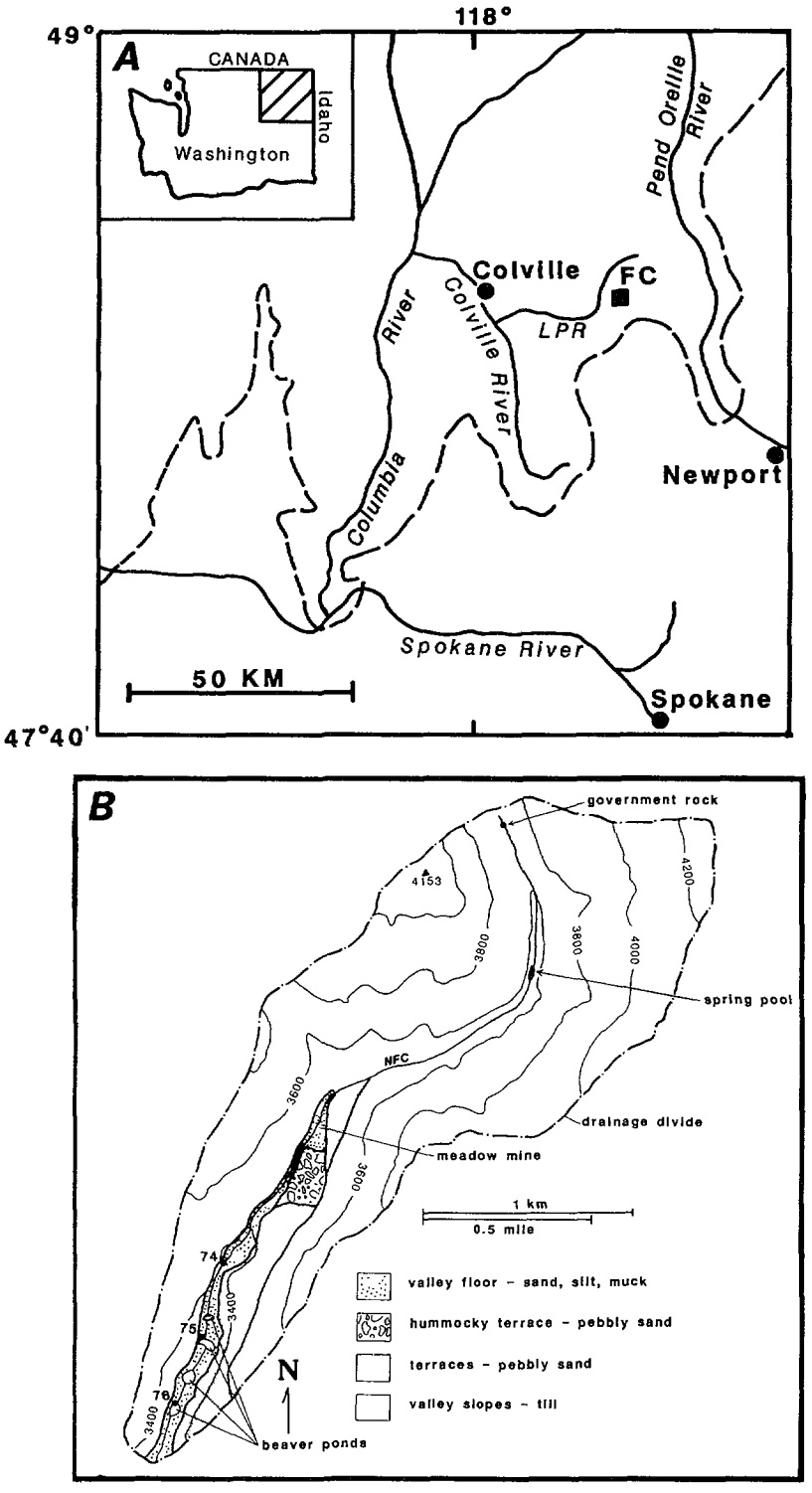

Figure 2. A.) Map showing the location of the study area in the Flodelle Creek drainage (FC), and its position relative to the approximate southern termination of the Cordilleran ice sheet during Fraser glaciation (dashed line). LPR = Little Pend Oreille River. Modified from [14]. B.) Map of surficial deposits of the north fork of Flodelle Creek (NFC) drainage basin. Contour intervals in feet. Modified from [14].

to the east and the valley wall to the west. The valley floor widens gradually downstream to the confluence of the north fork with the main fork of Flodelle Creek. Active beaver ponds occur in the lower part of this section (Fig. 2).

Uranium

The Flodelle Creek deposit is comprised of uraniferous, organic-rich, valley-bottom sediments that occur almost continuously from the drainage divide to the confluence of the north fork with the main fork of Flodelle Creek and constitute the Flodelle Creek deposit. Valley-bottom sediments include coarse-grained to granular glacio-fluvial sands that are overlain by as much as 4 m of fluvial and paludal sediments of varying uranium and organic matter content. These latter sediments range from fibrous woody mucky peat, 50-60 weight percent organic matter in content, to sand, silt, muck, and clay of lesser and highly variable organic content [13,14].

A volcanic ash-rich unit ranging in thickness from 0-60 cm is observed in many measured sections in cuts at the meadow mine, and in core and auger holes at some upstream localities from the spring pool northward (Fig. 2). A purified ash separate contained <2 ppm U. The ash was identified as the 6700-7000 year B.P. Mazama ash on the basis of shard chemistry and accessory mineralogy [10], and of bracketing ^{14}C ages [14].

Uranium contents of the organic-rich sediments range from <0.01 to 0.9 wt percent (dry basis) and are positively correlated with organic matter content [8]. The correlation coefficient for uranium and organic matter is 0.75 for 76 samples from the meadow mine, and 0.78 for 18 samples collected at the spring pool site [Fig. 3][14]. The association of uranium with organic matter was verified by fission-track radiography, which indicates preferential uptake of uranium by the finer grained, structureless, organic matter (humin?) and by charcoal fragments [8]. The mechanism of uranium uptake by organic matter is probably via adsorption, ion-exchange, reduction, or a combination of these

[22,23,24,25]. Microbial interactions also are possible. No uranium minerals are observed in the sediments, and waters in contact with the sediments are calculated to be undersaturated with respect to U(VI)-bearing minerals. Undersaturation with respect to U(IV)-bearing minerals such as uraninite and coffinite is also predicted by solution equilibria calculations as long as ambient Eh remains greater then 0.1 volt in the sediments [12].

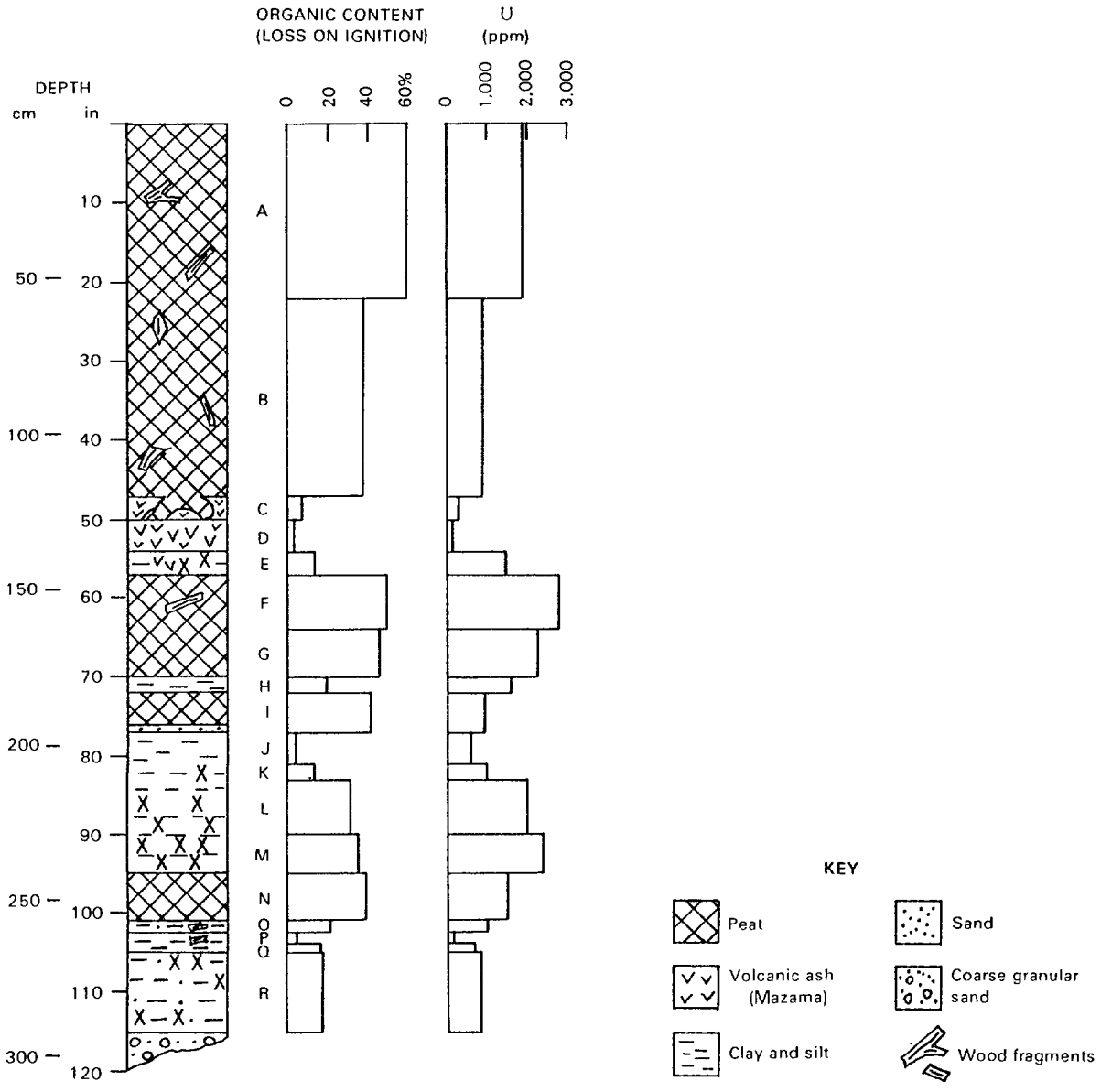

Figure 3. Generalized lithologic log of a core taken at the spring pool site, and variation of organic content and uranium content as a function of depth. Modified from [31].

Bedrock geology

The Flodelle Creek drainage is underlain by medium-grained, massive, muscovite-biotite quartz monzonite, with minor pegmatite and granodiorite. These rocks have been mapped regionally with the Phillips Lake granodiorite. Bulk composition of the quartz monzonite is mildly peraluminous, corundum appears in most normative calculations. Accessory minerals include apatite, zircon, allanite, magnetite, and monazite. Preliminary Sr-isotope data for the rock unit suggests an origin from pre-Belt continental crustal rocks; possibly with some interaction with sediments of the Belt Supergroup [26]. A sedimentary component in the source region is also suggested by the broadly S-type chemistry and mineralogy of this rock.

Outcrops in the drainage basin are sparse and occur mostly on the west side of the watershed. These rocks are commonly fractured, jointed, and sheared. Core samples of bedrock taken near the spring pool site show petrographic evidence of stress and shear, i.e., strained quartz, bent micas, and numerous microfractures filled with mineral debris. Minor quartz and calcite occur in some fractures. Plagioclase is partially altered to sericite ± minor epidote, and biotite is partially altered to chlorite.

The observations of fracture and shear in core samples and in outcrop are not surprising considering the proximity of the drainage to the Newport fault (Fig. 1). The drainage also lies within a 10-25-km-wide zone in which postemplacement heating has created discordant K-Ar ages in biotite-muscovite pairs [18]. The thermal overprint probably is related to a period of regional intrusive activity around 50 Ma, and contours of K-Ar age discordance suggest a heat source to the east of the drainage [18].

The uranium content of 13 core samples of bedrock collected over a depth ranging from 31.4-43.9 m averaged 15.8 ± 2.7 ppm. In contrast, 28 outcrop samples from throughout the drainage basin averaged 5.9 ± 4.2 ppm. Comparisons of fission-track radiographs between cores and nearby outcrop samples indicate that allanite was particularly susceptible to uranium loss

during weathering. Some of the mobilized uranium was redistributed in nearby biotite and microfractures. The regional average uranium concentration in Phillips Lake granodiorite is 12 ± 6 ppm [27], which is anomalously high compared to other granitic rocks that average about 4 ppm [28]. Likewise, the average thorium concentration in the core samples is 32 ± 4.0 ppm, which is anomalously high compared to typical granitic values of 10-20 ppm [29]. Unusually high radioelement contents of rocks in the drainage basin also are indicated by airborne radiometric surveys that have detected local anomalies of 1.5-4.0 times the normal background for the Phillips Lake Granodiorite [27].

No occurrences of uranium minerals have been reported from the bedrock of the drainage, but uraniferous pegmatites and fracture coatings of secondary minerals (autunite, meta-autunite) are reported from several localities within the Phillips Lake granodiorite. The nearest group of localities, including mines with as much as 14 tonnes of uranium production, is along a 15-km-long, north-northwest-trending lineament approximately 8 km east of the drainage [27].

Glacial and postglacial geology

During the last period of glaciation, the Cordilleran ice sheet covered the Flodelle Creek area, and it terminated several kilometers to the south (Fig. 2). As glaciers retreated from the area about 12,000 years B.P. [14], the valley slopes were mantled with as much as 2 m of massive, poorly sorted, sandy, glacial till of largely "granitic" parentage (Fig. 2). This coarse till is overlain by as much as 40 cm of silt loam and sandy loam which is capped by 2-4 cm of organic litter [30]. The silt loam (loess?) contains abundant volcanic ash, which is probably reworked Mazama ash.

Discontinuous remnants of a 10-30 m high terrace deposited by early-postglacial meltwaters occur on the east side of the valley floor, from the meadow mine south to the confluence of the north fork with the main part of

Flodelle Creek [Fig. 2; 13,14]. The variable degree of sorting and stratification and the coarse grain size of most of the terrace sediments suggest deposition by high energy braided streams of considerably larger discharge than that of the present creek. Both the deposition and the subsequent incision of this glaciofluvial outwash probably occurred as the ice margin receded from the drainage and crossed the drainage divide to the north.

An area of hummocky terrain that is similar in composition and texture to the terrace sediments occurs just south of the meadow mine, on the east side of the valley floor (Fig. 2). This feature is interpreted as a section of collapsed terrace that was initially supported by stagnant ice [13,14]. The resulting hummocky (kame) terrace is presently several meters above the valley floor and shows no evidence of dissection by the stream.

The sedimentary section exposed in trenches and in samples from auger and core holes at the meadow mine indicates that shortly after glacial retreat, the relatively wide and flat meadow was a site of continuous deposition from a fluvial system of greatly diminished size and vigor (Fig. 4A). Stream outflow from the meadow appears to have been diverted to the west side of the valley by the downstream kames. This pattern of sedimentation persisted at least until the deposition of the Mazama ash at 6700-7000 years B.P. About 5000 years B.P. the meadow was occupied by beavers (Fig. 4B). Buried beaver dams are preserved in an organic-rich layer containing abundant chaotic masses of sticks that exhibit characteristic tooth-marked terminations. Wood fragments from the layer yielded a ^{14}C age of 5100±110 years B.P. [13,14]. Ponds created by one or more of these beaver dams provided an environment for the accumulation of organic matter in the meadow. Departure of the beavers and gradual filling of the ponds with sediment caused a return to fluvial deposition in channel and flood plain environments [Fig. 4C]. Diatomite layers of several cm thickness are observed in the downstream area of the meadow and suggest that small ponds persisted on parts of the flood plain.

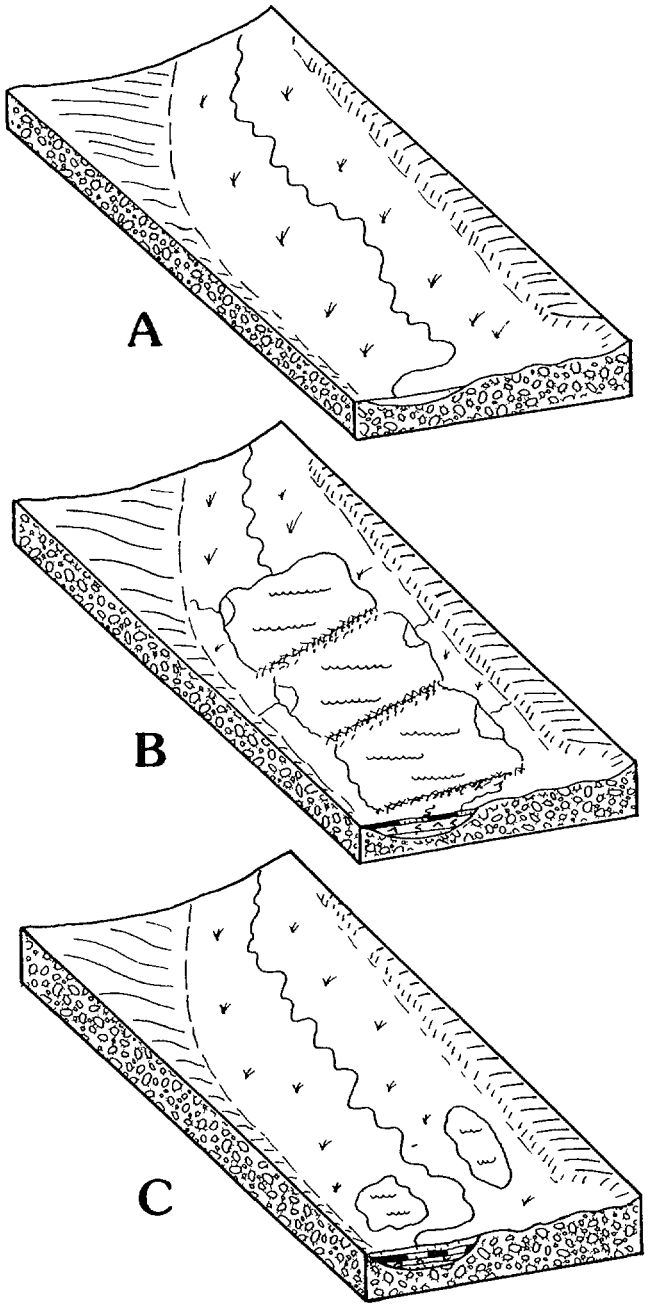

Figure 4. Reconstruction of postglacial sedimentary history of the meadow mine area. A. A small postglacial stream flowed through the wide meadow and was partly diverted and restricted by kames at the lower end of the meadow. B. At ~5000 years B.P. beavers built one or more dams in the meadow causing ponding. C. Beaver ponds filled with sediment and a fluvial drainage was reestablished. Small flood plain ponds still persisted. From [13].

The sediments at the spring pool site (Fig. 2) indicates a different postglacial history. Drainage was impeded shortly after deglaciation by unconsolidated glacial sediments that slumped off the relatively steep valley

walls [Fig. 5A][13,14]. Local ponding behind this impediment [Fig. 5B] created an environment suitable for the deposition and preservation of organic-rich sediments that were then able to extract uranium from coexisting waters. A nearly continuous postglacial history of uranium emplacement at this site is confirmed by an increase of daughter product concentraions with depth, and by U-series ages of peat that closely mimic independently estimated depositional ages of host sediment [31].

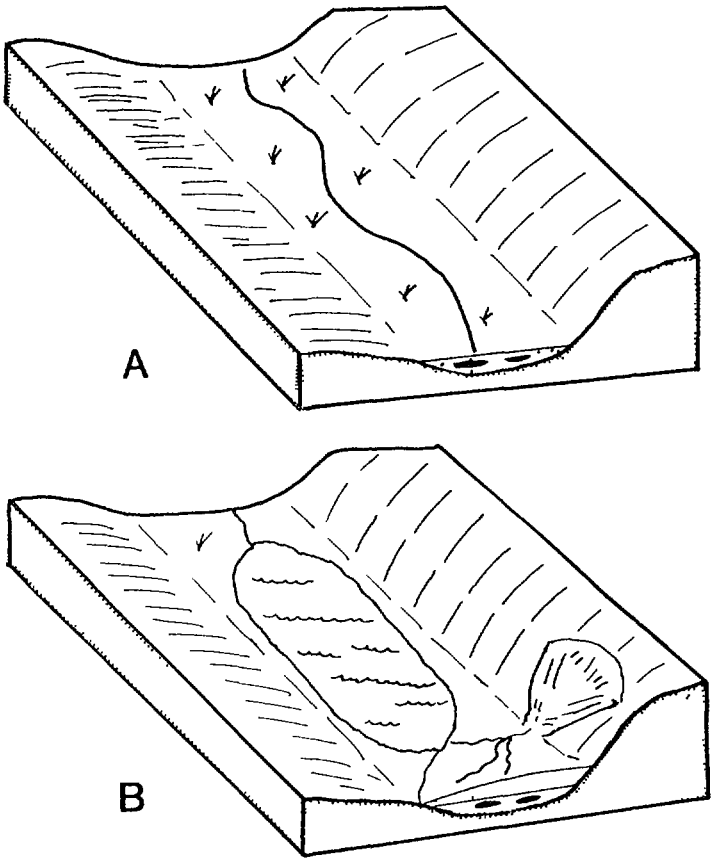

Figure 5. Reconstruction of postglacial sedimentary history of the spring pool site. A. Small postglacial stream flowed through the narrow valley. B. Unconsolidated glacial deposits slumped off valley walls and blocked drainage, creating a small pond. From [13].

Hydrology

Local ground and surface waters provide the necessary transport medium for uranium from uraniferous soils and bedrock to the organic-rich sediments of the valley bottom. Spring, stream, and near-surface waters collected in

the drainage are of the calcium-bicarbonate chemical type and are chemically similar to waters draining other granitic terrains, i.e., low conductivity (<150 μmho/cm), near-neutral pH (5.85-7.55), saturated with respect to quartz and kaolinite, and undersaturated with respect to calcite. Near-surface waters collected from auger holes in the valley-fill are the more acidic of the sampled waters,probably due to increased contact with decaying organic matter [12].

Trace element abundances in the waters are likewise unremarkable, except for uranium. The measured waters contain 17-318 μg/l (ppb) U, compared to an average of 2.4±1.9 μg/l U for springs and streams in nearby areas [32]. High degree of correlation bewteen dissolved uranium and bicarbonate content as well as thermodynamic calculations of uranium speciation, indicate that most of the uranium is transported as inorganic complexes with carbonate or phosphate ions.

The Flodelle Creek area receives an average annual precipitation of approximately 60 cm, most of which falls between the beginning of October and the end of March [30]. During periods of rainfall or snowmelt, runoff is carried along several small intermittent tributaries (Fig. 2), or moves downslope in the shallow subsurface. Shallow subsurface flow seems most likely because of the high permeability of the sandy till that mantles the less permeable granitic bedrock [33]. Local variations in subsurface structure or sediment permeability often causes this subsurface flow to be diverted to the surface and issue as springs from till-covered slopes. Other flow paths may cause springs that well up in valley bottom sediments. Upwelling ground water has produced the 2.5-m-wide pool at the spring pool site; it maintains water-saturated conditions in the organic-rich sediment column. Upwelling ground waters are also important transporters of uranium. Water collected at the spring pool and at other springs on the valley walls contains 100-150 μg/l U [11,12].

Model for Deposit Formation

The unusually high concentrations of uranium observed in young organic-rich sediments of this drainage indicate that a very efficient mineralizing system has been in operation at least since early postglacial time. Although sedimentary deposits of uranium in the drainage prior to glaciation cannot be ruled out, the proposed model suggests that glaciation was crucial for establishing the present mineralizing system with its sources-transport-traps.

Radioelement-rich bedrock has existed in the area since Cretaceous emplacement of uranium-rich igneous rock, but glaciation provided several mechanisms for abruptly increasing the leachability of bedrock uranium. First, glacial erosion of previously weathered outcrop exposed relatively fresh uranium-rich rocks to the zone of leaching. Second, glacial abrasion created surficial deposits (till) composed of comminuted bedrock with high surface area and permeability. Third, erosional unroofing and isostatic rebound of previously buried granitic rocks probably promoted renewed fracturing [34]. Other processes such as uranium redistribution during earlier (Tertiary ?) shearing and fracturing may have made the contained uranium more available for leaching by groundwater.

In addition to source rock modification, glaciation was also crucial in forming local environments in which organic-rich sediments could accumulate (Figs. 4, 5). The proximity of these organic-rich traps to sources of labile uranium in bedrock and till, and the funneling of surface and ground waters into these traps, made for a very efficient mineralizing system. The spring pool site is perhaps an optimum example of how efficient and long-lived such a system can be. Ponding in the meadow mine was directly related to beaver activity, but indirectly related to glaciation, which provided a suitable wide, low-gradient beaver habitat.

Conclusions and Suggestions for Future Studies

The low-radioactivity surficial uranium deposit of the north fork of Flodelle Creek, Stevens County, Washington, represents a significant recent

example of uranium enrichment in organic-rich sediments. Deposit formation was strongly influenced by recent glaciation that provided for increased exposure, comminution, and leachability of local granitic bedrock, and that also provided new sedimentary environments where organic matter could accumulate and extract uranium from local waters. At the spring pool site, ponding occurred shortly after glacial retreat when unstable unconsolidated till slumped off the valley walls onto the valley floor. At the meadow mine site, postglacial drainage was initially restricted by relict glacial topography (kames) on a low-gradient valley floor created by glaciofluvial erosion. Ponding was initiated around 5000 years B.P. when beavers occupied this suitably prepared habitat.

Based on the observations and interpretations made at the Flodelle Creek locality, future exploration for surficial uranium deposits of this type (valley-fill wetland) should concentrate on other low-order drainages in recently glaciated uranium-bearing granitic terrains. Sampling should focus on the low gradient sections of drainages where organic matter is more likely to have accumulated. Radioelement-rich fractured granites containing allanite and uranium mineralization are particularly favorable source rocks. Drainages containing numerous springs, abundant wetlands, and/or uraniferous waters should receive special attention. Reconnaissance sampling is best accomplished by augering of organic-rich sediments followed by chemical analysis or low-energy gamma radiometric determinations for uranium [35,36]. Scintillometers and gamma-ray spectrometers are not reliable indicators of surficial uranium.

Silicic extrusive igneous rocks, particularly glassy varieties, also can be excellent sources of uranium [37], and also may host surficial uranium deposits, although this remains to be investigated. More research is also needed to investigate the nature and the strength of U-organic bonding, and the physicochemical conditions most likely to produce uranium release from these deposits. Leaching experiments of variably sized components of the

organic matter from a variety of depths and depositional environments could contribute to the understanding of U-organic associations in these as well as more ancient uranium deposits, and will allow more accurate assessment of the potential health hazard posed by cultural disturbance of surficial uranium deposits.

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REGIONAL LITHOGEOCHEMISTRY OF THE EASTERN PART OF THE ATHABASCA BASIN URANIUM PROVINCE, SASKATCHEWAN, CANADA

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Abstract

Data from 6500 core samples from exploration drill holes have been studied in a compilation of the lithogeochemistry of the eastern part of the Athabasca Basin uranium province, Saskatchewan. Both regional and deposit-scale lithogeochemical patterns in the the Helikian Athabasca Sandstone and underlying basement rocks have been assessed, using lithogeochemical plans and cross-sections.

Uranium deposits in the study area (eg. Key Lake, Cigar Lake) have alteration halos which extend through the overlying sandstone. The alteration halos are characterized by illitization, kaolinitization and dravitization as well as trace element enrichment. Very large regional alteration patterns have also been outlined. The results have been applied to exploration programs, and have been used to assist in our understanding of the ore deposits.

INTRODUCTION

A regional lithogeochemical study of the eastern part of the Athabasca Basin was initiated with the objectives of assessing the average background lithogeochemistry of the Athabasca Sandstone and underlying basement, of determining regional patterns of variation, and of determining lithogeochemical alteration patterns around uranium mineralization.

Most of the data used for the program are from routine exploration holes. In a few cases re-sampling has been carried out, and some re-analysis has been done where the original analysis was inadequate. For the regional part of the program, data have been included for over 4500 samples, from 206 holes. For the detailed studies of mineralized zones data for over 2000 samples from over 100 holes have been considered. Data

for nine constituents, Al_2O_3, Fe_2O_3, MgO, K_2O, B, Pb, Ni, Cu and U, are included, although many samples have missing data for one or more variables.

Presentation of the results includes summary statistics, both regional and deposit-scale contoured lithogeochemical cross-sections, and regional contoured plan-view maps.

SAMPLING

The distribution of samples for this study is controlled by the distribution of exploration drill holes. Unfortunately that distribution is anything but regular, or even random. Most holes have been drilled, using geophysical information, to intersect pelitic - particularly graphitic - horizons in the basement. Areas of non-pelitic basement, especially those remote from any areas of mineralization, are significantly under-sampled. Considering only the 206 regional holes, the average drill hole density is low, at 1 per 50 square km. (The study area can be assumed to comprise the easternmost 50 km of the Athabasca Basin, extending from Key Lake in the south to Hatchet Lake in the north.) The total area is roughly 10,500 km^2 (Fig. 1). There are some regions of several hundred square km extent where there are no drill holes, and other regions where the density is better than 1 per km^2.

In most cases the core has been sampled systematically throughout the hole. Sample spacing ranges from 5 to 30 m. Some holes have been sampled at uniform intervals, irrespective of lithology (except the sub-Athabasca unconformity), and others have been sampled non-uniformly, using lithology and the incidence of fractures and alteration to control the sample distribution.

Two main sampling procedures have been followed, namely 'point' sampling and 'interval' sampling. For 'interval' sampling each interval (eg. 10 m) is represented by a series of systematically spaced chip samples. The sample depth is taken as the midpoint of the interval. 'Point' samples are individual 5 to 15 cm pieces of core taken at a single point.

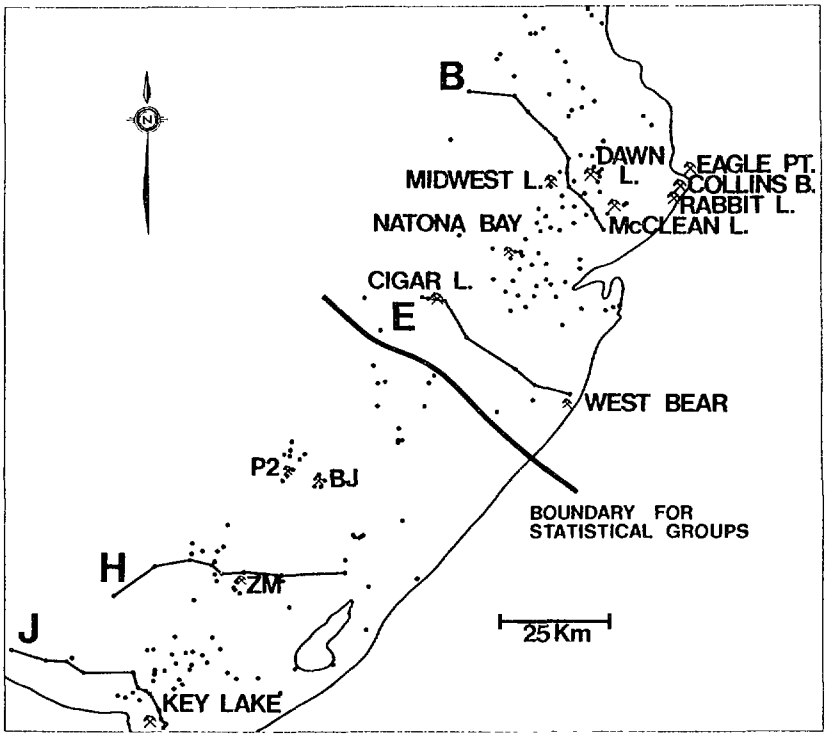

Figure 1 The eastern part of the Athabasca Basin showing 206 regional drill holes, 4 regional cross-sections, and important U deposits and prospects. The eastern edge of the Athabasca Sandstone is shown as a solid line.

ANALYSIS

Because various different laboratories and techniques have been used in sample analysis there are some discrepancies between groups of samples. These have been minimized as much as possible by rejecting certain analyses from some data sets. The greatest source of discrepancy is in the analysis of U. Some operators have reported total U (either by Delayed Neutron Counting, or by fluorimetry following an HF extraction) while others have reported partial U (by fluorimetry following HNO_3/HCl extraction). Most of the U analyses are 'partial', and represent only the easily soluble U oxides and any adsorbed U. In order that the two types of U analyses can be compared a set of 150 samples with both 'partial' and 'total' U data was studied. The two variables are well correlated (r=0.82). Within the range 0 to 5 ppm U, which includes almost all of the regional data, the relationship between 'partial' and 'total' U values can be expressed as follows: $U_p = 0.0 + 0.28(U_t)$. In cases where the two types of data have to be compared (eg. if both types were reported on one cross-section) this relationship was used to estimate 'partial' U values from 'total' U analyses.

The oxides Al_2O_3, Fe_2O_3, MgO, K_2O, were normally determined by Atomic Absorption Spectrophotometry (AA) or by Plasma Emission Spectrophotometry (ICP), following digestion in HNO_3, $HClO_4$ and HF acids. For most labs analysis of major elements is by routine procedures at levels well above the instrumental detection limit. For the samples included in this study there is no evidence of serious inaccuracies in the major element data.

B was determined by ICP following fusion with KOH and digestion in HNO_3 and HCl acids. The B results are reliable, although the limited sensitivity affects the data in the range 0 to 20 ppm.

Pb, Ni and Cu were determined either by AA or by ICP using either 'partial' or 'total' extraction. In this environment these elements are quite sensitive to the extraction procedure so the 'partial' and 'total' data cannot be directly compared. Analysis of Ni and Cu is routine by either AA or ICP, so the analytical method is not a factor in these cases. On the other hand, both instruments, but especially the ICP, give poor Pb results at levels below 2 ppm. This is particularly true if a 'total' extraction has been used with a relatively small sub-sample and a relatively large volume of acid. Pb analyses carried out for SMDC within the past two years have been done using a relatively high sample to acid ratio to allow for greater sensitivity at low levels. These data have shown that the Athabasca sandstone has a Pb background of less than 1 ppm.

DATA PROCESSING

Clay mineral proportions have been determined for Athabasca sandstone samples using a normative technique. The algorithm is based on the premise that the only important Al_2O_3-bearing phases within the sandstone are kaolinite, illite, Mg-chlorite and dravite, and that these minerals have relatively consistent stoichiometry across this part of the basin. Several years of experience with this procedure have shown that the results are reliable, and are generally comparable to XRD determinations on clay mineral fractions separated by centrifugation. Two advantages of the chemical method are that it provides quantitative and absolute clay mineral levels, and it is not dependent on the questionable assumption that all, or even a representative proportion of the clay fraction can be isolated by centrifugation.

Normative clay mineral determinations, as applied here, require data for Al_2O_3, MgO, K_2O and B. In many cases B data are lacking, but, in some such cases, where the B background is consistently low, as it is in the northern part of the study area, the calculation has been carried out using a default B level of 10 ppm. For some samples from the Cigar Lake area, MgO data are not available. Other results from that area have shown a consistent relationship between Al_2O_3 and MgO (in the ratio 1.0 to 0.02), hence, for the purpose of clay mineral determinations, estimated MgO values (based on that ratio) have been used.

RESULTS

Regional data - statistical summary

For the purposes of a statistical summary the regional data set has been divided into sandstone and basement subsets, and into northern and southern subsets. This division is based on an observed difference in sandstone lithogeochemistry which will be described below.

Only a very simple statistical analysis has been carried out, with the main objectives of determining background levels and comparing sandstone and basement, and the northern and southern parts of the study area. The results are summarized in Table 1. The 'background' levels shown here are generally similar to those reported by Quirt(1985) for the Manitou Falls Formation. Quirt's values for Pb, Ni, Cu and U are higher than those shown here, but this is probably due to his use of a total extraction. Statistical parameters for all of the analyzed constituents are based on $\log_{10}$-transformed data because all of the populations have lognormal-type distributions. Statistical parameters for the derived clay variables are based on un-transformed data.

The basement has higher levels of all constituents than does the sandstone. The greatest differences are for MgO (30 times), K_2O (9 times), Al_2O_3 (6 times) and U (4 times), while the smallest differences are for Pb (1.7 times), Cu (2.1 times) and B (2.1 times).

Comparing the southern and northern areas (cf. Fig. 1), for the sandstone, the south is significantly higher in MgO (2.3 times), B (2.1

Table 1 Comparison of group means for eastern Athabasca Basin Lithogeochemical data[1]

Constituent	Sandstone all	Sandstone north	Sandstone south	Basement all	Basement north	Basement south
Al_2O_3 (%)	2.08 (3973)	2.22 (1495)	2.00 (2478)	11.8 (513)	12.7 (158)	11.4 (355)
Fe_2O_3 (%)	.64 (2412)	.56 (581)	.67 (1774)	2.33 (467)	2.56 (126)	2.25 (341)
MgO (%)	.05 (3973)	.03 (1495)	.07 (2478)	1.46 (513)	1.65 (158)	1.38 (355)
K_2O (%)	.16 (3973)	.15 (1495)	.16 (2478)	1.39 (513)	1.47 (158)	1.36 (355)
B (ppm)	37.9 (2990)	20.8 (540)	43.4 (2449)	78.5 (412)	141 (50)	72.4 (342)
Pb (ppm)	1.2 (1595)	1.2 (152)	1.1 (1255)	2.0 (305)	1.1 (22)	2.1 (247)
Ni (ppm)	6.0 (1626)	4.4 (152)	6.3 (1255)	17.0 (315)	12.1 (22)	16.4 (247)
Cu (ppm)	4.7 (1439)	2.5 (152)	5.1 (1286)	9.8 (273)	5.3 (22)	10.5 (247)
U (ppm)	.37 (3319)	.32 (1186)	.40 (2110)	1.6 (605)	1.6 (236	1.7 (369)
Clay (%)	.78 (3914)	.82 (1472)	.75 (2440)			
Illite (%)	37.4 (3914)	32.6 (1472)	40.3 (2440)			
Chlorite (%)	3.8 (3914)	2.6 (1472)	4.6 (2440)			
Kaolinite (%)	57.8 (3914)	64.8 (1472)	55.2 (2440)			

1) Geometric means are shown for all constituents except the calculated clay values. Numbers of samples are shown in parentheses.

times) Cu (2.0 times) and Ni (1.4 times), while for the basement, the north is significantly higher in Pb (1.9 times) and B (1.9 times). Other differences are relatively small, or statistically insignificant. For the sandstone clay variables, the south is significantly higher in chlorite (1.8 times), slightly higher in illite, and slightly lower in total clay and kaolinite.

Regional data lithogeochemical cross sections

The locations of four representative lithogeochemical cross-sections across the geological trend of the Wollaston and Mudjatik fold belts are shown on Fig. 1. These sections are intended to provide a view of background sandstone lithogeochemical trends, thus holes within a few hundred m of known mineralization have been avoided. It should be noted that the regional cross-sections are several tens of km long and only about 500 metres high (vert. exaggeration is 40 times). Contouring lithogeochemical data between holes 10 km apart is speculative at best, and there is no question that there are many ways to interpret the data. In all cases the simplest interpretation has been followed, although considerable lateral interpolation has been used.

The clay distribution for section E is shown in Fig. 2. The general trend is of increasing clay content with depth in the section. A clay content of less than 5 % is typical of the upper 100 to 200 m of the

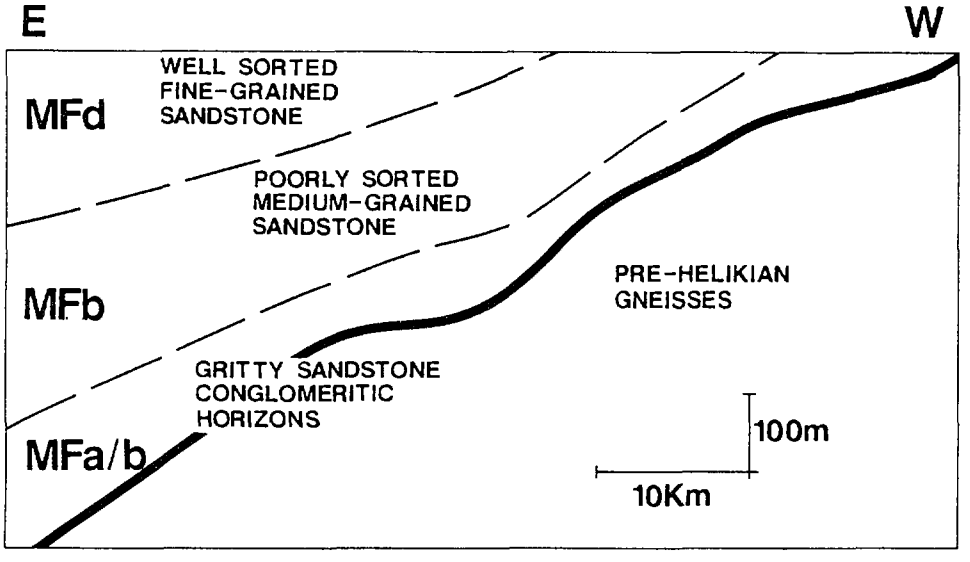

Figure 2 Schematic cross-section of the Manitou Falls Formation in the eastern Athabasca Basin (after Ramaekers, 1981).

sandstone in the western part of the area. No rigorous correlation can be made between lithogeochemistry and the members of the Manitou Falls Formation (eg. Manitou Falls d - MFd, MFc etc.) because consistent and detailed sandstone logging procedures were not followed until the past two or three years, but it is apparent that the clay-poor (less than 5%) upper part of the section corresponds generally with the well sorted MFd sandstone (Fig. 3). The lower, less well sorted and variously conglomeritic, Manitou Falls units MFa, MFb and MFc have variable clay contents, in the range 5 to 20%.

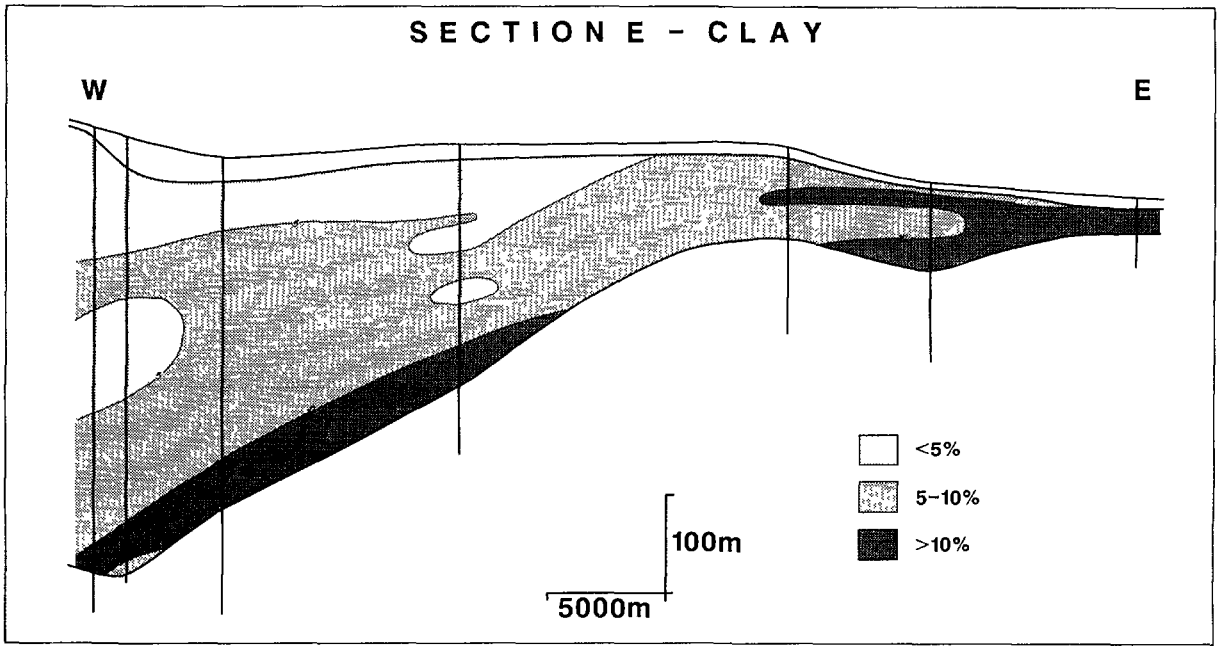

Figure 3 Clay content of the Manitou Falls Formation on regional cross-section E.

Thin (10 to 20 m) clay-rich or clay-poor horizons with continuity in the range of several km have been noted in studies of individual properties, but they are not generally visible on regional sections such as these. Possible examples include a clay-poor horizon near the base of the sandstone in the western part of section H, and a clay-rich horizon near the base of the sandstone in the eastern part of section H.

Illite and kaolinite distribution for the four sections are shown in Fig. 4 to 7. The results are expressed as % I/I+K (illite/(illite+kaolinite)). Samples with less than 40% I/I+K are considered to be kaolinitic, those from 40 to 60% are illite/kaolinite mixtures, and those greater than 60% are illitic. Sections B and E are dominated by kaolinite, with I/I+K ratios generally ranging from 0 to 40%.

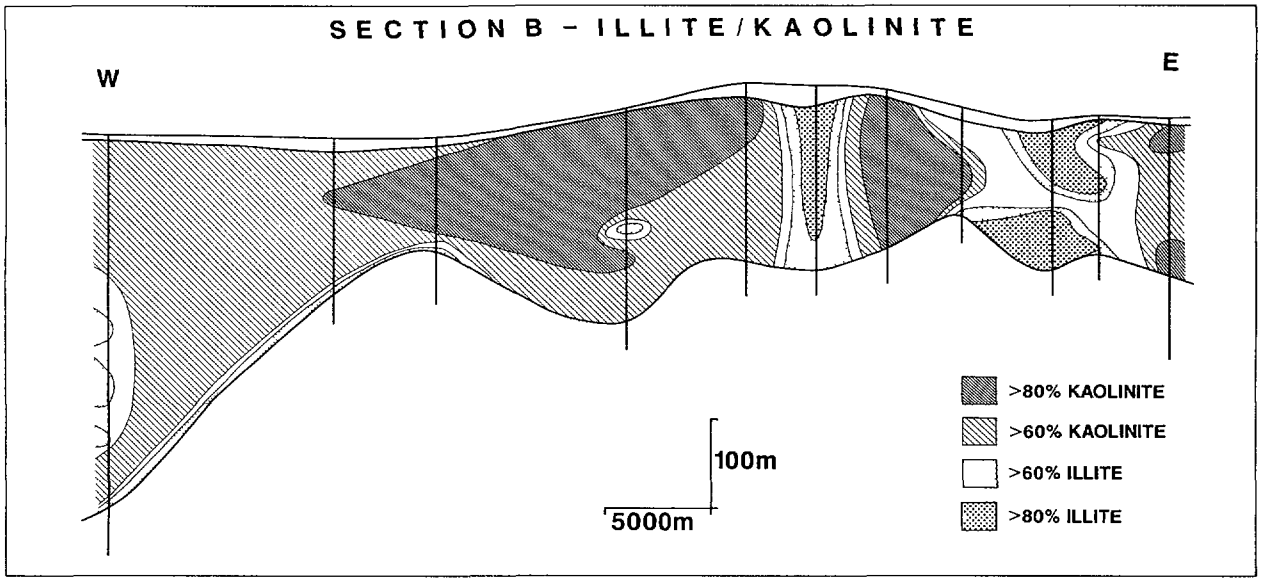

Figure 4 Illite and kaolinite proportions of the Manitou Falls Formation on regional cross-section B.

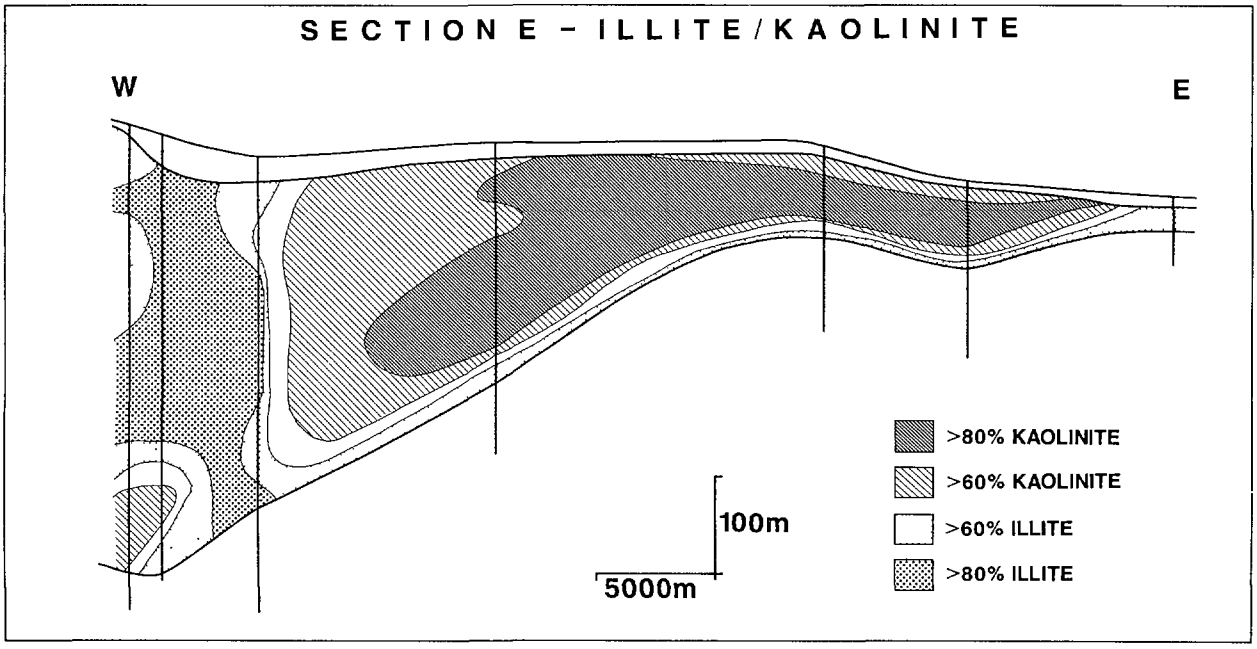

Figure 5 Illite and kaolinite proportions of the Manitou Falls Formation on regional cross-section E.

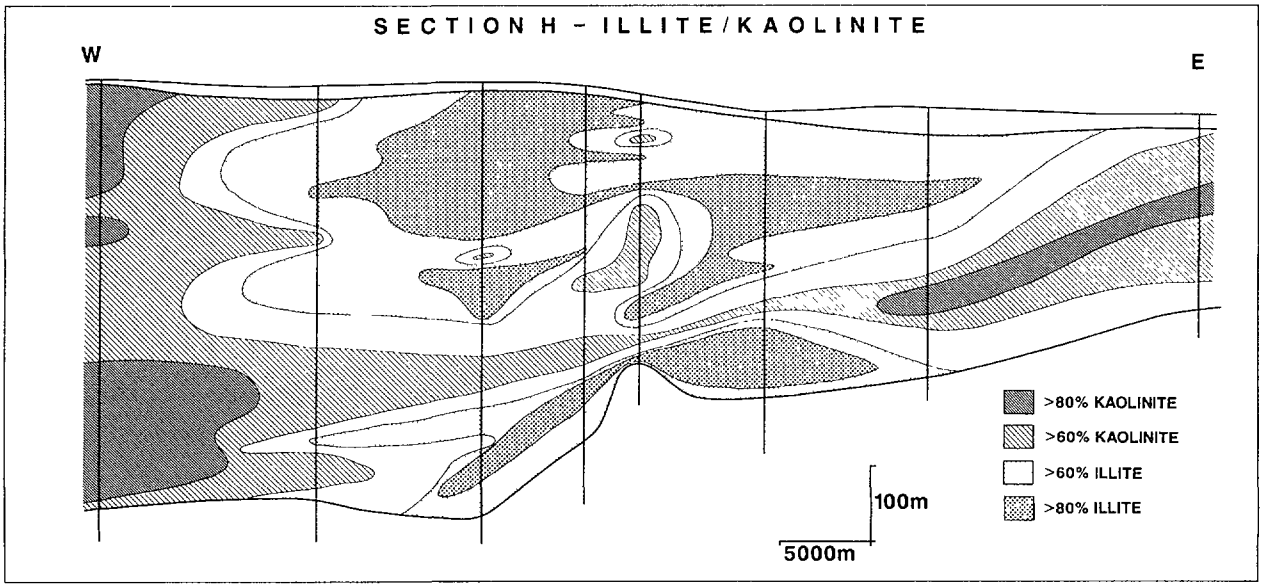

Figure 6 Illite and kaolinite proportions of the Manitou Falls Formation on regional cross-section H.

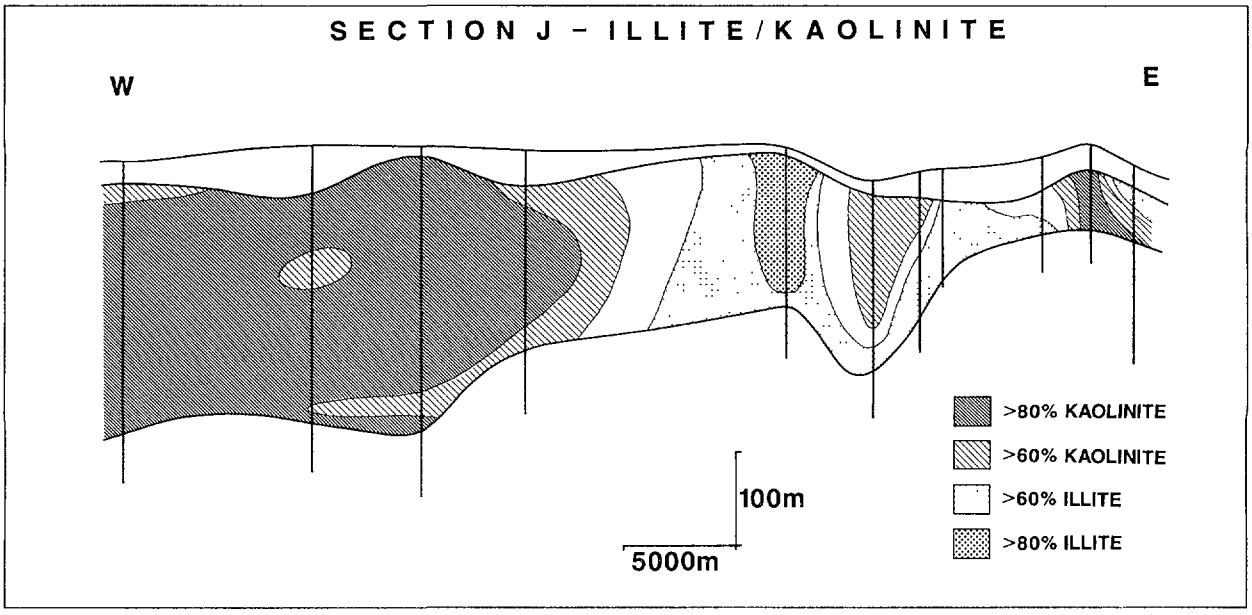

Figure 7 Illite and kaolinite proportions of the Manitou Falls Formation on regional cross-section J.

Hoeve et al (1981) report average I/I+K ratios of 67% for the upper Manitou Falls Formation (MFc and MFd), and 42% for the lower Manitou Falls Formation (MFa and Mfb), but these results are based on comparative data from only two holes. There is no evidence, from the present data, of stratigraphic control over the illite/kaolinite ratio, although the lower 10 to 20 m of the sandstone is normally illite-rich. Strong zones of illitization - extending through the sandstone - are evident in the Cigar Lake area, in the area northeast of and along strike from Midwest Lake, and along the trend west of the McLean Lake mineralization.

Illite is dominant in the central part of section H, forming two lobes separated by a thin kaolinitic horizon. This horizon comprises the only evidence of stratigraphic control over the distribution of kaolinite and illite. Kaolinite is dominant in the peripheral holes on the section.

Kaolinite is dominant on section J, except in the area around Key Lake. As will be discussed below, sandstone in the vicinity of the Key Lake Deilmann Deposit is dominantly kaolinitic.

The chlorite distribution on section H is shown on Fig. 8. Chlorite is virtually absent from the northern part of the study area, except within a 10 to 20 m horizon immediately above the unconformity. On section H there is an extensive zone of chloritization in the upper sandstone in the vicinity of the quartzite ridge, and a broader zone at the unconformity.

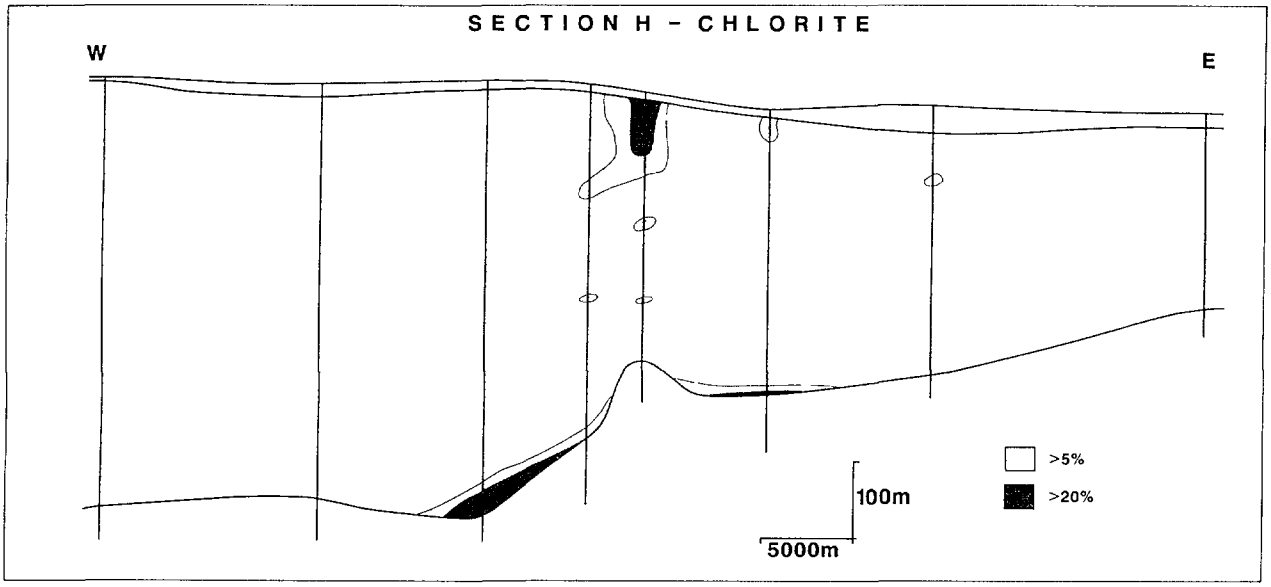

Figure 8 Chlorite content of the Manitou Falls Formation on regional cross-section H.

The B distribution on section H is shown on Fig. 9. Again, the northern part of the area is virtually free from B enrichment. On section H there is strong B enrichment coincident with, but more extensive than the quartzite ridge chloritization, and similar B enrichment in the lower part of the sandstone.

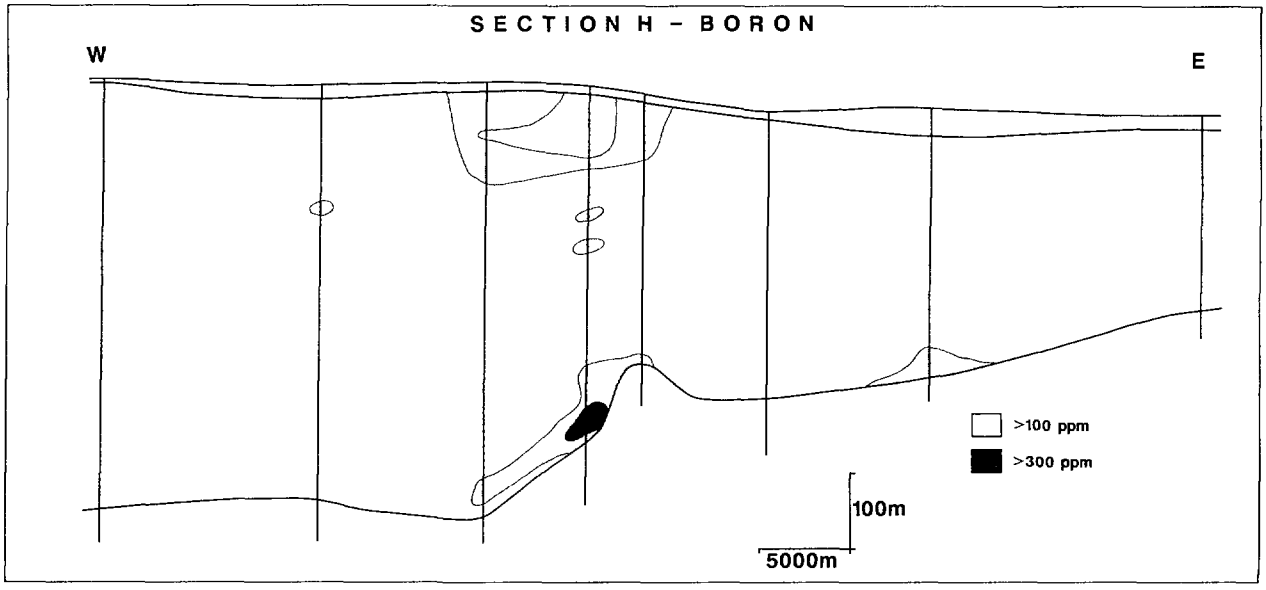

Figure 9 Boron content of the Manitou Falls Formation on regional cross-section H.

Regional data plan distributions

For the plan distributions data from all 206 regional holes were considered. For any individual hole the statistical distribution is quite irregular and is commonly bi-modal; hence the mean is not a particularly useful statistic to represent the hole. Instead, a threshold value is chosen and, for each hole, the proportion of samples which exceed that threshold is determined. For example, for I/I+K the threshold is set at 60% for illitic samples. If 10 of the 40 samples from a hole have greater than 60% I/I+K the hole is considered to be 25% illitic. In the following plan distributions the lower 10 or 20 m of the sandstone have been omitted because, as noted above, the basal sandstone is commonly quite different from the rest of the sandstone (eg. it can be particularly illitic or chloritic) and it does not necessarily reflect the diagenetic or hydrothermal alteration which is characteristic of the rest of the hole.

The plan distribution of illite is shown in Fig. 10. Most of the study area, especially in the north, is characterized by less than 25% illitic (or greater than 75% kaolinitic) sandstone, but all of the known U mineralized zones lie within areas of greater than 25% illitic sandstone. There is a strongly illitic zone which encompasses the McLean Lake, Dawn Lake and Midwest Lake prospects. The Cigar Lake area is also significantly illitic, as is a broad area around the West Bear prospect. The Natona Bay area is weakly illitic. In addition, there are several areas of illitic sandstone which are not known to be mineralized, but have favourable geological features.

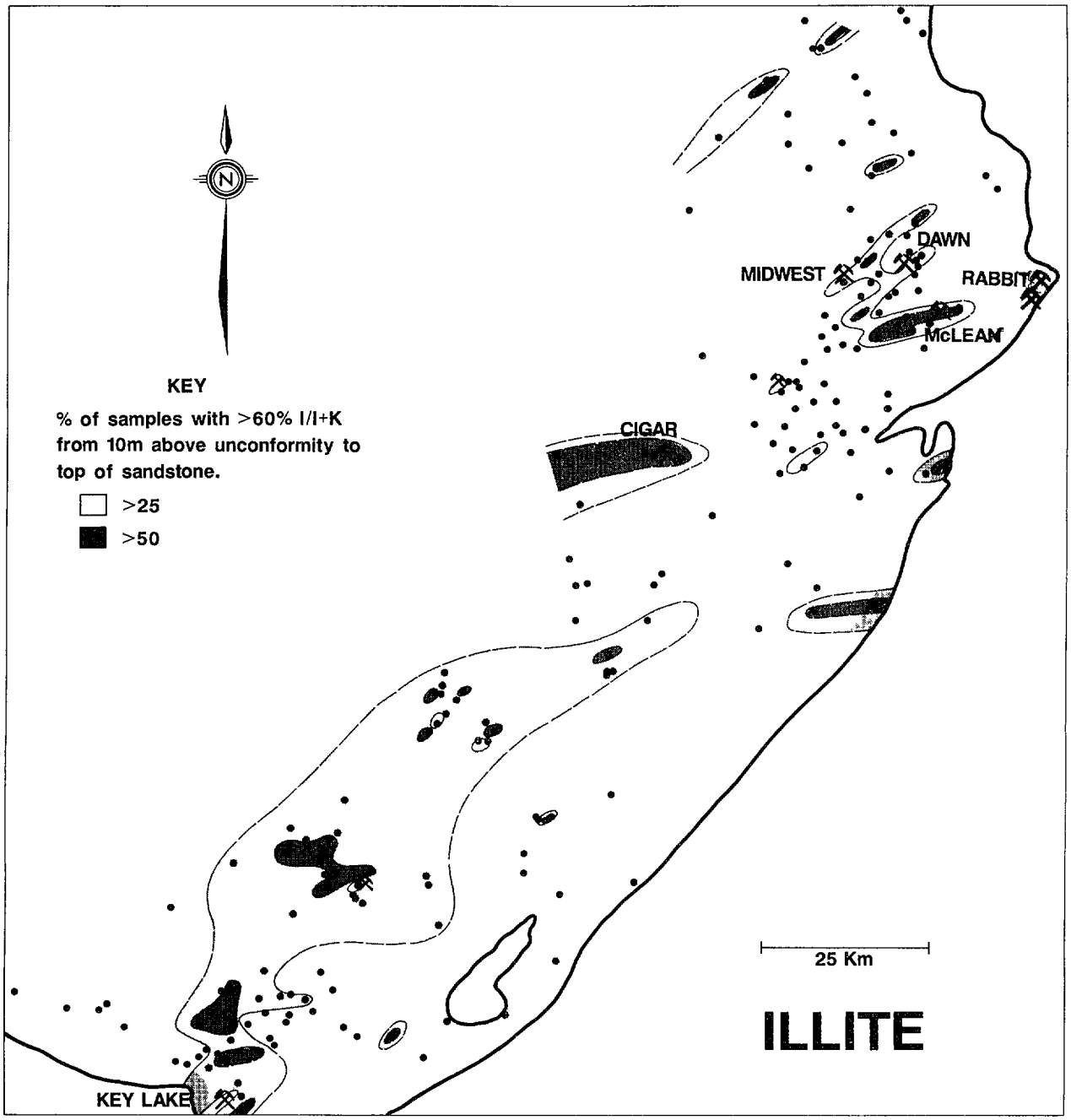

Figure 10 Distribution of illite in the Athabasca Sandstone based on 206 regional drill holes.

The southern part of the study area is characterized by a very large illite anomaly, approximately 100 km long in the northeast-southwest direction, and up to 30 km wide. This zone circumscribes all of the known mineralization in the area, including Key Lake and ZM and the P2 and BJ areas on the McArthur River properties, however these occurrences all lie within small illite-poor zones within the large illite-rich anomaly.

Chlorite-rich sandstone (> 10%, Fig. 11) is mainly restricted to a narrow belt extending northeast from the quartzite ridge basement high near

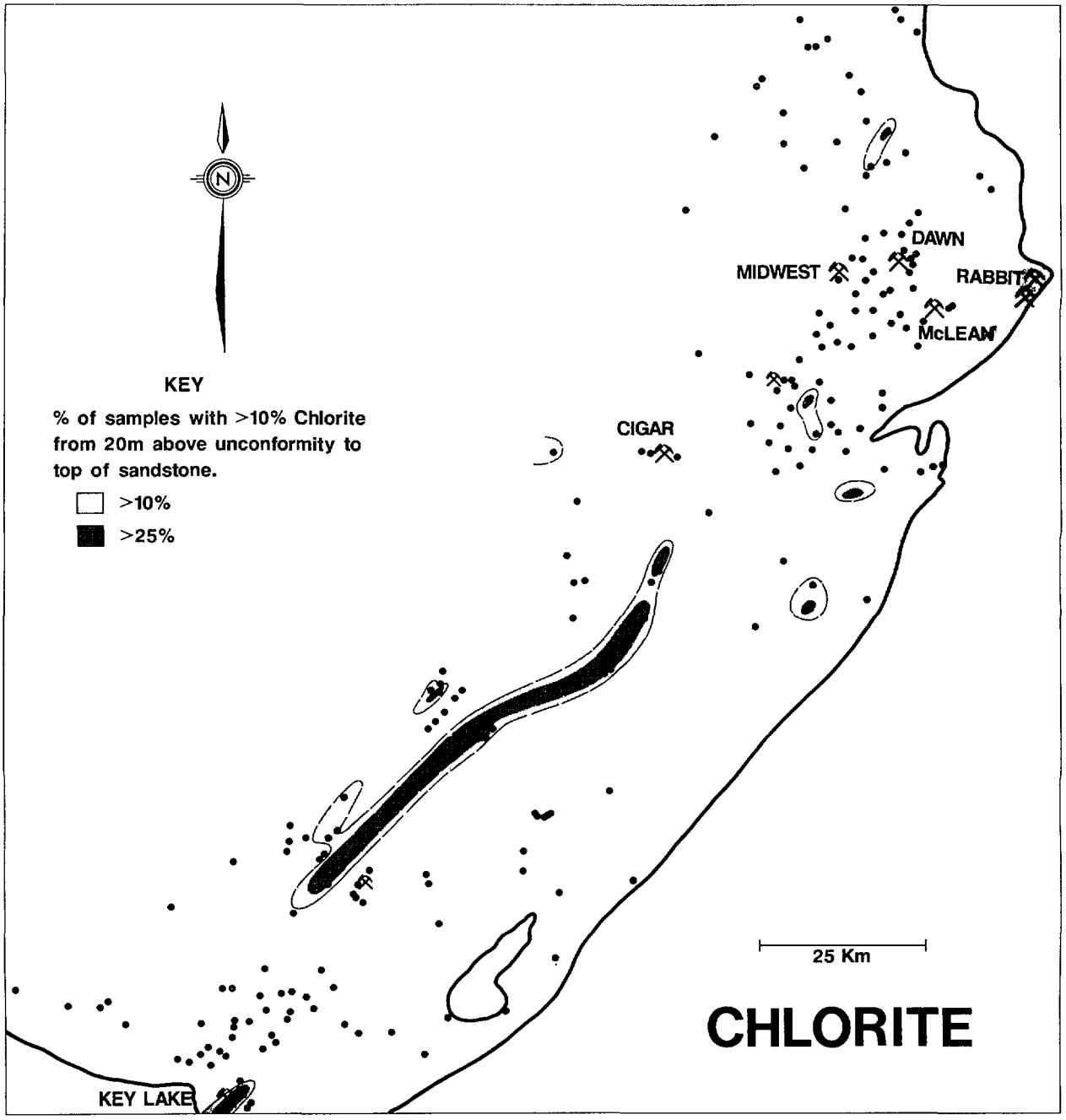

Figure 11 Distribution of chlorite in the Athabasca Sandstone based on 206 regional drill holes.

ZM, through the BJ area and towards the northeast. This feature appears to comprise an axis to the regional illite anomaly. At BJ the most intensive mineralization is associated with a zone of chlorite depletion within the regional chlorite anomaly. Other chloritic sandstone is observed at Key Lake, Hughes Lake and Read Lake, West Bear and in several other localized occurrences.

Boron is also restricted to a narrow belt, nearly coincident with the chlorite anomaly, but displaced to the west (Fig. 12). The main linear B

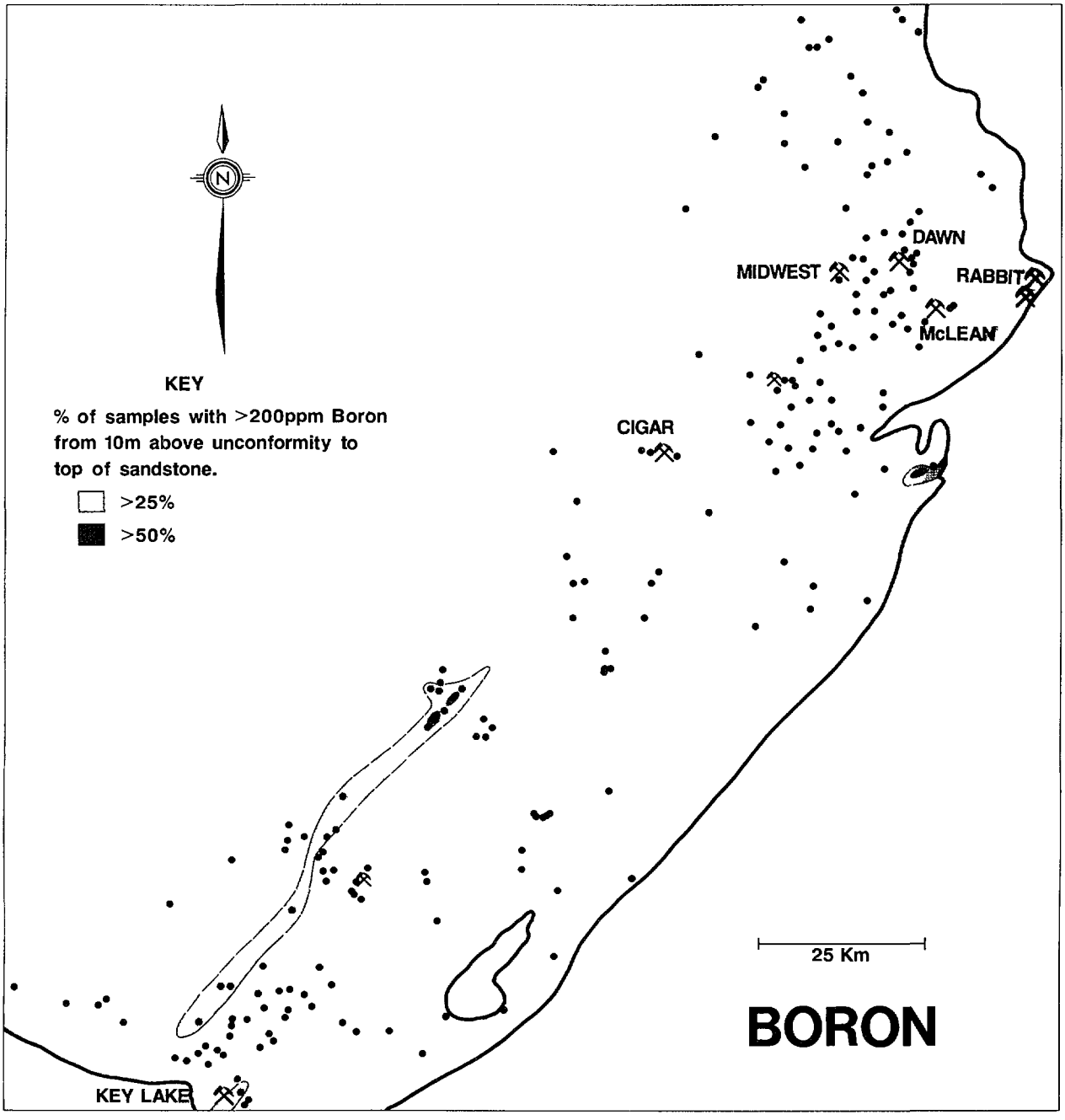

Figure 12 Distribution of boron in the Athabasca Sandstone based on 206 regional drill holes.

anomaly extends southwest towards the Key Lake area. There is no significant regional B enrichment north of P2 and BJ.

The Key Lake - McArthur River regional illite anomaly, along with its associated chlorite and B anomalies, coincides generally with a belt of low magnetic susceptibility, as defined by a regional air-borne magnetic survey (Fig. 13). The magnetic low, defined here as the 60900 gamma isopleth, is assumed to be related to a zone of pelitic and semi-pelitic rocks in the underlying basement, as compared to arkosic and granitic rocks in the magnetic highs. The coincidence of the magnetic low with the illite anomaly is evident in a detailed sense as well as in the general sense, as can be seen just a few km north of Key Lake where both patterns appear to be affected by a 10 km sinistral offset.

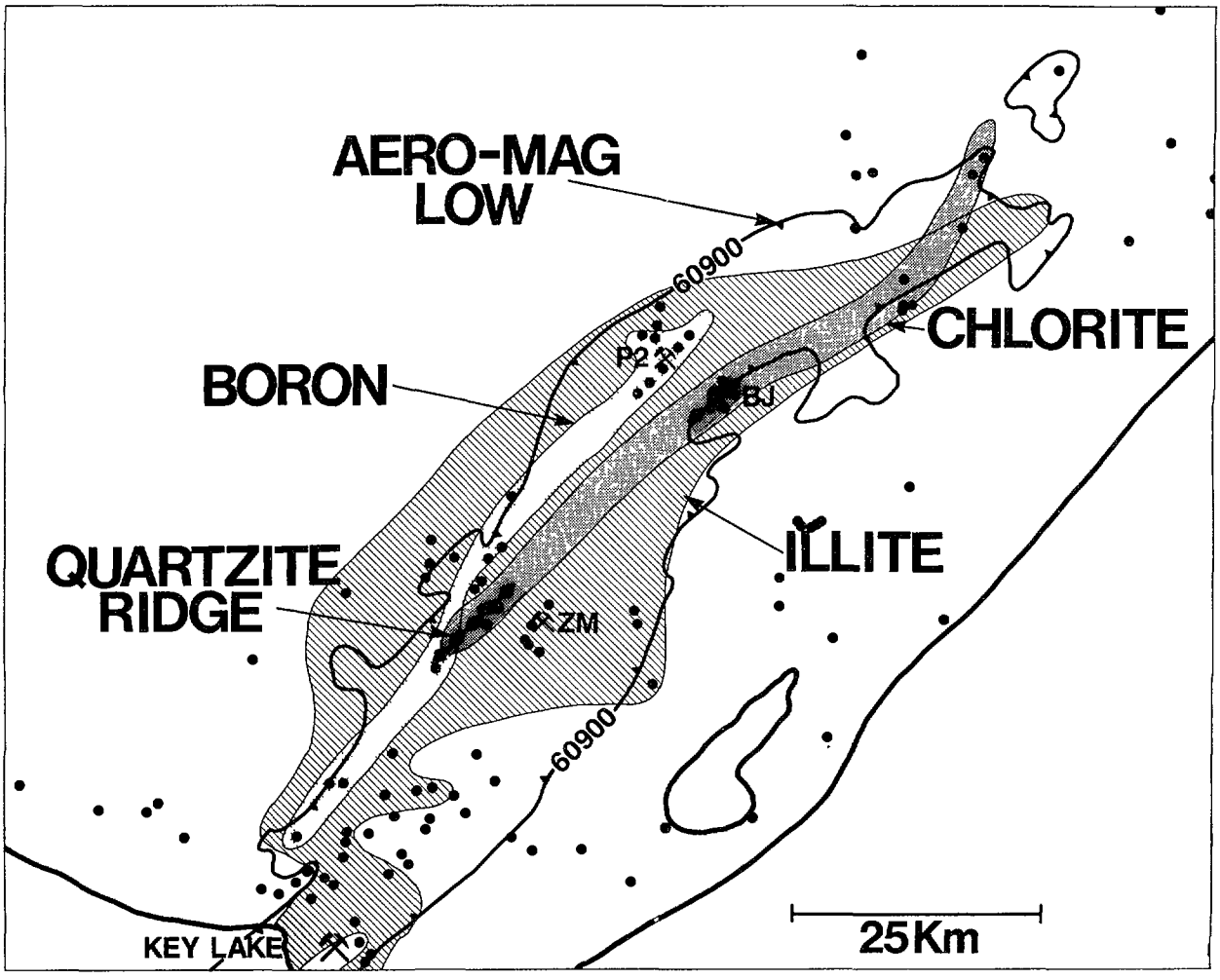

Figure 13 Compilation lithogeochemical map of the southeastern part of the Athabasca Basin, showing regional illite, chlorite and boron anomalies, a region of low magnetic susceptibility, and basement quartzite ridges.

In the northern part of the study area there is no obvious relationship between sandstone lithogeochemistry and basement geology. A comparison of sandstone lithogeochemistry based on differences in basement geology is given in Table 2. The illite/kaolinite ratio is consistently low in the centres of the magnetic highs, but relatively high on the edges of the magnetic highs - where much of the U mineralization is localized. Sandstone overlying the magnetic lows has an intermediate illite content - perhaps reflecting a combination of some mineralization-related illite enrichment, with a general low illite background.

Table 2 Average sandstone lithogeochemistry based on basement geology, for the northern part of the study area.

	Centres of Magnetic-highs (7 holes) (n=77)	Edges of Magnetic-highs (19 holes) (n=298)	Magnetic-lows (80 holes) (n=1103)
Clay (%)[1]	.81	.76	.84
Illite (%)	20.5	37.6	32.0
Kaolinite(%)	73.1	61.5	65.2
Chlorite(%)	6.4	4.7	2.8
Boron (ppm)	23	17	22

1) 'Clay' is total clay in sandstone. Illite, chlorite and kaolinite are expressed as proportions of the clay fraction of the sandstone.

Mineralized zone cross-sections

Lithogeochemical data from most of the Athabasca Basin U mineralized zones have been studied, although only selected examples will be shown here. They included the Natona Bay prospect, Midwest Lake, Cigar Lake, the ZM prospect, and the Key Lake Deilmann deposit.

Unlike the regional cross-sections which have been plotted with substantial vertical exaggeration, the detailed cross-sections have been

plotted at equal vertical and horizontal scales. To facilitate comparison, all of the sections are plotted at the same scale.

Midwest Lake

The lithogeochemistry of the Midwest Lake deposit has been described previously by Sopuck et al (1983), and Wray et al (1985). The results reported here are similar to those of Sopuck et al. The clay mineral alteration at Midwest Lake has been studied by Hoeve (1984), who also reports illite and kaolinite results similar to those shown here.

The Midwest Lake data are shown on Fig. 14. The section crosses the thickest part of the deposit, towards its northern end. In contrast to a kaolinitic background, there is a 150 m wide chimney of strong illitization above the mineralization. The B background at Midwest Lake is less than 20 ppm, and there is a chimney of weak B enrichment above the mineralization and extending to surface. In the immediate vicinity of the mineralized zone B levels exceed 100 ppm. The U halo at Midwest Lake, as defined by the 3 ppm contour, extends for 100 m above the mineralized zone, but does not reach surface.

Natona Bay

The Natona Bay cross section is in the southern part of this small mineralized zone on the edge of Waterbury Lake (Fig. 15). The clay pattern is generally similar to background, but there is a zone of anomalously high clay levels (> 25% with several over 70%) in the immediate vicinity of the mineralization. The illite/kaolinite distribution shows a kaolinitic background, with a restricted zone of illitization around the mineralization, and along a westerly-dipping trend, extending upwards through the section. The normal basal sandstone chlorite enrichment is evident in the peripheral holes with levels in both cases in excess of 25%. Near to mineralization the strong chlorite is absent, but there is a zone of weak chloritization which coincides roughly with the extent of the mineralization.

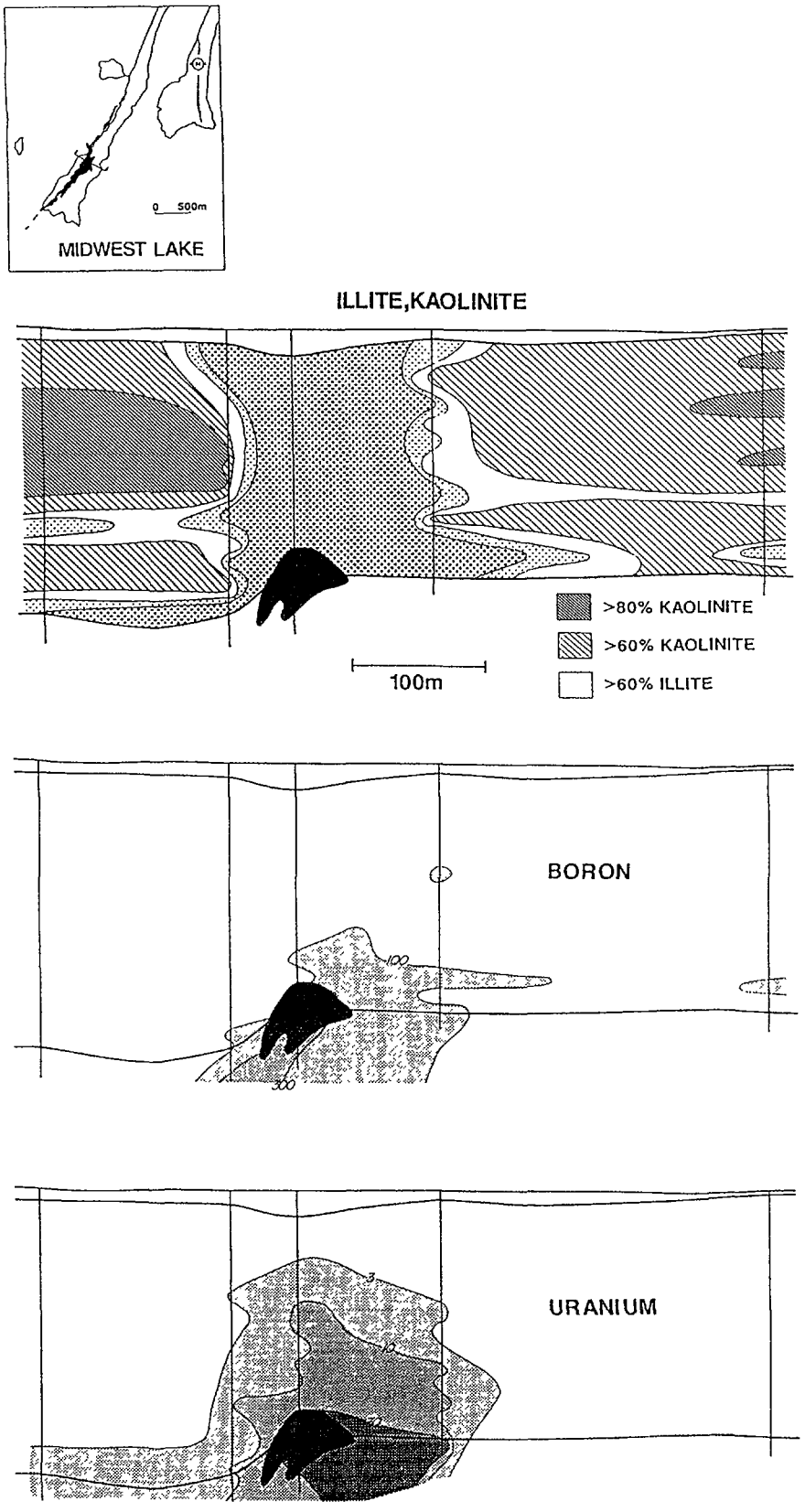

Figure 14 Lithogeochemical cross-sections of the Midwest Lake U deposit.

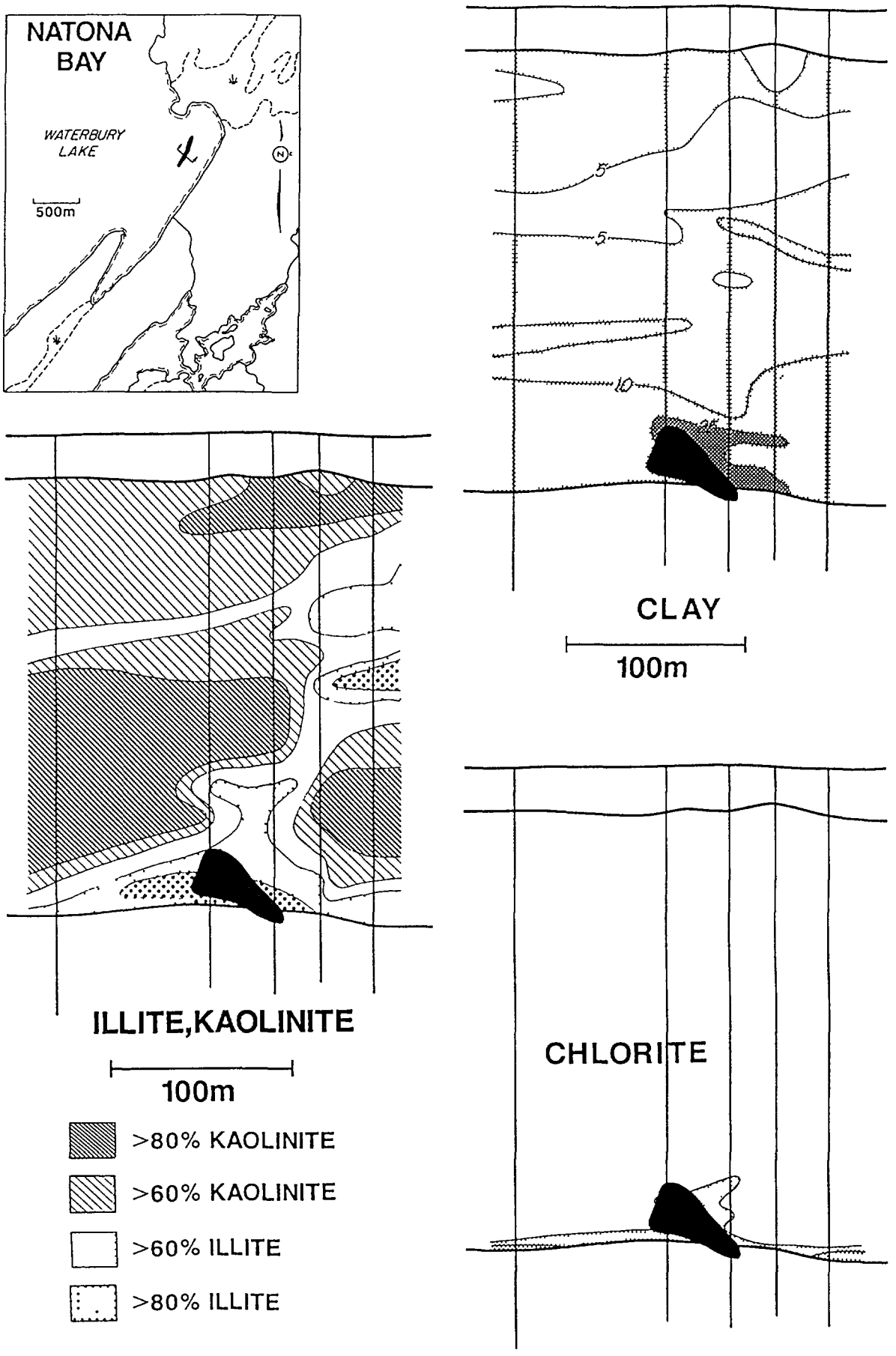

Figure 15 Lithogeochemical cross-sections of the Natona Bay U prosepct.

Cigar Lake

Lithogeochemistry of the Cigar Lake area has been reported by Clark (1987) and by Learn (1987). Clark defined sub-outcrop anomalies of U and Pb and of several other constituents not being considered here (eg. V, Sr and Zn).

The lithogeochemical cross-section studied is in the eastern and richest part of the deposit (Fig. 16). Analytical values are only

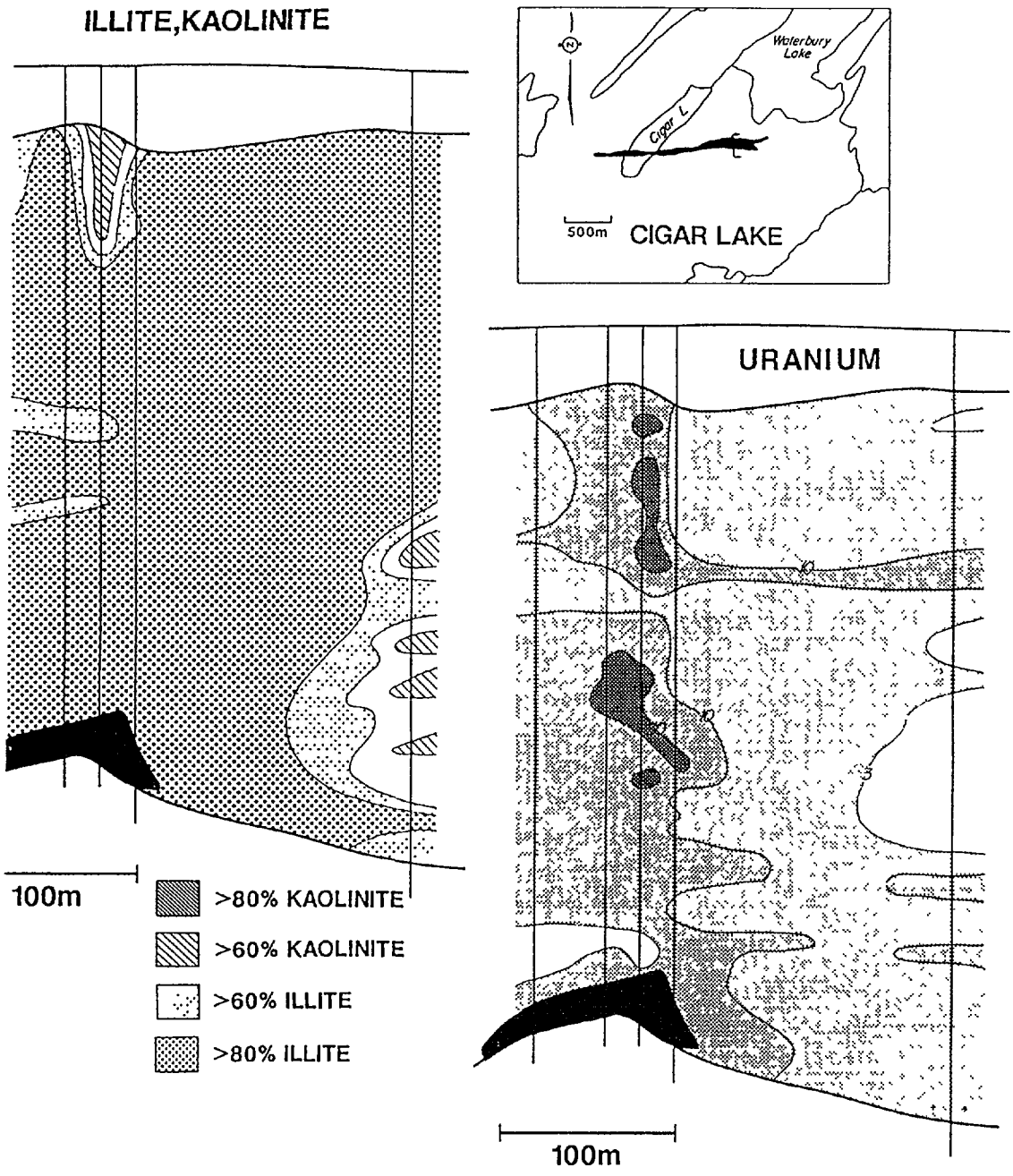

Figure 16 Lithogeochemical cross-sections of the Cigar Lake U deposit.

available for Al_2O_3, K_2O and U. Other samples from the Cigar Lake area have shown that B levels are consistently around 10 to 20 ppm, and a default B level of 15 ppm has been used to allow calculation of clay mineral proportions. Similarly, other data indicate that the Al_2O_3 to MgO ratio is consistent (at 1.0 to .02), thus estimated MgO values (based on that ratio) have been used for clay mineral calculations. Since estimated MgO and B levels have been used, the calculated chlorite values are not reliable, however the illite and kaolinite levels should be reliable. The sandstone in the holes studied is almost entirely illitic, although there are some remnants of kaolinite in the lower part of the southernmost hole, and at the top of the section. Similarly, there is intense U enrichment throughout the holes sampled. There are only a few samples with U levels below 3 ppm, and most of the sandstone above the mineralization, right to surface, has more than 10 ppm U.

ZM

The ZM mineralization on the Wheeler River property is quite small, and the section studied is at the southwestern end of the mineralized zone (Fig. 17). The background clay patterns for this area are exemplified by the holes on the edge of the section. The upper sandstone is clay-poor and there is a 100 m thick clay-rich layer 100 m above the unconformity. There is also a 75 m thick clay-poor layer 25 m above the unconformity. Directly above the mineralization the clay-rich layer is absent across a width of at least 50 m. This clay-poor zone is coincident with a chimney of kaolinite dominance in a background of illite-rich sandstone, and of intense dravitization, with B levels in excess of 2000 ppm. There is significant U enrichment to surface. The highest U values are near to the unconformity, and in the middle of the sandstone.

Key Lake - Deilmann Deposit

The lithogeochemistry of the Key Lake area has been described by Sopuck et al (1983), who described similar patterns to those shown here. The section shown here is at the northeastern end of the Deilmann Deposit, so chosen because there is a significant thickness of sandstone at this location (Fig. 18). The sandstone is strongly kaolinitic throughout most of the section (most samples have 100% kaolinite in the clay fraction).

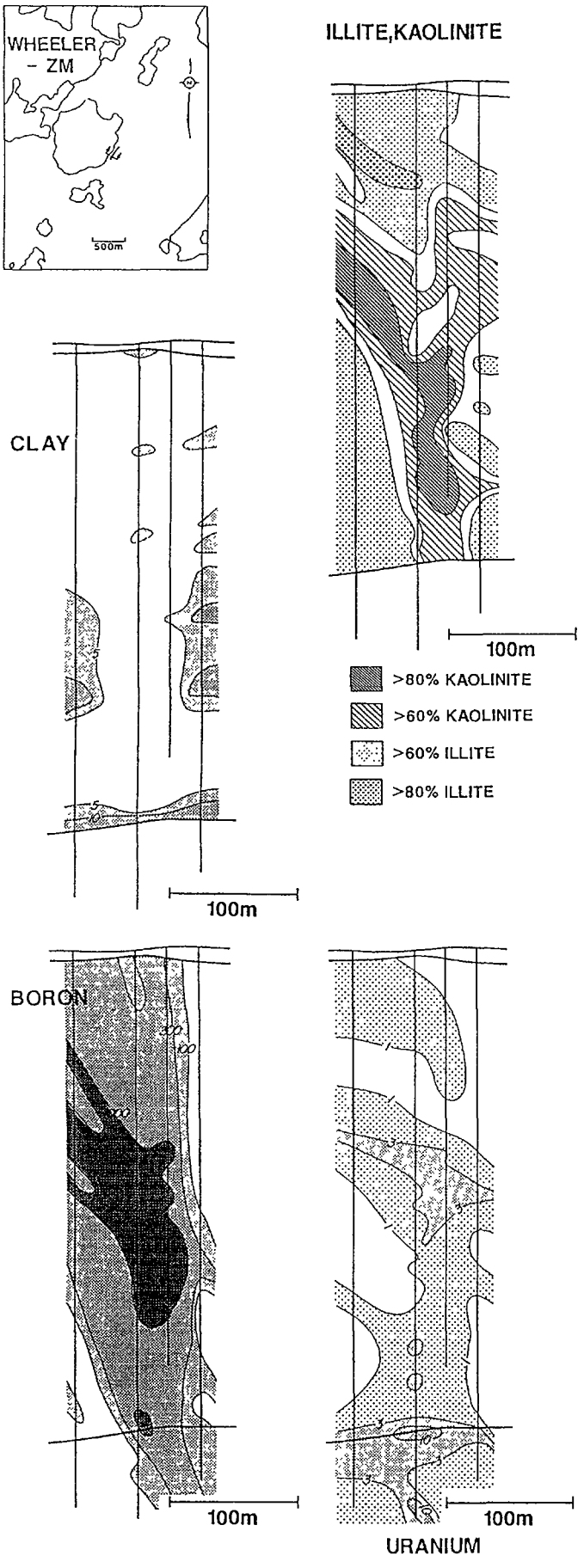

Figure 17 Lithogeochemical cross-sections of the ZM U prospect.

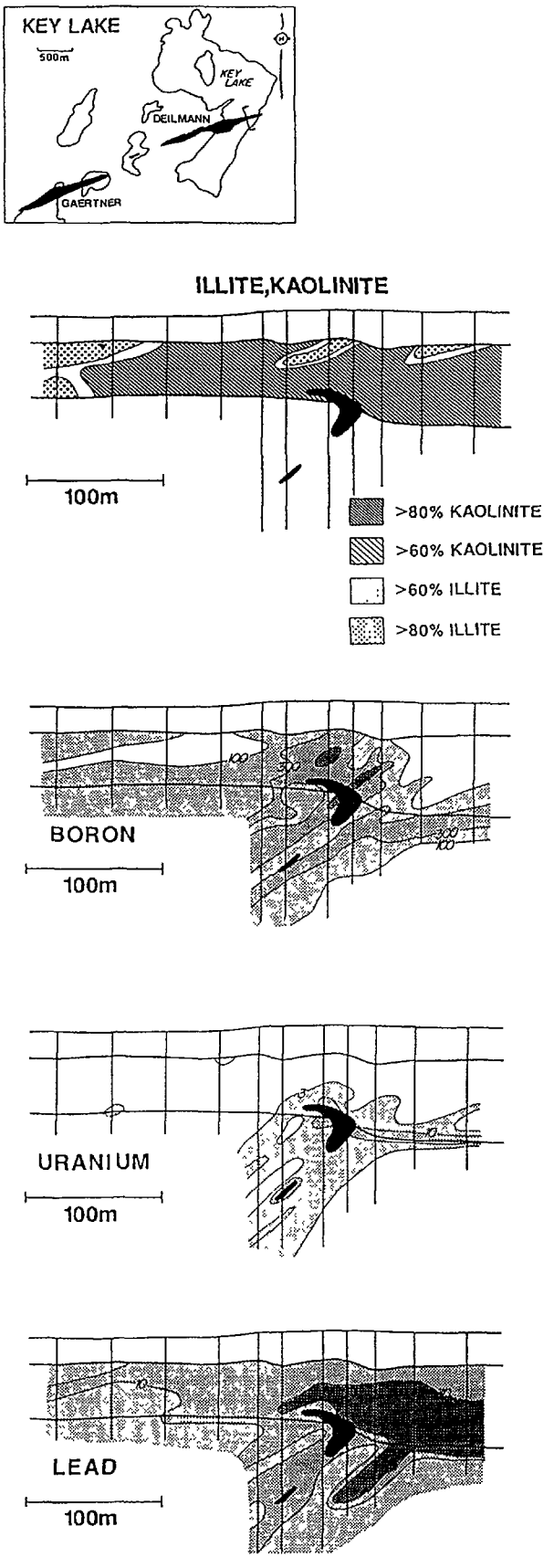

Figure 18 Lithogeochemical cross-sections of the Key Lake U deposit.

There is significant dravitization of both sandstone and basement for 100 to 200 m across strike in both directions, but particularly on the footwall side (southeast). U enrichment is extensive in the basement rocks, but limited, in a vertical sense at least, within the sandstone. There is a lateral sandstone U halo in the footwall direction, and considerable U enrichment along the unconformity in the footwall direction. Pb, on the other hand, is strikingly enriched in the sandstone throughout the section studied, and presumably for some distance beyond that shown here, particularly on the footwall side.

Summary of mineralized-zone lithogeochemistry

Although all of the mineralized zones studied have many geological features in common, there is no macroscopic lithogeochemical alteration feature which is universally characteristic of all eastern Athabasca Basin U mineralization. All of the northern area mineralized zones have illite alteration halos or plumes which extend through the existing sandstone section. These plumes range in width from less than 50 m (at Natona Bay), to well over 200 m (at Cigar Lake). All of the southern mineralized zones, on the other hand, have halos of kaolinite dominance within a regional illite anomaly. Again the plumes range in width from less than 50 m (at ZM) to several hundred metres (at Key Lake). Although all mineralized zones show microscopic evidence of clay alteration (ie. development of clay minerals), there is little evidence of large-scale argillization. Some clay enrichment is evident (eg. at Natona Bay), but in other cases, (eg. at ZM), clay depletion is the rule. Chloritization is evident in some cases, but at the same time, there is evidence of depletion of a presumably pre-existing zone of chlorite at the base of the sandstone.

B enrichment is observed in all cases where data are available, but the magnitude varies from around 100 ppm in the northern mineralized zones, to several thousand ppm in the southern mineralized zones. Both U and Pb halos are present in the sandstone above mineralization, but there is considerable variation in their extent. Cigar Lake, for example has a large and rich U halo, while Deilmann has a relatively small U halo and a very extensive halo of high Pb values.

DISCUSSION

The results presented above will be discussed in terms of their contribution to an understanding of the stratigraphy and diagenesis of the Athabasca Sandstone, and of hydrothermal alteration associated with U mineralized zones. These parameters will then be summarized to review the application of lithogeochemistry to exploration in the eastern Athabasca Basin.

Lithogeochemical variations related to stratigraphy

The only consistent stratigraphy-related lithogeochemical variation in the Manitou Falls Formation is of the total clay content, which increases with depth. The upper Manitou Falls Formation (MFd) has consistently low clay levels (< 5%) while the underlying MFa, b and c have variable, but relatively high clay levels - presumably reflecting their poor sorting, or indicating that they originally contained relatively high levels of detrital feldspar, mica and lithic fragments.

There is no regionally consistent relationship between stratigraphy and the kaolinite and illite content of the clay matrix. This observation is in contrast to that of Hoeve et al(1981), but they examined only two holes which cut through both the lower (MFa and MFb) and upper (MFc and MFd) units of the Manitou Falls Formation. Various examples of apparent stratigraphic control on illite/kaolinite levels have been noted in studies within individual properties spanning a few km, but these characteristics are not consistent from one area to another. The observed lack of stratigraphic control, based on nearly 200 widely distributed holes which intersect both the upper and lower parts of the Manitou Falls Formation, suggests that if there was any stratigraphy-related variation in the sandstone matrix it has been overprinted by subsequent alteration. Both illite and chlorite show some enrichment in the basal 10 to 20 m of the sandstone. Although this could be a stratigraphic feature, it seems more likely to be the result of diagenesis under conditions of a significant geochemical gradient between the MgO- and K_2O-rich basement and the MgO- and K_2O-poor sandstone.

Ramaekers (1987) has recognized statistical lithogeochemical variations in several minor elements, (eg. Zr, Y, Ba, Th and La), which can

be related to heavy mineral facies of the sandstone. These constituents were not included in this study, but they may not have shown regionally consistent patterns in any case, as the heavy mineral facies are thin and probably not regionally continuous. There is some petrographic evidence for stratigraphic variability in the content of detrital tourmaline (Sopuck et al, 1983), but the B data studied here do not indicate the presence of any such features. If they do exist, they may not have sufficient thickness, regional continuity or lithogeochemical contrast, to be detected.

Lithogeochemical variations related to diagenesis

As suggested above, alteration processes, rather than stratigraphy, are likely to be the main factors responsible for the lithogeochemical characteristics of the Manitou Falls Formation. Diagenesis, in the broad sense, includes all mineral transformations, either pro-grade or retro-grade, up to the onset of metamorphism - that is, up to 200° C (Winkler, 1974). Since there is no evidence that temperatures in the eastern Athabasca Basin ever exceeded 200° C, all alteration processes can be described as having occurred in the context of diagenesis. It is likely that the original matrix of the sandstone consisted of a mixture of montmorillonite, kaolinite, chlorite and illite, and that the framework included detrital feldspar, mica and lithic fragments along with the dominant quartz (Ramaekers, 1987). The present complete absence of montmorillonite (Hoeve et al, 1981) suggests that the entire sequence has been subjected to "deep diagenesis", at a temperature of more than 100° C. In most relatively permeable sediments, particularly in older ones such as these, kaolinite should be destroyed at around 100° C (Dunoyer de Segonzac, 1970). Its dominance throughout much of the eastern Athabasca Basin suggests that kaolinite must have been preserved or even formed during pro-grade diagenesis. That may have been the case if the appropriate dilute and acidic formation waters were present (Dunoyer de Segonzac, 1970, Kulbicki and Millot, 1961, Glass et al, 1956). Alternatively, kaolinite may have been re-introduced during retro-diagenesis, under acidic conditions, following erosion and uplift (Dunoyer de Segonzac,1970). Hoeve et al(1981) have suggested a retro-diagenetic origin for 'fault-controlled' kaolinite-rich zones in the Athabasca Basin. The same mechanism could apply, on a much broader scale, in the area studied here, but that seems unlikely because the regional kaolinite-rich areas are not generally associated with zones of significant tectonism.

Lithogeochemical variations related to hydrothermal alteration

Large-scale lithogeochemical patterns can be used as supporting evidence in studies of ore deposit genesis because they provide a view of the broad effects of the mineralizing and alteration processes. On the other hand, they do not provide precise information on alteration mineralogy or on the relative timing of events. Detailed petrographic studies of the various deposits have shown that mineralization, alteration and remobilization took place in various stages over a period of up to 1000 Ma (Heine, 1986, Lainé, 1986, de Carle, 1986). In most deposits, however, the age of the major episode of mineralization lies within the range from 1300 to 1100 Ma. Geochronological studies of clay minerals at the McLean Lake deposit and in the Carswell area indicate that the alteration halos have a similar age (Wallis et al, 1986, Clauer et al, 1985). On the other hand, there is some discrepancy over the timing of mineralization versus alteration in the Key Lake area. Wilson and Kyser (1987) suggest that the kaolinite alteration above the Key Lake deposit is the result of late and low-temperature (50° C) alteration. A similar event could have affected other southern area deposits.

There is little doubt that the clay mineral and trace element alteration zones around the major U deposits and prospects are a product of alteration under hydrothermal conditions. The large concentrations of U observed can only have been deposited from large volumes of water. Based on mineral-pair geothermometry, fluid inclusion studies and clay-mineral crystallinity studies the temperatures were probably in the range 150 to 200° C (Wallis et al, 1986, de Carle, 1986, Pagel et al, 1980, Hoeve, 1984). In the absence of evidence that temperatures exceeded 200° C, the alteration processes can still be properly called diagenesis - in this case with slightly elevated temperatures and increased flow of water through zones of structurally enhanced permeability.

One possible explanation for the Key Lake - McArthur River regional illite anomaly is that it is a diagenetic feature related to compositional differences between the underlying low magnetic susceptibility pelitic and semi-pelitic basement rocks, and the surrounding high magnetic susceptibility granitic and arkosic basement rocks. Such profound effects on sandstone lithogeochemistry do not appear to exist in the northern part of the study area, however, hence it seems more likely that the feature is

actually a manifestation of a very large hydrothermal system, centred on the quartzite ridge structure. Kotzer (1987) has found that fluid inclusions in the abundant druzy quartz within the illite anomaly have homogenization temperatures of around 200° C and salinities of greater than 30 wt.%. Quartz overgrowths, on the other hand, which are ubiquitous in the sandstone, have salinities of less than 10% and homogenization temperatures of less than 170°. The hydrothermal explanation would be consistent with the observed zones of chlorite and B enrichment, which fall within the illite anomaly, and appear to have a spatial relationship to the quartzite ridge. Various authors have attributed high B mobility to high salinity (Walker,1968, Cody,1971, Ricketts,1978). High Mg levels in a brine could also have led to formation of chlorite (Dunoyer de Segonzac,1970).

Although most of the alteration plumes directly associated with U mineralization extend through the remaining sandstone, actual elevation of total clay levels is either not evident, or is restricted to small zones immediately adjacent to mineralization. In these clay-rich zones there is presumably some quartz dissolution and argillization of the rock. Elsewhere, however, the alteration merely involves replacement of one clay mineral with another. For the northern deposits, that involves illitization due to K-metasomatism and/or to intensification of the diagenetic process by an increase in temperature and solute flow. Other processes include destruction of a pre-existing unconformity-related chlorite zone, along with enrichment of chlorite in the immediate vicinity of the U mineralization. The implication is that temperatures and/or fluid compositions suitable for chlorite stability were only obtained within close proximity to the zone of ore deposition. B halos are similarly restricted, again suggesting a limited extent to the zone of relatively high temperatures and/or salinities necessary for dravite stability.

In the southern mineralized zones the major clay mineral of the alteration halos is kaolinite. There is some question about whether this kaolinite dominance is a result of enrichment of kaolinite, or to depletion of illite. The low clay levels seen at ZM and P2, for example, suggest that clay has been removed, but there are kaolinite-dominant clay-rich zones at Deilmann and elsewhere, and kaolinite enrichment is observed on a hand-specimen scale around mineralization at P2 and BJ.

One of the striking features of the southern mineralized zones is the intensity and extent of dravitization. In addition to the B enrichment associated with U mineralization, there is the regional B anomaly which has a width of several hundred metres, and extends over tens of km. This anomaly, which is not only associated with U mineralization, is characterized by B levels in the range of a few hundred ppm, as compared to a few thousand ppm for the mineralization-related anomalies. The B distributions support the idea that the hydrothermal conditions in the southern part of the study area were quite different from those in the north. It follows, therefore, that the solutions must have been more concentrated, and/or hotter, or the hydrothermal systems must have been larger. As indicated by the statistical summary given above, there is no evidence that the basement rocks of the south are more B-rich than those in the north, in fact the opposite is the case. Nor is there any evidence of regional disparities in the detrital tourmaline content of the sandstone (Ramaekers, 1987).

Exploration implications

The regional and mineralized-zone lithogeochemical characteristics summarized above have obvious applications to present and future exploration projects in the eastern Athabasca Basin. It is important to re-state, however, that there are many lithogeochemical differences between mineralized zones - hence there are no lithogeochemical exploration criteria which can be applied universally to all parts of the eastern Athabasca Basin, much less to the rest of the basin.

In the northern part of the region, including the Cigar Lake, Midwest Lake and Dawn Lake areas, the presence of illite in the sandstone indicates the existence of hydrothermal alteration which is likely to be related to U enrichment. In the southern part of the study area the exploration criteria are more complicated. In the area from Key Lake northeast to McArthur River, where illite-rich sandstone is a background feature, a hole with zones of clay depletion, kaolinite dominance, B enrichment, U enrichment or Pb enrichment would be of interest.

The sandstone lithogeochemical patterns shown in this report support the theory of Clark (1987, and this volume) that sub-outcrop sampling could be a viable exploration tool in the Athabasca Basin. Most of the deposits

and prospects studied have distinctive lithogeochemical halos that reach the sub-outcrop, even through up to 600 m of sandstone. On the other hand, the great diversity of alteration characteristics dictates that the technique cannot be applied without a priori knowledge of the type of mineralization and alteration being sought. For example, one would not look for illite halos in the Key Lake - McArthur River area.

In the northern region the constituents giving the most extensive sub-outcrop lithogeochemical anomalies with the greatest contrast to background, are illite and U. Other constituents which might be anomalous in some cases are Pb, B and Cu, as well as some of those noted by Clark (1987), including V, Zn and Y. In the southern region (ie. within the regional illite anomaly), the best constituents for sub-outcrop lithogeochemistry are chlorite, B and U. Other useful constituents are kaolinite and clay.

CONCLUSIONS

The clay matrix of the Athabasca Group Manitou Falls Formation has been altered under diagenetic conditions, and now consists predominantly of kaolinite and illite - largely kaolinite in background areas. On a regional scale the levels of kaolinite and illite are not dependant on stratigraphy. The total clay content, on the other hand, is significantly lower in the upper Manitou Falls Formation (MFd) than in the underlying members. In many areas the basal 10 to 20 m of the Manitou Falls Formation are significantly more illite- and chlorite-rich than the rest of the formation. It is likely that this is a result of metasomatic redistribution due to juxtaposition of the relatively "pure" sandstone with MgO- and K_2O-rich basement rocks.

There is large regional illite enrichment zone extending for 100 km northeast from Key Lake. This zone, which coincides roughly with a belt of pelitic basement rocks, circumscribes all of the known mineralization in the southern part of the study area. Sub-parallel linear zones of chloritization and dravitization form an axis to the illite anomaly. The illite, chlorite and B enrichment zones are postulated to have resulted from the existence of a region of relatively concentrated, or relatively high temperature formation waters, and from greater than average tectonic

disturbance. The coincident belt of pelitic basement rocks may be only indirectly responsible for the sandstone lithogeochemical anomaly, as a locus for increased tectonism.

In the northern part of the study area the sandstone overlying pelitic rocks is only slightly more illitic than that over the arkoses and granites, and in fact the strongest illitization is at the edges of the magnetic highs - the presumed contacts between granitic rocks and pelites - and again, preferential sites for tectonic activity.

The northern mineralized zones, such as Cigar Lake and Midwest Lake, are accompanied by variably-sized halos of strongly illitized sandstone, and small halos of weak B enrichment. The southern mineralized zones, such as Key Lake, are characterized by extensive halos of strong B enrichment, kaolinite dominance and clay depletion. In general, the halos are symmetrical in cross-section, and all have some manifestation at the top of the sandstone, even where the section is greater than 500 m thick. On this macroscopic scale argillization is not a significant feature. Some zones have very restricted clay enrichment, while others show pronounced clay depletion. U, Pb and Cu are enriched to varying degrees in the halos around all mineralized zones.

In the eastern Athabasca Basin sandstone lithogeochemistry is a powerful tool when applied to exploration for U deposits. The study of lithogeochemical patterns enhances the probability of detecting mineralized zones, both in a lateral sense, if a deep drill hole misses a target, and in a vertical sense, through application of surface or sub-outcrop sampling to detect targets at depth. Furthermore, as this study has shown, a knowledge of regional lithogeochemical patterns can add to our understanding of the processes of U mineralization.

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URANIUM DEPOSITS IN THE BEAVERLODGE AREA, NORTHERN SASKATCHEWAN: THEIR RELATIONSHIP TO THE MARTIN GROUP (PROTEROZOIC) AND THE UNDERLYING BASEMENT

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Abstract

The rocks of the Martin Group crop out in an area 60 km by 50 km north of Lake Athabasca near Uranium City, northern Saskatchewan. This area has numerous uranium showings within a few kilometres of the unconformity below the Martin Group. Mineralization occurs in fault zones, in basement rocks and in sedimentary and volcanic rocks of the Martin Group.

Martin Group sediments accumulated in alluvial fans, braided streams, and ephemeral lakes. The thickest sequence (8 km to 10 km) is preserved in the Beaverlodge area, near Uranium City. The style of sedimentation changed through time as the basin evolved from deposition of conglmeratic detritus along fault scarps to the accumulation of silt in ephemeral lakes. The uneven nature of the sub-Martin unconformity surface, the lithotype of the lowermost conglomerates and breccias (Beaverlodge Formation), and the shape of the the basin fill indicate deposition in fault-controlled basins.

The earliest economic uranium mineralization in the rocks of the Martin Group was epigenetic. The mineralization was coeval with that in basement rocks. Economic mineralization in basement rocks and in the lowermost formation of the Martin Group is close to the unconformity. Epigenetic uranium mineralization thus appears to have resulted from processes that were related,

in time and space, to either the formation of the unconformity or the deposition of the Martin Group or both.

Introduction

Conglomerates, sandstones and siltstone of the Proterozoic Martin Group crop out north of Lake Athabasca in the Beaverlodge area of northwestern Saskatchewan (Figure 1). The most

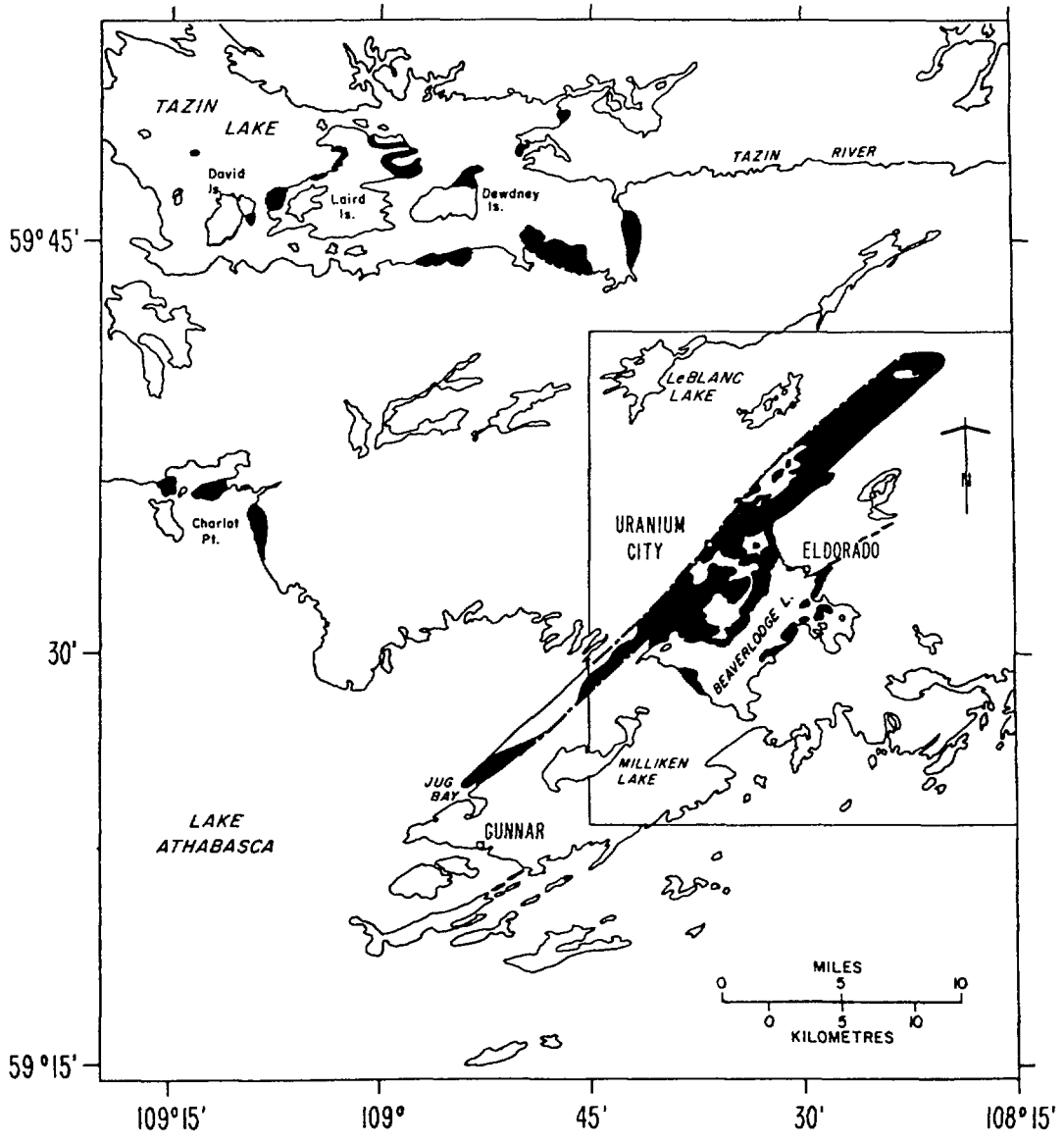

Figure 1: Outcrop map of the Martin Group in the Greater Beaverlodge area (shaded) and in the Beaverlodge Lake area (inset).

extensive outcrops of the Martin Group are along the west and north sides of Beaverlodge Lake. Small outcrops occur around the other shores of the lake (Figure 1). Outliers of the Martin Group crop out, to the west near Charlot Point, and to the northwest around Tazin Lake.

Pitchblende deposits in the Beaverlodge area provided the major mineral production of the province of Saskatchewan from 1955 to 1975. Mineralization occurred both within the crystalline basement and in the Martin Group. The numerous pitchblende showings appear to be restricted to within a few kilometres of the area of outcrop of the Martin Group (Kalliokoski et al., 1978; Beck, 1969, map 126b). The range of ages of uranium mineralization in the Beaverlodge area is 1900 Ma to 40 Ma (Tremblay, 1972; Koepel, 1968).

General Geology

The term Martin Group was introduced by Langford (1981) to replace Martin Lake Series (Gussow 1957,1959), and Martin Formation (Fahrig, 1961; Tremblay, 1972). He subdivided the group and made correlation with the occurrences at Jug Bay, Charlot Point, and Tazin Lake (Figure 2).

In the Beaverlodge Lake area, the Martin Group rocks unconformably overlie a basement of Early Proterozoic to Archean age consisting of granites, granite gneisses and paragneisses. At Charlot Point and Tazin Lake, the Martin Group also overlies the slightly metamorphosed but highly deformed Thluicho Group (Scott, 1978) which is younger than the basement. Rocks of the basement underwent partial anatexis and several phases of plastic

Area	Beaverlodge Lake	Jug Bay	Charlot Point	Tazin Lake
Athabasca Group			Fair Point Fm.	
Martin Group	Melville Lake Fm.			
	Seaplane Base Fm.			
	Gillies Channel Fm.	Gravel Islands Fm.	Charlot Point Fm.	
	erosion	erosion	erosion	erosion
	Beaverlodge Fm.	Jug Bay Fm.		Taz Bay Fm.
			Ellis Bay Fm.	
Thluicho Group			Thluicho Group	Thluicho Group
B A S E M E N T				

(After Langford, 1981; Scott, 1978; Mazimhaka and Hendry, 1985).

Figure 2: Corelation table of the Martin Group among several structural basins within the Greater Beaverlodge area, and the relative stratigraphic position of the Martin Group with respect to other cover sequences in the area. Locality names refer to figure 1.

to brittle deformation during the Hudsonian, 1890-1830 Ma in age, (Krupicka and Sassano, 1972; Lewry et al. 1985). Rocks of the Martin Group are unmetamorphosed, steeply folded, intensely faulted, and intruded by basic dykes. Cataclastic zones occur close to major faults.

At Beaverlodge Lake, the Martin Group rocks occupy a basin partly defined by three major faults (Figure 3), along which are some of the largest uranium deposits. Eldorado's Ace-Fay and Verna orebodies lie along the Saint Louis Fault (Figure 3,

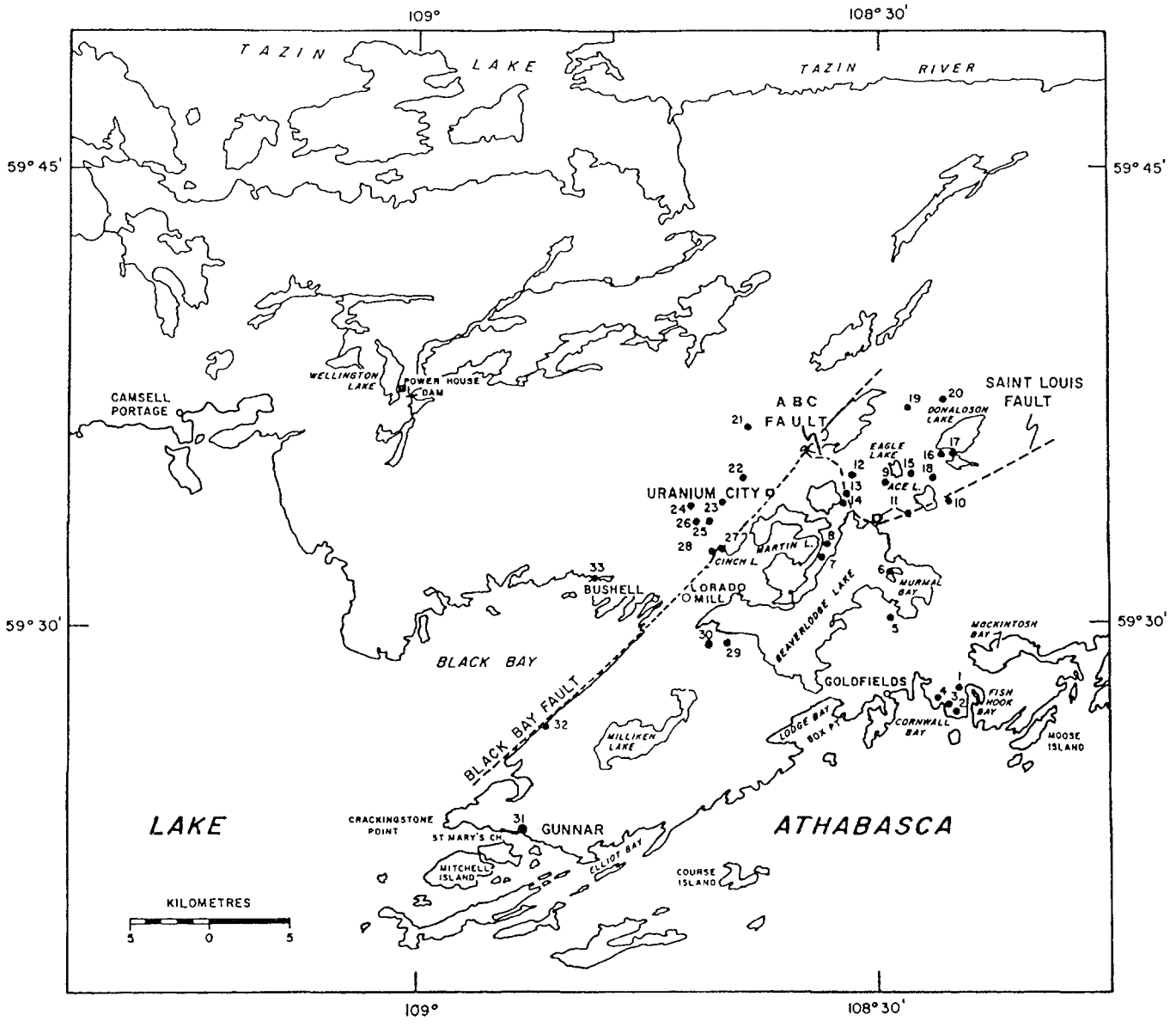

Figure 3: Major faults and major uranium deposits in the Greater Beaverlodge area (modified after W.O.Kupsch, 1978).

numbers 11 and 10); the ABC deposit is on the ABC Fault (Figure 3, numbers 13 and 14); and the Gulch, Cinch and Cenex deposits lie along the Black Bay Fault (Figure 3, number 32, 27 and 28). The deposits were not localised in the faults themselves but were in subsidiary fractures and joints (Tremblay, 1972; Tortosa, 1983).

Early workers in the Beaverlodge area recognised that uranium showings occurred close to major faults and close to the contact between Proterozoic cover rocks and the basement. After the discovery of the Ace deposit along the Saint Louis Fault in 1948, several workers suggested that major faults in the Beaverlodge area were good exploration targets (Lang, 1953). A genetic relationship between uranium mineralization and the contact between the Martin Group and the basement was suggested by Joubin (1955) and Robinson (1955a). Johns (1970) predicted that similar relationships should exist in the Athabasca basin: a prophesy that was amply fulfilled in the next two decades.

Martin Group sediments were likely deposited in fault basins that developed at the close of the Hudsonian Orogeny. Faulting, mylonitization and brecciation, accompanied by retrograde metamorphism, occured during the uplift and erosion of the Hudsonian orogen (Krupicka and Sassano, 1972; Tortosa and Langford, 1986). Basins in which the Thluicho and Martin Group rocks were deposited were initiated during these late phases of the orogeny. Faulting and mobilization and localization of uranium ore minerals continued during and after deposition of Martin Group sediments (Beck, 1969; Tremblay, 1972; Krupicka and Sassano,1972; Tortosa and Langford, 1986).

Geological History of the Martin Group

The sub-Martin unconformity

The unconformity is very irregular and presently displays 300m to 1000m of relief (Mazimhaka and Hendry, 1984), but such great relief probably did not exist at the time of deposition of the sediments because there are no widespread thick deposits of

talus or rockfall. It is likely that the present relief was developed as a result of faulting during accumulation of sediments.

Most exposures of the the sub-Martin unconformity show a sharp, clean contact, although in some places thin weathering crusts are present. At Lorado Mill, (Figure 3), the surface of the unconformity displays spheroidal weathering. From the Eagle Shaft workings north of the Saint Louis Fault (Figure 3; 12), Smith (1986) described a talus-like regolith consisting of locally derived granite fragments cemented by a black chloritic ground rubble of the same rock. In the Fay deposit along the Saint Louis Fault (Figure 3;11), he described a gradational contact at which the conglomerates tend to grade downward from sub-rounded boulders of mylonitized granite into a talus-like regolith of angular fragments and boulders of granite.

Stratigraphy

Langford (1981) divided the rocks of the Martin Group in the Beaverlodge Lake area into four formations (Figure 4):

1.The Beaverlodge Formation

The Beaverlodge Formation is well exposed along the south and east shores of Beaverlodge Lake and north of the ABC Fault (Figure 3). In these areas it is very variable with respect to its total thickness, thicknesses of the different lithofacies, and the sequence of lithofacies. Generally the formation consists of up to 600m of a Conglomerate Member, commonly with coarse, angular, locally-derived clasts of basement rocks. The overlying Sandstone Member is 1500m thick and consists of sandstone with some conglomerate beds, as well as units of siltstone up to 500m thick (Figure 4).

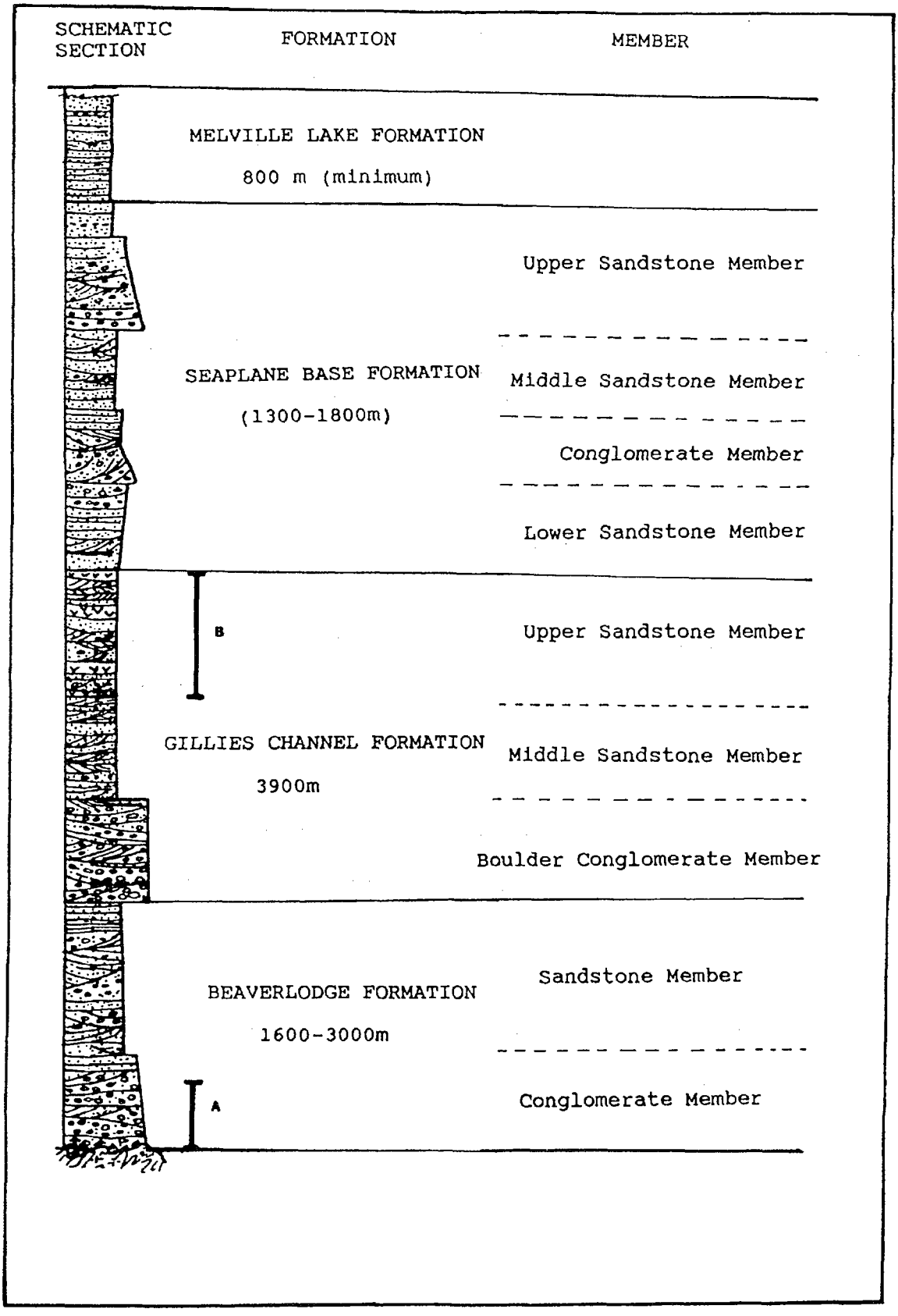

Figure 4: Composite stratigraphic section of the Martin Group in the Beaverlodge Lake area. Relative range of uranium mineralization in the Beaverlodge Formation (A) and in the Gillies Channel Formation (B).

2.The Gillies Channel Formation

The Gillies Channel Formation is exposed in a horse-shoe shaped outcrop between Martin and Beaverlodge lakes and along the Black Bay Fault, north of the ABC Fault. It is subdivided into three members (Figure 4):

The Boulder Conglomerate Member, at the base of the formation, contains boulder-sized clasts near the base but for the most part it is a well rounded cobble-grade conglomerate interbedded with sandstone beds and lenses. Clasts in the conglomerate are predominantly of basement rocks but sedimentary rocks, particularly siltstone, make up to 12 percent of the clasts at some localities.

The Middle Sandstone Member is a predominantly grey coarse--grained sandstone interbedded with pebble conglomerates. There are few exposures of this member because most of the sandstone is covered by water. North of the ABC fault, areas underlain by the Middle Sandstone Member are marked by deeply weathered sandy soils underlain by coarse crumbly sandstone, and narrow ridges underlain by conglomerate beds.

The Upper Sandstone Member is a coarse-grained reddish brown, orange-grey and purple sandstone interbedded with pebble conglomerates. It contains flows and sills of alkali basalts.

3. The Seaplane Base Formation

The Seaplane Base Formation is well exposed between Martin Lake, the ABC and the Black Bay faults, and on the peninsula in Martin Lake (Figure 3). It has a distinct pinkish red colour and is 1800m thick in the Uranium City area. Generally, the Seaplane

Base Formation becomes finer grained up-section and laterally to the southeast. It is divided into four members (Figure 4):

The Lower Sandstone Member overlies the uppermost lava flow in the Gillies Channel Formation. The sandstone is purplish--pink, grey and orange. Thin pebble beds, 30 cm thick on average occur throughout the sandstone. Some of the clasts have the same texture as the underlying igneous rocks and likely were derived from them.

The Conglomeratic Member contains bright pink sandstone, and conglomerate with thin siltstone beds. Intraformational siltstone clasts are very common at the bases of many sandstone and conglomerate beds.

The Middle Sandstone Member contains a bright pink medium--to coarse-grained sandstone and thin siltstone beds. Fine--grained sandstone beds are rippled on top and siltstone drape the ripple mark tops.

The Upper Sandstone Member consists of conglomerate, sandstone, and siltstone beds. The conglomerate is coarse--grained but restricted to the area north of Uranium City. To the southeast, it passes into planar bedded sandstones with rippled beds, mud-cracked surfaces, and mud drapes.

4.The Melville Lake Formation

The Melville Lake Formation consists of 800m of siltstone and argillite. The formation crops out in the area between the eastern north shore of Martin Lake and the ABC Fault. It is cut off by the ABC fault to the northeast (Figure 3). The Melville

Lake Formation contains a lower part which consists of dark brown siltstone, interbedded with pinkish grey coarse-grained sandstone beds and very thin green or brown argillite beds with green reduction patches, and an upper part which consists of red--brown sandstone , a few siltstone and argillite beds , and conglomerate.

History

The Martin Group rocks in tbe Beaverlodge Lake area are progressively finer-grained from the base to top of the sequence (Figure 4). Both the percentage of sandstone and siltstone increases up-section, and in the conglomerates the sizes of clasts decrease and roundness and sorting increase. The style of sedimentation and the apparent stability of sedimentary environments also appear to have changed systematically throughout the period of deposition from the Beaverlodge to the Melville Lake Formation (Mazimhaka and Hendry, 1984).

The Beaverlodge Formation has a wide range of poorly sorted conglomerates and breccias which were deposited on a highly irregular surface of the igneous and metamorphic basement, and sand and siltstone which were deposited on alluvial fans and in lakes. The juxtaposition, within the Beaverlodge Formation, of coarse-grained poorly sorted breccias and conglomerates, and thick evenly-bedded siltstone, indicates that the depositional environments in the early stages of basin development were diverse. Such diversity was likely caused by contemporaneous tectonism which led to the formation of a number of rather small sub-basins. Basins which were cut off tectonically from a supply of gravel would receive fine-grained sediment, particularly silt, which could accumulate in both shallow and deep, tectonically--

controlled lakes. Change from conglomerate to sandstone may be interpreted as a result of deposition at an increasingly greater distance from the source area, perhaps by back-faulting of the basin margin.

Deposition of the lowermost conglomerate of the Gillies Channel Formation suggests a high-relief source area, but well--rounded clasts in the conglomerates indicate that the distances of transport were probably greater than those for the material in the Beaverlodge Formation. Evidence for uplift and erosion of some of the Beaverlodge Formation indicates that faults were active within the basin too, and that some of the well rounded clasts may be the result of reworking of material in the Beaverlodge Formation. Once again, the upward trend from coarse to fine within the Gillies Channel Formation could be explained by an initial period of uplift, to give high relief at the source, followed by retreat of the source area by both erosion and back-faulting of the basin margin. During deposition of the Upper Sandstone Member of the Gillies Channel Formation, a very large volume of alkali basalts extruded into the basin which indicates renewed tectonic activity.

The Seaplane Base Formation records one major and one minor pulse of tectonic reactivation at the source and along the basin margin. The Lower Conglomerate Member of the Seaplane Base Formation included clasts of sediments of the Gillies Channel Formation, which indicates uplift within the basin, though it may have been at the margin. Further uplift developed the conglomerate in the Upper Sandstone Member of the Seaplane Base Formation. After this, increasingly fine-grained sediments were deposited, and the sedimentary record of the basin is terminated

by the siltstones and fine-grained sandstones of the Melville Lake Formation.

Uranium Mineralization in the Martin Group

Uranium mineralization in both Martin Group rocks and in the basement, occurs mainly as veins in fractures. The main gangue minerals are hematite and calcite. Mineralization in the Martin Group in the Beaverlodge Lake area is limited to the Beaverlodge and Gillies Channel formations. The mineralogy and mode of occurrence of these deposits is similar to those that occur in the basement rocks and make the principle mines in the area.

A. Mineralization in the Beaverlodge Formation.

Within the Beaverlodge Formation, mineralization is in conglomerates and sandstones immediately above the unconformity (Figure 4 A). At the Meta Uranium Mine on the west side of Umisk Island (Figure 3, number 6), mineralization in this underground prospect is in the Conglomerate Member of the Beaverlodge Formation. Conglomerates and sandstones on Umisk Island reach a thickness of 200m to 300m. Pitchblende occurs within zones of shearing and in northwest-trending fractures at the unconformity, and in both the conglomerate and basement quartzites. The small mineralized zones are filled with carbonate and hematite (Beck, 1969; Tremblay, 1972).

The Ura ore bodies were located in Martin Group rocks in the hanging wall of the Saint Louis Fault and formed the west end of the Ace-Fay mining zone (Figure 3, number 11). Pitchblende was found throughout the Conglomerate Member of the Beaverlodge Formation and to a lesser extent in the underlying basement gneisses as disseminations, fracture fillings, and veinlets.

These formed a series of irregular small orebodies at the unconformity which were mined for a total of 362,787 kg U_3O_8 (Smith,1986).

B. Mineralization in the Gillies Channel Formation

In the Gillies Channel Formation, uranium deposits are in the Upper Sandstone Member and, in particular, within the alkali basalt flows and sills interbedded with the sandstones (Figure 4B).

The Pitch Ore Prospect is located on the east limb of the Martin Lake syncline, between the Beaverlodge and Martin lakes (Figure 3, number 7). Mineralization occurs in fractures and faults in the lavas flows and in adjacent sandstone beds. Alteration of the wall rock by hematitization and carbonitization is particularly marked in the massive flows although it is present in adjacent sandstones as well. Pitchblende occurs as colloform masses in veinlets and stringers within calcite veins and in fault breccia cemented with calcite. It is also present as finely disseminated grains in fault gouge and in hematitized wall rocks (Beck, 1969).

The Martin Lake Mine has a similar geological setting to that of the Pitch Ore Prospect (Figure 3, number 8). Major faults strike east to northeast and dip 50° to the south. There is a dip-slip displacement of about 30m on major faults. Minor faults and shear zones are filled with calcite which, like the wall rock, is heavily stained by dusty haematite (Beck, 1968).

Pitchblende occurs in northeast-striking veins. Almost all radioactive fractures are situated totally within volcanic rocks. The fractures are barren of anomalous radioactivity where they pass through sandstone beds. In sandstones beds the veins are

tight, whereas in lava flows they are brecciated, vuggy, mineralized tension cracks (Smith, 1986).

Basin evolution and uranium mineralization

The basins into which Martin Group sediments were deposited developed on a basement that consisted of Archean to Early Proterozoic granitic rocks and remnant platform cover. Deformation and widespread granite plutonism affected the area during the Hudsonian Orogeny from 2340 Ma to 2000 Ma (Krupicka and Sassano, 1972; Lewry et al., 1985; van Schmus et al., 1986). The Martin basins developed at the time of the tensional collapse, or relaxation, following post-Hudsonian uplift and deformation indicated by K-Ar mica ages of 1720 Ma to 1790 Ma (Stevens et al., 1982).

The unconformity surface beneath the Martin Group is highly irregular and thick deposits are preserved locally in grabens and other down-faulted structures within the basement (Tremblay, 1972; Mazimhaka and Hendry, 1984). The sediments are compositionally immature, red, and upward-fining. As a result of palaeomagnetic studies, Evans and Bingham (1973) placed this area at latitude 16° during the deposition of the Martin Group. Such a palaeopole position gives the Martin Group a minimum age of 1730 Ma which is similar to the ages of the major episode of uranium mineralization (Figure 5). Koeppel (1968) measured the ages of uranium mineralization in the area. He found that the time of the earliest mineralization, developed syngenetically during Hudsonian granitization, was 2400+/-100 to 1950+/-40 Ma. The epigenetic mineralization which produced the commercial orebodies, gave dates of 1780+/-20, 900+/-50, 200+/-20, and 0-100

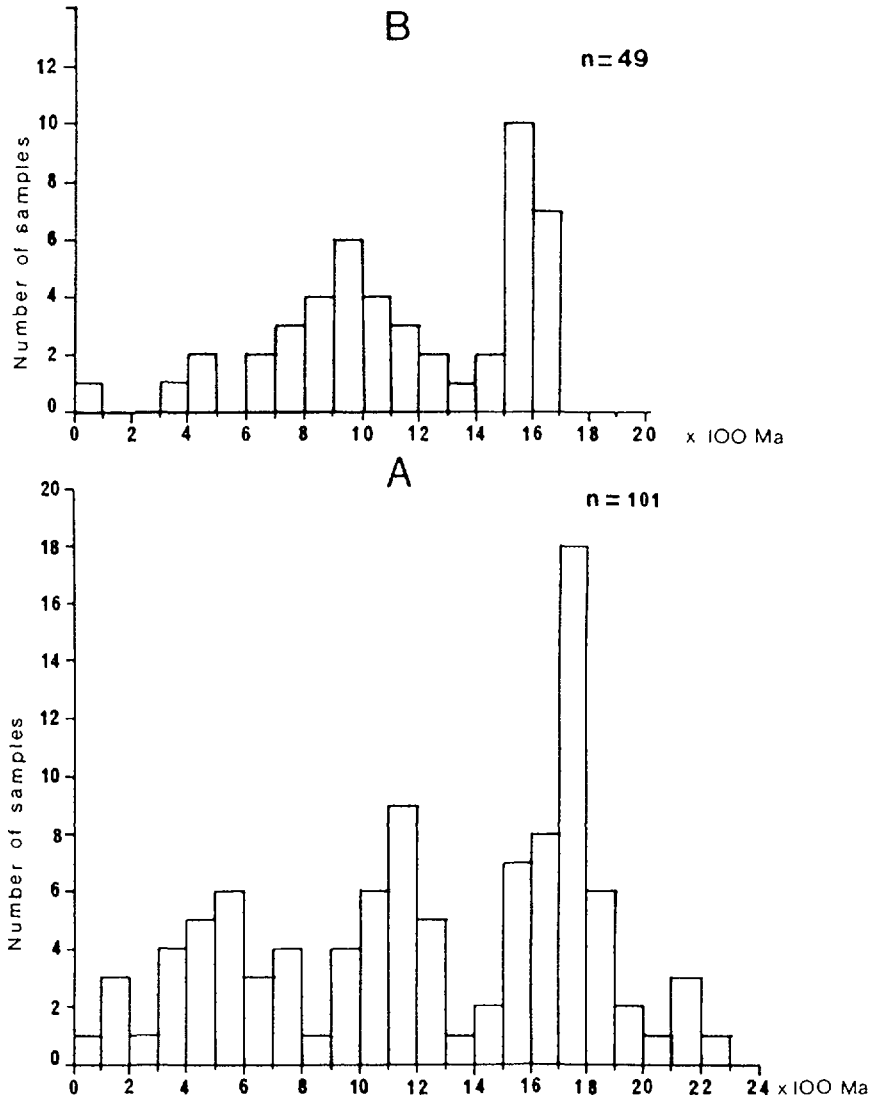

Figure 5: Histograms based on all published Pb^{207}/Pb^{204} ages of pitchblende from the Greater Beaverlodge area. Ages of pitchblende hosted by basement rocks (A) and by the Gillies Channel Formation of the Martin Group cover rocks (B). Data from Tremblay (1972) and Koeppel (1968).

Ma. He interpreted the 1780+/-20 age to represent the primary mineralization, and the later dates to represent reworking of the earlier minerals.

The oldest episode of epigenetic uranium mineralization in basement rocks, 1780+/-20 Ma, coincides with the indicated age for post-Hudsonian uplift (Tortosa and Langford, 1986), and time

of deposition of the Martin Group. Although the dates of mineralization within the Gillies Channel Formation are slightly younger than dates in the basement they are close enough that they are either within the error of measurement or represent a continuing period of primary epigenetic mineralization. Thus there appears to be a synchroneity of late-stage Hudsonian tectonism, basin formation, and uranium mineralization in basement rocks. The distinctly younger ages of epigenetic mineralization (around 900-1100 Ma) represent episodes of periodic reworking (Koeppel, 1968) that probably coincide with episodes of post-orogenic isostatic adjustment and late-faulting, which affected both basement and Martin Group rocks.

Discussion

Immature, red continental sediments of the Martin Group were deposited in isolated basins on a highly irregular surface. Given the low-latitude position for the depostional basin inferred from palaeomagnetic studies (Evans and Bingham, 1973), deep weathering might have been expected, but there is no evidence of regolith preserved beneath the Martin Group; only locally was the underlying basement weathered spheroidally. It is possible that high rates of uplift during deposition of the Martin sediments limited deep weathering and resulted in the erosion of any soils.

The stratigraphic sequence in the Martin Group records several episodes of apparent uplift of the source area which, in some instances, included parts of the Martin basin. The tectonic regime was characterised by episodic uplift, collapse, and extrusion of basaltic lava into parts of the basin.

The Martin Group rocks do not posses all the characteristics that are commonly associated with sandstone-type uranium mineralization (Finch and Davis, 1985). Yet, mineralization in the Beaverlodge area is spatially and stratigraphically related to the Martin Group. All major uranium deposits in the area occur in fault zones and related fractures. Although many of the fault zones are major regional structures, uranium mineralization in these structures occurs only in the vicinity of the Martin Group rocks.

If, as it is generally assumed, the Martin Group basin developed at the close of the Hudsonian Orogeny, then the age of uranium mineralization and that of Martin Group deposition are close if not overlapping. Although no dates have been measured on the showings in the Beaverlodge Formation and adjacent basement, the available data does suggest they differ from those of the epigenetic deposits further from the unconformity. The age of the mineralization in the Gillies Channel Formation (1500 to 1600 Ma) may be slightly later than the early epigenetic mineralization in basement rocks (Figure 5). Koeppel (1968) does not separate them on the basis of age. The Gillies Channel mineralization like other later episodes of mineralization (900 to 1000 Ma) likely resulted from ore mobilization during isostatic adjustment and later faulting which affected both basement and Martin Group rocks.

In conclusion it appears that the epigenetic uranium mineralization resulted from processes that were related in time and space with either the formation of the unconformity or the deposition of the Martin sediments or both.

ACKNOWLEDGEMENTS

This paper presents some material from a wider study of the sedimentology and stratigraphy of the Martin Group. The study was conducted at the University of Saskatchewan with funding provided from the Saskatchewan component of the Canada/Saskatchewan Subsidiary Agreement on Mineral Development 1984/1989, and the University of Saskatchewan. We are also grateful to Dr F.F.Langford for inviting the paper and for discussions during its preparation. Dr W.O. Kupsch kindly provided the original diagram on which figure 3 is based.

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BASEMENT GEOCHEMISTRY AND POSSIBLE LINKS BETWEEN 'BEAVERLODGE' AND 'ATHABASCA' TYPE URANIUM MINERALIZATION

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Abstract

Regional studies of the distribution of U, Th, and K in the Saskatchewan Shield do not reveal any obvious zones of radioelement enrichment that may have acted as precursors, and thus sources, for the uranium deposits of the Beaverlodge vein type or the higher grade Athabasca unconformity type.

On the other hand, uranium enriched granites (HHP or high heat production granites) have been identified in the general area. Using the model of HHP granites as long term heat pumps affecting the groundwater flow regimes and tectonics as the factor controlling rock permeability, a relationship between the Beaverlodge and Athabasca type deposits can be proposed and also the periodic remobilizations of uranium minerals within the deposits can be explained.

GEOCHEMISTRY IN ATHABASCA BASIN EXPLORATION, CANADA

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Abstract

Background for uranium in centre lake sediment samples is about 1 ppm in a range of 0,5 to 3, although values in the 100s of ppm are occasionally found in till areas rich in granite boulders. Careful work in areas near known subAthathabsca uranium deposits generally gives values less than 2 5 ppm which are difficult to distinguish from background variations Soil radon data are erratic due to granitic boulders in the sandy till Soil sampling is hampered by leached, very sandy soils and acidic pine humus Uranium scavenging in bogs, occasionally to over 1 %, occurs rarely in the less sandy basement areas Dunn (1983) showed that uranium in black spruce twig ash exceeds 100 ppm in a 500 km^2 area centred on the Rabbit Lake deposits within a 5000 km^2 area of greater than 10 ppm

Drill core lithogeochemistry shows well defined haloes in the basement and extending vertically through the overlying sandstone to surface (Sopuck, et al , 1983) An alteration chimney at least 200 m wide extends to subcrop nearly 200 m above the Midwest deposit and contains 2 to 13 ppm uranium, up to 100 ppm boron, and K_2O Al_2O_3 ratios of 0 10 to more than 0 15

As exploration is now most active in areas with 500 to 800 m of sandstone cover, the cost of drill holes to test the basal unconformity is enormous A lithogeochemical technique to map the subcrop of the alteration chimney with drill holes 10 m into sandstone was devised by Clark (1985, 1987) In an orientation survey, well developed anomalies were defined 400 to 430 m vertically above the Cigar Lake deposit Total and leachable uranium are 8 to 13 times the background values of 1 3 and 0 4 ppm, respectively Other elements 4 to 8 times background, in order of intensity, include V, Zn, Sr, Y, Pb, Th, As and P Na_2O has a pronounced negative anomaly At the Dawn Lake deposit, the strongest subcropping anomalies are in boron and MgO

THE JABILUKA AND RANGER URANIUM DEPOSITS, AUSTRALIA — IMPLICATIONS FOR GENESIS OF UNCONFORMITY-TYPE DEPOSITS

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Abstract

The Jabiluka and Ranger unconformity-type uranium deposits, Northern Territory, Australia, share a similar geologic setting and suite of alteration minerals, but Ranger is approximately 300 million years older than Jabiluka. At Ranger, the U-Pb isotopic age indicates that mineralization preceded deposition of the clastic sediments of the middle Proterozoic Kombolgie Formation that overlie a regional unconformity. In contrast, the U-Pb isotopic age at Jabiluka is clearly younger than that of the Kombolgie Formation. The Jabiluka deposit is the larger of the two deposits and may contain uranium that was remobilized from smaller Ranger-like deposits.

Brecciated early Proterozoic metasedimentary rocks host both deposits. At Ranger, carbonate dissolution along low-angle structures apparently caused large-scale collapse, whereas at Jabiluka some dissolution of thin carbonate beds may have occurred but was less extensive than at Ranger. Siliceous breccias within the Jabiluka ore zones contain strained and recrystallized quartz grains and may mark major shear zones. Apparent thickening of graphitic layers at Jabiluka may be due to repetition caused by folding and faulting.

The alteration zones at Jabiluka and Ranger are similar and contain many of the minerals found in the altered zones around Canadian unconformity-type deposits: magnesium-rich chlorite that has low oxide and cation totals, white mica, dravite, quartz, apatite, carbonaceous matter, and at Jabiluka, 7Å-amesite. At both Jabiluka and Ranger, the overlying sandstone of the Kombolgie Formation is altered. Our study indicates that unconformity-type deposits formed during both the early and middle Proterozoic eras, and that, for deposits such as Ranger, the presence of the middle Proterozoic sandstone was not necessary for ore concentration. The presence of altered sandstone at Ranger indicates that in unconformity-type deposits, fluids repeatedly moved through the deposits. In contrast to the Canadian deposits, the fluid moving through the Australian deposits did not deposit significant amounts of uranium in the middle Proterozoic sandstone.

1. INTRODUCTION

Jabiluka and Ranger are unconformity-type uranium deposits in the Alligator Rivers Uranium Field (ARUF) of the Pine Creek geosyncline, Northern Territory, Australia (Fig. 1). These deposits are hosted by altered and brecciated early Proterozoic metasedimentary rocks and are below and near a regional unconformity that separates the metasedimentary rocks from middle Proterozoic sedimentary rocks. Jabiluka and Ranger, the largest of four known unconformity-type deposits in the ARUF, together contain more than 300,000 tonnes U_3O_8 [1]. In addition, the larger Jabiluka deposit contains economic concentrations of gold.

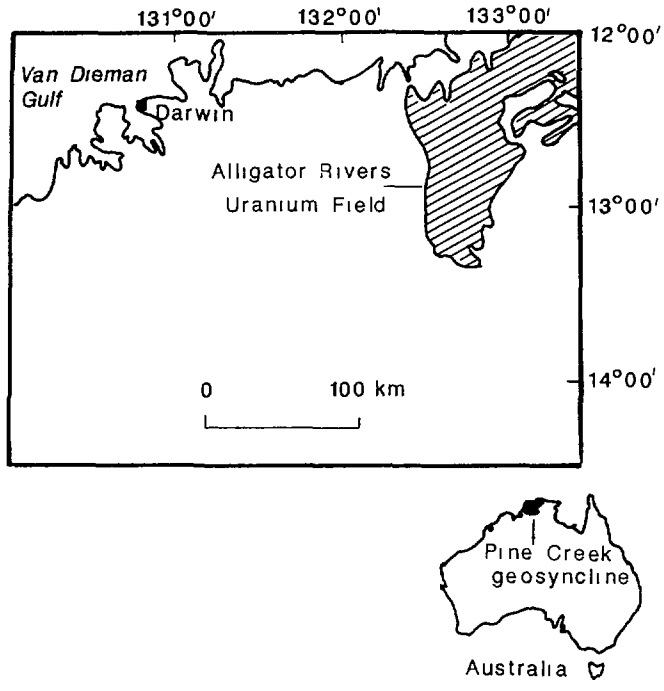


FIG 1 Maps showing the locations of the Pine Creek geosyncline and the Alligator Rivers Uranium Field (ARUF). The ARUF is in the eastern part of the Pine Creek geosyncline.

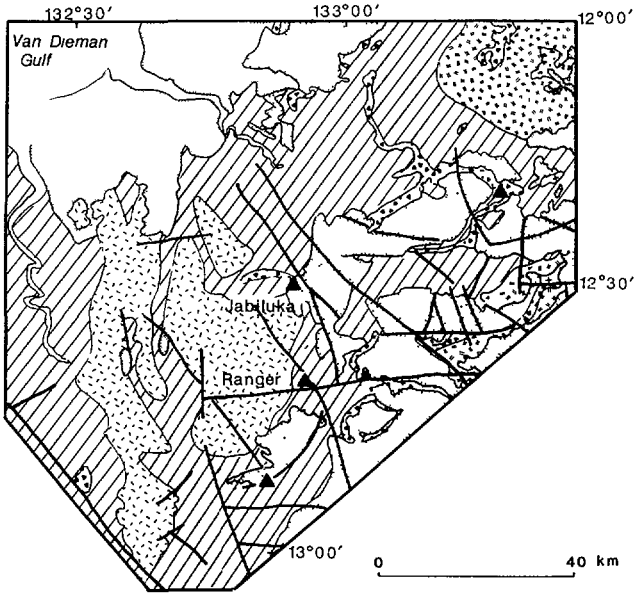
Although the geologic setting of the two deposits is similar, whole-rock U-Pb data of Ludwig et al. [2] show that the deposits formed about 300 million years apart. The whole-rock U-Pb age of ore from Ranger is 1737 ± 20 m.y., an age that apparently predates deposition of the middle Proterozoic sandstone that overlies the deposits. In contrast, the whole-rock U-Pb age of 1437 ± 40 m.y. for ore at Jabiluka clearly postdates deposition of the sandstone. Our study revealed both similarities and differences between the two deposits. Here we discuss some characteristics of these deposits and the implications that such information has for the genesis of unconformity-type deposits. Our paper emphasizes the Jabiluka deposit.

Our study of these unconformity-type deposits is based on drill-hole core samples collected when we examined the deposits in 1980. We logged and sampled 19 cores from the Jabiluka

deposit (C.J. Nutt and R.I. Grauch) and 28 cores from the Ranger deposit (D. Frishman and J.T. Nash). Since 1980, the open-pit at Ranger has been extensively mined; Jabiluka has not yet been mined. We are indebted to personnel at Pancontinental Mining Limited and at Ranger Uranium Mines who allowed us to examine company data and gave us access to core.

2. GEOLOGIC SETTING OF JABILUKA AND RANGER

The geology of the ARUF is described in Needham and Stuart-Smith [3] and Ewers et al. [1] and is only summarized here. Jabiluka and Ranger are hosted by early Proterozoic metasedimentary rocks. This approximately 3000-meter-thick unit is part of a thick early Proterozoic sequence of sedimentary and subordinate volcanic rocks deposited in a near-shore environment on Archean basement that is now exposed in the Nanambu Complex (Fig. 2). Between about 1890 and 1800 m.y., this sequence was intruded by granitic rocks of the



EXPLANATION

- Unconformity-type uranium deposit
- Fault

MESOZOIC	Sandstone, siltstone
MIDDLE PROTEROZOIC	Sandstone, minor volcanics, Kombolgie Formation
	Granite
EARLY PROTEROZOIC	Dolerite, Oenpelli Dolerite
	Amphibolite-facies metamorphic rocks, includes Cahill Formation
	Migmatite, granite, Nimbuwah Complex
ARCHEAN to EARLY PROTEROZOIC	Granite, metamorphic rocks, Nanambu Complex

FIG. 2. Geologic map of the Alligator Rivers Uranium Field and location of the Jabiluka and Ranger deposits. Modified from Ewers et al. [1].

Nimbuwah Complex and metamorphosed to greenschist to amphibolite facies [4]. Peak metamorphism was followed by another period of granitic intrusion at about 1732-1755 m.y. (Rb-Sr data [4]). Continental tholeiitic lopoliths of the Oenpelli Dolerite that were emplaced at 1682 ± 64 m.y. (Rb-Sr data of Page et al. [4], interpreted by Ludwig et al. [2]) mark the last igneous event before a major period of erosion and subsequent deposition of sandstones of the middle Proterozoic Kombolgie Formation. A volcanic member in the Kombolgie Formation has an Rb-Sr isotope age of 1648 ± 29 m.y. [4]. Mafic dikes that cut sandstones of the Kombolgie Formation have K-Ar ages of 1200-1316 m.y. [4], which should be considered minimum ages for emplacement [2].

Jabiluka and Ranger, as well as two other deposits and many uranium prospects in the ARUF, are hosted by altered and brecciated rocks of the early Proterozoic Cahill Formation or equivalent units. The Ranger deposit is above a carbonate-rich sequence near the base of the Cahill Formation, whereas Jabiluka is higher in the sequence where carbonate rocks are subordinate to pelitic rocks [5]. The host metasedimentary rocks are unconformably overlain by sandstone of the Kombolgie Formation and are near Archean basement of the Nanambu Complex. At both deposits, pelitic and psammitic schists have undergone pervasive retrograde metamorphism and now comprise an assemblage of quartz+chlorite±muscovite±graphite.

3. U-Pb AGES OF JABILUKA AND RANGER

Whole-rock U-Pb isotopic ages indicate that the Ranger deposit formed at 1737 ± 20 m.y., whereas the Jabiluka deposit formed at 1437 ± 40 m.y. [2]. Analytical data for 51 samples from Jabiluka show no evidence for earlier mineralization there. Both ages coincide with thermal events: the age of the Ranger deposit is within the range of ages determined for the post-metamorphic granites and the Oenpelli Dolerite, whereas the age of the Jabiluka deposit is near the minimum age for middle Proterozoic mafic dikes.

4. JABILUKA

4.1. Description

The Jabiluka deposit consists of two orebodies (Fig. 3): Jabiluka 1, which contains 3,000 tonnes of U_3O_8 at a grade of 0.25 percent U_3O_8, and Jabiluka 2, which contains a minimum of 204,400+ tonnes of U_3O_8 at a grade of 0.39 percent U_3O_8 and 260,100 oz of Au at a grade of 15.3 gm/t [1]. Uranium ore at Jabiluka occurs near the unconformity as well as more than 500 meters below it (Fig. 4). Jabiluka 1, the first orebody discovered, is exposed in a window eroded through sandstone of the Kombolgie Formation, but Jabiluka 2 is covered by 20-220 meters of sandstone. The Jabiluka 2 orebody extends beyond the limits of drilling to the east, southeast, and at depth. Ore encountered during drilling to the south may be part of a third orebody (unpublished data, Pancontinental Mining Limited).

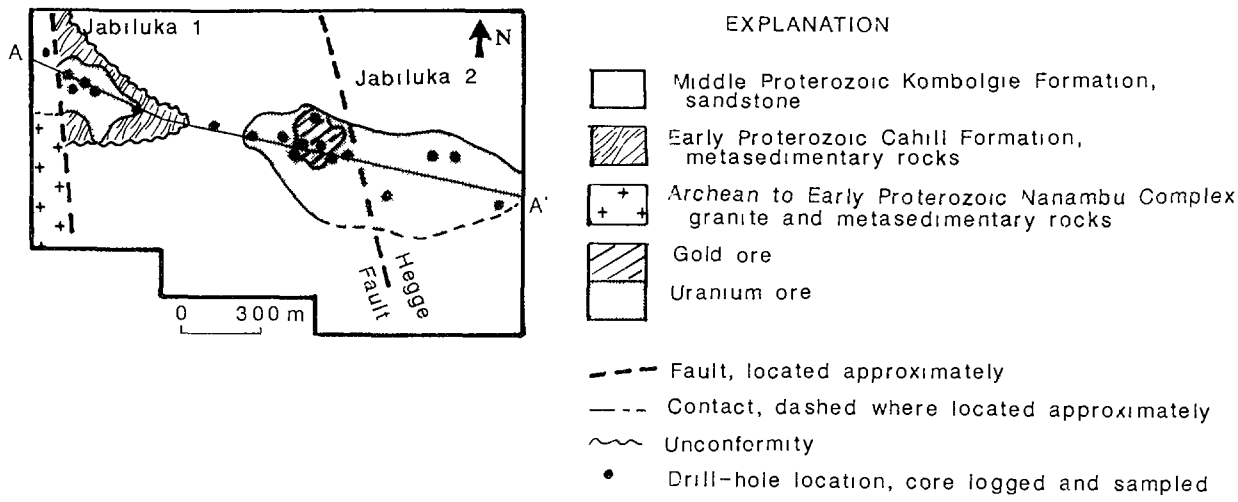


FIG. 3. Geologic map of the Jabiluka deposit showing the bedrock geology and the projection of the orebodies to the surface. Drill holes from which cores were sampled and section A–A' are shown Cores were sampled from drill holes GNO42V, ANO45V, ANO48V, BNO54V, YO57ND, YO69V, X102V, V111V, V123V, T129V, U132V, V135V, U138V, T141V, T147V, O162ND, S177V, S189V, and N204V. Modified from Ewers et al. [1].

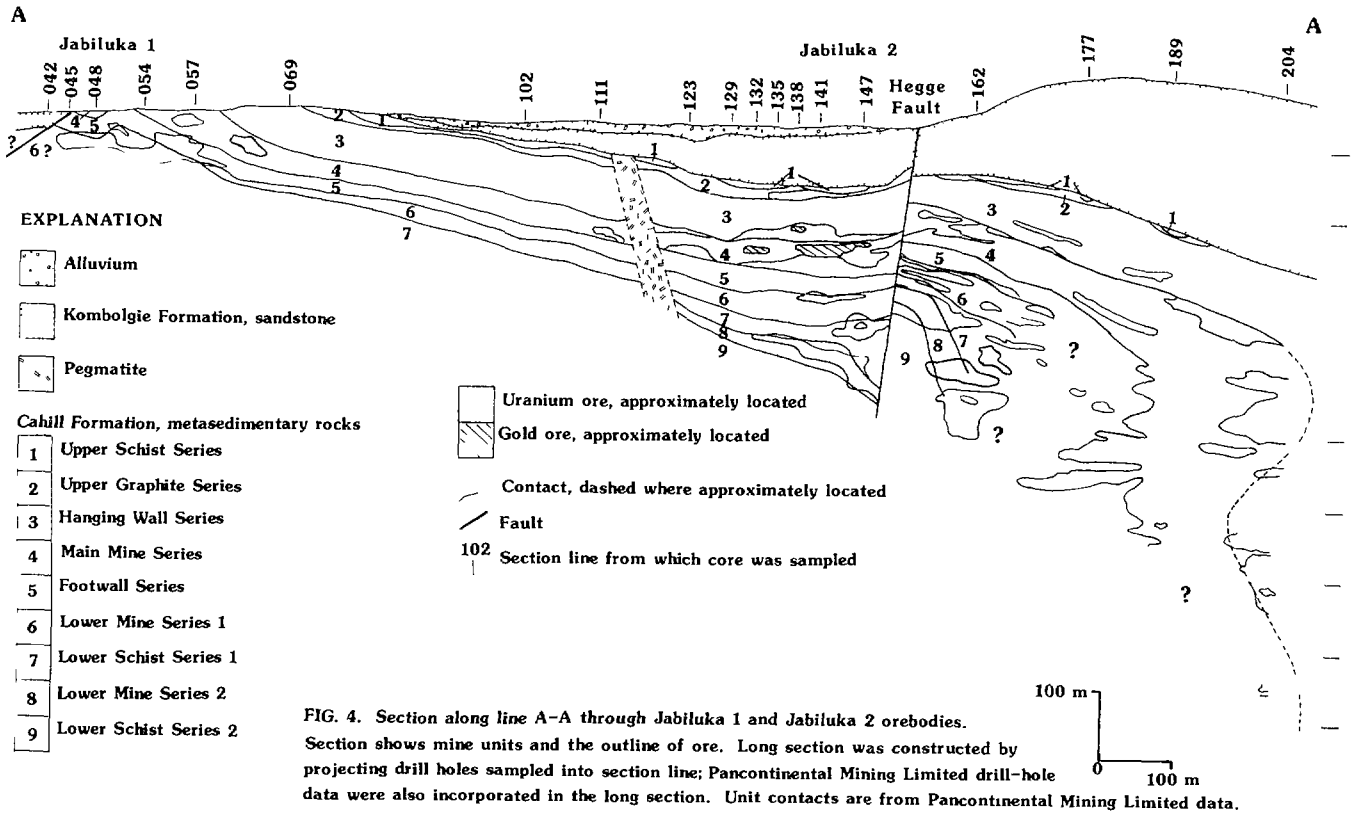


FIG. 4. Section along line A–A through Jabiluka 1 and Jabiluka 2 orebodies. Section shows mine units and the outline of ore. Long section was constructed by projecting drill holes sampled into section line; Pancontinental Mining Limited drill-hole data were also incorporated in the long section. Unit contacts are from Pancontinental Mining Limited data.

Our sampling program was planned so that a long section (A-A', Fig. 3) through the Jabiluka 1 and Jabiluka 2 orebodies could be constructed by projecting the sampled cores into this section line (Fig. 4). Data provided by Pancontinental Mining Limited from drill holes that we did not sample are also incorporated into the section. Stratigraphic units, ore, breccias, siliceous breccias, graphite-rich schists, and carbonate rocks are plotted on figures 4, 5, and 6. Units are not shown in the eastern part of Jabiluka 2 because stratigraphic control is poor in that area.

The orebodies are in a sequence of chloritized quartz+chlorite±muscovite±sericite±graphite pelitic schists that Pancontinental Mining Limited geologists divided into mine and barren schist series (Fig.4). All rocks at Jabiluka are chlorite-altered, but barren series typically contain the least-altered and least-disrupted quartz-chlorite-muscovite schists. Compared with barren series, the ore-bearing mine series schists are more brecciated and altered; they are predominantly composed of quartz-chlorite schist, quartz-chlorite-sericite schist, graphitic schist, massive chlorite rock, and breccias (Figs. 4, 5, and 6).

Dolomite and magnesite units as thick as 20 m [6] occur primarily between the Jabiluka 1 and Jabiluka 2 orebodies and at depth in the eastern part of Jabiluka 2, but they are rare within the orebodies. The carbonate rock is typically brecciated and contains local concentrations of uranium in chlorite layers or patches. A 7-meter-thick interval of garnetite in core from a hole drilled west of the deposit may be a skarn, although the iron- and manganese-rich composition and fine-grained texture of the garnets are similar to those of garnets in metamorphosed siliceous and manganese-rich sediments [7].

A tourmaline pegmatite swarm and rare amphibolite dikes cut metasedimentary rocks at Jabiluka, and Needham and Stuart-Smith [3] reported a metamorphosed dolerite beneath Jabiluka 1. A thick amphibolite sequence (metamorphosed dolerite?) was also penetrated by one hole drilled west of Jabiluka 1. Although fractures in chloritized pegmatite contain spotty uranium concentration, igneous rocks are generally barren.

The Cahill Formation at Jabiluka is pervasively chloritized in a zone that extends at least 500 meters into the country rocks [8, 9]. Schistosity is largely preserved, but feldspars and garnets are ubiquitously and completely replaced by sericite and chlorite. Within the orebodies, altered zones are dominated by very fine grained magnesium-rich chlorite. Crosscutting relationships among different varieties of chlorite indicate more than one period of chloritization. Based on microprobe analyses, chlorite typically has low oxide totals and high $^{VI}Al/^{IV}Al$. [10]. In addition to chlorite, altered zones contain 7Å-amesite, white mica (sericite), dravite (magnesium-rich tourmaline), and apatite [10]. All alteration minerals except 7Å-amesite have also been observed in the barren sandstone of the Kombolgie Formation. In our sample set, cores from the eastern part of Jabiluka 2 are noticeably less altered, but more sericite-rich, than cores from the western side [10].

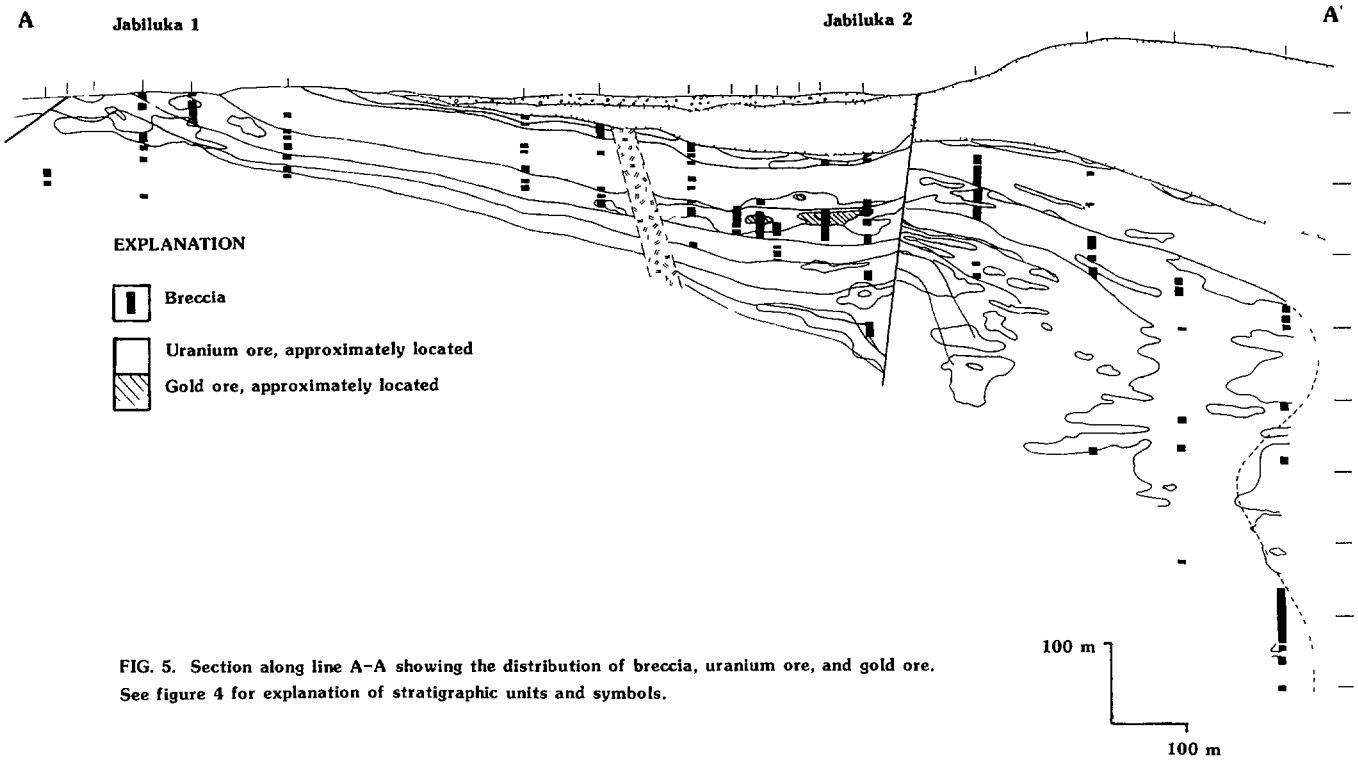


FIG. 5. Section along line A-A showing the distribution of breccia, uranium ore, and gold ore. See figure 4 for explanation of stratigraphic units and symbols.

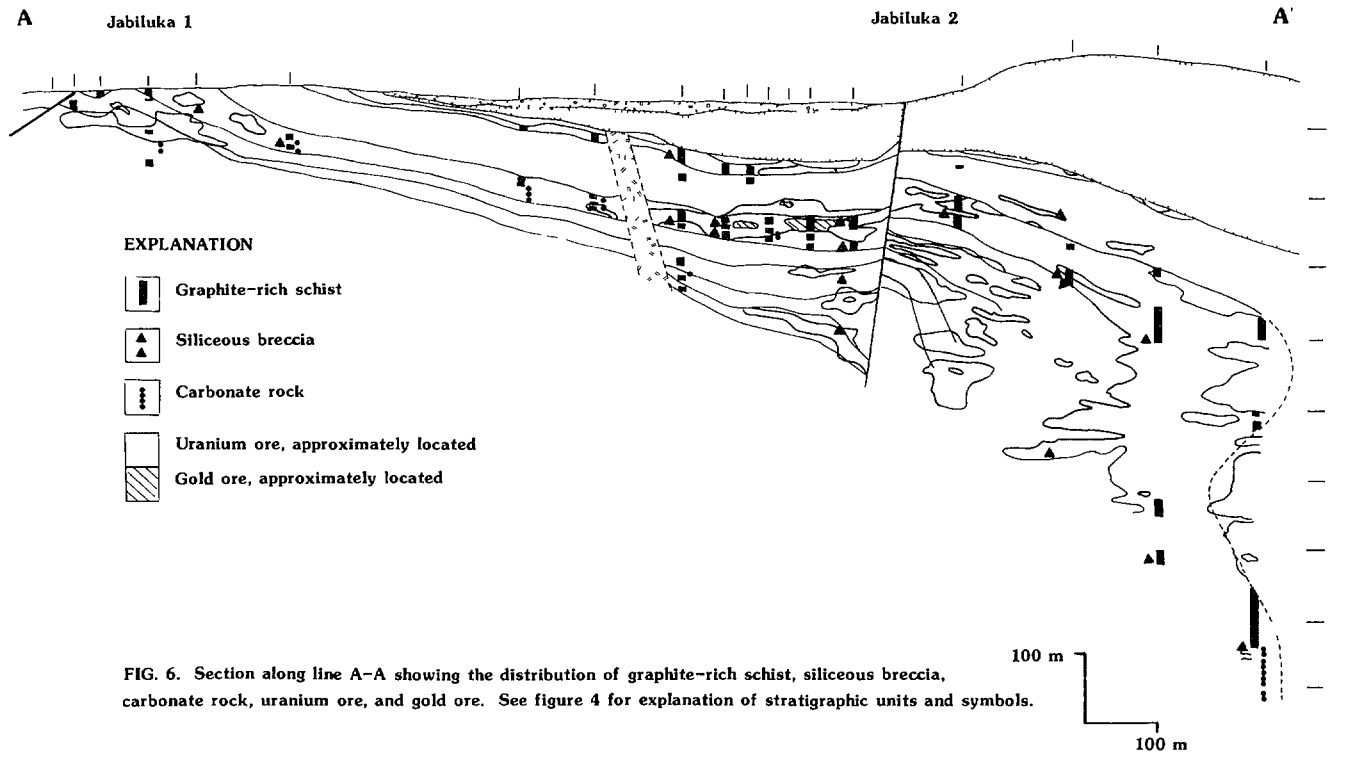


FIG. 6. Section along line A-A showing the distribution of graphite-rich schist, siliceous breccia, carbonate rock, uranium ore, and gold ore. See figure 4 for explanation of stratigraphic units and symbols.

Uranium ore minerals are uraninite and uranium-silicate (coffinite) and titanium-uranium-silicate phases. Commonly, the coffinite partially replaces uraninite. Veins of organic matter, in places with cores of uraninite, cut the rocks. These black veins of organic matter are most abundant in the eastern part of the deposit where they are easily mistaken for veins of uraninite. Ore minerals occur in breccia, in veins,

and as disseminated grains in massive chlorite rock. Gold-bearing mineral assemblages which include uraninite and tellurides apparently formed late in the complex ore paragenesis [11].

4.2. Structure

The stratigraphic units at Jabiluka have typically been represented as occurring in a fairly simple "layer-cake" stratigraphy [12], but near the end of the drilling program overturned strata were encountered in the eastern part of Jabiluka 2 (Fig. 4). During our logging of cores, it became evident that because unique marker beds are largely absent, it is difficult to distinguish among units and that sequences could have been repeated. At Jabiluka, ore is largely strata-bound in the mine units. Ore is less confined to mine units in the eastern part of Jabiluka 2, but because of poor stratigraphic control we can not with certainty identify the host units.

The distribution of breccias in cores that we sampled is shown in figure 5. Breccias typically consist of fragments of metamorphic rock, similar to the surrounding rock, set in a matrix of chlorite, quartz, quartz+dravite, 7Å-amesite, or 7Å-amesite+apatite. Ore minerals are in breccia matrix, in schist fragments, and in vein fragments. Because the breccias are the main ore hosts, their distribution roughly coincides with outlines of the orebodies. Distinctive siliceous breccias, typically about a meter thick, are plotted on figure 6. These breccias consist of fragments of strained and sheared quartz grains set in a matrix of fine-grained, and, in places recrystallized, quartz.

The distribution of graphite-rich schist is also shown in figure 6. Comparison of the distribution of graphite-rich schist (Fig. 6), breccias (Fig. 5), and siliceous breccias (Fig. 6) shows that sequences with graphite-rich schist layers are commonly brecciated and therefore host ore. In detail, the ore is typically in breccias or chlorite rock within graphite-rich sequences. In the cores that we sampled, the graphitic schist sequence appears to be thicker in the orebodies than in the area between Jabiluka 1 and Jabiluka 2 (Fig. 6).

Intercepts of carbonate rock in cores that we sampled are plotted on figure 6. In most cores, the carbonate rock is brecciated. An absence of carbonate rock in the orebodies was noted during the early stages of drilling [6], but near the end of the drilling program carbonate was intersected at depth in the eastern part of Jabiluka 2 (Fig. 6). In this core, siliceous breccia separates carbonate rock from the overlying graphitic schist.

4.2.1. Interpretation

The distribution of ore, breccias, siliceous breccias, graphite-rich schist, and carbonate rock suggests that ore is structurally controlled. Siliceous breccias, which contain strained and sheared quartz grains, probably mark zones of

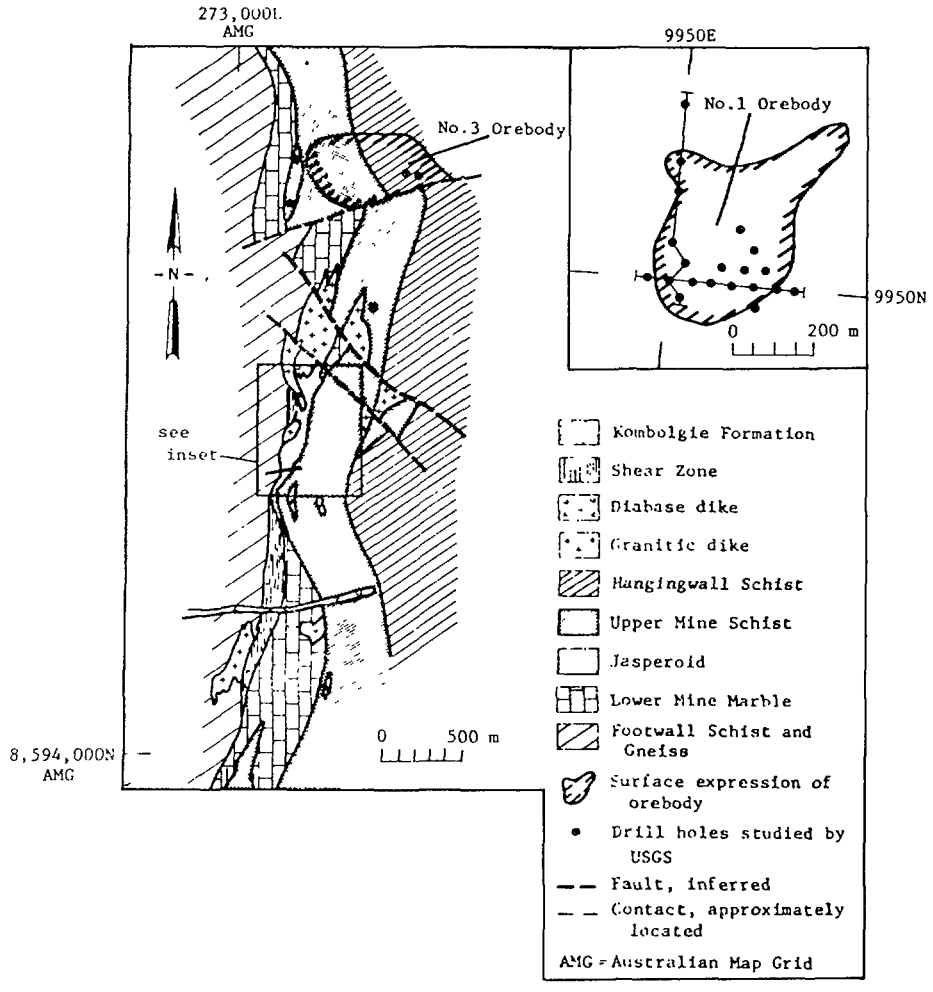


FIG. 7. Geology of the Ranger mine area modified from Eupene et al. [11] and data from Ranger Uranium Mines (as of 1979). Precambrian geology is projected to the surface and is based chiefly on drill data. Inset shows the outline of the No.1 orebody; dots show the locations of drill holes examined.

faulting or shearing. The localization of siliceous breccias in graphitic sequences and between graphite schist and carbonate rock suggests that shearing may have been concentrated along contacts between brittle rocks (i.e. quartz-rich strata, silicified carbonate rock, and carbonate rock) and more ductile graphite-rich rocks. The strata-bound character of the ore reflects the strata-bound concentration of breccias, and probably faulting, in the graphite-rich sequences.

In the cores that we sampled, the graphite-rich sequence of the Main Mine Series appears to be thicker within the orebodies than between orebodies. The thickening of graphite schist accompanied by a decrease in carbonate could be due to pre-metamorphic, sedimentary facies changes, but we suggest mechanical repetition of graphite-rich units by faulting and (or) folding as an alternative explanation. This hypothesis is supported by the observation that the graphite-rich sequences are almost invariably brecciated.

5. RANGER

The Ranger No.1 and No.3 orebodies are two of many radiometric anomalies discovered in the Ranger project area in 1969 and 1970 (Fig. 7). Open-pit mining started in 1980 at the No.1 orebody. The orebodies are about 1500 meters apart at the same stratigraphic horizon at the base of the Cahill Formation and adjacent to the Nanambu Complex. The local stratigraphy, as defined by Eupene et al. [13], is, from bottom to top: the Footwall Sequence, consisting of gneisses and schists; the Lower Mine Sequence, which is dominated by carbonates or stratigraphically equivalent silicified rock; the Upper Mine Sequence, composed of chloritized schist; and the Hangingwall Sequence, a relatively non-retrograded sequence of pelitic and psammitic schists. Both chloritized pegmatite and diabase dikes cut the orebodies. Stratigraphy of the two orebodies is similar, but No.3 orebody contains more carbonate rock and apparently is both less disrupted and less altered than the higher-grade No.1 orebody [14]. Combined reserves and production are 51,500 tonnes U_3O_8 at an average grade of 0.3 percent U_3O_8 at No.1 orebody and 48,850 tonnes at an average grade of 0.2 percent U_3O_8 at No.3 orebody [5]. Ranger contains notable quantities of gold, and our gold assays of individual hand specimens show as much as 6 gm/t Au, but overall the gold does not appear to occur in economic concentrations or geometries.

Alteration at Ranger is extremely intense in the ore zone, but unreplaced feldspar is a common phase in both the Hangingwall and Footwall Sequences at Ranger and garnet is locally preserved. Magnesium enrichment, as seen by the ubiquitous presence of magnesium-rich chlorite [15], is the dominant form of alteration. No 7Å-amesite has been recognized. Ranger was also affected by silicification as well as minor sericitization and enrichment of phosphorous and boron. Silicification was extensive, and apparently the thick carbonate unit in Ranger No.1 was replaced by jasperoid. Very fine-grained dravite grains have been recognized and their presence suggests a period of boron metasomatism, but the extent of the alteration is unknown. The rocks at both Ranger orebodies are enriched in phosphorus [15, 16]. Nearly all of the phosphorus is tied up in apatite that occurs as stubby euhedral prisms and as rounded grains. Secondary chlorite, sericite, and apatite are in the Kombolgie Formation sandstone as well as in the metasedimentary rocks.

Ore, in the form of uraninite and uranium-silicate and uranium-titanium-silicate phases, is concentrated in disrupted and brecciated schists and massive chlorite zones. Rare blebs of organic matter also occur within ore zones. Discrete veins are rare, but where present are less than 1 millimeter wide and are both oblique and parallel to foliation. Locally, sandstone of the overlying Kombolgie Formation is enriched in uranium.

Breccias of at least two different origins occur in the Ranger orebodies, but commonly they can not be differentiated in hand specimen. Fault breccias formed along both pre- and post-ore low-angle faults as well as along post-ore high-angle faults, and collapse breccias formed by solution and

replacement of the thick carbonate rocks [14, 15, 17]. Breccia intercepts in cores range in thickness from less than 10 centimeters to many meters in thickness. The deformation is expressed as zones of disrupted foliation, zones of broken, angular rock fragments in a matrix of fine-grained chlorite, or intervals of rubbly core and poor recovery.

6. DISCUSSION

Both Jabiluka and Ranger are large-tonnage, high-grade, strata-bound uranium deposits in early Proterozoic metasedimentary rocks beneath both a regional unconformity and overlying sandstone of the Kombolgie Formation. Both deposits have ages that roughly coincide with regional thermal events in the ARUF [2]. The similarities between the two deposits are so striking that a common origin has generally been assumed. The differences in isotopic ages of the two deposits, however, suggest that the unconformity and sandstone had no function in early concentration of uranium at Ranger and imply that either the unconformity is not important at Jabiluka or that other fundamental differences exist between the two deposits.

The primary ore mineralogy at the two deposits is similar. Uraninite and uranium-silicate and uranium-titanium-silicate phases have been identified in breccias, in veins, and as disseminated grains. Organic matter, mostly associated with uranium enrichment, occurs as blebs in veins and is disseminated in the metasedimentary rocks. No organic matter has been observed in the sandstone of the Kombolgie Formation. Both deposits contain anomalous amounts of gold.

The alteration assemblage at both deposits consists primarily of chlorite, dravite, apatite, and sericite; 7Å-amesite has been recognized only at Jabiluka. Chlorite, dravite, and apatite occur in both ore-bearing metasedimentary rocks and barren sandstones. The presence of altered sandstones at Ranger implies that some of the alteration must have taken place long after initial ore emplacement and only locally remobilized uranium.

Both deposits are structurally controlled by the distribution of breccias. Breccias appear to be largely fault-controlled, although at Ranger carbonate solution and collapse probably resulted in much brecciation. Wall et al. [18] suggested that breccias at the unconformity-type deposits in Australia formed along low-angle faults that were localized at the unconformable contact between the sandstone and metasedimentary rocks. At Jabiluka, our data neither confirm nor contradict this proposal, but we suggest that brecciation was dominated by brittle deformation along faults and shear zones such as those marked by siliceous breccias. Fracturing due to fluid movement and solution as well as minor carbonate collapse may have further brecciated the rocks. At Ranger, the U-Pb isotopic age implies that much brecciation preceded deposition of the Kombolgie Formation sandstone, although the presence of down-dropped blocks of sandstone in the Ranger No.3 orebody shows that some faulting also occurred after sandstone

deposition and lithification. The distribution of ore in the overturned strata at Jabiluka suggests that metamorphic structures may also have exerted some control on ore distribution.

Although the deposits are generally similar, differences do exist, most notably that Jabiluka is a larger and higher-grade uranium deposit that contains more gold than Ranger. At Ranger, the ore is mostly disseminated in massive rock whereas at Jabiluka the ore is primarily in well-defined centimeter-thick veins and in meter(s)-thick breccia zones. Alteration at Ranger was so intense that foliation is largely destroyed, but this alteration was restricted to the orebodies. At Jabiluka, the alteration was less intense but more pervasive in the barren rocks; foliation is well-preserved outside breccia zones. In addition, Ranger and Jabiluka are at different stratigraphic horizons in the Cahill Formation. The position of Ranger in the thick lower carbonate section places the deposit stratigraphically near the Archean basement.

7. IMPLICATION FOR GENESIS

Ranger and Jabiluka formed in the early and middle Proterozoic eras, respectively. This difference in ages indicates that unconformity-type deposits did not form during a unique period of geologic time, but instead formed over a prolonged period. In larger deposits such as Jabiluka, the presence of cross-cutting relationships among chlorites and ore-bearing veins, and the presence of ore in broken veins, matrix, and schist fragments indicate that repeated episodes of fluid movement and mineral deposition occurred.

The isotopic ages of ore from Jabiluka and Ranger indicate that all unconformity-type deposits may not have a common genesis. The Ranger deposit apparently formed prior to deposition of the sandstones of the Kombolgie Formation, and, therefore, the primary role of the sandstone may have been to preserve the deposit from erosion. At Ranger, the diagenetic-hydrothermal model [19] that is the accepted model for uranium mineralization at many of the Canadian unconformity-type deposits is not applicable. In particular, uranium at Ranger was not derived from the sandstone, a conclusion supported by recent Sm-Nd work on these deposits [20].

Alteration products are similar at Jabiluka and Ranger, and at both deposits the overlying sandstones of the Kombolgie Formation were altered. In contrast to the Canadian deposits, sandstones at these two Australian deposits are almost never enriched in uranium even where altered to an assemblage similar to that of ore-bearing zones in the metasedimentary rocks. The presence of altered sandstone at Ranger implies that some of the alteration at Ranger was subsequent to primary mineralization, perhaps by tens of millions of years or more. The alteration data emphasize the difficulty of deciphering paragenetic sequences, especially when the association between ore and alteration minerals appears to be merely spatial.

Dahlkamp and Adams [21] classified Jabiluka and Ranger as strata- and structure-bound deposits. Our data, as well as that of Johnston [17] and Wall et al. [18], suggest that

brecciation and ore are largely controlled by faults and shear zones. At Jabiluka, brecciation is largely confined to the graphite-rich sequences. At Ranger, solution and collapse brecciated the rocks and, therefore, collapse breccias host ore. The contrast between the extensive carbonate collapse at Ranger and only minor, if any, collapse at Jabiluka emphasizes that mineralization was not confined to one type of structure.

The study of Jabiluka and Ranger indicates that exploration for unconformity-type deposits should target faulted and disrupted early Proterozoic rocks that have been affected by post-metamorphic thermal events. In Ranger-type deposits, the presence of an overlying sandstone is apparently not essential for ore deposition.

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SIMILARITIES AND DIFFERENCES BETWEEN UNCONFORMITY-SPATIALLY RELATED URANIUM DEPOSITS FROM AVEYRON, FRANCE, AND SASKATCHEWAN, CANADA

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Abstract

The formation of all main uranium deposits, which are spatially related to an unconformity, have been dated between 1.7 and 0.9 Ga. It is thus a challenge to understand if this apparently strict limitation in time for the genesis of this type of deposits is real or if it is conceivable to find such deposits in more recent epochs. For this purpose, uranium deposits from Aveyron (France), which have low grades and low tonnages but which are spatially related to a major unconformity, are described and compared to the unconformity - spatially related uranium deposits from Saskatchewan (Canada).

In Aveyron, the deposits are situated near an unconformity between a metamorphosed basement and a Stephano-permian cover. The deposits are located in the basement (Bertholène), in the cover (Bennac) or both (Le Roube). The Bertholène deposit was formed during the Jurassic, 176 $\pm$ 3 Ma (Lancelot et al, 1985). It is, thus, very important to note that these deposits are temporally related to a global tectonic event which corresponds to the first stage of opening of an ocean and which is marked in the region by the intrusion of basic rocks.

The nature and the temperature of the mineralizing solutions in Aveyron are quite similar to those in Saskatchewan. These solutions are brines with temperatures between 110 and 165 °C (George,1985) and stable isotopic data indicative of formation waters issuing from a sedimentary basin (Charef and Sheppard, unpublished). α U3O7 has been recognized in the Le Roube deposit (George et al, 1986).

Despite these comparable genetic processes, important differences are noted:
(1) Albitization is well developped in Aveyron whereas it is absent in Saskatchewan. This albitization is attributed to the diagenesis of the sediments comprizing some volcanic components.
(2) The clay paragenesis associated with the mineralizing event differs strongly. Illite and smectite are the main clays at Aveyron and Fe rich chlorite is present before the U deposition. In Saskatchewan, illite and Al Mg chlorite are present.
(3) The metal paragenesis is more simple in Aveyron than in Saskatchewan.
(4) The nature of the basement in mineralized areas is quite different and especially the graphite- bearing horizons are of minor importance in Aveyron.
(5) The sedimentary cover shows contrasting redox formations in Aveyron whereas in the precambrian district the sedimentary cover is homogeneously oxidized.

GEOLOGY AND GENESIS OF THE ATHABASCA BASIN URANIUM DEPOSITS

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Abstract

The Athabasca Basin contains a 1400 m thick, redbed succession, the Athabasca Group of Paleohelikian (ca. 1450 Ma) age, and occupies an area of some 100 000 km^2. Fluviatile quartz sandstones and conglomerates give way upward to finer marine clastics and these in turn to stromatolitic and oolitic dolomite. Cross-cutting northwesterly trending diabase dykes are dated at between 938 and 1230 Ma.

The Athabasca Group is underlain by a lateritic weathering profile in crystalline basement rocks belonging to two major subdivisions of the Saskatchewan Shield, the Cree Lake (Mobile) Zone and Western Craton. These are separated by a major shear zone, within a zone of low gravity which is locally intruded by Hudsonian (ca. 1750 Ma) uranium enriched 'granite'. The Cree Lake high-grade metamorphic zone comprises Lower Proterozoic shelf-type supracrustals (Wollaston Group) overlying predominantly granitoid basement, which was variably remobilized into gneiss domes and recumbent gneiss lobes during Hudsonian (sensu lato) orogenesis. In part, the supracrustals have become incorporated in the granitoid infrastructure. The Western Craton shows similar ages of rocks, but on a large scale has suffered plastic rather than ductile deformation, with the development of geologically complex zones of Hudsonian (sensu lato) reworking surrounding Archean granulite facies cratonic nuclei.

Recognizable controls of Athabasca Basin uranium mineralization are a) the sub-Athabasca Group unconformity, b) fracturing and faulting, and c) graphite in basement rocks. The deposits exhibit, to varying degrees, complex mineralogy and geochemistry (U $\pm$ Ni, Co, As, Cu, Pb, Zn, Ag, Au, Pt group elements, Mo, V, Se, Mn and Fe). They are surrounded by extensive argillic alteration haloes in the Athabasca Group and more restricted haloes in the basement. Redox relationships are characteristic of most deposits. Dating of pitchblende and alteration minerals suggests epigenetic emplacement beginning 1350 Ma ago. Fluid inclusion studies indicate deposition from saline mineralizing fluids at temperatures between 150 and 225° C.

The most acceptable model of deposit genesis, the diagenetic-hydrothermal model, involves interaction of hot, oxidized, metalliferous formational waters of the Athabasca Group with the underlying 'reduced' basement. Mineralization was episodic and likely triggered by tectonic events, possibly related to diabase dyke emplacement and/or uplift. The model requires neither local repeated enrichment by diverse processes throughout earth history, nor the existence of a specialized, uranium-enriched source.

ALTERATION HALO CHARACTERISTICS OF URANIUM DEPOSITS IN THE ATHABASCA BASIN, NORTHERN SASKATCHEWAN

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Abstract

Most of the uranium deposits in the eastern part of the Athabasca Basin of northern Saskatchewan are situated at the unconformable contact between Helikian quartz sandstones of the Manitou Falls Formation (Athabasca Group), and Aphebian metasediments of the Wollaston fold belt. The main post-diagenetic matrix mineral of the Manitou Falls Formation is kaolinite, but hydrothermal alteration processes associated with unconformity-type uranium mineralization have lead to pronounced alteration of the sandstone matrix.

In the northern part of the district, around deposits such as Cigar Lake and Midwest Lake, kaolinite has been replaced by illite, and - immediately adjacent to ore - by chlorite. These illite "chimneys" are 100 to 200 metres wide, and they extend vertically through up to 400 metres of sandstone. In the southern part of the district, at Key Lake for example, the zone of illite alteration is much larger, apparently up to 10 kilometres wide. The sandstone immediately above mineralization is illite-poor because illitization has been inhibited by earlier dravitization and silicification. This illite alteration zone forms part of a regional illite anomaly which extends for several tens of kilometres northeast from Key Lake, and circumscribes all of the known uranium mineralization in the southeastern part of the Athabasca Basin. The central axis of this anomaly is characterized by dravitization and chloritization of the sandstone.

The clay-mineral alteration characteristics of the Manitou Falls Formation have important implications concerning the temperature and composition of diagenetic and hydrothermal fluids. Furthermore, a knowledge of the distribution of such alteration zones, some of which can be detected at the top of the Athabasca sandstone, is an important tool for uranium exploration in the basin.

GRAPHITE DISORDERING DURING THE GNEISSIC BASEMENT ALTERATION IN THE SASKATCHEWAN URANIUM DEPOSITS (CANADA)

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Abstract

Unconformity type uranium deposits in Northern Saskatchewan are frequently associated with graphite-rich Proterozoic gneisses. At the Athabasca Basin scale, a spatial relationship between graphitic basement rocks and uranium ore deposits has been noticed. During the hydrothermal alteration related to the mineralizing process, a progressive removal of graphite can be observed when approaching the unconformity. In the mineralized zones the graphite totally disappears and is partly replaced by blebs of carbonaceous material. Study of the graphite alteration has been undertaken by sampling a series of specimens at various distances from the unconformity.

X-Ray diffraction, reflectance measurents, Raman spectroscopy, high resolution transmission electron microscopy (HRTEM) and scanning electron microscopy (SEM) have been used in order to characterize the graphite structural parameters.

Results indicate that a disordering of the graphite layers progressively increases with decreasing distances to the unconformity. Structural defects have been evidenced on Raman spectra while micro-diffraction spectra (HRTEM) show that almost amorphous carbon phases develop inside graphite flakes near the unconformity. Furthermore circular holes have been observed in graphite. They are surrounded by poorly organized carbon phases and could correspond to radiation damages.

Emphasis has also been laid on the relationships between the graphite alteration and the occurence of carbonaceous material containing hydrogen and oxygen in the mineralized areas.

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1 INTRODUCTION

Organic material is frequently associated with uranium mineralizations in sedimentary environments. Kerogens, coals, wood fragments, tree trunks oils or bitumens have been recognized in uranium ore deposits and are generally considered as powerful reducing agents for uranium [1] [2] [3] [4] [5].

Most of these organic materials still contain hydrogen and oxygen and their maturation stage range between the begining of diagenesis ($T < 50°C$) to the metagenetic stage ($T > 150°C$). Graphite represents the ultimate stage of organic matter thermal maturation and corresponds to pure and perfectly ordered carbon structures.

The spatial association of graphite rich gneisses with unconformity-related uranium deposits is a very common phenomenon. In this case too, graphite is believed to have acted as a reductant for oxidizing uranium-carrying solutions and can be considered as an efficient exploration tool [6] [7].

In the alteration zones where the uranium mineralizations are generally observed, the graphite completely disappears and gives place to solid black bitumen blebs [7]. A relationship between the graphite disappearance and the genesis of hydrocarbons has already been suggested and is supported by the fact that graphite seems to be the only carbon source available in the environment of these deposits [8] [9].

It is why it was interesting to undertake a detailed study of the graphite alteration along a basement profile in order to get a better understanding of the degradation processes involved in the destruction of graphite.

In this study the graphite has been characterized by Raman spectrometry, high resolution transmission electron microscopy (H.R.T.E.M.), scanning electron microscopy (S.E.M.), reflectance measurements and petrographic observations.

2 EXPERIMENTAL

The first order Raman spectra were recorded on a monochanel micro Raman spectrometer MOLE [10] manufactured by Jobin-Yvon company. The exciting radiation is the 514.5 mm line of an Ar^+ laser and the microscope objective is a Leitz UTK x 50. In these conditions the spectral resolution is 5 cm^{-1}.

The second order Raman spectra were recorded on a multichanel micro-Raman spectrograph MICRODIL 28 manufactured by DILOR company. The microscope objective is an Olympus x 100.

A simple orientable stage using a glass needle has been specially designed to study the effect of orientation of graphite on the Raman spectra. Results have shown that the $\theta = 90°$ geometry (θ = angle between the graphite C axis and the optical axis of the laser beam) was the best way for indentifying defects in the graphite crystals.

T.E.M. measurements were performed by J. DEMAI on a 200 CX JEOL. For this type of experiments the graphite leaves were softly ground then suspended in a $CH_3(CH_2)_2CH_2O$ solvent and then deposited on the copper grid of the sample holder. Crystal lattice images were obtained with a 650 000 magnification.

3 SAMPLING AND SAMPLE PREPARATION

Seven samples of a graphitic metapelite have been collected in the same drill hole at distances from the unconformity ranging between 5 and 87 m. The samples are labelled A, B, C, D, E, F, G, G being the deeper sample and A the closest sample to the unconformity. The distance to the lower boundary of the major uranium concentration are respectively A=1 m, B=5 m, C=19 m, D=40 m, E=64 m, F=70 m and G=84 m.

Doubly polished thin sections are used for reflectance measurements. For Raman, T.E.M. and S.E.M. analyses, samples were prepared by crushing the whole rock in an agate mortar to roughly separate the different rock forming minerals. Crushed samples have been poured into water and floating graphite leaves have then been collected. No chemical attack has been used.

Polishing and grinding effects on Raman spectra have been tested. Results clearly indicate that strong grinding and thin section polishing can induce defects in the graphite structure

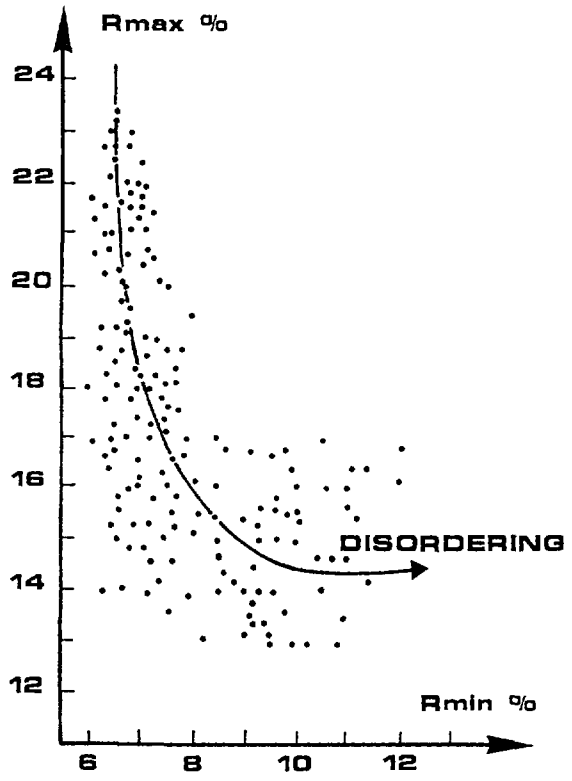

Figure 1 : maximum reflectance (R_{max} %) versus minimum reflectance (R_{min} %) diagram. Reflectance is measured in air on a Leitz microscope with a λ = 546 mm monochromatic light.

wich are recorded by Raman spectrometry. This is due to the weakness of the van der Vaals bonds insuring the linkage between aromatic layers.

4 PETROGRAPHIC OBSERVATIONS

Several alteration features concerning the shape, the surface and the reflectance of the graphite flakes can be observed under an optical microscope. In unaltered facies, graphite leaves exhibit straight boundaries and regular cross angles. Some tectonic deformations can be observed in several cases. Near the uranium ore (sample A), graphite flakes are frequently broken and clay minerals occur inside aromatic layer stacks. Correlatively, the graphite maximal reflectance in air moves from 20-22 % in nonaltered sample G to 14-16 % in sample A. Then the reflectance anisotropy (R_{max} - R_{min}) drastically decrease from roughly 15 in sample G to 5 in sample A. The evolution from sample G to sample A displays opposite characteristics to those of a classical organization trend of carbonaceous material [11].

Two kinds of defects are observed: interference zones and hollow points (Fig. 2). The interference zones exist in almost all the samples but their frequency of appearence increases from

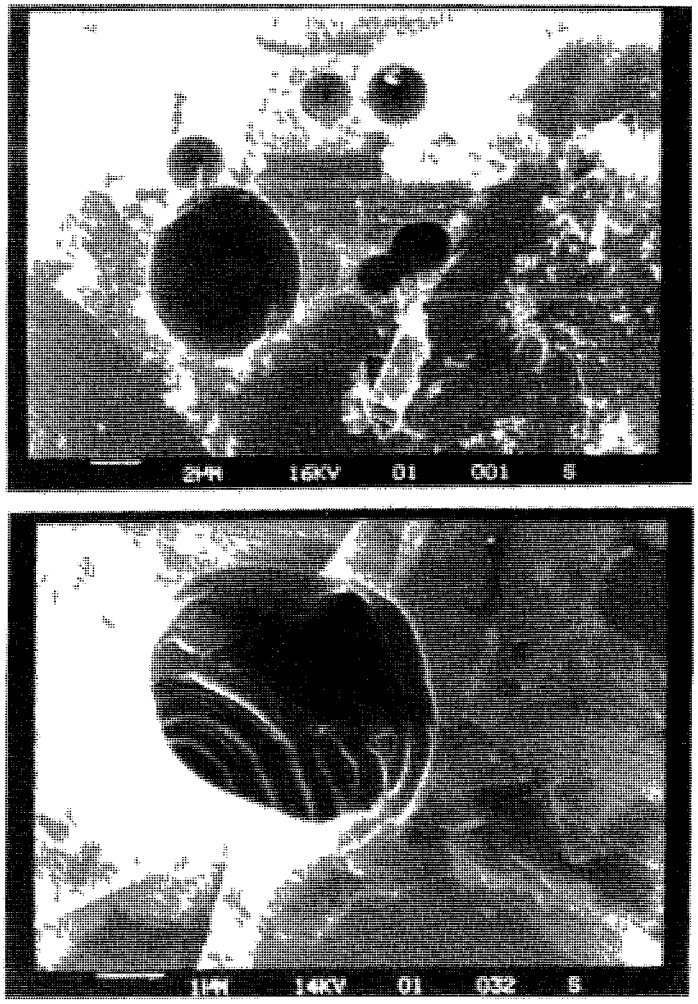

Figure 2 : S.E.M. microphotograph of a hollow point in a graphite leave of sample G.

sample G to A. There is no obvious regularity in the distribution size of these zones of interferences. This phenomenon probably reflects slight irregular modifications of the crystal surface which size is probably of the order of magnitude of the visible light. The hollow points are observed only on the surface of sample A. Their size is very variable: it ranges between some micrometers and several hundreds of angstroms. Small and large hollow points often coexist and sometimes connect each other to form a line or a group. In sample A, hollow points are also present in the interference zones.

5 CHARACTERIZATION OF THE GRAPHITE FLAKES ALTERATION

In order to obtain more details on this degradation of the graphite flakes a Raman and T.E.M. study has been undertaken following the proceduce previously described.

Comparison of first order Raman spectra of the two extreme samples (A and G) can be seen on Figure 3. In sample G spectrum, one single band located around 1575 cm^{-1} and corresponding to the C-C vibrations in the aromatic layer is observed. In sample A, a second broad band located at 1350 cm^{-1} appears. This band has been attributed to defects in the graphite structure [12] [13].

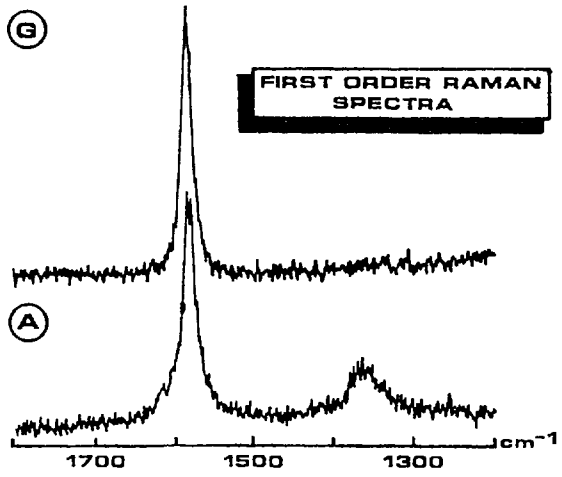

Figure 3 : First order Raman spectra of samples A and G.

It has been previously demonstrated that with increasing cristallinity of graphite, the position of the 1575 cm^{-1} peak tends to shift toward lower wave numbers while the half height width tends to decrease [13]. An inverse trend is observed there with a broadening of the 1575 cm^{-1} peak and the shifting towards higher wave numbers when approaching the unconformity (Fig. 4). This strongly suggests a partial disorganization of graphite.

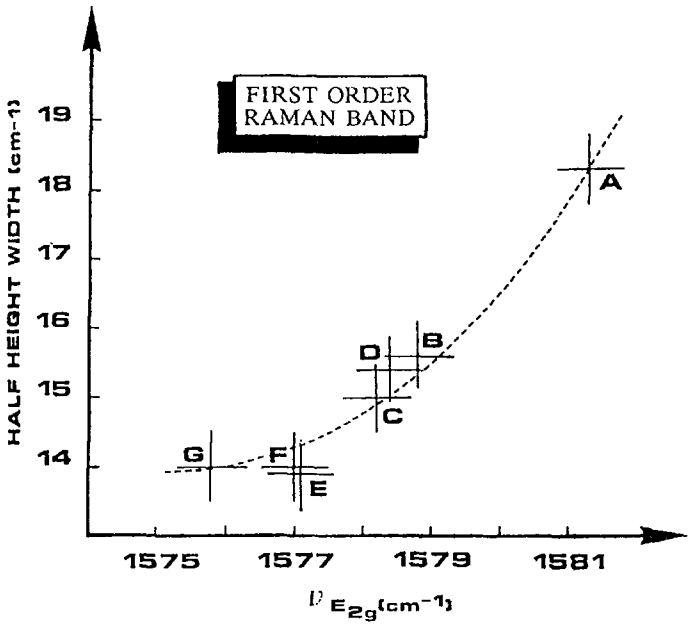

Figure 4 : Plot of half height width versus wavenumber (νE_{2g}) of the 1575 cm^{-1} Raman band. Disorder increases from sample G to sample A.

Second order Raman spectra have also been obtained. Contrary to first order spectra, perfect graphite is characterized by two bands respectively located at about 2730 cm^{-1} and 2690 cm^{-1} as it is observed in the deeper sample. In an intermediate sample C, the two bands are closer and in the upper sample A, it is quite difficult to distinguish the two bands. This tendancy was proved by the results of computered decomposition of the two bands which shows that the difference in wave number between the two bands gradually decreases from sample G to sample A and that the intensity ratio (I_{2690}/I_{2730}) also regularly increases from G to A (Fig. 5).

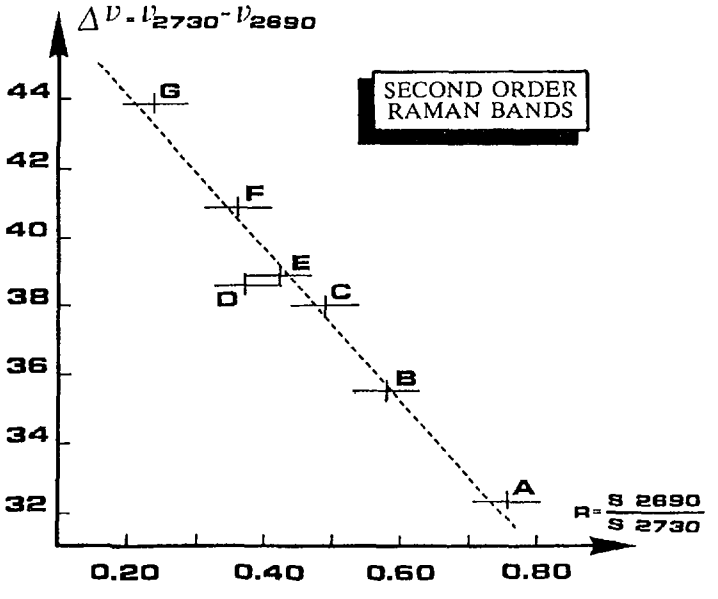

Figure 5 : Plot of the wavenumber difference ($\Delta\nu$) versus integrated intensity ratio (R) of the two second order Raman bands of graphite. Disorder increases from sample G to sample A.

High resolution transmission electron microscope photographs of lattice image indicate that sample G displays perfectly ordered aromatic layers which stack up regularly keeping its periodic structure in three dimensions. Disorder increase from sample G to B can be observed. The distances between the aromatic layers have been measured and calculated directly from these lattice images by using a calibrated micrometer. From sample G to B the average distance between two aromatic layers increases from 3.3 Å to 3.8 Å (Fig. 6). By contrast, the d_{100}, d_{110} and d_{200} which represent the distances between carbon atoms in the aromatic layer, measured from the electron diffraction pattern, do not show any significiant variations. This indicates that the disorder in the aromatic layer does not result from the changes of bond length and angle between bonds. The examination of the microphotographs (Fig. 7) shows that the extension of the

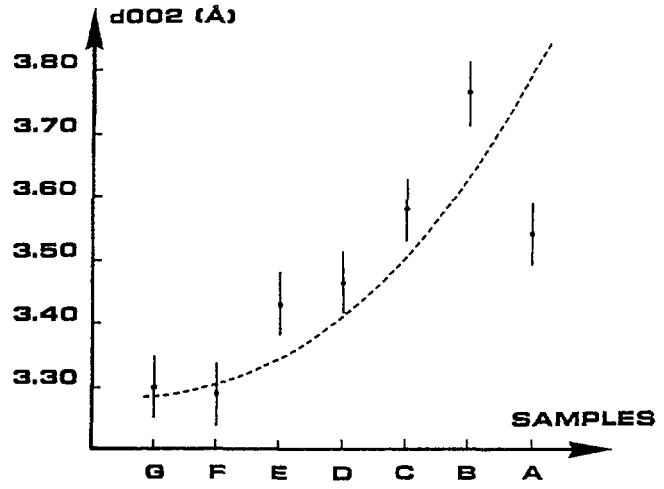

Figure 6 : d_{200} determined for each sample by electron diffractograms.

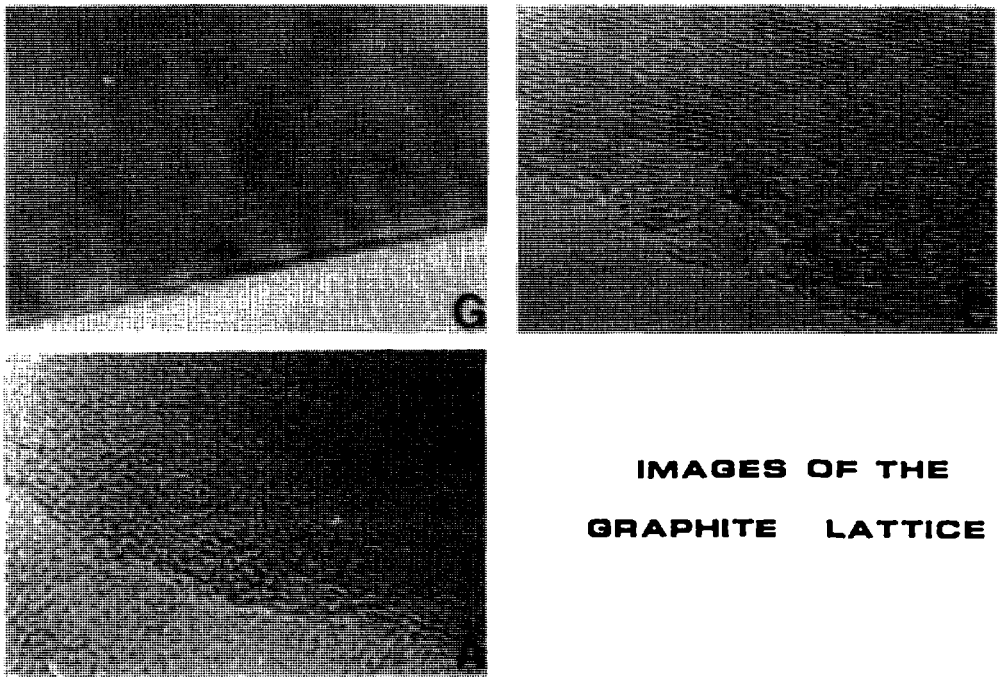

Figure 7 : T.E.M. lattice images showing the decrease in size of the aromatic layer and the correlative disordering along the c axis.

aromatic layer orientation strongly decreases from sample G, where they appear to be "infinite", to sample B or A where they can be reduced to a ten of angstroms. However sample A seams to exhibit a better order from TEM data. In conclusion TEM data show that the disorganization mainly occurs along the c axis whilst the aromatic layers seem to keep their hexagonal planar geometry.

Results from both Raman and T.E.M. techniques show that the disordering of graphite along this profile is mainly due to deffects in the third dimension. No proof of disordering inside the aromatic layers have been found and, as far as our results are concerned, no transformation inside the aromatic stacks has been demonstrated.

6 CHARACTERIZATION OF THE SURFACE DEFECTS

Some surface defects such as interference zones have been observed but will not be discussed here. Nevertheless it must be pointed out that their concentration increases with dicreasing distance to the unconformity. On another hand hollow points have been observed in sample A located near by the unconformity.

Their size range between several hundreds of angstroms to several micrometers. Small or large hollow points can coexist and somtimes connect each other to form a line or a group (Fig. 2).

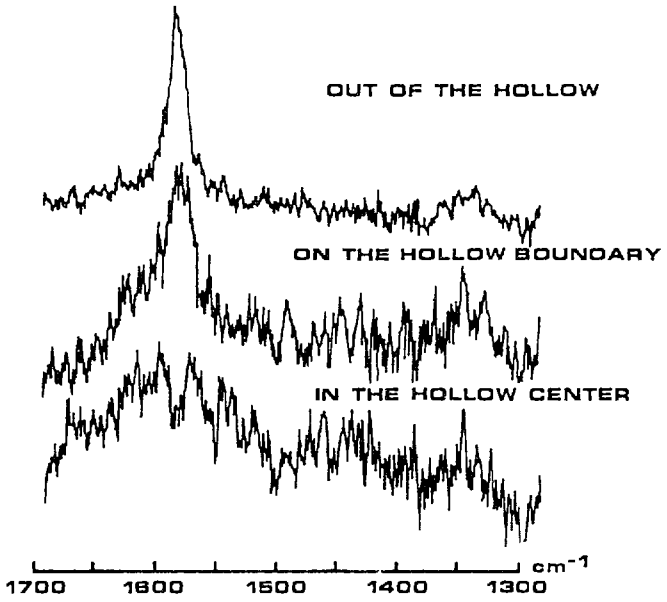

Figure 8 : First order Raman spectra of the hollow points.

The Raman spectra clearly show three types of carbonaceous material:

- a slightly distorted graphite outside the hollow (Fig. 8a)
- a more or less disorganized carbonaceous material at the boundary of the hollow with an enlarged 1575 cm^{-1} band and a more important defect band (Fig. 8b)

- vitrous or amorphous carbon in the center of the hollow dislaying only broad bands corresponding to poorly organized coals (Fig. 8c).

H.R.T.E.M. results indicate similar stucture evolution. Diffractograms show that in the center of the hollow a complete disorganization of the periodic structure can be observed whereas in the boundary zone, some organization is still preserved. This clearly contrasts with the slight loss of order limited to the third dimension which characterizes the host graphite matrix previously described. In the hollow points, aromatic layers structure are perturbed and an enlargement of the C-C distances have been measured on electron diffractograms.

Almost 2500 hollow points from 11 graphite leaves have been observed and described in terms of size and localization. Nevertheless the origin of these hollow points remains still poorly understood.

However an explanation is proposed which involves the damages due to radiation. This explanation is supported by the fact that hollow points are only observed in the sample located near by the mineralization (1 m from the lower boundary of an highly mineralized zone) and containing 500 ppm uranium. Furthermore, the shape, the morphology and the size distribution of the hollow points are comparable to damages experimentaly provoked by the fission reaction products of ^{238}U [14].

7 DISCUSSION

One of the goals of this study was to emphasize the possible relationships between the degradation of the metamorphic basement graphite and the genesis of carbonaceous material in the mineralized zones. As a matter of fact, carbonaceous material containing hydrogen and oxygen are observed within the ore zone in a lot of unconformity uranium deposits in Saskatchewan [6] [8] [15] [16]. In previous studies, it has been shown that those carbonaceous materials were obviously migrated products and that they could derive from very aliphatic hydrocarbons [8]. Traces of oxidation have been evidenced and can be related to the mineralizing process or to radiation damages [17].

The study of a graphitic basement profile has shown that the degradation associated with the hydrothermal alteration process can be responsible for inducing disturbancies in the third dimension periodic structure. No amorphization of the graphite has been observed in connection with the hydrothermal alteration. Amorphous carbon phases are only noticed in the uppermost sample and could derive from radiation damages.

Then, no obvious drastic alteration of the graphite has been demonstrated in this study and, on the basis of our results, it is still difficult to propose a genetic link between the graphite and the bitumens. Nevertheless, graphite only disappears in highly altered zones which have not been sampled in this study. Then, more work is needed espacially concerning

the upper samples where graphite can still be observed. Lastly, it must be pointed out that Raman spectrometry is a very sensitive technique for studying such alteration phenomena and that the analytical procedure developped for this study enables to optimize the efficiency of Raman spectrometry.

ACKNOWLEDGEMENTS

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ALTERATIONS IN THE CARSWELL STRUCTURE (SASKATCHEWAN, CANADA): PETROLOGY, MINERALOGY AND STABLE ISOTOPES GEOCHEMISTRY

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Abstract

As a prerequisite to geochemical study of trace elements in the Athabasca Province and to the modeling of the formation of the uranium deposits which are related to the Proterozoic unconformity, a petrological, mineralogical and isotopic characterization of the various alterations recognized in this area is needed. The following alterations have been distinguished :

(1) In the late hudsonian penetrative alteration, the paragenesis is : albite, adularia, pistachite, calcite, anatase, pyrite, aluminous 2M illite and Fe to FeMg chlorite. Locally, some dequartzification zones have been observed. The paragenesis is in accordance with conditions in the greenschist facies and temperatures between 310 and 230 °C have been derived from the Al(IV) content of chlorite according to Cathelineau and Nieva (1985).

(2) Under the Athabasca sandstones, the basement is characterized by an upper zone with 1T kaolinite, quartz, hematite, 1M Al-illite, diaspore, crandallite and a lower zone with 1M illite, sudoite and clinochlore. The temperature derived from chlorite, 220-20 °C and the hydrogen and oxygen isotopic compositions of the fluid in equilibrium with illite (δD = - 56 to - 48 ‰, $\delta O18$ = -1 to +2 ‰ SMOW) suggest that the lower zone has been reequilibrated by formation waters issuing from the Athabasca sandstones. The presence of 1T kaolinite at the base of the Athabasca sandstones is interpreted as due to the erosion of the weathered basement.

(3) During the Athabasca sandstone "diagenesis" quartz overgrowth, dickite, 2M illite, sudoite, hematite, anatase, crandallite and apatite were formed. Fluid inclusions give 220 °C for the maximum temperature event. For these temperatures, the calculated δD for the fluid in equilibrium with illite is : - 54 to - 33 ‰ and for $\delta O18$: - 2 to + 5 ‰ (SMOW).

(4) In the halo, there is formation of aluminomagnesian chlorite (sudoite) and ferromagnesian 3T illite associated with aluminous 1M illite. A magnesian alkali-deficient tourmaline is sometimes present. The fluid in equilibrium with the illite at 200 °C has a calculated stable isotopic composition (δD and $\delta O18$) similar to the formation waters in the Athabasca sandstones.

(5) In the mineralized zone, a magnesian chlorite becomes more predominant over the preceeding association. The δD obtained on these magnesian chlorites is low (-89 to - 182 ‰). There is a correlation between the lowering of δD and, on one hand, the U content in the sample and, on the other hand, the K/Ar "age". This relation is interpreted as due to recent reequilibration of hydrogen with cold meteoric waters.

From these data, the circulation pattern, the chemistry and the temperature of the alteration fluids at different epochs are reconstructed.

HYDROGEOCHEMISTRY AND URANIUM FIXATION IN THE CIGAR LAKE URANIUM DEPOSIT, NORTHERN SASKATCHEWAN

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Abstract

The 1.3 billion year old Cigar Lake uranium deposit, discovered by COGEMA in 1981, is a very rich and large mineralization of uraninite-pitchblende and coffinite in the Athabasca Sandstone in northern Saskatchewan. The mineralization occurs at the ~450 m deep unconformity contact of the sandstone with the underlying high-grade rocks of the basement. The sandstone, particularly its basal unit, is the regional aquifer and, due to permeability caused by extensive fracturing, groundwater is found in all parts of the deposit. The composition of this groundwater has been studied in detail over the past 3 years.

The compositions of the groundwaters from different parts of the deposit reveal a reduced, redox-buffered, steady-state system of water interaction with the ore and host rock. All groundwaters, including those in contact with the mineralization, are dilute, neutral pH waters containing low concentrations of dissolved uranium ($\sim 10^{-7.9}$ to 10^{-9} mol/L U). Concentrations of dissolved radium-226 and radon-222 are also low except in groundwaters sampled within the ore zone. The redox chemistry is controlled by a number of different processes, including inorganic and organic reactions, bacterial activity and radiolysis of water in the ore zone. The iron-redox couple is the main process controlling the redox conditions in the present dynamic system. The formation of iron colloids in the ore zone and the retention of these colloids in the bordering clay zone restrict the migration of naturally occuring radionuclides, such as uranium, thorium and radium, from the ore. Information from the redox, colloid and isotope chemistries is used to discuss the history of uranium fixation in this deposit.

LEAD AND URANIUM ISOTOPES IN GROUNDWATERS AROUND THE CIGAR LAKE URANIUM DEPOSIT (SASKATCHEWAN, CANADA): PRELIMINARY RESULTS

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Abstract

Fourteen piezometers around the Cigar Lake Uranium deposit (Northern Saskatchewan, Canada) have been sampled in July 1985 for lead and uranium isotope studies. The principal aim of this study was to test new methods of prospecting for concealed uranium ore deposits from groundwater analyses, that could be effective even in reducing conditions, which do not allow the appearance of U anomalies in groundwaters. The solubility of lead is not influenced by redox condition, but by the presence of complexing ligands (mainly carbonates and chlorides). The search for ^{206}Pb anomalies in groundwaters is thus a potential tool that is likely to be rather independent of oxido-reduction conditions. Total lead (dissolved + particulate phase-bound) has been analysed. Significant ^{206}Pb anomalies are found in waters that have been sampled in mineralized drill-holes. The most important anomaly is found in drill hole W-91, in which the extension of the mineralization is maximum. An interesting point is that in some cases where clear ^{206}Pb anomalies are found, (W-77, W-137), U concentrations are not anomalous. The efficiency of this method for the prospection of uranium in reducing conditions is thus proved. $^{234}U/^{238}U$ activity ratios are low (between 1 and 2) in groundwaters from mineralized drill-holes. This was not expected since $^{234}U/^{238}U$ activity ratios are generally high in reducing groundwaters especially around uranium mineralizations. Different explanations can account for these results : 1) the mineralization is very massive so ^{234}U access to the fluid phase after recoil or selective leaching is difficult, 2) the extremely reducing conditions encountered in this deposit cause very rapid re-precipitation or sorption of ^{234}U; 3) ageing is important relatively to other parameters, and causes a tendancy to reequilibration between ^{238}U and ^{234}U.

STRUCTURAL AND HYDROTHERMAL MODIFICATION OF THE GAERTNER URANIUM DEPOSIT, KEY LAKE, SASKATCHEWAN, CANADA

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Abstract

The Key Lake uranium deposits are located at the southeastern edge of the Athabasca Basin, approximately 240 km north of La Ronge, Saskatchewan. Key Lake Mining Corporation is at present the world's largest uranium producer with an annual rated production of approximately 12 million pounds of U_3O_8.

The Gaertner deposit consists of massive aggregates of uranium and nickel minerals immediately above the Early/Middle Proterozoic unconformity at its intersection with the Key Lake structural zone. Peripheral ore shoots extend along fractures into the wall rocks. The main ore minerals are uraninite and coffinite which are accompanied by Ni-arsenides, Ni-sulpharsenides and Ni-, Fe-, Pb-, Co- and Cu-sulphides.

Radially textured anisotropic uraninite in the Gaertner deposit represents the oldest mineralization phase dated at 1255±12 Ma. A series of tectonic events and accompanying hydrothermal mobilization and alteration resulted in modifications of the original monomineralic uranium orebody.

Based on ore microscopic examinations and field observations in the Gaertner open pit, the following modification stages are identified:

1. ~900 Ma: Fracturing of radially textured anisotropic uraninite, the oldest recognized uranium ore, subsequent introduction of Ni, As, S, Fe, Co and Cu. Radiometric dating of associated coffinite indicates an age of approximately 900 Ma.

2. ~300 Ma: Renewed fracturing of the nickeliferous uranium ore stockwork, hydrothermal carbonate and clay alteration with dispersion of mobilized elements into the wall rocks, and multiple redistribution/introduction of U under varying physico-chemical conditions. On the basis of isotropy and optical reflectivity, four uraninite/pitchblende generations are distinguished in addition to a second nickel mineral suite and a coffinite phase.

3. < 300 Ma: Vertical offset within the deposit under shallow conditions. Hydrothermal activity is not apparent.

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1. INTRODUCTION

The Key Lake uranium deposits are located approximately 240 km north of La Ronge, Saskatchewan (fig. 1) at the southeastern rim of the Athabasca Basin and the western edge of the Wollaston Fold Belt. The desposits consist of two orebodies, the Gaertner and the Deilmann (Fig. 2). The G a e r t n e r orebody was discovered in 1975 by Uranerz Exploration

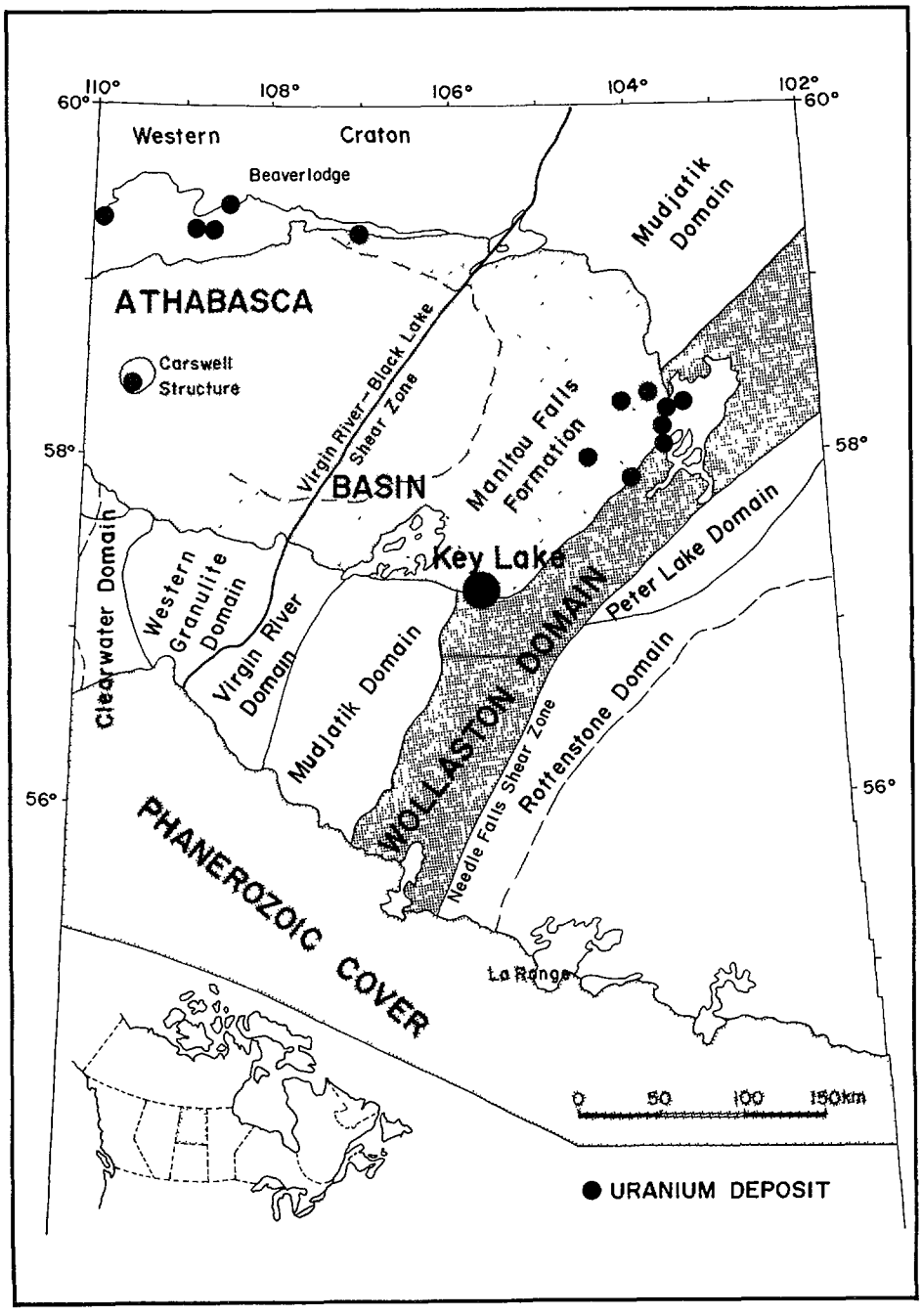

FIG. 1.

General geological map of Northern Saskatchewan. Modified after Lewry and Sibbald 1978.

and Mining Limited (U.E.M.), operator of a joint venture including Saskatchewan Mining Development Corporation (S.M.D.C.) and Inexco Oil Ltd after five years of intensive exploration effort that entailed radiometric prospecting, sampling of lake bottom sediments, surficial geology, geophysical surveys and diamond drilling. The D e i l m a n n orebody was discovered on strike of the Gaertner orebody in 1976.

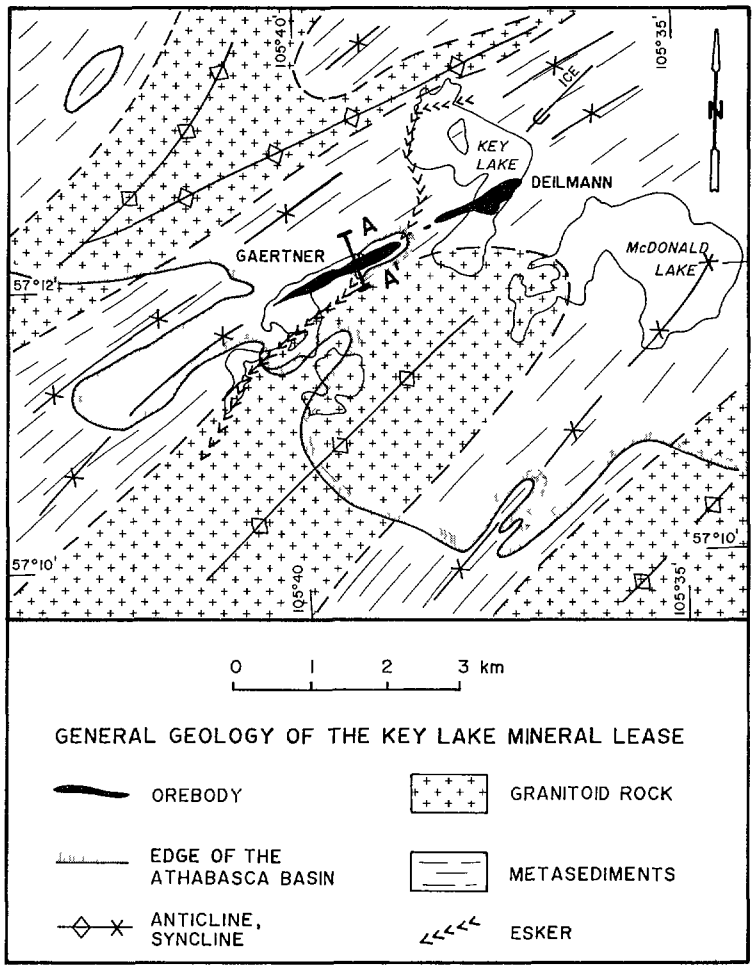

FIG. 2.

A detailed account of the exploration history is provided in several papers ([1], [2], [3]). Present owners are Saskatchewan Mining Development Corporation (50%), Uranerz Exploration and Mining Limited (33$^{1}/_{3}$%)and Eldor Resources Limited (16$^{2}/_{3}$%). Key Lake Mining Corporation, instituted in 1979 by the owner companies as the operator of the mining and milling project started production in 1983 and is at present the world's largest uranium producer with an annual rated production of 12 million pounds of U_3O_8.

2. HOST ROCKS OF THE GAERTNER DEPOSIT

The oldest units within the limits of the Gaertner open pit are Early Proterozoic grey-green migmatitic quartz-feldspar-biotite gneisses (Fig. 3). Coarse-grained anatectic stratiform layers of felsic material are frequent. Sillimanite-and cordierite-bearing graphite-rich gneisses are present in two units which may represent one isoclinally folded horizon. The "main graphite" is located adjacent to the ore zone. It is strongly sheared and contains up to 30% graphite in fist-sized samples. A series of migmatitic quartz-feldspar-biotite gneisses approximately 20 m

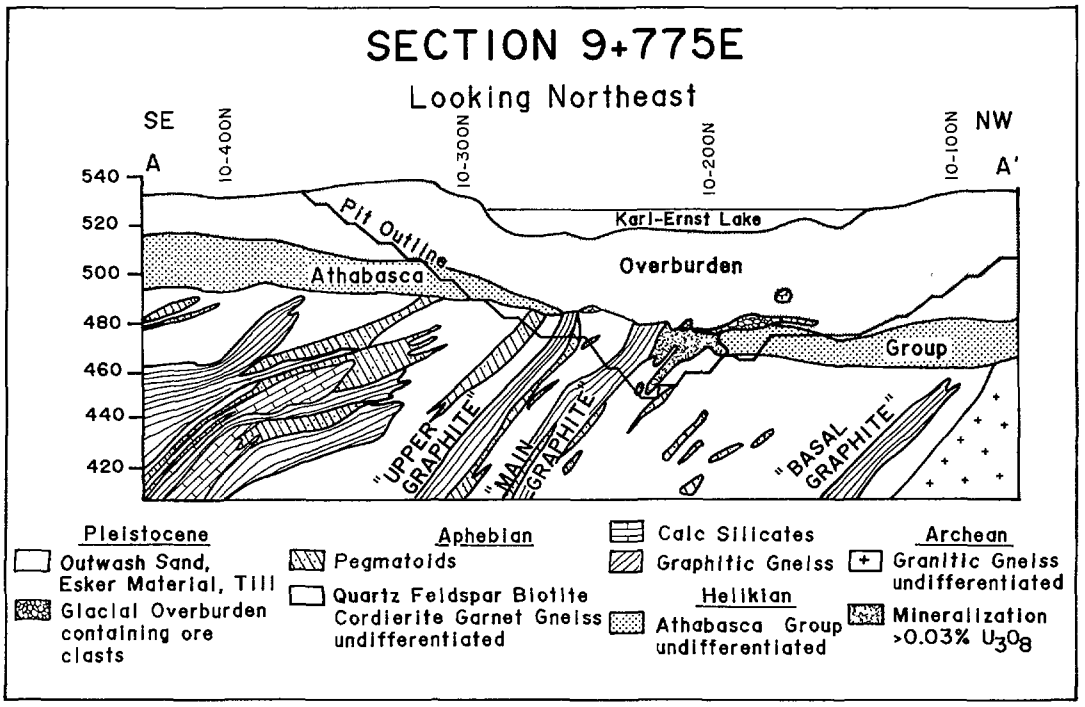

FIG. 3.

thick separates the "main graphite" from the "upper graphite" to the north. Less abundant rock types are amphibolites, calc-silicates and mylonites. The Aphebian gneisses (outside the pit also Archean granite gneisses) are unconformably overlain by unmetamorphosed subhorizontally bedded sedimentary rocks of the Middle Proterozoic Athabasca Group.

The bedrock has undergone a complex sequence of alteration consisting of paleoweathering of the basement rocks as well as hydrothermal processes that affected both basement and Athabasca Group rocks. The intensity of the hydrothermal alteration generally increases toward the orebody. Clay minerals and sericite in addition to sulphides, Fe-oxides and hydroxides, carbonates and tourmaline are the most prominent alteration products surrounding the orebody. Details are given in [4], [5], [6] and [7].

The structural development includes pre-Athabasca folding and faulting, post-Athabasca reverse strike-faulting ([8], [9]) that predates the mineralization and post-ore faulting along subvertical planes slightly oblique to the foliation. The east-northeasterly trending steeply north dipping Key Lake structural zone features a series of subparallel faults which splay and recombine along strike. The amount of vertical offset ranges up to 40 m. Cross faults with vertical displacement trend northwards, and are generally downthrown to the east. Moderate changes in the strike direction of faults have resulted in a lenticular pattern of the structural zone [6]. The Athabasca Group sedimentary rocks in the hanging wall of the structural zone are strati-

graphically equivalent to those in the footwall, and paleocurrent directions (which are oblique to the Key Lake structure) cross the fault zone without change. This suggests that, at the beginning of the Athabasca sedimentation, differences in topographic relief along the Key Lake structure were small [10].

The bulk of the mineralization is located above the intersection of the Early/Middle Proterozoic unconformity and a series of steeply dipping subparallel faults which trend slightly oblique to the basement foliation.

Glacial overburden is present with a thickness ranging up to several decametres. Fracture zones in the bedrock as well as strongly clay altered material have been preferentially eroded and filled. The overburden consists of lodgement till, esker material, glacial outwash sand and lacustrine sediments. A portion of the bedrock hosted ore has been glacially eroded and incorporated in the overburden.

3. ORE TYPES

Based on ore grades and mineralogy, two main types of bedrock-hosted ore are distinguished [11]: Massive ore aggregates/veins and disseminated impregnation of both Athabasca Group rocks and basement rocks (Fig.4).

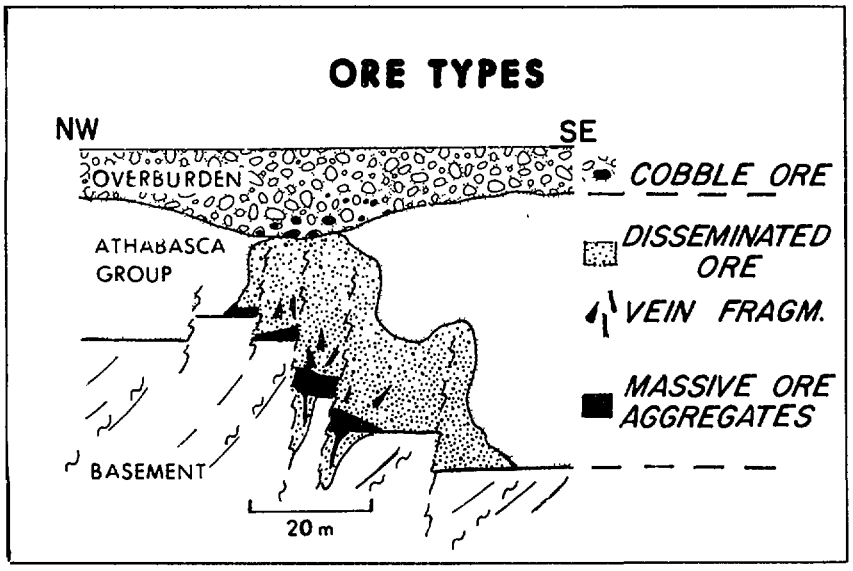

FIG. 4.

The bulk of the mineralization is hosted by Athabasca Group rocks as discontinuous massive aggregates of high-grade replacement ore immediately above the unconformity. The aggregates measure up to two metres in thickness and five metres in width. Ore shoots extend from this high grade core of the orebody as veins in both Athabasca Group rocks and to lesser extent

along gneiss hosted fractures in a vertical distance of up to 30 m. The veins have a thickness ranging from a few millimetres to 30 cm. In the basement, they are locally preserved over a length of several metres whereas in Athabasca Group rocks, generally only fragments are found. Grab samples collected in the open pit from either veins or replacement aggregates assay generally in the range from 10 to 50% U and from less than 1000 ppm to approximately 18% Ni.

The mineralogy of massive replacement ore and of the veins is characterized by the presence of radially textured anisotropic uraninite. Uraninite is also present as isolated or contiguous cubes or as a series of colloform phases that are distinguished by optical reflectivity. Coffinite is the only other uranium mineral. Nickel minerals in the massive ore shoots are massive and disseminated aggregates of gersdorffite, millerite, nickeline, and varying amounts of bravoite, maucherite, rammelsbergite and hauchecornite all of which are younger than the anisotropic uraninite. Millimetre thick blebs of hydrocarbon appear locally in the massive ore.

Locally, nickel-rich ore grading in excess of 40% Ni with uranium assaying less than 1000 ppm is found in basement fractures as well as in Athabasca Group hosted pods of approximately 3 m thickness and up to 5 m in diameter. Predominant Ni minerals are rammelsbergite ($NiAs_2$), nickeline (NiAs), gersdorffite (NiAsS) and millerite (NiS).

Disseminated ore is present in basement rocks adjacent to mineralized fractures, in sandstone relicts within locally strongly clay altered structures and in a dark grey sandstone that forms a halo around the vein and aggregate ore. The uranium content in grab samples ranges up to approximately 2% U. Ni values vary up to 18%.

The mineralogy of disseminated ore is characterized by the presence of coffinite/pitchblende that coats detrital quartz grains. Anisotropic uraninite grains are rare. Sulphides are represented in highly varying quantities by pyrite (FeS_2), marcasite (FeS_2), maucherite ($Ni_{11}As_8$), vaesite (NiS_2), bravoite ($[Fe,Ni,Co]S_2$), gersdorffite (NiAsS), millerite (NiS) and bismuthinite (Bi_2S_3). Carbonaceous matter is locally present as interstitial felty material. Chlorite, rutile, and carbonates that are partially pseudomorphosed by goethite and lepidocrocite are the main matrix minerals.

The mineralogical observations indicate that the disseminated ore differs from the veins and replacement ore by the virtual absence of anisotropic radially textured uraninite, greater variety of Ni-minerals and relative higher abundance of Fe-sulphides.

4. PARAGENETIC SEQUENCE

4.1 Procedure

The deciphering of a paragenetic sequence in a multimineralic deposit is complicated by the fact that generally no polished section of ore contains all minerals that are present in an orebody. The relative mineral sequence has to be assembled from a number of observations made on material taken from different locations within the orebody. Some of the observations may therefore reflect only local conditions which are not representative of the overall mineralization sequence.

A preliminary paragenetic sequence was established according to the following procedure:

4.1.1. Data collection

Ore and gangue minerals were listed according to their relative age relationships as observed under the microscope. Ambivalent relationships caused by sequences such as mineral A replaced by mineral B (A-->B) in one polished section and B-->A in another section (to be interpreted as either one of the possible mineral sequences A-->B-->A or B-->A-->B) were avoided by introducing second mineral phases (e.g. A'-->B-->A" or B'-->A-->B") with the objective to minimize the number of mineral phases. Subsequent processing of the relationships resulted in a network diagram showing the interrelationship between the various minerals by arrows pointing from older to younger minerals. In the future, additional observations on paragenetic relations may require a modification of the established sequence.

4.1.2 Data interpretation

The diagram was then rearranged without disturbing the established age relationships to accomodate absolute radiometric age dates of certain minerals as well as groups of gangue minerals. For instance, calcite, siderite, dolomite and undifferentiated carbonates were grouped into one mineralization phase without altering the paragenetic sequence.

4.2 Results

Microscopic observations indicate that highly reflective anisotropic uraninite found in massive aggregates and extending veins represents the oldest mineralization. Radiometric U/Pb age dating performed to date identifies it also as the oldest U-phase with an age in the range of 1255±12Ma [12]. This may represent the recrystallization age of an older phase.

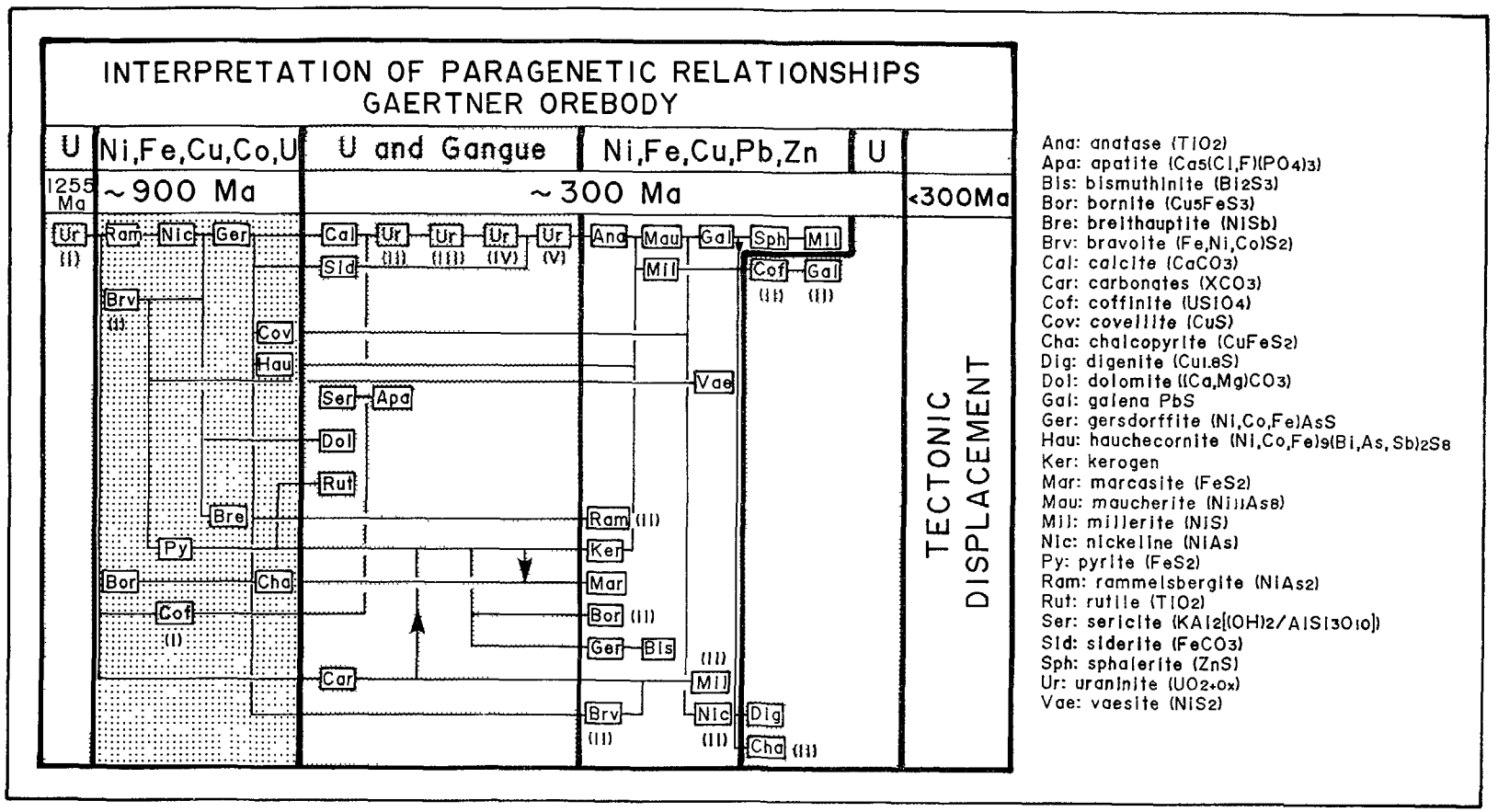
INTERPRETATION OF PARAGENETIC RELATIONSHIPS
GAERTNER OREBODY
U
Ni,Fe,Cu,Co,U
U and Gangue
Ni,Fe,Cu,Pb,Zn
U
1255 Ma
~900 Ma
~300 Ma
<300Ma
TECTONIC DISPLACEMENT
Ana: anatase (TiO2)
Apa: apatite (Ca5(Cl,F)(PO4)3)
Bis: bismuthinite (Bi2S3)
Bor: bornite (Cu5FeS3)
Bre: breithauptite (NiSb)
Brv: bravoite (Fe,Ni,Co)S2)
Cal: calcite (CaCO3)
Car: carbonates (XCO3)
Cof: coffinite (USiO4)
Cov: covellite (CuS)
Cha: chalcopyrite (CuFeS2)
Dig: digenite (Cu1.8S)
Dol: dolomite ((Ca,Mg)CO3)
Gal: galena PbS
Ger: gersdorffite (Ni,Co,Fe)AsS
Hau: hauchecornite (Ni,Co,Fe)9(Bi,As,Sb)2S8
Ker: kerogen
Mar: marcasite (FeS2)
Mau: maucherite (Ni11As8)
Mil: millerite (NiS)
Nic: nickeline (NiAs)
Py: pyrite (FeS2)
Ram: rammelsbergite (NiAs2)
Rut: rutile (TiO2)
Ser: sericite (KAl2[(OH)2/AlSi3O10])
Sid: siderite (FeCO3)
Sph: sphalerite (ZnS)
Ur: uraninite (UO2+ox)
Vae: vaesite (NiS2)

FIG. 5.

This original ore was modified in three stages as illustrated on a simplified network chart (Fig. 5):

i. Fracturing of uraninite and introduction of Ni-arsenides, Ni-sulpharsenides, Fe- and Cu-sulphides, precipitation of coffinite.

A series of Ni minerals are observed in fractures of anisotropic uraninite as well as in Ni-rich pods of replacement ore whereby a paragenetic sequence from Ni-arsenides to Ni-sulphides evolved [13]. This is illustrated in an example of a vug filling (Fig. 6). The mineralization process started out with a thick lining of rammelsbergite ($NiAs_2$) that was followed by nickeline (NiAs), gersdorffite (NiAsS), millerite (NiS) and carbonates. Radiometric age dating of coffinite which formed during the precipitation of the arsenide-sulphide suite suggest an U/Pb age of this event in the range of 903±40 Ma [14].

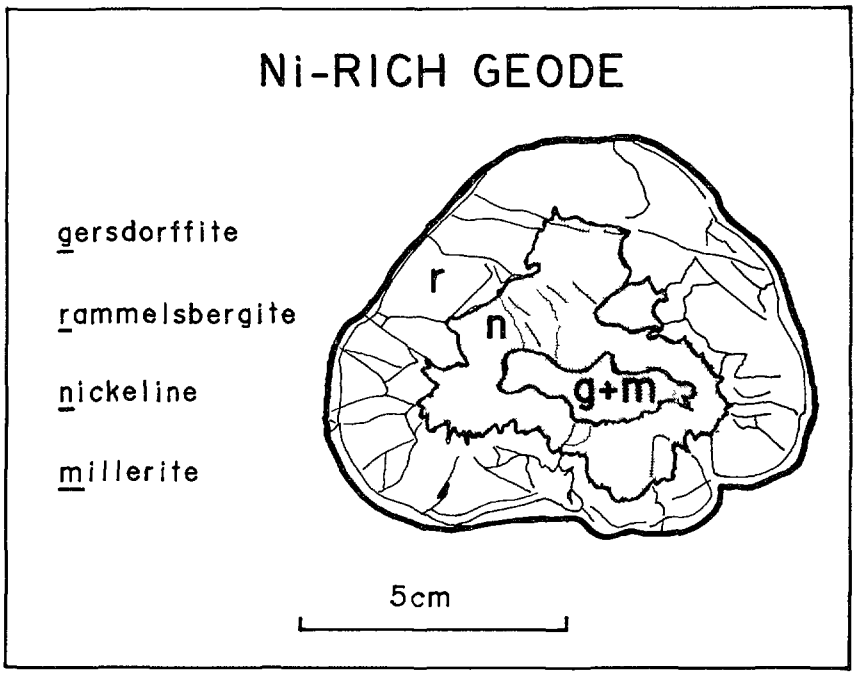

FIG. 6.

ii. Corrosion and redistribution of U, Ni, Fe, Cu, release of radiogenic lead and addition of Zn.

The first U-generation of this second mineralization phase consists of less reflective pitchblende at the rim and along fractures of radially textured highly reflecting uraninite (Fig. 7). The darker reflecting portions contain preferentially Ni-sulphides and galena which probably contains radiogenic lead. The formation of darker reflecting uranium oxide was followed by a multiple precipitation

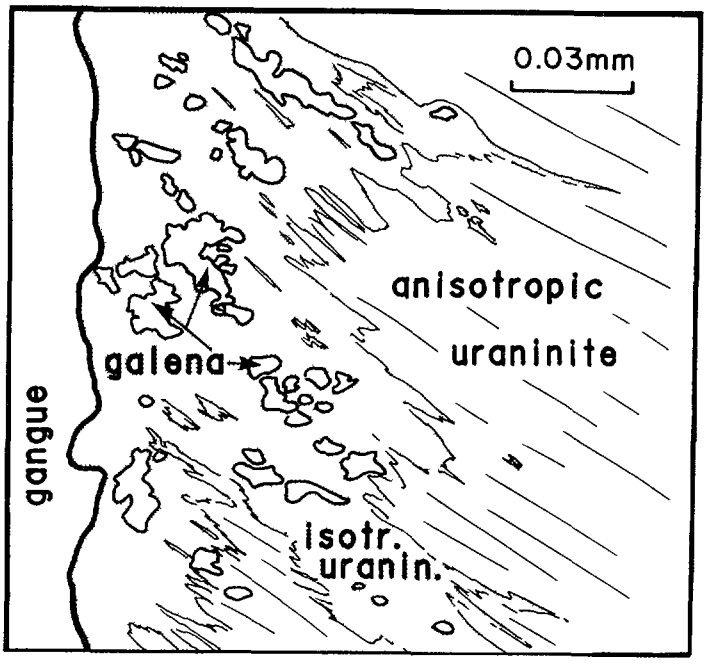

FIG. 7.

Anisotropic uraninite is replaced along radially oriented crystal boundaries by less reflective isotropic uraninite. Radiogenic? lead is concentrated in galena grains within the isotropic uraninite.

of pitchblende with varying optical reflectivity suggesting oscillating Eh/pH conditions (Fig. 8). Carbonates (i.e. dolomite, $[Ca,Mg]CO_3$, siderite, $FeCO_3$) and one phase of phyllosilicates seem to be associated mostly with this stage although an earlier precipitation of some of the carbonates, particularly calcite, can not be ruled out.

Ni-arsenides (maucherite, $Ni_{11}As_8$), Ni-sulpharsenides (e.g. gersdorffite II, [Ni,Co,Fe]AsS) and Ni,Fe,Cu-sulphides (millerite II, NiS, digenite, $Cu_{1.8}S$, chalcopyrite II, $CuFeS_2$) form after the redistribution of uranium. A second coffinite phase may be coeval with part of the Ni-sulphide precipitation of this stage.

The source of the constituents of the newly formed minerals is thought to be the high grade massive U-Ni-ore aggregates which were partially dissolved by hydrothermal solutions mobilized during the uplift of the Athabasca Basin around 300 Ma [4]. The ore was corroded by oxidizing solutions which caused the formation of clay minerals (Fig. 9), especially chlorite, smectite and mixed layer clays and subordinately kaolinite. At the same time, the illitic matrix of the surrounding barren Athabasca Group host rock and in structures also the detrital quartz grains were kaolinitized. Due to the lack of suitable anions, kaolinite formed as principal clay mineral in barren

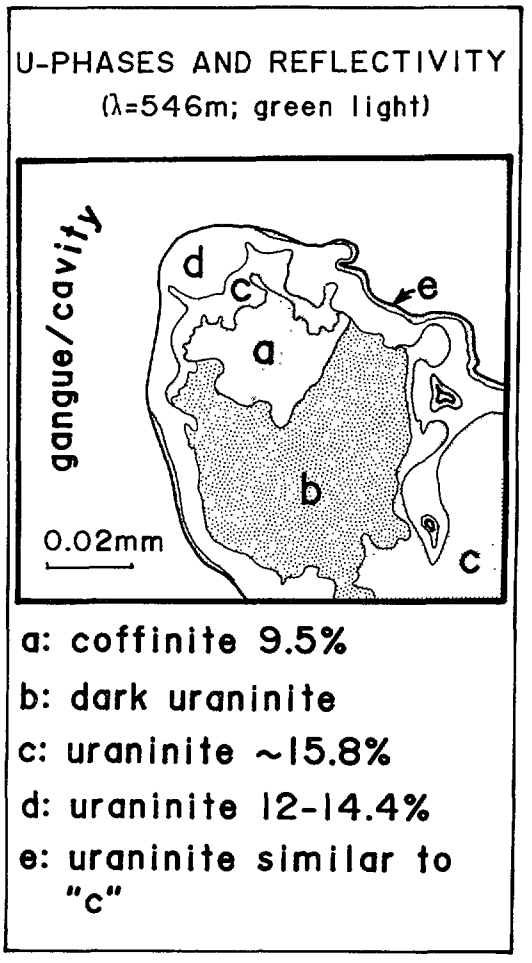

FIG. 8.

Coffinite (a) is coated by dark reflecting uraninite (b) which in turn, is enveloped by uraninite generations c,d and e. The uraninite phases are distinguished by their reflectivity in green light (λ = 546nm).

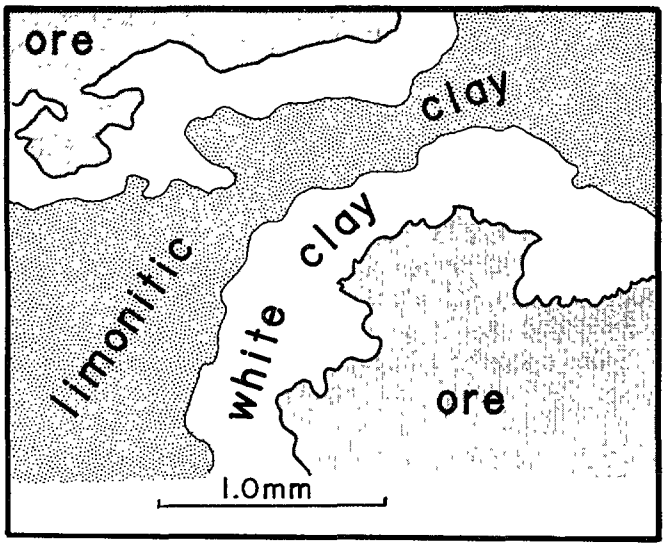

FIG. 9.

Embayments in ore indicate corrosion. Clay minerals, in part limonitic replace the ore.

wall rocks. Stable isotope data from kaolinite and Fe-Mg chlorites indicate a temperature of approximately 50°C [7].

Sphalerite appears as a new mineral which was not observed in the original mineral association. This suggests the influx of new material in addition to remobilized original elements.

iii. Structural adjustment

The Gaertner orebody is vertically displaced along a strike fault with a throw of up to 40 m. The fault movement affected the clay altered rocks of the Athabasca Group causing a foliated texture in kaolinitized Athabasca Group sandstone. No hydrothermal activity appears to be associated with this tectonic event.

5. CONCLUSION

The Gaertner uranium mineralization at Key Lake formed as a monomineralic deposit around 1255 Ma (Fig. 10, A) or possibly earlier. It is hosted mainly by tectonized Athabasca Group rocks above a sheared graphitic basement unit. The deposit was modified structurally and hydrothermally in three phases by:

i. Introduction of Ni, Fe, Co, Cu and formation of coffinite I at approximately 900 Ma (Fig. 10, B). The introduction of these elements may have been caused by either the extension of the structurally rejuvenated hydrothermal system into source rocks of different chemistry or a new pulse of hydrothermal solutions of different physico-chemical properties capable of mobilizing these non-uranium elements.

ii. Oxidation and corrosion of the U-Ni-Fe-Co-Cu mineral association, reprecipitation of pitchblende under variable physical and chemical conditions, and the formation of another generation of Ni and Cu minerals simultaneously with coffinite II. This redistribution phase occurred during the uplift of the Athabasca Basin around 300 Ma (Fig. 10, C). The appearance of Zn points to an influx of new material in addition to the remobilized elements during this phase;

iii. A post-ore, shallow vertical offset of the Gaertner deposit (Fig. 10, D), not associated with hydrothermal alteration.

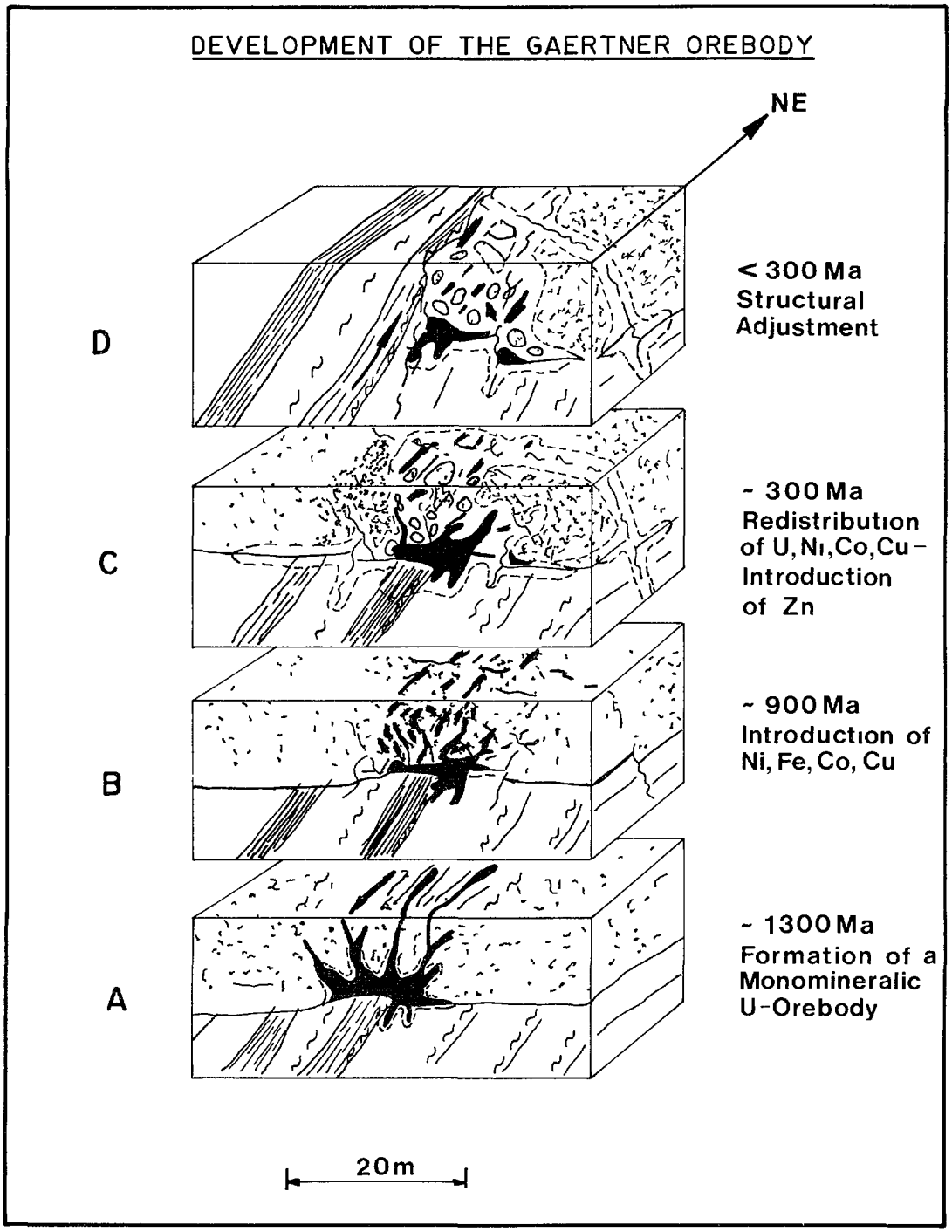

FIG 10

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ALTERATION PARAGENESES OF THE HELIKIAN SANDSTONE AND THE APHEBIAN BASEMENT OF THE KEY LAKE MINE AND OTHER URANIUM DEPOSITS IN THE EASTERN ATHABASCA BASIN (SASKATCHEWAN, CANADA)

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Abstract

The paragenetic evolution of the diagenetically and hydrothermally altered hostrocks of the Key Lake orebody and other uranium deposits of the eastern part of the Helikian Athabasca basin will be discussed. These include older unconformity-related and younger sandstone-hosted fracture-controlled mineralizations. The objective of the study is to construct a composite regional paragenetic scheme, incorporating all major alteration events observed in the deposit areas, that may provide a means for correlating and relative dating of the various uranium mineralizations recognized in the eastern Athabasca sandstone basin. Illustrations of microscopic relative age relationships and other diagnostic alteration features of the Helikian sandstone and the metamorphic Aphebian basement will be presented.

The sandstones of all deposit areas were affected by a common simple succession of early alteration events: silicification, kaolinitization, tourmalinization and finally illitization. This paragenetic sequence predates the deposition of the "unconformity-ore". The alterations postdating the "unconformity-ore" are more complex and differ between deposit areas as a result of localized younger tectonic activity and varying degrees of deformation. These younger alteration assemblages comprise several generations of clay minerals, quartz, chlorites, hematite, sulphides and tourmaline. They should not be confused with the early pre-"unconformity-ore" paragenesis, when interpreting mineralogical or geochemical halos around deposits. For instance, early kaolinite is associated with the "unconformity-ore" at Key Lake, whereas younger kaolinite is a dominant phase in sandstone-hosted mineralization elsewhere.

AGE DETERMINATION OF BASEMENT UNITS IN THE KEY LAKE URANIUM DEPOSIT AREA, SASKATCHEWAN, CANADA

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Abstract

The Key Lake area is situated in the Churchill Structural Province of the Canadian Shield. It lies along the western side of the Wollaston Domain within the transition zone to the more highly metamorphosed Mudjatik Domain.

The basement rocks in the Key Lake area consist of granite gneiss complexes which are unconformably overlain by Aphebian supracrustals. During the Hudsonian Orogeny both units were folded and metamorphosed forming NE striking elongated antiforms. The granite gneiss complexes are assumed to be of Archean age based on lithostratigraphic differences to the overlying Aphebian, but until now only a few radiometric age determinations confirmed this assumption because of the intense Hudsonian overprinting within the whole of the Wollaston Domain.

For the granitoid antiform 3 km NW of the Key Lake uranium deposit a Kenoran age of 2.60 ± 0.06 Ga has been obtained by Rb/Sr whole rock determination. The same samples yielded 2.7 ± 0.8 Ga by Sm/Nd whole rock determination. This age complements a similar zircon crystallization age (2600 ± 18 Ma) of the Zimmer Lake antiform SE of Key Lake (Krogh and Clark, 1987) and supports the only other Archean Rb/Sr age at the mineralized sites in the Wollaston Domain found at the Midwest uranium deposit (2613 ± 93 Ma: Worden et al., 1985). Biotites and hornblende from the same granitoid antiform (NW of Key Lake) document the Hudsonian event by concordant K/Ar dates of 1723 ±5 Ma for biotites and 1759 ± 10 Ma for hornblendes.

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1. INTRODUCTION

Remarkable progress in the geochronology of the western Churchill (structural) Province has been achieved by various programs, especially during the last few years. Although not exclusively, the attention has been focused on dating the Trans-Hudson Orogen (and its related gold potential), and on a detailed revision of the Beaverlodge district

(formerly producing uranium from albitite type of deposits), both areas extending beyond the principal uranium accumulations of the unconformity type.

The unconformity type has also been broadly assessed by dating directly the uranium mineralization which has yielded exclusively post-Athabascan ages. On the other hand, the search for such deposits is principally guided by basement structures, the definition of which still remains a complex task.

The Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Federal Republic of Germany) in cooperation with Uranerzbergbau GmbH (UEB, Bonn, FRG) and Uranerz Exploration and Mining Limited (UEM, Saskatoon, Canada) has initiated and sponsored an age-dating program which contributes to the assessment of the unconformity type of uranium deposits of the Athabasca Basin.

Part of the program focuses on the basement lithologies, and this report contributes on the dating of the Archean basement in the immediate vicinity of the Key Lake deposit, which is currently the largest producer of uranium in the Western World.

2. GENERAL STRUCTURAL SETTING OF THE REGION

The Athabasca Basin uranium province includes the unmetamorphosed, and subhorizontally resting early paleo-Helikian Athabasca Basin and the immediate lateral extension of the subjacent folded and metamorphosed Archean and early Proterozoic basement.

The Basin rests in the center of the western Churchill Province which is, in turn, bordered by Archean cratonized Slave and Superior provinces, and became consolidated during the early Proterozoic.

Three principal blocks form this part of the Churchill Province. In a sequence from NW to SE (Figure 1, part A) these are: 1) The Western Craton (or approximate equivalents in this and other distal regions: Amer Lake Zone, or Rae Block, or Keewatin) consolidated during the early Aphebian by the Blezardian Orogeny as defined by Stockwell [1]; 2) The Cree Lake Zone, overprinted by the late Hudsonian Orogeny; 3) The Reindeer Lake Zone, generated within the late middle and late Aphebian ensimatic regime, possibly related to a subduction. Only few specific blocks within this zone include proven Archean basement, while all terrain NW of this zone, i.e. including those subjacent to the Athabasca Basin, are ensialic with a widespread Archean basement. Major structural breaks separating the above mentioned zones are (Figure 1, part A): Great Slave Tectonic Zone - GSTZ, Virgin River Shear Zone - VRSZ, Needle Falls Shear Zone - NFSZ, and Nelson Front - NF.

In the Reindeer Lake Zone, the early Proterozoic metavolcanics (+ metasediments?) have recently been defined as essentially late middle Aphebian (Van Schmus et al. [2]). The depositional age of early Proterozoic (predominantly metasedimentary) supracrustals in the two other (ensialic) zones, though possibly confined between various pulses of the intrusives, remains poorly defined.

3. REVIEW OF GEOCHRONOLOGICAL DATA OF THE REGION

3.1 Earliest Data

Some thirty years ago age determinations were available for few pegmatites located in the center of the Wollaston Domain (Cumming et al. [3]). A few years later, possibly the first attempt to date the metasediments in the domain produced a K-Ar age of 1670 +- 60 Ma on biotites from a sillimanite paragneiss (Lowdon et al. [4]). Undoubtly, in this early period of geological knowledge within the region, this reference has been seen of such significance that it has, for example, encouraged Chadwick [5] to declare the

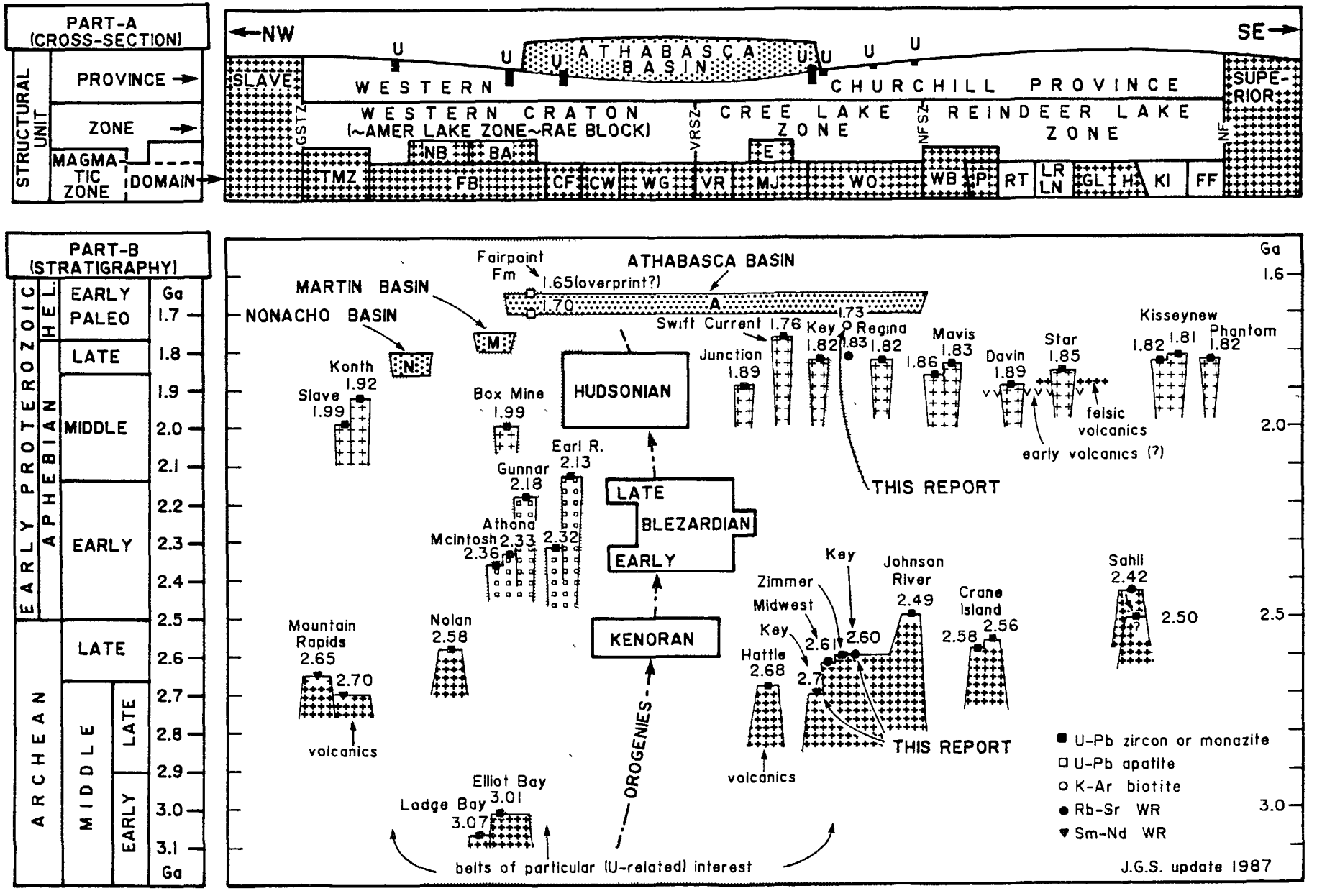
PART-A
(CROSS-SECTION)
STRUCTURAL UNIT
PROVINCE
ZONE
MAGMATIC ZONE
DOMAIN
NW
SE
SLAVE
WESTERN
ATHABASCA BASIN
CHURCHILL PROVINCE
SUPERIOR
GSTZ
WESTERN CRATON
(~AMER LAKE ZONE~RAE BLOCK)
VRSZ
CREE LAKE ZONE
NFSZ
REINDEER LAKE ZONE
NF
TMZ
NB
BA
FB
CF
CW
WG
VR
E
MJ
WO
WB
P
RT
LR
LN
GL
H
KI
FF
PART-B
(STRATIGRAPHY)
EARLY PROTEROZOIC
HELIKIAN
APHEBIAN
ARCHEAN
EARLY PALEO
LATE
MIDDLE
EARLY
LATE
MIDDLE
LATE
EARLY
Ga
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
3.1
Ga
Fairpoint Fm
1.65(overprint?)
ATHABASCA BASIN
MARTIN BASIN
NONACHO BASIN
1.70
1.73
Swift Current 1.76
Key 1.82
Regina 1.83
1.82
Mavis 1.83
1.86
Junction 1.89
Davin 1.89
Star 1.85
felsic volcanics
early volcanics (?)
Kisseynew
1.82
1.81
Phantom 1.82
Konth 1.92
Slave 1.99
Box Mine 1.99
HUDSONIAN
Earl R. 2.13
Gunnar 2.18
Athona 2.33
McIntosh 2.36
2.32
LATE
BLEZARDIAN
EARLY
THIS REPORT
Key
Zimmer
Midwest
Key
2.61
2.60
Johnson River 2.49
Crane Island 2.58
2.56
Sahli 2.42
2.50
Hattle 2.68
2.7
Mountain Rapids 2.65
2.70
volcanics
Nolan 2.58
KENORAN
OROGENIES
Elliot Bay
Lodge Bay 3.01
3.07
belts of particular (U-related) interest
THIS REPORT
volcanics
U-Pb zircon or monazite
U-Pb apatite
K-Ar biotite
Rb-Sr WR
Sm-Nd WR
J.G.S. update 1987

FIGURE 1.

Update of geochronological data in greater Athabasca Basin region. Part-A (cross-section): U-principal locations of uranium deposits; main structural breaks: GSTZ-Great Slave Tectonic Zone, VRSZ-Virgin River Shear Zone, NFSZ-Needle Falls Shear Zone, NF-Nelson Front; magmatic zones: TMZ-Taltson Magmatic Zone, WB-Wathaman Batholith; structural domains located north of the Athabasca Basin: NB-Nonacho Basin, BA-Beaverlodge area, E-Ennadai Group, structural domains distinguished mostly south of the Athabasca Basin: FB-Firebag Domain including CF-Cluff Lake area (or Carswell Structure) as an isolated basement uplift within the Athabasca Basin, CW-Clearwater Domain, WG-Western Granulite Domain, VR-Virgin River Domain, MJ-Mudjatik Domain, WO-Wollaston Domain, P-Peter Lake Domain, RT-Rottenstone Domain, LR, LN - La Ronge, Lynn Lake Domain, GL-Glennie Domain, H-Hanson Block, K-Kisseynew Belt, FF-Flin Flon Belt. RT, LR, LN, KI, FF are mostly ensimatic domains, other domains are ensialic. Part-B (stratigraphy) shows critical age dated sites and their stratigraphic position. A - Athabasca Basin, M-Martin Basin, N-Nonacho Basin. The names for dated sites are abbreviated; full names are mentioned in the text.

crystalline rocks around the Wollaston Lake as "almost certainly of Precambrian age".

3.2 Present Data

Numerous geochronological data have been added during the last few years by several regionally and/or locally oriented programs. Most of the progress has been achieved by the U-Pb systematics on zircon, monazite, and apatite, representing mostly emplacement ages for granitoids and felsic volcanics. Several Rb-Sr, K-Ar and Sm-Nd data support the interpretation of these and other events.

The following review maintains the stratigraphic sequence of events and within these, the data depict the situation in three principal structural zones. Figure 1 provides in a cross-sectional representation an orientation among the available determinations within the sequence of structural zones and subordinate domains which traverses the entire western Churchill Province from NW to SE.

3.2.1 Archean and Kenoran Events

Both volcanic and plutonic events were indentified by zircon ages. A few data based on Sm-Nd, Rb-Sr, and K-Ar helped to outline crustal residence, metamorphism and cooling ages respectively.

In the Western Craton the oldest ages of 3.07 and 3.01 Ga were received on zircons of the sub-Murmac Bay Group basement at Lodge Bay and Elliot Bay (Beaverlodge area) respectively (Van Schmus et al. [6]). In contrast to these early middle Archean granitoids, the megacrystic granite from Nolan Lake yielded a common late Archean (Kenoran) age of 2.58 Ga. In the Taltson Magmatic Zone (beyond the Western Craton) Burwash et al. [7] found (by Sm-Nd) the Mountain Rapids granodiorite to be a 2.65 Ga old intrusive into approx. 2.70 Ga old metavolcanics.

In the Cree Lake Zone the oldest Archean zircon age (3.03 Ga) has been received recently (personal communication, G.L. Cumming, 1987) on a granodioritic rock from the broader vicinity of Charlebois Lake, an area known for its uraniferous pegmatites. Chiaranzelli and MacDonald [8] dated 2.68 Ga - old rhyolites of the Ennadai Group located at Hattle Lake in the far NW extension of the zone. At the Midwest uranium deposit (150 km NE of Key Lake) the "western granitic gneisses" yielded (Worden et al. [9] an age of 2.61 Ga. A similar age (2.60 Ga) has been attributed to the Zimmer Lake granite gneiss inlier from a site 4.5 km south of the Key Lake uranium deposit (Krogh and Clark [10]). A substantially younger age of 2.49 Ga was yielded by the Johnson River granite at Bailey Lake located at the SE-margin of the zone (Ray and Wanless [11]). Gneissic granites collected from a sizeable area (66 x 15 km) at the Geikie River (60 km E of Key Lake) have produced (Baer [12]) a similarly "younger" age of 2.51 Ga (±70 Ma) and an extremely low initial Sr-intercept of 0.6977 by Rb/Sr.

The recent revision of the few suspected Archean terranes within the generally ensimatic and substantially younger Reindeer Lake Zone yielded Archean rocks within two blocks. In the Peter Lake Domain, the Crane Island locality resulted 2.58 and 2.56 Ga old ages for the grey and pink varieties respectively (Bickford et al. [13]). The Sahli granite in the Hanson Block, provided a Rb-Sr age of 2.42 Ga (Bell and MacDonald [14]), for which a crystallization age of 2.5 Ga has been recently suggested [2].

3.2.2 Blezardian Events

According to Stockwell [1] the early Aphebian extends from the close of the Kenoran Orogeny to the close of the Blezardian Orogeny at approx. 2.14 Ga on a Rb-Sr scale. Although the type region of this orogeny is the distant Southern Province, it seems that certain segments of the western Churchill Province, especially the NW half (Western Craton, at least) was cratonized by this particular early

Proterozoic event, which here "substitutes" for the younger (Hudsonian) consolidation otherwise almost omnipresent and typifying other parts of the province.

Two particular domains of the Western Craton yielded Blezardian granitoids. In the Beaverlodge area the early Blezardian phase is typified by the 2.36 and 2.33 Ga old McIntosh and Anthona Mine granites and the younger phase by 2.18 Ga Gunnar granite [6]. To a younger offshoot of late Blezardian events probably belongs the metasomatic and auriferous Box Mine granite dated as 1.99 Ga [6]. In the Cluff Lake area (Carswell Structure) Bell's [15] samples from the "quartzfeldspathic" Earl River complex have produced both the early Blezardian (2.32 Ga) and the late Blezardian phases (2.13 Ga).

3.2.3 Hudsonian Events

Volcanic and plutonic activities dominating this particular period are listed here by their zircon-based chronology.

The Western Craton (WC), in contrast to the other more easterly units, seems to be specific in its general lack of Hudsonian plutonism. The only major exclusion is the Taltson Magmatic Zone (TMZ) which extends beyond the WC along the western extremities of the Churchill Province. Here (in the TMZ), plutonism spread mainly from 1.99 Ga (Slave monzogranite) to 1.92 Ga (Konth syenogranite), with some minor younger (undated) granitoids (Bostock, [16]).

In the Cree Lake Zone, the oldest dated Hudsonian pluton is also the most westerly located (at the NW periphery of the zone) Junction granite, 1.89 Ga old. Importantly, it postdates the early mylonites of the Virgin River Shear Zone. The youngest plutons were identified both in the sub-Phanerozoic extension of the Cree Lake Zone as the 1.76 Ga biotite granite in the Swift Current oil well (Bickford et al., [13]) and the sub-Athabascan 1.82 Ga

granodiorite in the Key Lay area. A similar age (1.83 Ga) has been obtained by Rb/Sr from Aphebian gneiss below the Key Lake orebodies [33].

In the Reindeer Zone (RZ), the Carrol Lake gneiss from the assumed Archean provided the oldest Hudsonian age of 1.89 Ga, which is considered by Van Schmus et al. [2] as a basement for the Glennie Domain supracrustals. Within the RZ the zircon ages of the felsic volcanics and the tonalitic gneiss of the Davin Lake Complex (Rottenstone Domain), as well as the metarhyolites from the McLennan Lake and Palf Lake (La Ronge and Glennie domains respectively) yielded nearly the same age of 1.88 Ga. Postvolcanic plutons are 1.865 to 1.850 Ga old (Van Schmus et al., [2]), including the gold-hosting Star Lake pluton of 1.85 Ga. Among the youngest intrusives is the 1.84 Ga old post-Eyahpaise pluton granodiorite in the Glennie Domain which is contemporaneous with the earliest dated undeformed granitic sheet of the Wathaman Batholith at Mavis Lake (Bickford et al., [13]). With the emplacement of enderbite sills (Kisseynew belt) at 1.83 Ga, the gold-tungsten hosting Phantom Lake pluton of 1.82 (Flin Flon - Snow Lake belt) (Galley and Franklin [17]), and with the anatectic granitoids at 1.82 and 1.81 Ga in the Kisseynew belt (Gordon et al., [18]), the Hudsonian plutonism culminates. However, the youngest intrusion (in the Reindeer Zone) has been recently dated from the Jan Lake granite [36]. Its age of 1.77 Ga is now comparable with the Swift Current granite (Cree Lake Zone), 1.76 Ga old.

3.2.4 Platform Sediments

Among the major advances in dating late Aphebian basins is the Van Breemen et. al. [25] dating of the Konth granite (1.922 Ga) and the observation (Bostock, [16]) that its younger phases provided material for the Nonacho Basin basal conglomerates.

Probably the most important new observation related to the metallogeny of the unconformity type of uranium deposits

is the 1.7 Ga (U-Pb on apatite) depositional age of the Athabasca Basin reported recently by Cumming et al. [19].

4. LOCAL GEOLOGY

4.1 Stratigraphy

The local pre-Athabascan (+1.70 Ga) stratigraphy encompasses the Archean basement and early Proterozoic supracrustals, both of which are folded and metamorphosed. The Archean (in fairly well known outcropping and drilled areas) consists of strongly foliated Kenoran (2.6 Ga) granite gneiss. The prevailing unit is commonly pink or reddish and may include a white facies at some portions of the Archean endo-contact. Also Kenoran, and only apparently (?) younger unit, is beige, expressively fine-grained, felsic and locally is richer in uranium. Above the Archean-Proterozoic transition, other pink lithologies are locally developed and these may include either the products of Hudsonian granitization (as proposed by J.G.S. in this paper) or (as assumed by some geologists) the earliest Proterozoic meta-arkose.

Although commonly not thick (-100 m?), the major part of the basal Proterozoic consists however, of grey plagioclasic metamorphics with minor amphibolitic intercalations, locally with some graphite found in few intersections. The peri-basal Proterozoic is represented by a critical lithology, the graphite-rich metapelites, having also a mafic affinity (Strnad, [20]). The upper sequence is predominantly meta-arkosic, in places with thicker quartzitic facies and minor meta-calcareous layers. Localized post-Hudsonian sodic and U-rich white granodiorite phase (1.82 Ga) and distinct and sizeable sodic (and potassic) metasomatites (Strnad, [21] [22]) are among the youngest of the early Proterozoic lithologies.

4.2 Structures

During the Hudsonian orogeny, the folding (+1.85 Ga) of the Proterozoic supracrustals, produced relatively narrow synformal belts wrapping the Archean cores of an elongated or rhomboid geometry. The synforms are commonly asymmetric, moderately dipping at the boundary closer to the upright Archean core and with steep to recumbent attitudes on the opposite limbs. Mechanical anisotropy of the soft graphitic lithology sandwiched between the rigid footwall (Archean + plagioclasic basal Proterozoic unit) and the hanging-wall of the upper meta-arkose controlled the location of mylonites and younger shears. The principal brittle tectonics (and perhaps mylonites as well) are thrusts or reverse faults. Most of the shears occur in an imbricate array, and while cutting at a low angle to the dip of strata, generally follow the strike of belts. Synforms oriented at larger angles to the main stress at the time of the brittle tectonics host thrusts of a transpressional type. Both the up-dip and horizontal components lead frequently to both the multiplication of strata, especially of tightly folded graphitic lithologies, and to other complexities (disappearance of strata etc.).

5. LOCATION AND GENERAL CHARACTERISTICS OF THE SAMPLED MATERIAL

Within the present program several areas of the Western Craton and the Cree Lake Zone basement were sampled mostly in domains of the past or active uranium exploration at the margins of the Athabasca Basin.

Principal attention has been focused on the area surrounding the Key Lake uranium deposit.

5.1 Key Lake Area Sampling Sites

Aside from the importance that the area is centered by a major uranium deposit, in comparison to other areas, this terrane offers a unique abundancy of assumed Archean

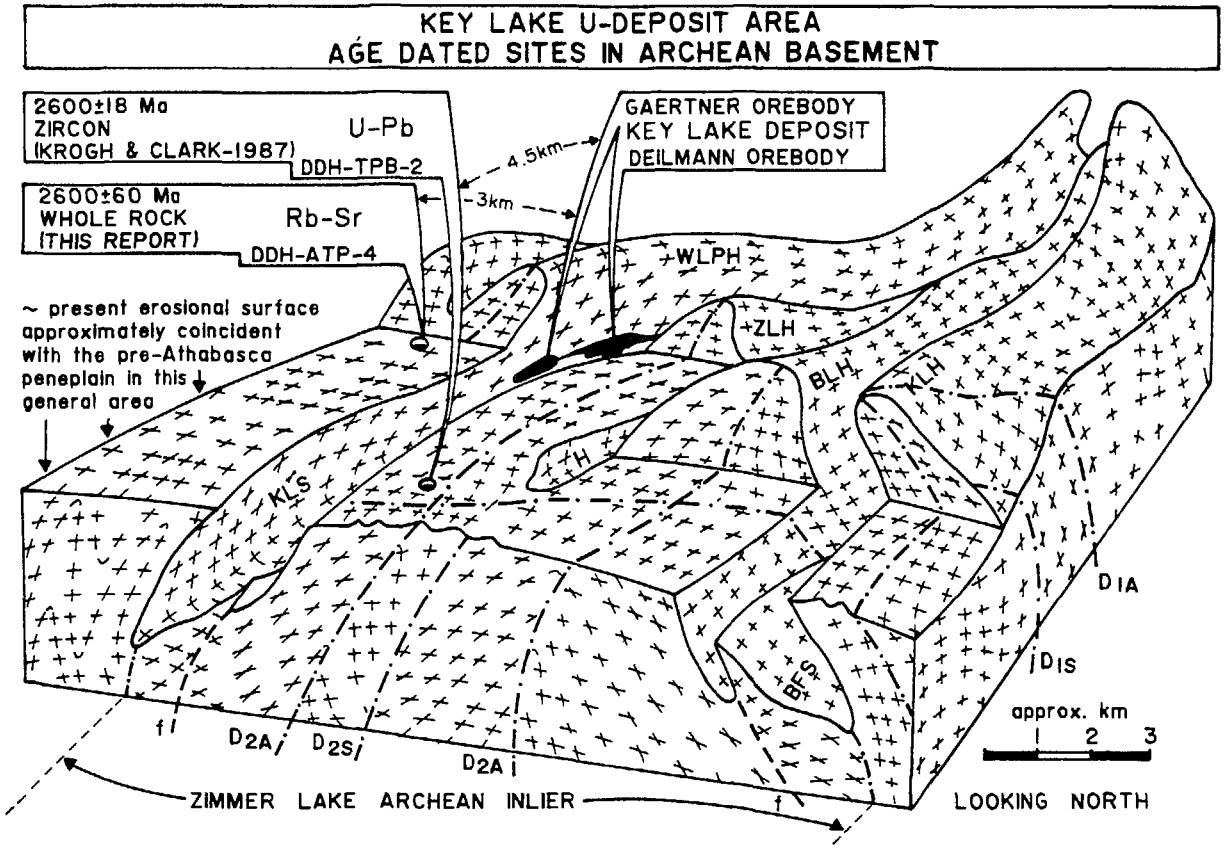

FIGURE 2

Key Lake U-deposit area, age-dated sites in Archean basement. The reader looks towards the north diagonally across the principal NE-oriented structures. The situation is schematic and not to scale, the approximate scale shown is valid only for the area between the dated locations and the deposit.

For simplification, Archean compositional and structural inhomogeneity formed prior to the Hudsonian overprint is not shown. The block diagram, therefore, depicts the Archean basement achieved by the Hudsonian folding of two stages: early, grossly EW-oriented: D-1A-early antiforms, D-IS-early synforms: late, grossly NE-oriented: D-2A-late antiforms, D-2S-late synforms and by Hudsonian fault tectonics: f-early mylonites and/or late shears, both mostly thrusts, some with a larger strike-slip component. Aphebian and Athabscan covers are removed in order to show the Archean basement. In the southern part (closer to viewer) the subhorizontal surface shows approximately the present erosional surface which is grossly coincident (in this general area only) with the pre-Athabascan peneplain. All apexes of antiforms above this subhorizontal plain (shown in the northern part of the diagram) were eroded prior to the deposition of the Athabasca. Among these antiforms are: WLPH - Wilson Lake periphery high, ZLH - Zimmer Lake high, BLH-Boundary Lake high and KLH-Kapesin Lake high. Three synforms (filled with Aphebian metamorphics) are: KLS-Key Lake synform (which at its SE-limb hosts the Key Lake deposit), H-Hourglass Lake synform and BFS - Black Forest synform. The principal (central) Archean structure, the Zimmer Lake Archean Inlier comprises of ZLH, H, and BLH between KLS and BFS. Granitoid materials from two shallow drillings (DDH-ATP-4 and DDH-TPB-2) were used for the present and earlier age-dating respectively.

lithologies. In addition to outcrops, more than one hundred drill-holes have penetrated into Archean basement and from among these, a few tens of sites have provided suitably unaltered material. Perhaps also unique is the availability of rocks from the inner portions of the Archean antiforms, although those from the contact with Proterozoic prevail. Most of the available (drilled) sites yielding pink granite gneiss from assumed Archean basement are located at the fringes of magnetic highs which mostly (but not exclusively) indicate Archean antiforms.

This report is concerned with one restricted location in the Key Lake area.

5.2 Structural Location

Figure 2 depicts the main structural pattern in the southern half of the sampled Key Lake area and shows the dated location(s) in relationship to the Key Lake uranium deposit.

The location of samples for dating is shown as DDH-ATP-4, and represents a shallow drilling located 3 km NW of the Gaertner orebody of the Key Lake deposit (57°12'30"N, 105°42'00"W, Canadian N.T.S. - 74 H/4).

It is located within a zone of magnetic high outlined in local terms as the Wilson Lake Periphery High (WLPH) and interpreted [24] as a complex (locally perhaps with a strong recumbent geometry) Archean antiform. This zone grossly separates [24] several rhombohedral blocks of Mudjatik-type which extend on NW beyond the WLPH (not shown on Figure 2) and the units on SE which all are strongly elongated in the common Wollaston Domain pattern. The SE contact of the SE branch in the WLPH antiform is subvertical, in other segments overturned and possibly formed (prior to erosion) a granitic overhang above the Key Lake synform (KLS). In detail, DDH-ATP-4 is approximately 1.1 and 0.5 km away from the SE and NW contacts respectively. This would indicate a

minimum of 500 m structurally beneath the contact. However, a magnetic low SW of this DDH suggests possibly a shallower (i.e. closer to the contact) structural position of the ATP-4 site. Foliation within the antiform (and elsewhere in Figure 2) is dominated by late D-2 deformation, while residuals of the early D-1 deformation make the pattern more complex. Dips of the foliation in ATP-4 ranges between 20 and 28° and averages 23°, possibly indicative of an influence of a local synform within the WLPH.

Diagonally across the Key Lake synform, earlier dating of zircon [10] yielded an Archean age for a granite gneiss from a site located 700 m from the NW contact of the Zimmer Lake High (ZLH) antiform. This distance indicates that this dated material rests some 500 m perpendicularly beneath the closest extrapolated contact.

5.3 Megascopic Appearance and Mode of Occurrence

The age-dated rock composed of feldspar, quartz, biotite and some amphibole is beige, fine grained and, in smaller fragments, it appears massive. The fine-grained (under 1 mm) and equigranular feldspathic (+ quartz) matrix yields the dominating beige colour peppered and streaked grey by fine biotite. Under a closer inspection the rock is foliated though to a lesser degree than the "hosting" variety in some other sites of the area. Thin laminae (under 1 mm) filled by fine biotite (and occasionally by subordinate amphibole), although inconsistent (invaded by later (?) feldspathization), enhance the otherwise subtle foliation, commonly at intervals of 3-15 mm.

This type of granite prevails in the fresh 20 m - thick basement interval (separated by 20 m regolithized crust from the superjacent Athabasca sandstone) intersected by DDH-ATP-4. A minor part (about 10%) of the fresh basement consists of several thin mafic intercalations and coarser (Hudsonian?) granitic mobilizates. A similar situation

(predominance of the beige, fine-grained variety) has been found in other DDHs of the ATP-group. This group of 4 DDHs (including ATP-4 located at the southern corner) forms a rectangle of 400 x 100 m, elongated along structural strike. All DDHs of this cluster have intersected fresh granite gneiss in a similar position i.e. grossly 20 to 40 m beneath the sandstone.

5.4 Other Observations on Geochronologically Processed Materials

Four samples of a granite gneiss of the DDH-ATP-4 formed part of the Rb-Sr systematics. Three of them (samples 11616, 13 and 11) from the interval 52 to 62 m yielded an isochron. This set of samples has been processed by microscopy and chemistry (+LOI).

Another complementary set of five samples has been collected from the same DDH and from approximately the same interval (44 to 58 m) and it is referred to as the ATP-4 undated set. In order to show the areal variation of the same type of rock, another nineteen samples were collected from three other DDHs of the ATP-group. All 24 samples of the group were taken within the approximately same depth interval beneath the Athabasca (minimum 14 m, maximum 37 m). This group of samples provided data on chemistry, LOI, density and magnetic properties.

5.5 Microscopy

A thin section of the uppermost sample 11616 represents a homogeneous microcline-plagioclase-biotite gneiss. Three lower samples (11615, 11613 and 11611) were inhomogeneous and included small layers of a hornblende-biotite-plagioclase gneiss variety beyond the above described predominant type. Sample 11613 yielded some diopside within a lighter transition zone between both types. The plagioclase-microcline-biotite gneiss and the hornblende-plagioclase gneiss could be interpreted as a granitic neosome and mafic

paleosome of the anatectic melt derived from a source having a more homogeneous composition.

The microcline-plagioclase-biotite gneiss (sample 11616) with equigranular honeycomb texture contains anhedral potassium feldspar in two generations: K-feldspar I is expressively perthitic with two generations, i.e. coarser poikiloblastic and very fine stringy perthitic plagioclase; K-feldspar II yields in the core very fine stringy perthitic plagioclase. Anhedral plagioclase in part of the cores is veined with Fe-oxides and chlorite. Quartz is also anhedral and also occurs as droplets in both feldspars. Biotite is fresh while hornblende is commonly pseudomorphosed by chlorite and in part by quartz and fluorite. Zircon is quite frequently found among other accessories (opaque minerals, allanite and apatite).

The plagioclase-microcline-biotite-hornblende gneiss (sample 11613) displays equigranular honeycomb texture with anhedral plagioclase and anhedral predominantly perthitic K-feldspar. Quartz is anhedral, frequently as droplet-like inclusions within feldspars. Characteristically this type carries common green hornblende with inclusions of quartz, apatite, allanite and zircon. Biotite is fresh, opaque minerals show some Ti-phases, accessories include apatite, allanite and zircon. The more mafic inliers include diopsidic clinopyroxene, in part altered into smectite.

5.6 Geochemistry

The average composition of the predominating fine-grained granite gneiss (24 samples in 4 DDHs including the dated ATP-4 DDH) is: SiO2 - 74.50%, TiO2 - 0.36%, Al2O3 - 12.60%, Fe2O3 - 3.04%, MnO-0.049%, MgO-0.46%, CaO-0.79%, Na2O-3.02%, K2O-5.37%, LOI (900°C)-0.2%, P2O5-0.07%, Ni-8 (this and all following elements are shown in ppm), Pb-20, As-0.4, Mo-10, Zn-68, Cd-1, Co-9, Cr-296, V-13, Be-3, Cu-12, Rb-204, Sr-67, Ba-615, B-16, U total-6.8, U leachable -4.1, Th-27, Y-41, Zr-318, La-77, Ce-140, Nd-65, Eu-0.7, Tb-3,

Dy-5.5, Er-2.9, Yb-3.4, Lu-0.6. (Assays by SRC-Saskatchewan Research Council, geochemical laboratory in Saskatoon; U-fluor.; Si, Al, Fe, Ca, Mg, K, Na, Ni, Pb, As, Rb-AA; others by ICP).

5.7 Physical Properties

LOI (1000°C) of four dated samples ranges between 0.38 and 0.68% between the bottom and the top samples within an interval of 10 m. The average of 0.50% is higher than in the additional set of five undated samples from ATP-4 which yielded 0.2% LOI (900°C). Also another 19 samples from other DDHs of the ATP-group yielded a very fresh rocks with only 0.2% LOI (900°C) average.

Densities varied between 2.63 and 2.66 and averaged 2.64 g/cm^3 in five undated samples of ATP-4. Within the 24 samples of the immediate area (ATP-4 inclusive) the densities ranged from 2.63 to 2.68 with an average of 2.66 g/cm^3.

Magnetic properties were also assessed on 24 samples from the area. The resulting units of magnetic properties were simply the direct scale readings (on the magnetic susceptibility BISON instrument) simulating approximately the outcrop situation. Therefore, the values have rather a relative value illustrating the variability within an apparently homogenous and fresh (0.2% LOI) rock. Five samples from ATP-4 yielded the lowest average of 360 units compared with 430,540 and 620 units in other DDHs and with the overall average of 510 units of the area. If the data from outcrops are taken into account the value of 510 would represent a moderately high magnetic susceptibility received on granitic rocks of the wider area.

6. NEW GEOCHRONOLOGICAL DATA

6.1 Analytical Procedure for Sm-Nd Separation

The analytical method for determining Sm-Nd concentrations and Nd isotopic composition is similar to that described by Richard et al. [26]. After addition of a composite spike (147 Sm - 148 Nd) the whole-rock powders (typically 100 mg) were decomposed by HF-HNO3 mixtures in teflon bombs, followed by repeated evaporation with 6 N HCl. The samples were finally dissolved in about 2 ml 2.5 N HCl and centrifuged. 1 ml of the solution was loaded onto a cation-exchange column of 10 ml AG 50 W x 12 resin (200-400 mesh). All major element were eluted with 100 ml 2.5 N HCl and after that the LREE were eluted with 64 ml 6.1 N HCl. This fraction was collected and evaporated to dryness, redissolved in 0.2 ml 0.8 N HCl, and loaded onto a HDEHP/ teflon ion-exchange column for separation of Sm and Nd. This was done by eluting the Nd and Sm with 0.18 N and 0.5 N HCl respectively. The isotopic determinations were done with a MAT 261 mass-spectrometer equipped with a variable five-collector system in static mode. The measured 143 Nd/ 144 Nd ratios were normalized to 146 Nd/144 Nd = 0.7219. During the course of this study the measured blanks are 80 pg and 400 pg for Sm and Nd, respectively. The Nd standard (La Jolla) yielded 143 Nd/144 Nd = 0.511866 ± 14.

6.2 Results of the Age Determination

The four whole rock samples of the gneissic sections of the ATP-4 core were analysed for Rb/Sr and Sm/Nd. The isotopic data are given in Tab. 1 and 2.

The four samples define an errorchron in the Rb/Sr isochron diagram (Fig.3) corresponding to an age of 2540 ± 150 Ma (MSWD = 9; the 2s-error of the age estimate has been expanded by SQR(MSWD)). Omitting sample 11615 the three remaining samples perfectly fit an isochron yielding a somewhat higher age of 2605 ± 62 Ma (MSWD = 0.7).

Table I: Rb-Sr isotopic ratios for basement samples of the Key Lake area

Sample-No. (Drill hole) (depth)	^{87}Rb (ppm)	^{86}Sr (ppm)	$^{87}Rb/^{86}Sr$ (s = ±1%)	$^{87}Sr/^{86}Sr$ (s=±0.03%)
11611 (ATP-4) (203.5')	36.52	11.833	3.051	0.82041
11613 (ATP-4) (198.5')	45.56	9.777	4.605	0.87727
11615 (ATP-4) (180')	52.24	5.665	9.115	1.03094
11616 (ATP-4) (170')	61.05	3.116	19.37	1.43685

Table II: Sm-Nd isotopic ratios and derived values for basement samples of the Key Lake area

Sample No.	^{147}Sm (ppm)	^{144}Nd (ppm)	$\frac{^{147}Nd}{^{144}Nd}$ s=±0.5%	$\frac{^{143}Nd}{^{144}Nd}$[a] s=0.002%	T^{Nd}_{CHUR}[b] (Ga)	$\varepsilon_{Nd}(T)$ T=2.6 Ga
11611 (ATP-4) (203.5')	1.2955	12.366	0.10262	0.511086	2.50	+ 1.2
11613 (ATP-4) (198.5')	1.3297	12.994	0.10025	0.511050	2.50	+ 1.3
11615 (ATP-4) (180')	0.8853	9.2421	0.09383	0.510974	2.46	+ 1.9
11616 (ATP-4) (170')	1.5539	15.7057	0.09692	0.510983	2.52	+ 1.1

a $^{143}Nd/^{144}Nd$ ratios are normalized to $^{146}Nd/^{144}Nd = 0.7219$

b model age calculated using equation of De Paolo and Wasserburg (31) Bulk Earth parameters used for calculation are:

$^{143}Nd/^{144}Nd = 0.512638$; $^{147}Sm/^{144}Nd = 0.1966$

$\lambda^{147}Sm = 6.54 \times 10^{-12} a^{-1}$

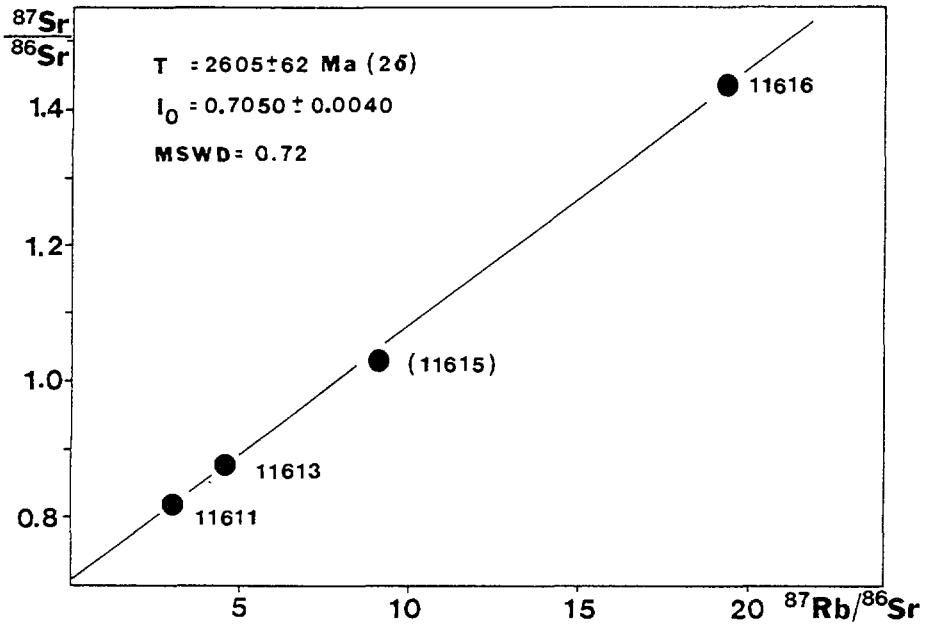

FIGURE 3

Rb/Sr isochron diagram for the ATP-4 samples.
(Age calculated with λ Rb = 1.42 x 10^{-11} a^{-1})

The same three samples also fit an isochron in the Sm-Nd diagram (Fig. 4) corresponding to an age of 2700 ± 800 Ma. The larger error is due to the very limited range of the Sm/Nd ratios. From the Sm/Nd data a model age T_{CHUR} can be calculated which is the inferred time at which the protolith separated from the mantle with Sm/Nd fractionation. The model age correspond to the time in the past at which the 143 Nd/144 Nd in the sample coincides with the 143 Nd/144 Nd in a chondritic uniform reservoir (CHUR). The chondritic uniform reservoir (Jacobson and Wasserburg, [27]; Hamilton et al., [28]) is taken as one possible analogue of the mantle source. The present day model parameters for CHUR are: (143 Nd/144 Nd) = 0.512638; (147 Sm/144 Nd) = 0.1966; decay constant of Sm = 6.54 x $10^{-12}a^{-1}$.

The calculated T_{CHUR} model ages for the ATP-4 samples are 2.5 Ga (Tab.2). If instead of CHUR a "depleted mantle" source (DM) is assumed (De Paolo, [29]; Miller & O'Nions, [30]) the model ages T_{DM} are about 2.7 to 2.8 Ga.

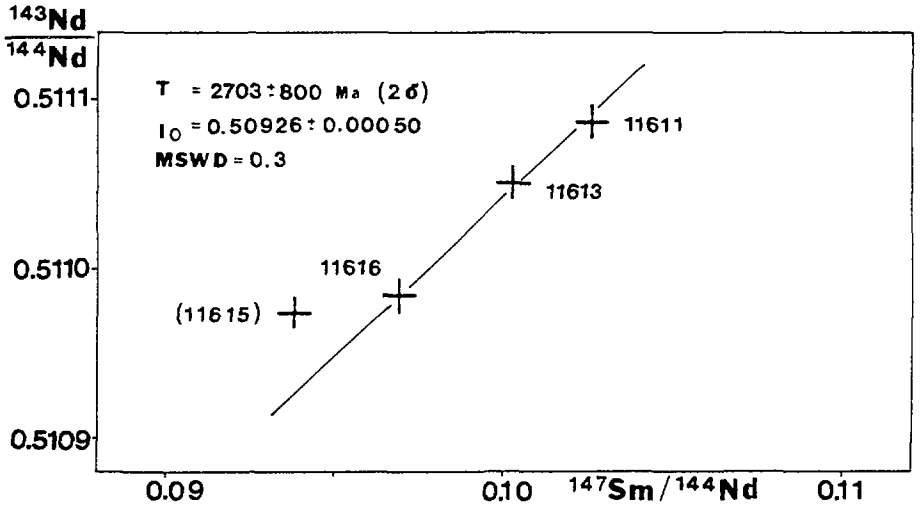

FIGURE 4

Sm/Nd isochron diagram for the ATP-4 samples.
(Age calculated with λ Sm = 6.54 x 10^{-12} a^{-1})

Taking together the calculated model ages and the Sm/Nd and Rb/Sr isochron ages a Kenoran age for the granitoid seems to be well established. As the best age estimate we consider the 2605 ± 62 Ma Rb/Sr isochron age which complements the zircon age (2600 ± 18 Ma) of the Zimmer Lake antiform SE of Key Lake (Krogh and Clark, [10]) and the Archean Rb/Sr age found at the Midwest uranium deposit (2613 ± 93 Ma; Worden et al., [9]) received on Archean from mineralized sites of the Wollaston Domain.

Taking T = 2.6 Ga as the time of crystallization ε_{Nd} values can be calculated which represent the fractional deviation in parts per 10^4 of the initial $^{143}Nd/^{144}Nd$ ratio from the $^{143}Nd/^{144}Nd$ ratio of CHUR at the time of crystallization (De Paolo and Wasserburg, [31]). The ε_{Nd} (2.6 Ga) values for the analysed samples are slightly positive (+1.2 ± 0.6) as has been found for most Archean igneous and metamorphic complexes (McCulloch and Compston, [32]). The positive $\varepsilon_{Nd}(T)$ suggests a derivation of the magma from the Archean mantle without major contamination by older crust. Chondrite-normalized REE signature of the dated granite gneiss is similar to late Archean potassic granites and

differs from Archean average sedimentary rocks (Australia) by higher LREE and by negative Eu anomaly. This seems to support the only negligable contamination by earlier intra-Archean lithologies. Similarly, the A/CNK index of 1.03 yields a subaluminous to weakly peraluminous signature indicative that the granites are not of the S-type.

The Archean Rb/Sr whole rock age found for the ATP-4 samples proves that in some parts of the Archean basement of the Key Lake area the Rb/Sr system within the size of the drill core samples has been preserved during the Hudsonian orogeny.

The Hudsonian overprint is clearly documented in the K/Ar system of biotites and hornblendes separated from the ATP-4 samples in the Key Lake area (Fig. 5). The concordant K/Ar biotite ages of 1723 ± 5 Ma indicate a complete reset of K/Ar system and date the cooling below about 300°C after the Hudsonian thermal event i.e. only about 10 Ma (ref. 3.2.4) prior to the sedimentation of the Athabasca. In our view (concordant with personal communication, G.L. Cumming, 1987) the Athabasca could have then settled on an unusually "warm" basement having a steep geothermal gradient. The new

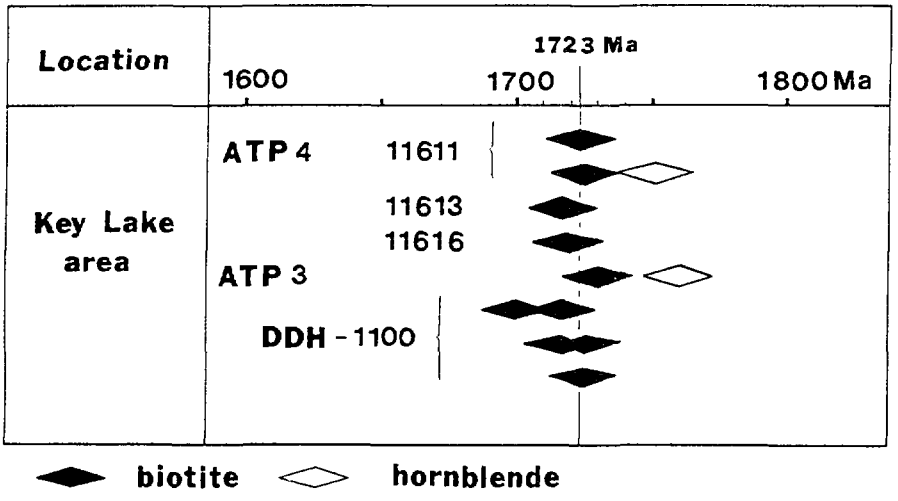

FIGURE 5

K/Ar mineral ages from basement units in the Key Lake area. (The size of the symbols indicates the 2s error interval)

Table III: K-Ar mineral data
(bi = biotite, hbl = hornblende)

Sample No. (Drill hole) (depth)	rock type	mineral (size fraction) (µm)	K (wt %)	K-Ar date *) (Ma)
11611 (ATP-4) (203.5')	gneiss	bi (125-250)	6.657	1725 12
	amphibolite	bi (125-250)	7.542	1728 12
	amphibolite	hbl (125-250)	1.159	1756 14
11613 (ATP-4) (198.5')	gneiss	bi (125-250)	6.313	1718 12
11616 (ATP-4) (170')	gneiss	bi (125-250)	7.030	1720 12
11617 (ATP-3)	amphibolite	bi (125-250)	7.743	1731 12
(212')		hbl (125-250)	1.235	1763 13
11618 (1-3) (DDH-1100) (296')	gneiss	bi (125-250)	7.165	1718 12
		bi (63-125)	6.929	1702 12
11618 (4-6) (DDH-1100) (298')	gneiss	bi (125-250)	7.025	1726 12
		bi (63-125)	6.609	1718 12
11618 (DDH-1100) (300')	gneiss	bi (125-250)	7.063	1727 12

*) Quoted errors represent the analytical uncertainty at a 95 % confidence level. The K-Ar ages are calculated using the IUGS-recommended constants (35).

age of Athabasca Group [19] according to most geochronological divisions (see Figure 1) is not anymore middle Proterozoic (as considered earlier) but belongs to the uppermost early Proterozoic and thus, it is more closely tight to the Hudsonian events. If by analogy with the Thelon Basin data [19] the age of the Athabasca could be extended to 1.72 Ga, then the youngest Hudsonian granitoids (Swift Current) of 1.76 Ga are only by 40 Ma older than the Athabasca. This gap must have accommodated uplift, part of cooling, peneplanization, weathering and erosion, all within

an unusual rapid sequence. Obviously, the cooling deeper in the basement could have been retarded by the deposition of Athabasca Group and thus the resulting again increased temperature of the basement could have been prolonged and support some of the post-Athabascan thermal events.

7. CONCLUSIONS

The new age determinations contribute to the definition of the Archean-Proterozoic boundary in the Key Lake area.

a) The age determination of the ATP-4 core samples confirms the Archean age of the beige granite gneiss in one Archean antiform, locally called the Wilson Lake Periphery High. The compositional similarity of the ATP-4 rocks with other samples intersected in the vicinity (up to 400 m on strike) allows the upper (drilled) part of the magnetic high of this segment to be considered as an Archean complex antiform.

b) The compositional similarity of the dated site with the site of the other (simplier) antiform dated as Archean by the primary crystallization age of zircon (Krogh and Clark, [10]) supports the interpretation that probably most of the pink granite gneiss (including its deeper portions) within the Zimmer Lake inlier is of Archean age.

c) The Archean Rb/Sr age proves, that the Rb-Sr system of the whole rock samples within the size of the drill core was not disturbed by the Hudsonian metamorphism, at least at some sites. The Hudsonian metamorphism is clearly documented in the K-Ar system of biotites and hornblendes and also seen in the lower intersection age of the zircon [10]. The Rb/Sr whole rock dating has therefore been shown to be a suitable method for identifying Archean basement in this metamorphic domain and also for mapping the gradient of the Hudsonian overprint.

d) The Sm/Nd systematics of the samples indicates that the magma was derived from the Archean mantle. Within the error interval the initial Sr-ratio is not incompatible with an assumed mantle source for the granite.

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GEOLOGY AND URANIUM POTENTIAL OF THE THELON BASIN AND ADJACENT BASEMENT IN COMPARISON WITH THE ATHABASCA BASIN REGION*

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Abstract

The Thelon basin is a Paleohelikian intracratonic basin similar to the Athabasca basin in tectonic setting, age and depositional environments. The two basins are 300 km apart and lie on basement that was affected by the Hudsonian orogeny ca. 1900 Ma ago. They contain mostly siliciclastic sediments, which are little disturbed and have a preserved thickness of over 1 km. The present areal extent of each basin is about 85 000 km^2. The sedimentation began approximately 1700 Ma ago according to isotopic dates on authigenic apatite in sandstones and on zircon in older rocks. Thick lateritic paleoregolith is preserved under the sandstones. Diabase dykes of the Mackenzie swarm intruded the sandstones approximately 1250 Ma ago.

Uranium exploration in the Thelon basin region has not been as intensive as that in the Athabasca basin region, mainly because of relative remoteness and exclusion from exploration of a large area covered by the Thelon Game Sanctuary. Nevertheless, several promising prospects and numerous occurrences have been discovered. These represent various types of uranium deposits found in the Athabasca basin region, considered broadly under the stratabound, granite-related and vein-type in the basement rocks and the unconformity-related type at the base of Paleohelikian sandstone. From the resource standpoint, the high grade vein-type and unconformity-related deposits are relatively more important in the Athabasca basin region. In the Thelon basin region, an example of the vein-type deposits is the LGT (Lac Cinquante) prospect. The unconformity-related deposits are represented by the Boomerang Lake U-Au prospect, which occurs in the basal Thelon sandstone above graphitic metapelite in the basement, and by the Kiggavik (formerly Lone Gull) deposit in a fault zone in the basement where the Thelon sandstone is eroded. The Kiggavik deposit may have had precursor vein-type mineralization.

The genetic models developed for the uranium deposits in the region of the Athabasca basin apply equally well to those in the geologically similar region of the Thelon basin. They imply a high resource potential for the Thelon basin region.

INTRODUCTION

The Thelon basin is geologically similar to the Athabasca basin [1], and the basement rocks in the two basins show similar geological evolution. The known uranium resources of the Thelon basin region are only a fraction of that in the Athabasca basin region. This is largely a reflection of relatively less intense exploration of the Thelon basin region, attributable in part to its remoteness and in part to the fact that a large area set aside as the Thelon Game Sanctuary (Fig. 1) is not open to exploration. From the regional metallogenic standpoint, however, it is significant that the various styles of uranium mineralization found in the Athabasca basin region are represented in the Thelon basin region, including the economically

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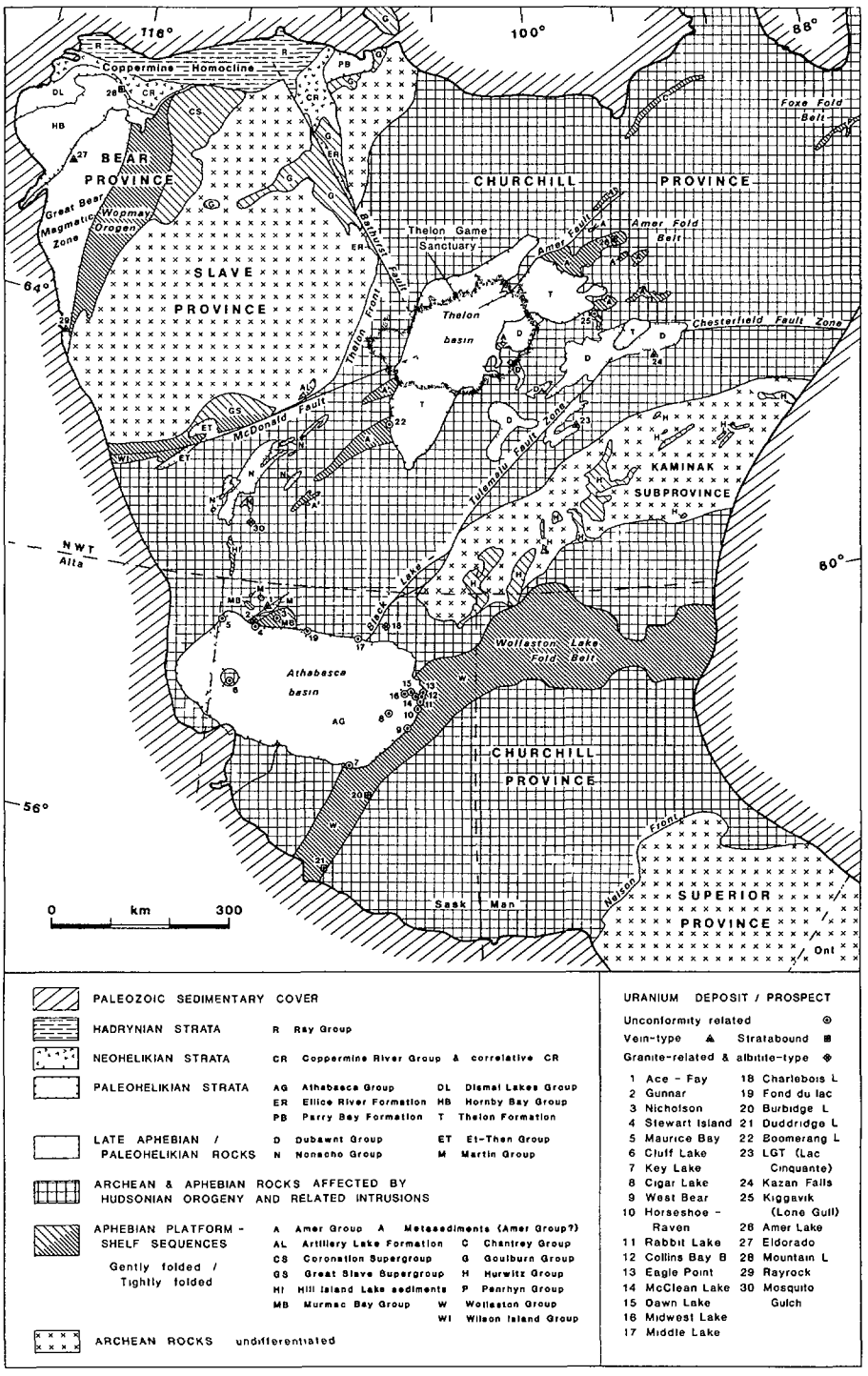

Fig. 1.

General geology and major uranium deposits and prospects of the northwestern Canadian Shield.

important unconformity-related type. This indicates a high uranium resource potential of the Thelon basin region.

GEOLOGY OF THE THELON AND ATHABASCA BASIN REGIONS

The Thelon and Athabasca basins are Paleohelikian intracratonic basins located in the western part of the Churchill structural province (Fig. 1). The sequences deposited in them, namely the Thelon

Formation and the Athabasca Group, contain thick sandstone strata that are generally flat-lying [1,2,3,4]. They are affected by faults, and are cut by Mackenzie diabase dykes (Fig. 2).

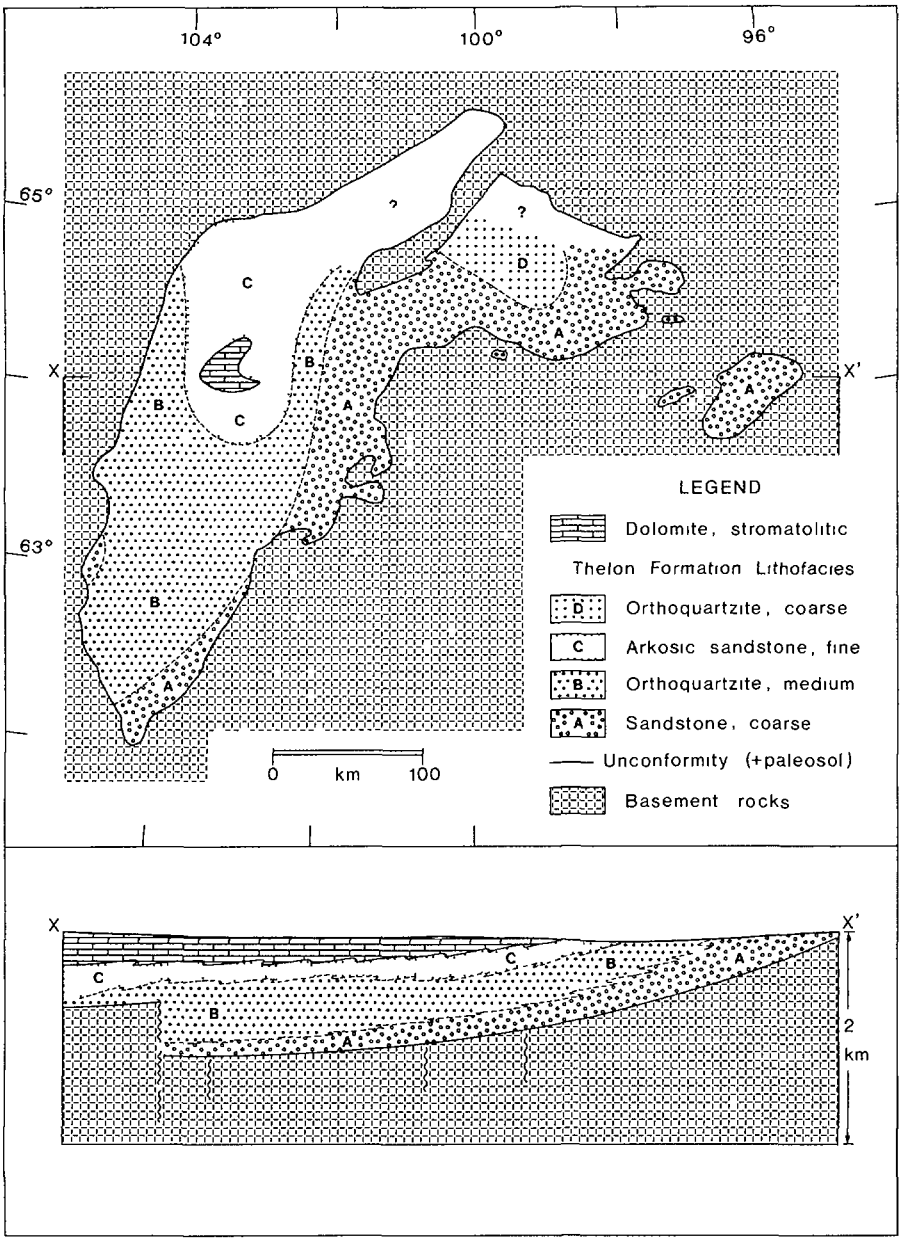

Fig. 2.

Plan and generalized stratigraphic section of the Thelon Formation showing lithofacies as defined by Cecile [16].

Basement Rocks

Underlying the Thelon Formation and Athabasca Group are Archean and Aphebian rocks that have been affected by the Hudsonian orogeny approximately 1900 Ma ago, post-tectonic Hudsonian granites and mafic intrusions, and unmetamorphosed sedimentary and volcanic rocks deposited in fault-controlled troughs [5]. Hudsonian deformation and metamorphism have obscured the distinction between Archean and Aphebian rocks that are now gneissic, but belts of Aphebian platform-shelf sequences are recognizable (Fig. 1). They are characterized by the presence of quartzites, carbonates, graphitic shales and

siltstones, and are variably deformed and metamorphosed. The Wollaston Group is the most extensive, and is in part covered by the Athabasca Group [6]. It is metamorphosed to upper amphibolite facies. The Amer Group northeast of the Thelon Formation is relatively less metamorphosed, and is folded and thrust-faulted [7,8]. More highly metamorphosed strata occurring on the regional strike of this group in the southwestern part of the Thelon basin appear to be equivalent to it, and suggest possible continuation of Amer rocks underneath the Thelon Formation [9]. Smaller isolated zones of paragneiss elsewhere in the Thelon and Athabasca regions may be remnants of these sequences. Lithological correlations over large distances, however, are not reliable considering the time span of the Aphebian era and lack of precise dates on strata in key areas. For example, the age of Amer Group is known only to be between 2617 and 1849 Ma [7]. The Murmac Bay Group in the well studied Beaverlodge area, which contains quartzites, garnet and biotite schists, metaconglomerates, dolomitic marbles and pillowed metabasalts, is bracketed between 3014 and 2356 Ma [10,11,12]. Furthermore, the Archean Prince Albert Group, located northeast of the Thelon Formation, contains quartzites and carbonates, and thus resembles the Aphebian sequences [13]. Greenstone-graywacke type strata, which are typical of the Archean supracrustal sequences in the Slave and Superior provinces, occur in some zones in the western Churchill province. Several Archean zircon dates on granites and gneisses in the vicinity of the Thelon and Athabasca basins have been reported [7,12].

The regional structural trend of the western Churchill province is northeast to east as reflected by the Wollaston Lake and Amer fold belts. Structure within the Wollaston Lake belt and adjacent region to its west is controlled by remobilization and ductile deformation of the Archean basement resulting in gneissic domes and lobes [13]. A number of cataclastic and mylonitic zones occur in the province; their trend is commonly north-northeasterly. Sections of some of the zones follow metasedimentary bands, including incompetent graphitic metapelites which tend to localize shear movements.

Boundaries of the western Churchill province with the Archean Slave and Superior provinces, are marked by major tectonic zones, namely the Thelon and Nelson Fronts respectively (Fig. 1). Lewry et al [14] regarded the Wollaston Lake fold belt and the region northwest of it as the foreland or ensialic miogeoclinal zone, and the region to its southeast as ensimatic arc - inter arc zone of the Trans-Hudson orogen. The Hudsonian orogeny resulted from northwesterly subduction of the Superior plate. Post-tectonic Hudsonian granites are widely distributed throughout the Churchill province, including the regions of the Thelon and Athabasca basins. Zircon age determinations show that they are close to 1900 Ma old [6,7,14].

Following the Hudsonian orogeny, fault-controlled basins developed, and thick fanglomeratic redbeds and volcanic rocks were deposited in them. They include the Thluicho, Ellis Bay and Martin Groups at the northwestern margin of the Athabasca Group [3,12]. South and east of the Thelon Formation, large areas are underlain by rocks of the Dubawnt Group (Fig. 1). During early reconnaissance mapping, the Thelon Formation was regarded as the uppermost unit of the Dubawnt Group [2,15,16], but later work separated it from the group [17,18]. The lower part of the Dubawnt Group, including the Kazan and South Channel Formations, is very similar to the Martin Group in that it contains subaerial mafic volcanic flows and red clastic sediments. In the Dubawnt Group, however, these are overlain by voluminous and widespread alkaline lavas and pyroclastic rocks of the Christopher Island Formation, redbeds of the Kunwak Formation and rhyolitic flows of the Pitz Formation with coeval fluorite-bearing granitic intrusions. Equivalents of these formations are not known in the Martin Group.

Thelon Formation and Athabasca Group

Sediments in the Thelon and Athabasca basins are dominantly fluvial sandstones. The preserved thickness of the sediments is up to 1.3 km in the Thelon basin [19], and up to 1.5 km in the Athabasca basin [3]. Their present areal extent in each of the basins is over 85 000 km^2. The strata in the two basins are little disturbed except for minor vertical displacements along moderately to steeply dipping faults.

The Thelon Formation comprises mature sandstone with associated quartzose conglomerate, fine grained sandstone and shale. Cecile [16] subdivided it into four facies as shown in Figure 3. The lower three facies (A,B & C) form a sequence increasing in thickness towards the deepest west central part of the basin. It is an upward fining sequence overall, showing as well an upward decrease in the proportion of kaolin-rich matrix, an increase in quartz overgrowth, and also the presence of authigenic feldspar in the upper part. The fourth facies (D) is an orthoquartzite which occurs only in the eastern part of the basin and rests directly on the lowermost facies (A). It contains chlorite and muscovite in the matrix.

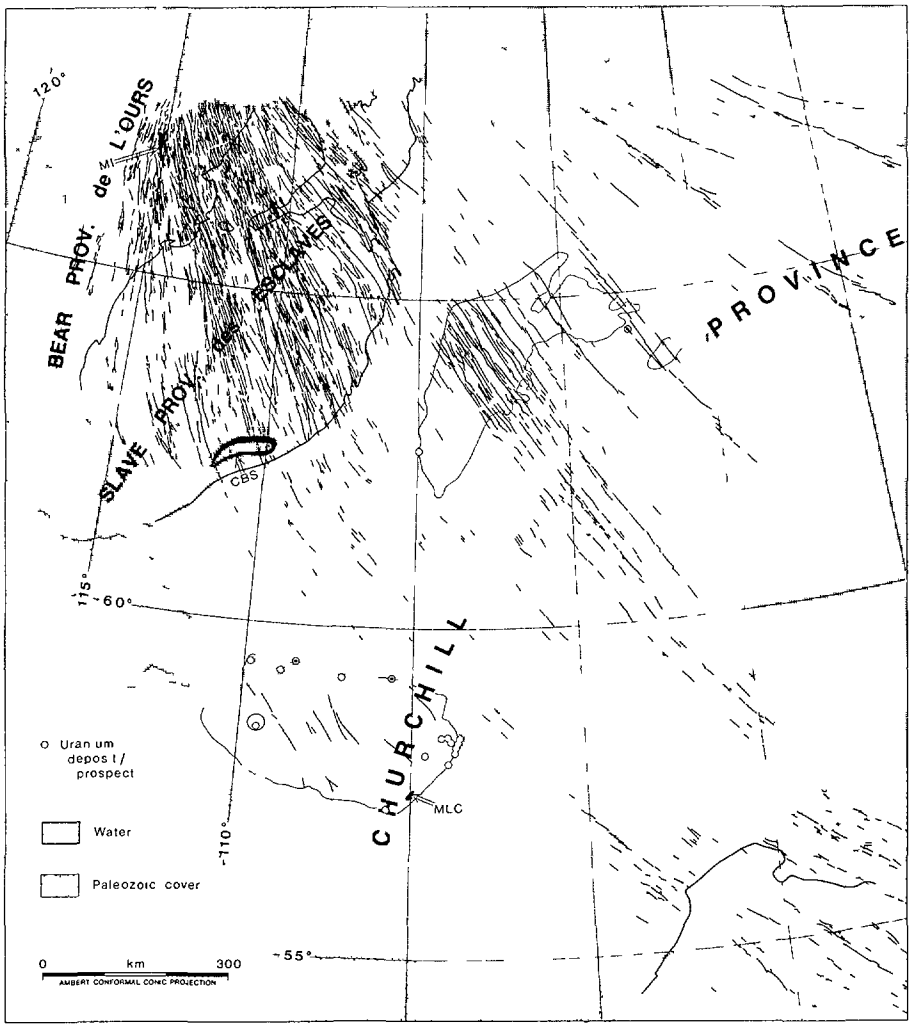

Fig. 3.

Mackenzie diabase dyke swarm and related gabbroic intrusions, after Fahrig and West [30]. MI : Muskox intrusion [32]; CBS : Christie Bay sills [33]; MLC : Moore Lake complex [12]. Note: location of dykes derived largely from aeromagnetic surveys.

The Athabasca Group comprises a fluvial lower part and a dominantly marine upper part [3,4]. The fluvial hematitic quartz arenites and conglomerates of the lower part, which make up the Fair Point and Manitou Falls Formations, are up to a kilometre thick in the eastern part of the basin but are thinner in the west. The upper part of the group, containing transgressive marine strata, is divided into eight formations. They include sandstones and subordinate siltstones, mudstones, phosphatic sediments, tuffaceous sandstones, and stromatolitic and oolitic dolomite.

The direction of fluvial transport in both basins was mainly from east to west. The basal conglomerates and sandstones in each basin were deposited on deeply weathered surface of low relief. The paleoweathering is lateritic and extends for several tens of metres in the basement [20,21]. Kaolinite is abundant in the weathered zone, and it also occurs as clay-rich clasts and as the dominant matrix mineral in the overlying sediments. Hematite is ubiquitous, and imparts characteristic red colouration to the weathered zone and the overlying sediments, although bleached zones are common.

Another mineral of interest in the sandstones is authigenic apatite. In the Thelon Formation, it is found throughout the basal part, in concentrations up to several per cent, and also occurs as fracture-fillings in the underlying paleoweathered zone [21]. It is commonly uraniferous, with uranium content up to 700 ppm. Similar apatite also occurs in the basal and higher horizons of the Athabasca Group. Several samples of apatite from the two sequences have been dated recently by U-Pb isotopic method, and have yielded dates in the range of 1650 to 1720 Ma [21,22,23]. The maximum age of the Thelon Formation is constrained by the 1760 Ma U-Pb zircon date on the underlying Fitz Formation felsic volcanic rock [22]. The paleoweathered basement gneiss beneath the Athabasca Group has a Rb-Sr isochron age of 1632 ± 32 Ma, which is interpreted as the time of homogenization due to weathering and/or diagenesis, and as close to the time of Athabasca sedimentation [24]. The time required for accumulation of the sediments in the two basins is not certain, but it may have been on the order of a few tens of millions of years.

It is apparent from the above that sedimentation in the Thelon and Athabasca basins was essentially synchronous. The present margin of the basins is an erosional boundary. In the case of the Athabasca basin, it has been conjectured that this margin corresponds fairly closely with the original basin limit [12]. However, the thick blanket-type sandstone sequence of the basin is likely to have been significantly more extensive than its present area. In this regard it is noteworthy that correlative fluvial sandstones of the Ellis River Formation [25] and the Hornby Bay Group [26,27] occur to northwest in the Bathurst Inlet area and in the Coppermine Homocline respectively (Fig. 1). The upper part of the Hornby Bay Group contains a mafic and felsic volcanic complex at Narakay Islands, which is dated by U-Pb zircon method at 1663 ± 8 Ma [28]. The Ellis River Formation is correlatable with the Hornby Bay Group [23].

The Hornby Bay Group unconformably overlies 1840 Ma old rocks of the Great Bear magmatic zone [28]. The group is approximately 3 km thick, and is disconformably overlain by up to 1 km of siliciclastic and calcareous strata of the Dismal Lakes Group. These in turn are conformably overlain by the Coppermine River Group, which is up to 5 km thick and contains abundant plateau basalts [26]. These basalts and associated diabasic sills are coeval with the Mackenzie diabase dyke swarm [26,29,30,31], the Muskox gabbro intrusion [26,32], the Christie Bay diabase sills [33], and the Moore Lake gabbroic complex [12], all of which were emplaced during the Mackenzie igneous activity approximately 1250 Ma ago (Figs. 1,3).

The Thelon Formation is overlain by Helikian dolomite and basaltic flows that are preserved in very small areas [15,16]. It is thus conceivable that it was at one time overlain by a few kilometres of sediments and basalts related to the numerous Mackenzie diabase dykes that cut it (Fig.3). This may also apply to the Athabasca

Group, and can explain the fluid inclusion data on the quartz overgrowths in the basal sandstones which suggest the temperature attained as close to 220 °C and a burial depth of 4 to 5 km [34].

Other noteworthy features in the Thelon and Athabasca basins are circular structures interpreted as meteorite impact craters. The Carswell structure within the Athabasca basin is 35 km in diameter, and has exposed the sub-Athabasca Group unconformity and uranium deposits associated with it [35]. It is believed to have formed during the Ordovician period. The Nicholson Lake structure in the southwestern Thelon basin is located a few kilometres east of the Thelon Formation, and contains tilted blocks of Ordovician limestone[36].

URANIUM METALLOGENY

Significant concentrations of uranium in the Athabasca basin and adjacent basement occur in (i) stratabound sedimentary zones in the Aphebian platform-shelf strata, (ii) granitized zones, pegmatites and hydrothermal veins related to the Hudsonian orogeny, (iii) veins formed along subsidiary fractures of late or post-Hudsonian major faults, and (iv) elongate or podiform zones at the sub-Athabasca Group unconformity. Economically the most important are the high grade unconformity-related deposits. Examples of all these styles of mineralization are found in the Thelon basin and adjacent basement, and they reflect overall similarities in the uranium metallogeny of the regions of the two basins.

(i) Aphebian stratabound deposits

This group of deposits includes syngenetic sedimentary concentrations and epigenetic sandstone-type deposits that occur in stratiform zones or stratabound lenses. The distinction between the two types is obscured by Hudsonian deformation and metamorphism. Local remobilization of uranium and associated metals into fractures and shears are common in the deformed host strata.

The Wollaston Group contains several uranium-bearing pelitic, arkosic and calcareous-siliceous strata (Fig. 4). Deposits at the Burbidge Lake and Duddridge Lake are good examples of this type [37]. At Burbidge Lake, uranium occurs as disseminated pitchblende grains in a hornblende calc-silicate gneiss at its contact with a meta-arkose unit in the upper part of the group. At Duddridge Lake, it occurs as disseminated pitchblende in graphitic metapelite lenses in arkosic rocks belonging to a lower unit of the group. Both these deposits and other similar occurrences contain molybdenite and copper sulphides. The mineralized zones are generally up to a few metres wide and a few hundred metres long, and commonly have average uranium grade of less than 0.25 per cent U.

The Amer Group in the Thelon basin contains numerous stratabound deposits and occurrences, most of which are hosted by lithologically variable siltstone-shale beds in the middle and upper parts of the group (Fig. 4). The occurrences are distributed along a 60 x 6 km strike zone trending northeasterly [7]. The host lithologies are siltstones, sandy siltstones, feldspathic siltstones and their calcareous equivalents. The host sediments are interpreted as deposited in tidal flat - restricted bay environments [17]. They are folded, thrust-faulted and metamorphosed to greenschist facies, but granitic intrusions are scarce in the fold belt and not found in the vicinity of the uranium deposits and occurrences. The mineralized zones are up to 5 m wide and 1500 m long, with average uranium grades generally less than 0.25 per cent. The largest known deposits are at Amer Lake at the east end of the strike zone [38]. Uranium minerals, mainly pitchblende and coffinite, are finely disseminated and associated with disseminated grains of molybdenite, base metal sulphides, pyrite, and traces of arsenopyrite and cobaltite. The radioactive zones are characterized by magnetite and reddish colouration due to intergranular hematite. They have yielded U-Pb and Pb-Pb dates close to 1835 Ma, which reflect isotopic re-equilibration during the Hudsonian deformation. The deformation may have in some places enhanced the economic potential of the deposits.

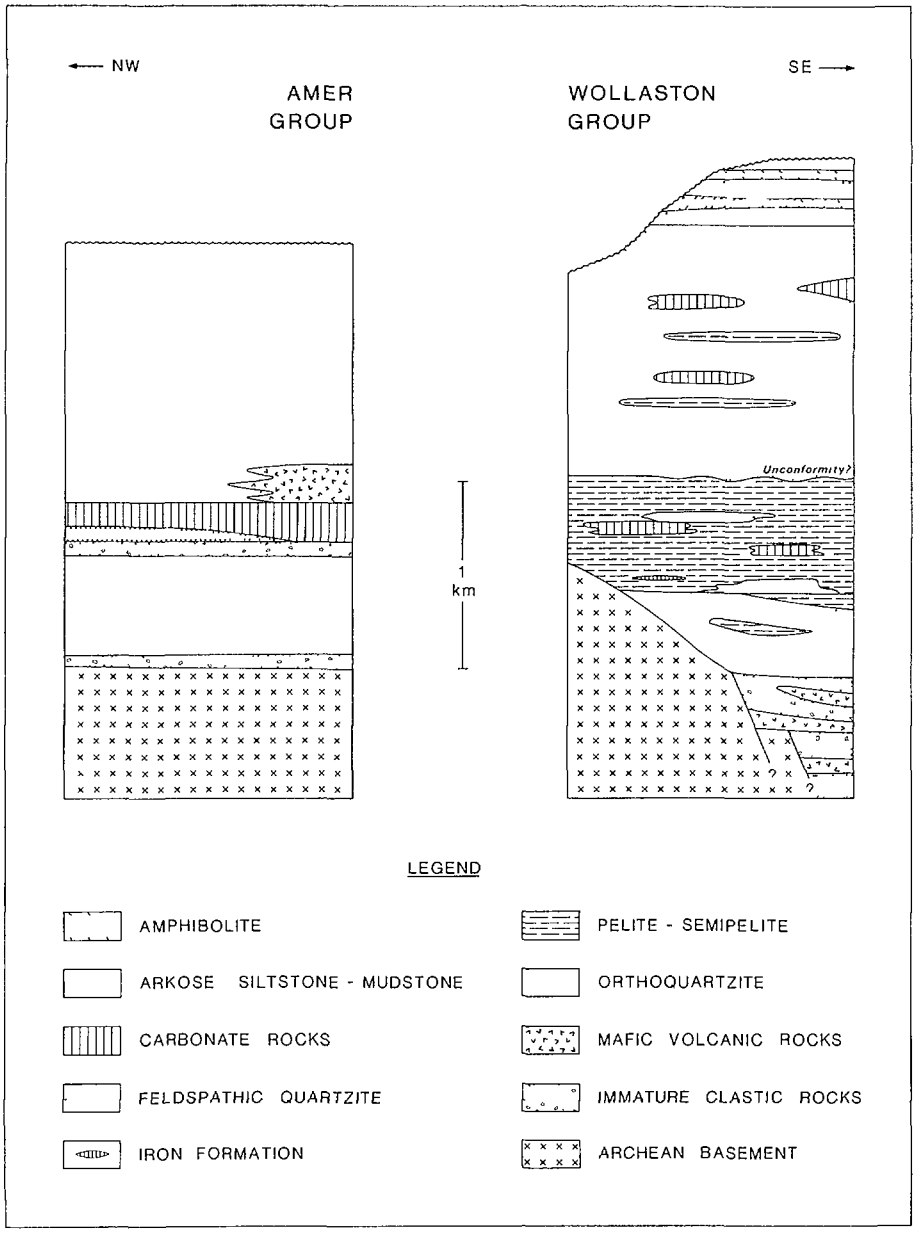

Fig. 4.

Generalized stratigraphy of the Amer and Wollaston Groups, after Patterson [8] and Lewry et al [14] respectively. Note the mafic volcanic unit in the Amer Group is not considered part of the group by Tella [7].

(ii) Hudsonian granite-related deposits

Granitization of supracrustal rocks and emplacement of syntectonic and post-tectonic granite intrusions during the Hudsonian orogeny ca. 1900 Ma represent a major uranium metallogenic episode throughout the Churchill province. It is reflected in uranium concentrations found in anatectic granitoids in metapelites, albitized granite, uranium-enriched granites and pegmatites, and granite-related hydrothermal veins. These veins however are not readily distinguishable from the profusion of veins that post-date the unmetamorphosed strata deposited in the fault-controlled basins after the emplacement of Hudsonian granites.

Significant concentrations of uranium are found in anatectic granitic and pegmatitic bodies at Charlebois Lake and in albitized granite at the Gunnar mine in the Athabasca basin. At Charlebois Lake, the radioactive bodies are roughly concordant to migmatized

metapelites which envelope dome-shaped masses of granite gneiss. Lewry and Sibbald [37] interpreted the granite gneiss as remobilized Archean basement and the uranium as derived from originally syngenetic sedimentary enrichments in the Aphebian metapelites. Uranium distribution is erratic, and although high grade concentrations are encountered locally the average grades are subeconomic. The larger mineralized zones are up to 3 m wide and 500 m long [37].

At the Gunnar mine in the Beaverlodge district, the orebody was pipe-like in form with a maximum diameter of 150 m at the surface. It plunged at 45° for more than 425 m. It produced 5 million tonnes of ore averaging 0.15 per cent U during the period 1956 to 1964. The mineralization was exclusively in strongly albitized 'syenite' part of the gneissic, two-mica Gunnar granite [39]. This alteration occurs close to the paragneiss-granite contact. The paragneiss is probably part of the Murmac Bay Group. The uranium minerals in the ore were pitchblende and uranophane, mostly finely disseminated, with local veins and aggregates of massive to botryoidal pitchblende. A pegmatite sample from the mine yielded a K-Ar date of 1815 Ma [40]. Several other pegmatites, migmatites and biotite segregations in gneisses in the Beaverlodge district have yielded U-Pb dates on contained pitchblende indicating their formation at 1930 ± 40 Ma [41]. Pitchblendes from the Gunnar deposit, however, are much younger, close to 1000 Ma , and indicate substantial later modification of what appears to be originally Hudsonian mineralization [40].

Abnormally radioactive granitoids, recognizable from regional airborne radiometric surveys, occur in the western part of the Athabasca basin and along a broad zone extending from there northeastwards through the Thelon basin [42]. The zone coincides with a broad negative gravity anomaly and subparallel narrower zones of low magnetic anomalies [42]. Many of the granitoids contain significantly more uranium and have higher U/Th ratios than average granites. Radioactive pegmatites, veins and fracture-fillings are associated with them. Most of the granites are syntectonic or post-tectonic Hudsonian intrusions,as seen from field relations and isotopic age determinations, but some others could be Archean.

A few occurrences of the types included in this group are known in the Thelon basin and number of others are likely to be present. They are however not the main targets of exploration done to date because of their low economic potential, and therefore are poorly documented.

(iii) Post-Hudsonian vein-type deposits

This group includes mineralogically simple veins and complex polymetallic veins, which are younger than and apparently not directly related to the Hudsonian granites. The most important are the pitchblende-brannerite veins of the Ace-Fay-Verna mines in the Beaverlodge district, which produced over 18 000 t of uranium during the period 1953 to 1982 [43]. The average ore grade was about 0.17 per cent U. The uranium minerals were deposited in subsidiary fractures of the St. Louis fault. This fault dips 50° to the southeast, and is one of the interconnected series of faults trending northeasterly. It is subparallel to the attitude of the metasediments in the footwall and hanging wall of the 'Fay Mine Complex' which is regarded as the lower part of the Murmac Bay Group [11,12]. Uranium minerals were in networks of fractures and in breccia matrix, mostly in the mylonitized metasediments and associated metasomatic quartz-feldspar granitoid rocks and some in the basal strata of the Martin Group. Isotopic dates on pitchblendes from the veins obtained by Koeppel [41] indicate initial mineralization at 1780 ± 20 Ma (Fig. 5). The sub-Martin Group unconformity is observed in the footwall and hanging wall of the St. Louis fault. This has led to suggestion that uranium was originally concentrated at this unconformity and was later redistributed [43]. In any event, the field relations show that vein formation post-dated deposition of the Martin Group, as pointed out by Koeppel [41]. The zircon dates on the Hudsonian granites are older than 1850 Ma, hence

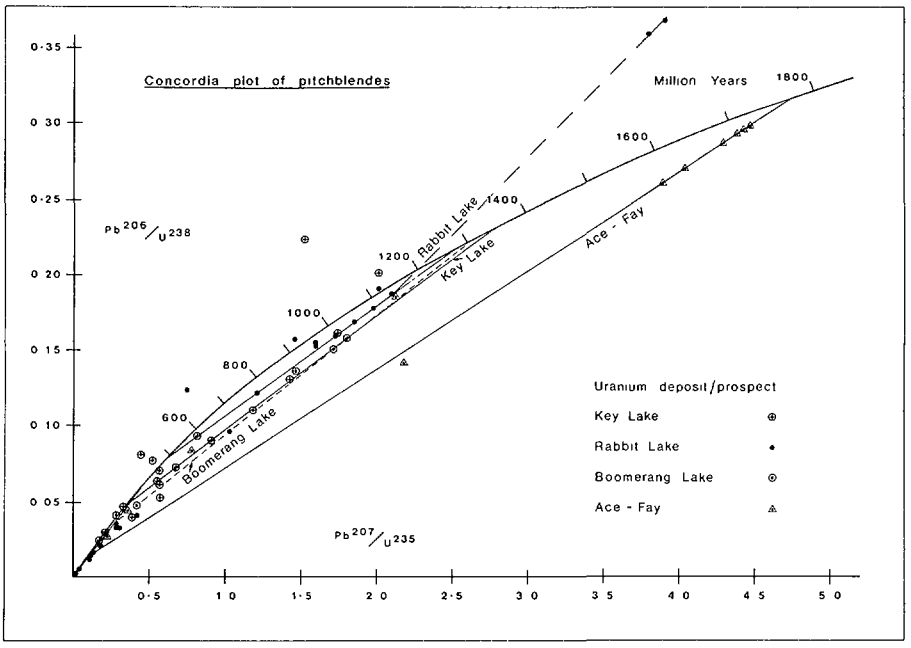

Fig. 5.

Concordia plot of pitchblendes from three selected uranium deposits and one prospect in the western Churchill Province : Ace-Fay deposit, from Koeppel [41]; Rabbit Lake deposit, from Cumming and Rimsaite [48]; Key Lake deposit, from Trocki et al [49] and Hoehndorf et al [50]; Boomerang Lake prospect, from Davidson and Gandhi [58]. Location of the deposits and the prospect in Figure 1.

there seems to be sufficient time between their emplacement and vein formation for the deposition of the Martin Group.

In the Thelon basin, numerous veins occur in the strata of the Dubawnt Group and in the basement rocks adjacent to it. The largest is the LGT (Lac Cinquante) deposit which has many features in common with the deposits in the Beaverlodge district. It is located in the southern part of the basin where the Christopher Island Formation conglomerate-sandstone unconformably overlies the Archean Henik Group [18]. Mafic metavolcanic rocks predominate in the Henik Group, and some tuffaceous metasediments and felsic volcanic rocks are interlayered with them. They trend east-southeasterly and are steeply dipping. Uranium occurs in steep northeast trending cross-faults and associated fractures, and is concentrated where these intersect graphitic tuffaceous metasediments containing pyrite and base metal sulphides. The main ore zone is 400 m long, over 270 m deep, and has an average width of 1 m. The deposit contains 4 500 t of U, with notable amounts of Mo and Ag [18]. The discovery resulted from follow-up of an airborne radiometric anomaly caused by uranophane in the nearby conglomerate of the Dubawnt Group.

There are numerous polymetallic veins hosted by redbeds and volcanic rocks of the Dubawnt Group in the eastern part of the Thelon basin near Baker Lake [15,44]. Pitchblende is closely associated with base metal sulphides and Se and Ag bearing minerals. Traces of Au are associated with them. Most of the veins are small and discontinuous, and have little economic potential. Some of them, particularly those along or close to cataclastic zones and major faults, may however be regarded as indicative of larger deposits in their vicinity that have little surface expression, as is the case for the deposits along the St. Louis fault in the Beaverlodge district.

Miller and LeCheminant [15] have described five sub-types of uranium occurrences : fracture-controlled, redbed associated, alkaline intrusion related, fluorite granite contact related and enrichments in

high silica rhyolite. The majority of the fracture-controlled occurrences are near the fault boundary of the Dubawnt Group, and occur in the basement rocks as well as in the Dubawnt Group sediments, volcanics and related trachytic dykes and sills. Examples include occurrences in or near the fault zone trending east-northeast along the Thirty Mile Lake. The redbed associated or 'Kazan-type' occurrences have mostly disseminated mineralization in arkosic and conglomerate beds, where they are reduced and chlorite-enriched and where they are cut by lamprophyre dykes. Copper sulphides, native copper and silver in these occurrences are interpreted as continental redbed-type, essentially syngenetic-early diagenetic concentrations. Uranium is believed to have been introduced later by circulating meteoric waters where they encountered reducing conditions viz. at the sulphide-bearing zones and in the contact zones of lamprophyre dykes. Examples of such occurrences are found on Christopher Island in Baker Lake and near Bisset Lake, 50 km to the southwest. Alkaline dykes, syenitic or bostonitic in composition, cut the Dubawnt Group. They are characterized by anomalously high radioactivity due to U and Th contained in accessory minerals and locally due to pitchblende in fractures and microbreccias. Fluorite-bearing granite stocks, coeval with the rhyolite of the uppermost Pitz Formation of the group, commonly have thermally altered aureoles. Pitchblende-bearing veinlets are found within the aureoles. The high silica rhyolite of the Pitz Formation contains welded crystal-lithic tuff and phenocryst-poor topaz-bearing flow-banded rhyolite in the lower part. The topaz-bearing rhyolite shows anomalously high radioactivity, and indicates a potentially uraniferous environment which warrants more exploration [15].

Veins containing U-Se-Ag-Au are known in the Beaverlodge district, for example, at the Martin Lake and Nicholson mines [43,45,46]. They are hosted by the Martin Group. Significant amounts of platinum group metals are found in mineralized zones of the Nicholson mine, and has spurred renewed exploration interest. The recent exploration was initiated on the basis of the deposit model of the Coronation Hill U-Au mine in South Alligator valley of the Northern Territory of Australia [47]. The mineralization at Coronation Hill is of the epigenetic sandstone-type, hosted by debris flow conglomerate. At the Nicholson mine, the mineralized zones contain narrow, steep veins and fracture fillings in quartzite and calc-silicate rocks of the Murmac Bay Group in the proximity of a sill-like ultramafic body near the sub-Athabasca Group unconformity. Hematization of the host rocks is intense. One of the mineralized zones contains a Ni-Co arsenide-rich pod similar to those in unconformity-related deposits. The pitchblende dates from the mine are 1100 Ma and younger [41]. It appears that there are two or more styles of superimposed mineralization at the Nicholson mine. The mine had a small production of Cu-Au ore in mid-1950's [46].

(iv) Unconformity-related deposits

Since the discovery in 1968 of the Rabbit Lake deposit, some 20 deposits and prospects of the unconformity-related type have been found in the Athabasca basin. Their uranium content exceeds 360 000 t [12]. Most have average ore grades in the range of 0.4 to 2.0 per cent U. However the largest of them is the as yet unmined Cigar Lake deposit which contains proven reserves of 110 000 t U in ore averaging 12 per cent U , and an additional estimated 38 000 t U in ore grading 4 per cent U. General features of the deposits in this group and their origin are briefly summarized below, and for further information reference should be made to the literature cited, in particular to the 'Uranium Deposits of Canada', CIM special volume 33 (1986).

The orebodies straddle the sub-Athabasca Group unconformity or occur within a few tens of metres above or below it. They are commonly elongate in plan, and in cross-section have oval or bulbous outline tapering downwards, but some orebodies are more irregular in outline. They range up to 1.2 km in length, 200 m in width and several tens of metres in thickness. The 'root' may extend in the basement for more

than 100 m, particularly where the deposit has been affected by post-ore fault movements and uranium is redistributed and/or additional uranium is introduced. The long dimension is controlled by a fault zone and/or certain metasedimentary horizons in the basement, mainly graphitic metapelites and calc-silicate units. The ore is made up mainly of one or more generations of pitchblende and coffinite, commonly accompanied by nickel arsenides and sulphides, and varying amounts of Co,Fe,Cu and Mo minerals, and, in a few deposits, by Au and selenides. Characteristic alteration minerals are illite in sandstone and chlorite in the basement rocks, and the associated secondary minerals are kaolin, sericite, quartz, hematite, and tourmaline in varying proportions. The mineral assemblages and fluid inclusions indicate temperature of formation in the range of 150 to 250 °C. The isotopic data on pitchblendes show considerable discordance and scatter, as seen from the plots shown in Figure 5 for two representative deposits, namely the Rabbit Lake and Key Lake deposits [48,49,50]. They indicate however that the oldest pitchblende phase formed approximately 1300 Ma ago.

Several hypotheses of origin of these deposits, involving hypogene, diagenetic or supergene processes, or a combination of these, have been proposed [51,52,53,54]. One that seems to better explain the characteristics of the deposits is the diagenetic-hydrothermal model, which postulates large scale circulation of oxidizing waters in the basin [52,55]. These waters scavenged uranium from the Athabasca Group and the basement rocks. At the unconformity, relatively greater porosity facilitated lateral flow. Uranium was precipitated from the solution where this flow encountered reducing conditions. This most likely happened where the flow met another circulation cell rising from the basement along fault zone or favourable strata and carrying reductants. An oxidation-reduction front was then established, and may have remained stationary over a certain length of time [55].

Localization of most of the deposits, including the large Key Lake and Cigar Lake deposits, at graphitic horizons in the basement is a feature important in exploration and assessment of resource potential of favourable areas. The horizons are garnetiferous metapelites containing up to 50 per cent graphite. They are metamorphosed to upper amphibolite facies, and graphite is therefore thermally highly mature and has high reflectance. It is apparently depleted at some of the orebodies. In the diagenetic-hydrothermal model, graphite at the unconformity is believed to have reacted with mineralizing waters and produced hydrocarbon reductants [52,55]. Other aspects of graphitic horizons that may have played a role in localization of the deposits are: electrical and thermal conductivities of graphite, presence of pyrite and other sulphides, syngenetic concentrations of uranium and other elements, and structural incompetency relative to other rocks in the basement favouring localization of faults and shear zones and thereby providing channelways for water circulation.

The temperature of formation of the deposits is believed to be in the range of 150 to 250 °C. This temperature is attainable through simple burial, since it is conceivable that the Athabasca Group, and also the Thelon Formation, were at one time overlain by a few kilometres of younger strata, as in case of the Hornby Bay Group mentioned before. An alternative to simple burial, invoked by Hoeve and Quirt [55], is the temporal variations in heatflow associated with episodic intrusions of the Mackenzie diabase dykes. In support of this, they cited two sets of dates showing overlap in the 1350 and 950 Ma range: the K-Ar dates yielded by the Mackenzie diabase dykes on one hand and the U-Pb pitchblende dates from the unconformity-related deposits on the other hand. Considerable variation however is inherent in the K-Ar age determination of these mafic intrusions, and hence the indicated time range must be regarded with caution. For example, three K-Ar whole rock dates obtained by the writer [33,56] from a 2 m thick Christie Bay sill (Fig. 2), representing the lower

chilled margin, the central part and the upper chilled margin, are 1219 ±14 Ma, 1085 ±34 Ma and 1249 ±15 Ma respectively. The Christie Bay sills are cut by the Mackenzie diabase dykes. Paleomagnetic data on various Mackenzie intrusions, in conjunction with the K-Ar age determinations and field relations, indicate ca. 1250 Ma as a reasonable time for the Mackenzie igneous activity [29,30,31,33]. Emplacement of the dyke swarm as visualized by Fahrig [31] resulted from a continental rift north of the Coppermine Homocline, upwelling of mafic magma along the rift and injection of dykes across it with mainly lateral propagation. He points out that the dykes all have their paleomagnetic poles within a rather small area, and all have the same magnetic polarity, indicating either rapid emplacement of the dykes or longer periods between magnetic reversals during the Proterozoic time than in the more recent time. Rapid emplacement of the dykes seems more likely. A direct relationship between the dykes and the formation of the unconformity-related deposits invoked in the diagenetic-hydrothermal hypothesis [55], is however difficult to establish. There are only a few dykes in the region of the Athabasca basin (Fig. 3), and none are reported in the ore zones. One of the dykes in the Thelon basin cuts the Kiggavik deposit and is thus clearly post-ore. Build-up of rich uranium concentrations seen in the unconformity-related deposits would appear to require a much longer time than the dyke emplacement and the attendant local heat supply over a short time. On the other hand, the isotopic equilibrium in the open systems represented by the deposits is highly susceptible to continuous as well as episodic resetting. This is clearly seen in the discordance and scatter of the points on the concordia plot (Fig. 5) that are typical for the deposits in this group. It can therefore be argued that the oldest dates merely reflect an episodic isotopic re-equilibration at the time of the Mackenzie igneous activity, and the initial and apparently the most important concentration of uranium in the deposits may be significantly older.

The source of uranium is debatable; some workers consider the Athabasca Group as an adequate source, while others think that uranium was derived from the basement rocks. There are certainly many fertile source rocks and protores in the basement as noted above. The role of paleoweathering may also be important in that it could have liberated uranium from the source rocks and rendered it labile. Additional uranium was likely brought in the basin during sedimentation. Mechanism to concentrate available uranium in the deposits was operative sometime during the following 400 million years. Some of the uranium that was fixed in the authigenic apatite, however, was not available for such concentration.

The geological setting of the Thelon basin is very similar to that of the Athabasca basin. Hence the processes that formed the deposits in the Athabasca basin may be expected to have operated in the Thelon basin. Evidence for this is recognizable in the Kiggavik deposit and the Boomerang Lake prospect (Fig. 1).

The Kiggavik (formerly Lone Gull) deposit is entirely in the basement rocks. The Thelon Formation is eroded at this locality, but some paleoweathering features are recognizable. The ore bodies are located in an east-northeast trending fault zone dipping steeply north and intersecting the contact between an impure quartzitic metasedimentary unit and intrusive fluorite granite [57]. The quartzitic unit is feldspathic wacke and contains biotite, muscovite, chlorite and sericite in variable amounts up to 40 per cent, and some disseminated pyrite. Some pelitic and iron-rich horizons are intercalated with it. It is believed to be Aphebian in age. Near the ore bodies, the quartzite and granite are strongly altered to illite, sericite, chlorite and hematite. Uranium occurs as pitchblende and coffinite, mostly in fractures cutting clay altered quartzite and granite. Pitchblende occurs as disseminated granules and colloform aggregates; coffinite is paragenetically younger. The deposit is mineralogically simple, but traces of chalcopyrite, galena, pyrite, molybdenite, clausthalite, Ni and Bi-Ag tellurides are present (14).

The main and central ore bodies are 500 m apart and plunge gently to the east-northeast. They contain a total of 15 000 t U with an average grade of 0.5 per cent U. A post-ore diabase dyke of the Mackenzie swarm cuts the main zone. Among the pitchblende dates obtained, the oldest is 1403 Ma and others range from 1000 to 1.8 Ma (W. Hilger, Urangesellschaft Canada Ltd., personal communication, 1987). K-Ar dates on intensely altered quartzite and granite are 1386 and 1362 respectively. Thus, it appears that the Kiggavik deposit has many features in common with the unconformity-related deposits, but also resembles the vein-type deposits in the structural control, rather simple mineralogy and non-graphitic host rocks. It is conceivable that older vein-type mineralization may have existed at the deposit, but is thoroughly reconstituted and enriched by the processes that formed the unconformity-related deposits.

The Boomerang Lake U-Au prospect is the first evidence of clearly unconformity-related mineralization hosted by the Thelon Formation [58]. Uranium and gold concentrations were encountered in three intersections, up to 2 m long within a 7.5 m length of a drill hole, in the basal Thelon sandstone, immediately above a graphitic and garnetiferous metapelite unit in the basement. An adjacent drill hole intersected uranium concentrations over a 3 m length in the basement rocks, 2 m below the unconformity. The best intersection assayed 0.42 per cent U and 25 ppm Au over 0.5 m, and it was in the sandstone at the unconformity. This mineralized section is mostly gray, friable material containing sand grains and clay minerals. Polished thin sections of less friable parts of the section show pitchblende concentrations mainly along the margins of pyrite veinlets, which cut authigenic apatite in the sandstone matrix. Associated minerals are galena, chalcopyrite, Co-Ni selenide, Cd-diselenide, Cr-V bearing illite, hematite, limonite and goethite. No visible or microscopic gold was found. Anomalously high contents of Pt and Pd were detected in a Se-rich sample. The altered rocks in the vicinity of mineralized intersections contain anomalously high amounts of Ni, Co, V and Cr. Isotopic analyses of two pitchblende-bearing samples indicate an age of approximately 1300 Ma for the mineralization (Fig. 5).

The graphitic metapelite in the basement at the Boomerang Lake prospect is one of several graphitic zones in a predominantly quartzo-feldspathic metasedimentary belt up to 10 km wide with a northeasterly trend and moderate to steep dips. Tight folds, faults and mylonitized zones are observed in the belt. The sequence may be highly metamorphosed equivalent of the Amer Group, but lithological correlation over the distance involved is not reliable. The graphitic zones have been detected by geophysical methods under the thick and extensive overburden for several kilometres southwest of the prospect, and they extend under the Thelon sandstone for a few kilometres northeastwards at increasing depth. In addition to these favourable graphitic zones, there may be fault structures similar to that at the Kiggavik deposit. The Boomerang Lake region is thus highly prospective for further exploration.

The U-Au-Se association found in the Boomerang Lake prospect is comparable to that in the 'D' ore body at Cluff Lake [35] and the Nicholson mine [45]. A similar metal association is also found in some pebbles in the glacial drift material in the Bathurst Inlet area near the Ellis River Formation [59], and in the region between Amer Lake and the margin of the Thelon Formation. The metal-rich pebbles are regarded as derived from undiscovered unconformity-related deposits.

CONCLUSIONS

Uranium potential of the Thelon basin region must be regarded from the standpoint of the geological similarity with the Athabasca basin region, and the parallelism of the history of the basement and the sandstone in the two basins. The uranium concentration mechanisms that operated in the region of the Athabasca basin certainly operated in the Thelon basin region, and most probably on the same scale. The

resultant resources known in the Athabasca basin region are large and potential for additional discoveries exists in this prolific region. The currently known uranium resources in the relatively much less explored Thelon basin region are only a fraction of those in the Athabasca basin region. Judging from the geological similarities of the two regions, the resource potential of the Thelon basin region must be rated very high.

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DISCUSSION

R. A. OLSON : I gather from your talk that there is a significant amount of gold associated with uranium in the Boomerang Lake deposit. Could you please give some assay results and tell us how reliable they are ?

H. FUCHS : Boomerang Lake we don't have a 'deposit' but only a 'prospect' at this stage, as Dr. Gandhi has properly called it. We like to emphasize that point here.

S. S. GANDHI : Yes, it is essentially a prospect at this time, although a promising one. Your question regarding the gold assays is important; I am sorry I forgot to give the assay values. The best assay is 25 parts per million gold associated with 0.424 per cent uranium over half a metre drill length in hole BL-83-21. The intersection was shown in one of the slides; it is in the Thelon sandstone right at the unconformity. Other uraniferous intersections also contain some anomalous gold and silver values. The gold values are from fire assays, and are supported by a second set of fire assays from another laboratory on the rejects of the split core samples. Of further interest is another analysis that I did not mention. It shows anomalously high contents of platinum and palladium in a selenium-rich sample from the high grade uranium-gold intersection. Analysis of this 10 gm piece of drill core showed 82 parts per billion platinum, 160 parts per billion palladium and 1229 parts per million selenium.

KIGGAVIK (LONE GULL): AN UNCONFORMITY RELATED URANIUM DEPOSIT IN THE THELON BASIN, NORTHWEST TERRITORIES, CANADA

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Abstract

Among several uranium prospects in the Baker Lake area, located at the northeastern rim of the Thelon Basin, the Kiggavik (Lone Gull) deposit is at an advanced exploration stage. Two ore zones, the Main and Centre Zones have been explored by drilling spaced 30 m x 15 m and reserves of over 40 million lbs U308 with an average grade of 0,6 % U308 are indicated.

The Kiggavik mineralization is basement hosted in mica rich quartz-feldspathic metasediments of probably Aphebian age and in a late Hudsonian granite. The level of erosion reached in the area of the deposit below the Middle Proterozoic Thelon Sandstone, has removed traces of the Aphebian paleo-surface and parts of the deposit, leaving the closest outcrops of the unconformity approximately 2 km to the north.

A post-ore diabase dyke has intruded the Main Zone with the effect that some ore was redistributed. Parallel, cigar-shaped ore lenses and the surrounding alteration halos are defined by sets of crosscutting structures. The strike of the lenses in the Main Zone is ENE and they plunge at 25° in the same direction.

In the Centre Zone, located on strike approxiamtely 600 m ENE of the Main Zone, the mineralization occurs in meta-arkoses and schists. A barren orthoquartzite horizon controls the form and separates two ore lenses. Graphitic series are not known in the vicinity of the deposit but organic matter is found in all ore zones.

Kiggavik is a monometallic deposit with pitchblende and coffinite as the main ore minerals.

Common features with uranium deposits in the Athabasca basin such as a general relation to the unconformity, similar alteration, structural control, presence of diabase dykes and chronology of the deposit etc., emerged in the course of exploration. However, Kiggavik possesses some features such as the particular form of the ore lenses in the basement and in the granite,the uncertain extent of these mineralized lenses towards the unconformity and the absence of graphitic horizons, which are not as generally known in these types of deposits and make in combination a unique setting.

INTRODUCTION

The Kiggavik project, previously called Lone Gull, lies in the Keewatin District of the Northwest Territories of Canada, about 80 km west of the Inuit Hamlet of Baker Lake, or 350 km west of the northwestern part of Hudson Bay (Fig. 1). Though Baker Lake Hamlet is regularly serviced by scheduled airline and in summer by barge service, the project site can only be reached from Baker Lake by float plane or helicopter.

Since 1974 Urangesllschaft has been working in the Baker Lake region. This area was selected for uranium exploration due to its apparent similarity with the eastern part of the Athabasca Basin. From the start the aim was to find a uranium deposit of the unconformity type. The envisaged size was that of Rabbit Lake. Due to severe land use restrictions in the late seventies and the extremely short field seasons the actual field work occupied only about three years since starting the project.

GEOLOGY

The Thelon Basin covers a large area of the western part of the Keewatin (Fig. 2). It overlies a series of rocks, ranging from Archaean Basement to Aphebian rocks of various metamorphic grades. Belts of Aphebian sediments and metasediments are folded into the Archaean Basement consisting of augengneiss, granodiorite gneiss and narrow greenstone belts. Shallow marine sediments of probably Early Aphebian age belonging to the Hurwitz (= Amer?) group (or Archaean?) were deposited on to the Archaean Basement. During the Hudsonian Orogeny they underwent various degrees of metamorphism - from lowest greenschist facies to upper almandine amphibolite facies. Late Hudsonian, post tectonic granites intruded in the metamorphic belt. These units were followed, after the formation of structurally controlled depressions, by the deposition of continental sediments and volcanics of late Aphebian age (Miller et al. 1986). They belong to the Dubawnt Group. The general structural trend of these rock units is 65° ENE.

The pre-Thelon rock formations underwent an intensive peneplanization, i.e. a strong weathering mainly under oxidizing conditions leading to strong laterization of the older crystalline basement rocks. This lateritic weathering surface is preserved regionally as regolith, which has been destroyed only partially by the transgression of the Thelon sediments of Helician age, being somewhat older than the sediments of the Athabasca Group. A flat lying thick sequence of mature sandstones, shales and conglomerates characterize this formation. Diabase dykes of Hadrynian age cut all older formations in a NNW direction.

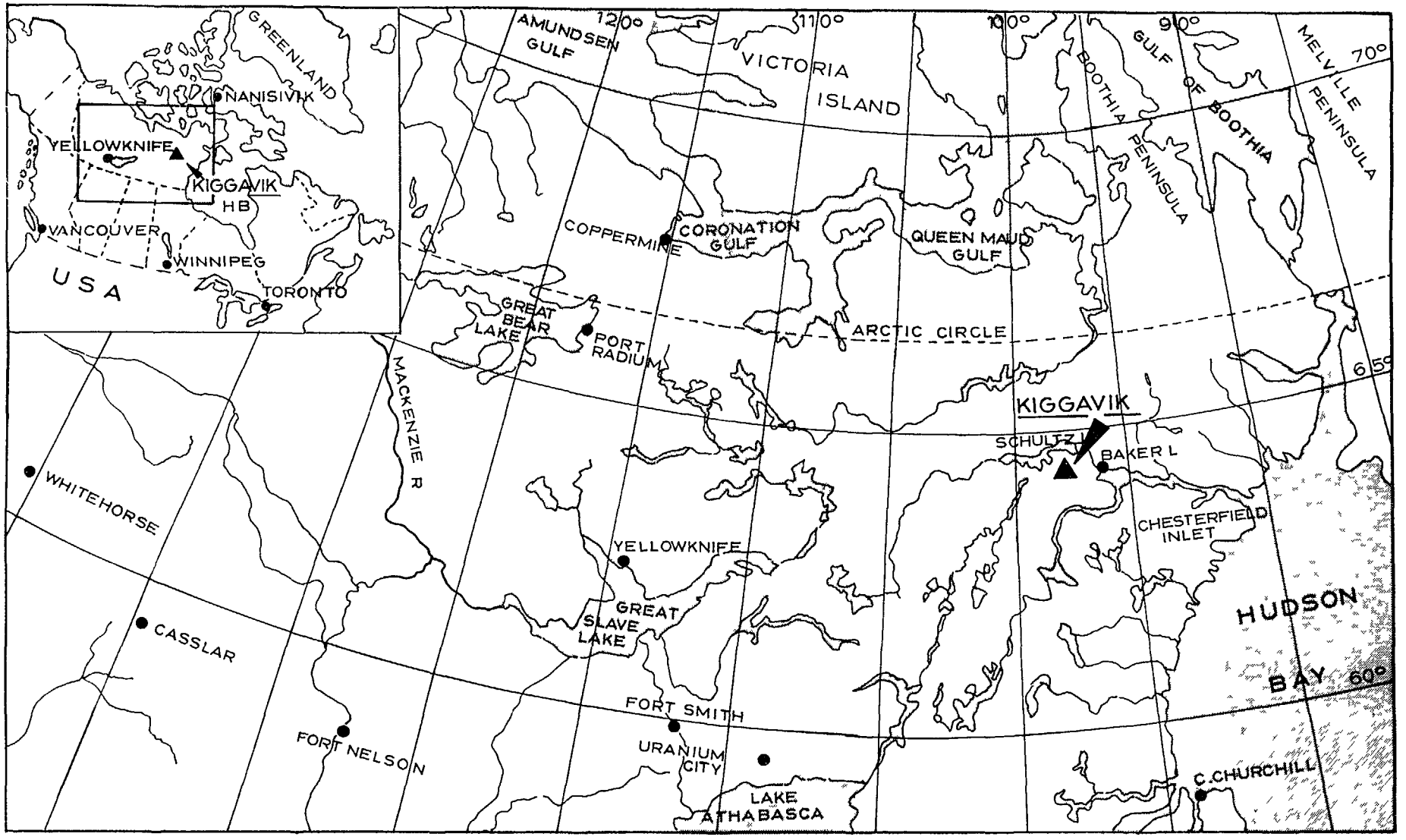

FIG 1 Kiggavik (Lone Gull): general location map

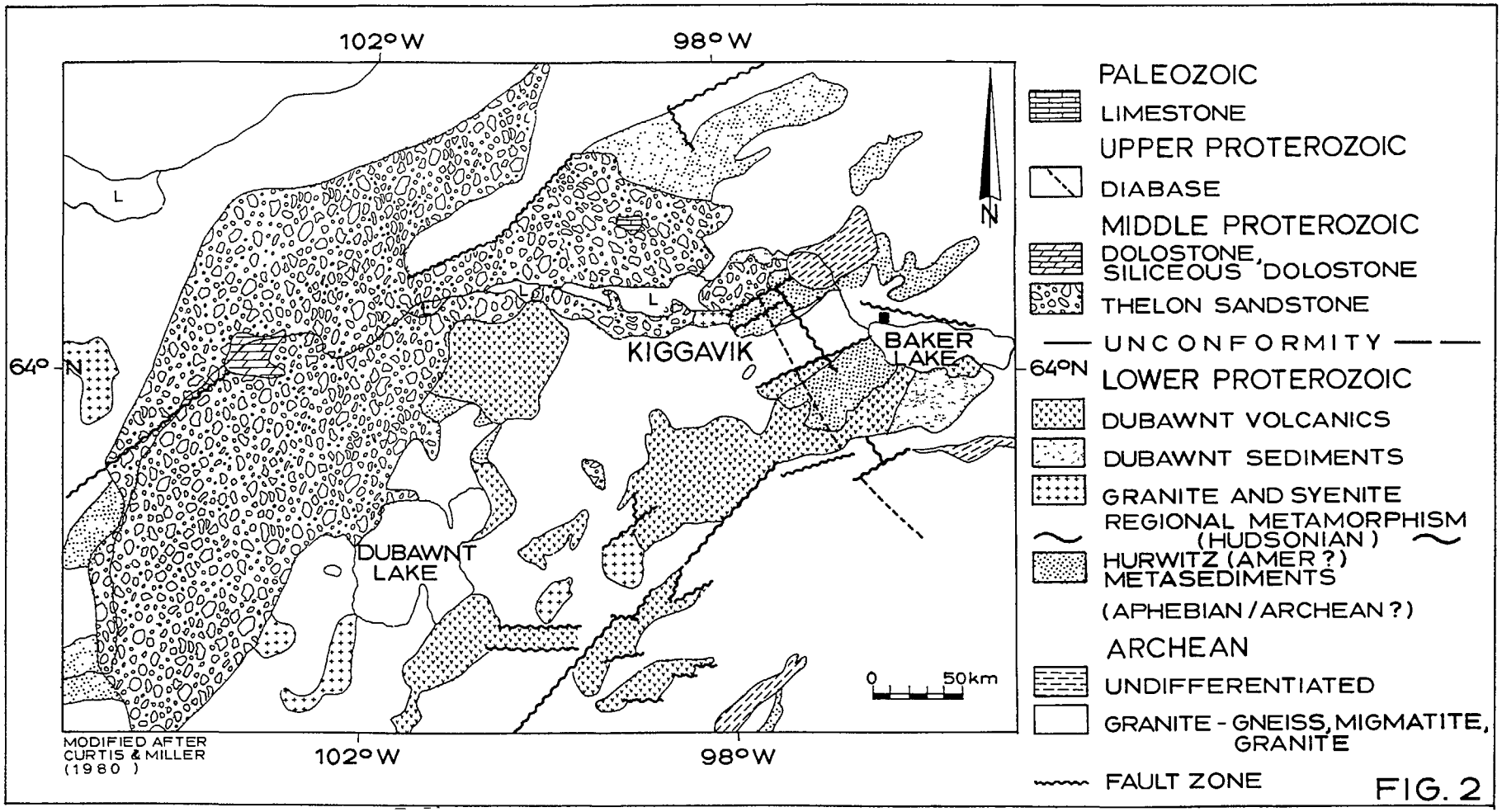

FIG.2. Kiggavik (Lone Gull): regional geological map of Central Keewatin N.W.T.

The uranium ore bodies of Kiggavik (Fig. 3) occur about 2 km south of a faulted contact with the Thelon sandstone within the lowermost metasediments of the Hurwitz (= Amer?) Group (Fig. 4). The host rocks are a sequence of metaarkoses and metapelites which are overlain by orthoquartzites. One of the ore zones reaches into an Hudsonian fluorite granite which is an S-type granite rich in K-feldspar with a high Ba content. This granite has no higher background in uranium.

Structurally the area around Kiggavik is situated between two ENE trending regional fault zones, the Thelon fault in the north and the North Sissons Fault Zone in the south, being about 11 km apart. The ore bodies lie in a small 95°E running graben structure cutting the granite with well developed 65° ENE shear zones (Fig. 5). Cross cutting faults of probably much younger (Hadrynian) age, sometimes filled with diabase, only affected very slightly the older geology.

DESCRIPTION OF ORE BODIES

At Kiggavik there are two ore bodies, the Main and Centre Zones, located 600 m apart following the same shear zone which has a 65°ENE direction.

In both zones two lenses are developed. In the Main Zone the 10N lens and the 65N lens, named after their relative position to the base line and a lower and upper lens in the Centre Zone.

A surface projection of the Main Zone ore body shows two parallel distinctly cigar-shaped lenses following the 65°ENE direction (Fig. 6). Only where the diabase cuts the metasediments and the granite, the ore lenses are somewhat deformed. There the ore follows the diabase structure downdip. Each of the lenses has a length of approximately 300 m and is originating at the intersection of a 65°ENE fault zone with a prominent 95°E fault direction separating the granite and metasediments. Some variation in width and thickness of the ore lenses can be seen from section to section, but in general a thickness of 20 to 30 m and a width of 30 to 50 m or more is observed. A plunge of approximately 25° in a 65°ENE direction is characteristic. The ore lenses in the sediments end at a depth of approximately 150 to 190 m below surface. Despite the possible presence of cross fault zones, there is at present no evidence that the ore is terminated or displaced by faults in a major way. In the west both ore lenses come to surface and are in part eroded. It only can be speculated how far the mineralization extended over the present level of erosion and a possible connection with the unconformity. Sections 8+00W, 0+0 and 5+50E (Fig. 7, 8, 9) illustrate the form and the position of the ore lenses and a longitudinal section provides a picture of the plunging lenses (Fig. 10).

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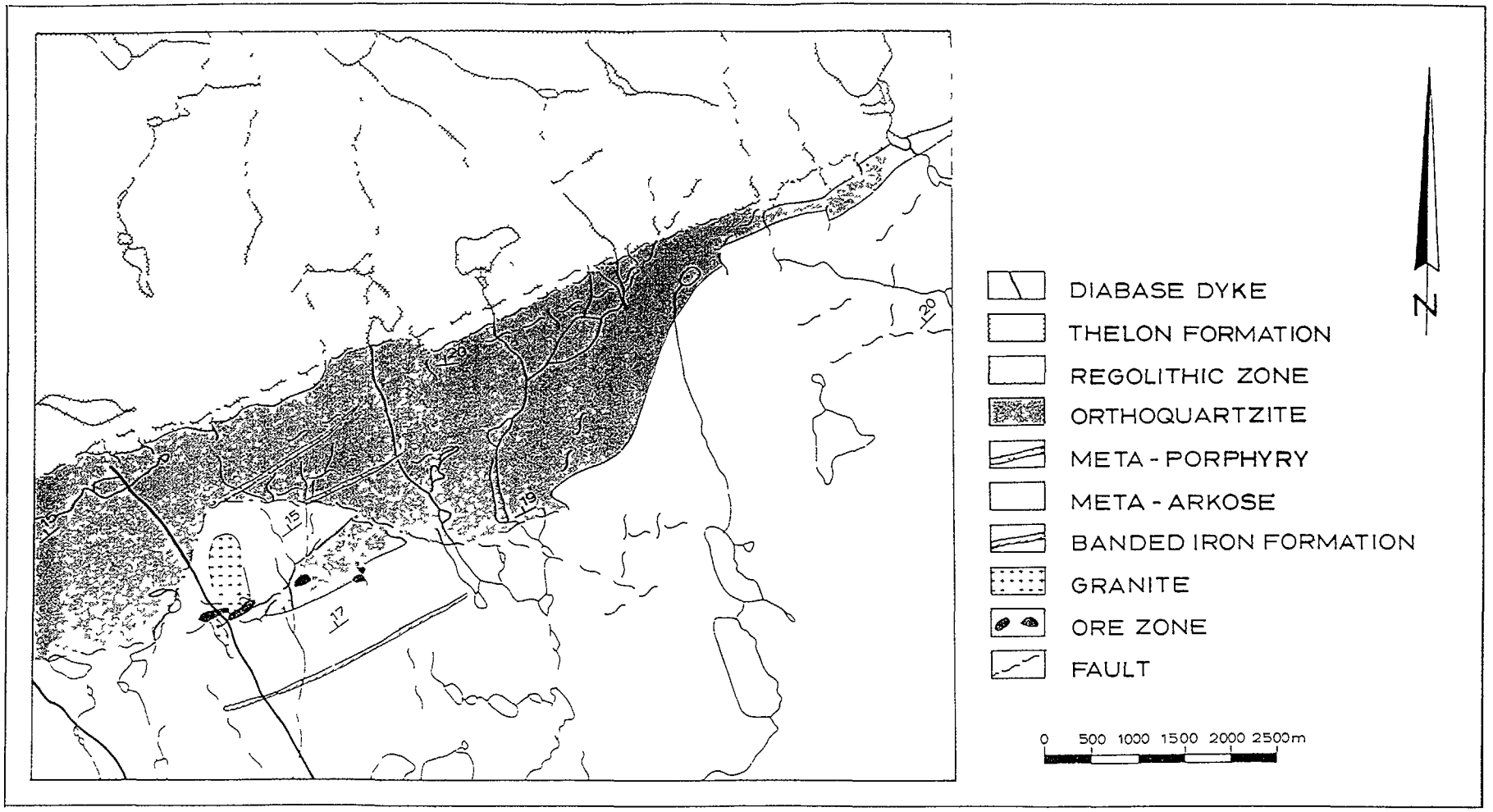

FIG 3 Kiggavik (Lone Gull) regional geological map

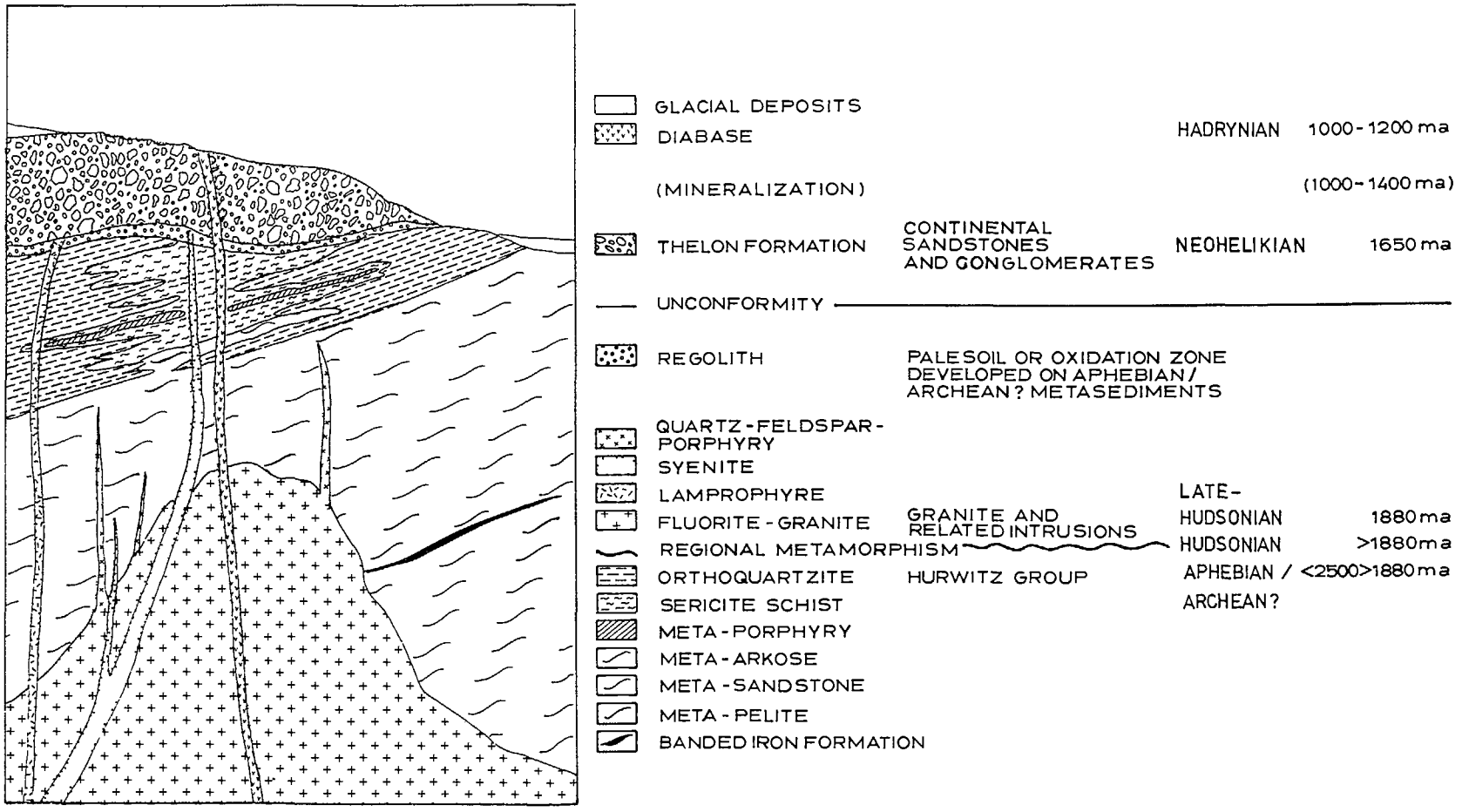

FIG.4. Kiggavik (Lone Gull): stratigraphic sequence.

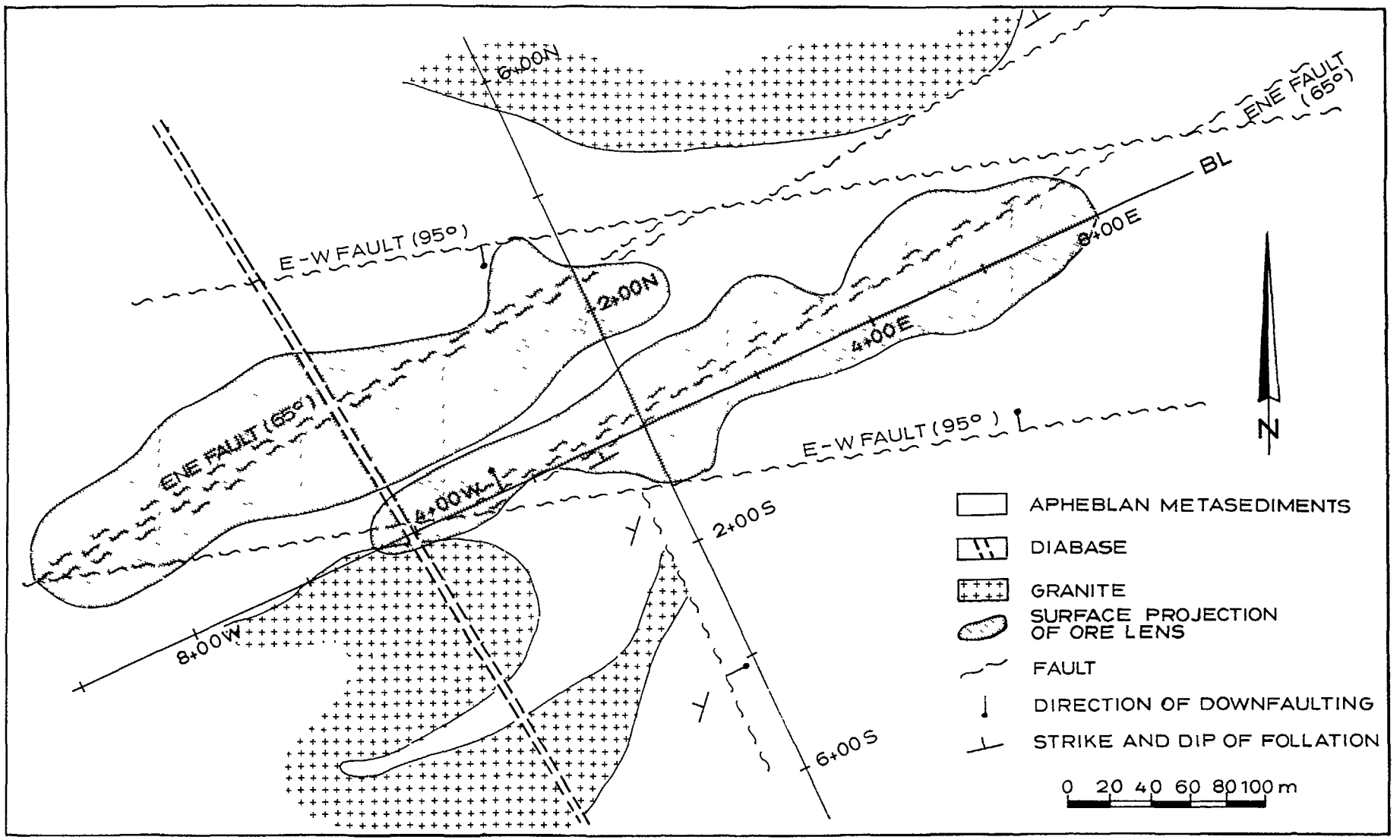

FIG.5. Kiggavik (Lone Gull): main zone — geological map.

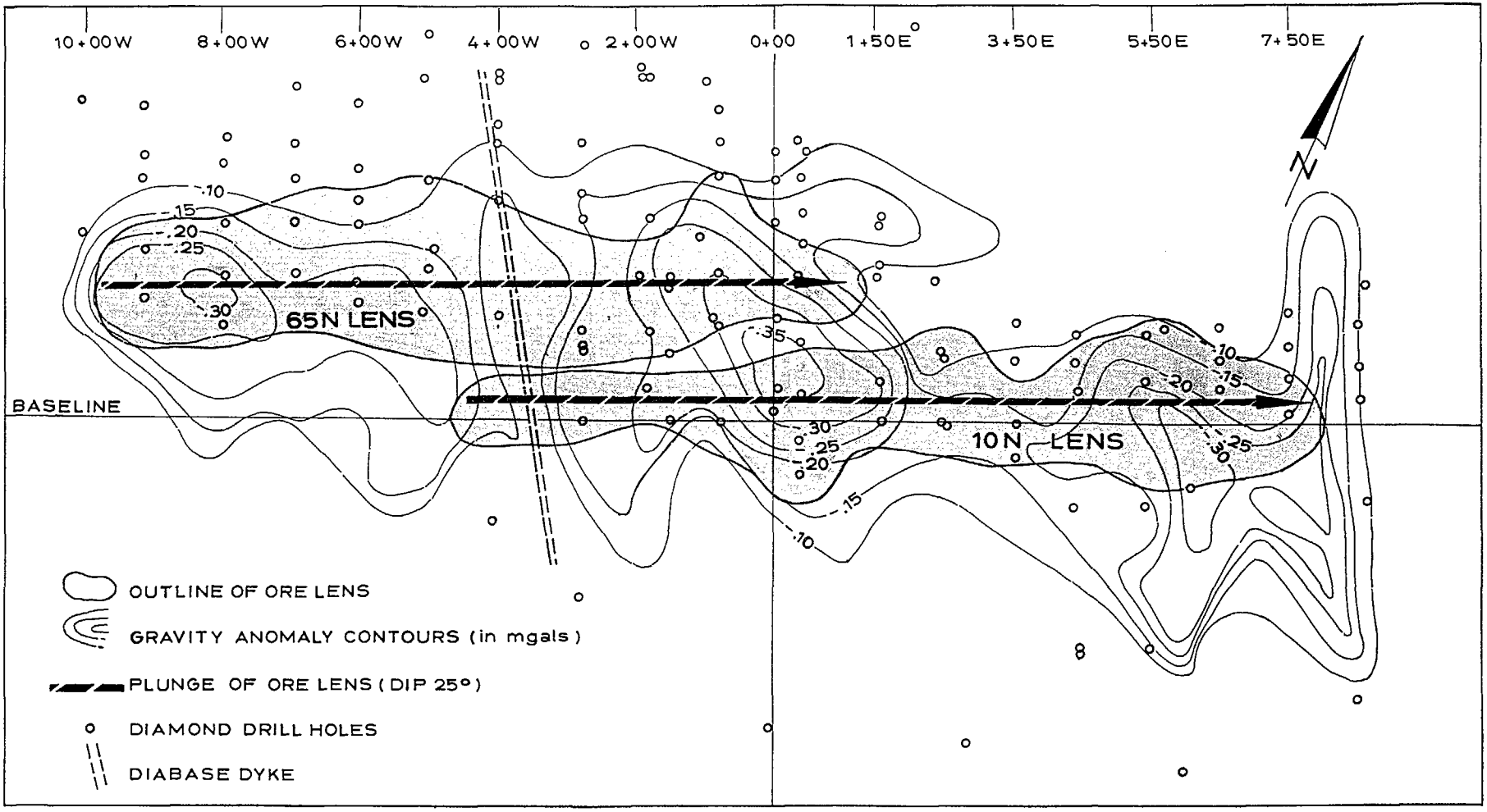

FIG.6. Kiggavik (Lone Gull): main zone gravity anomaly and ore lens.

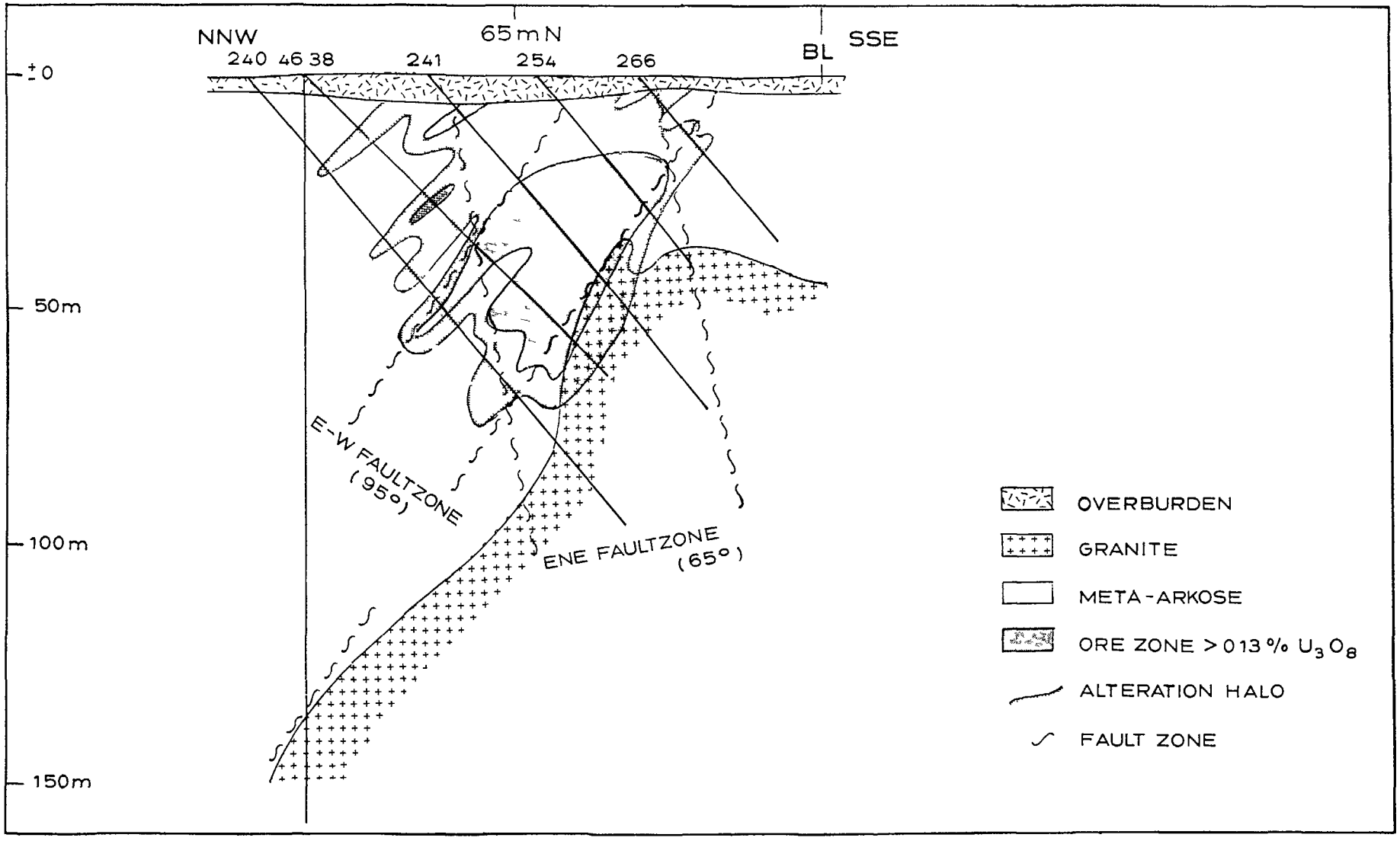

FIG 7 Kiggavik (Lone Gull) main zone, section 8 + OOW (240 m W)

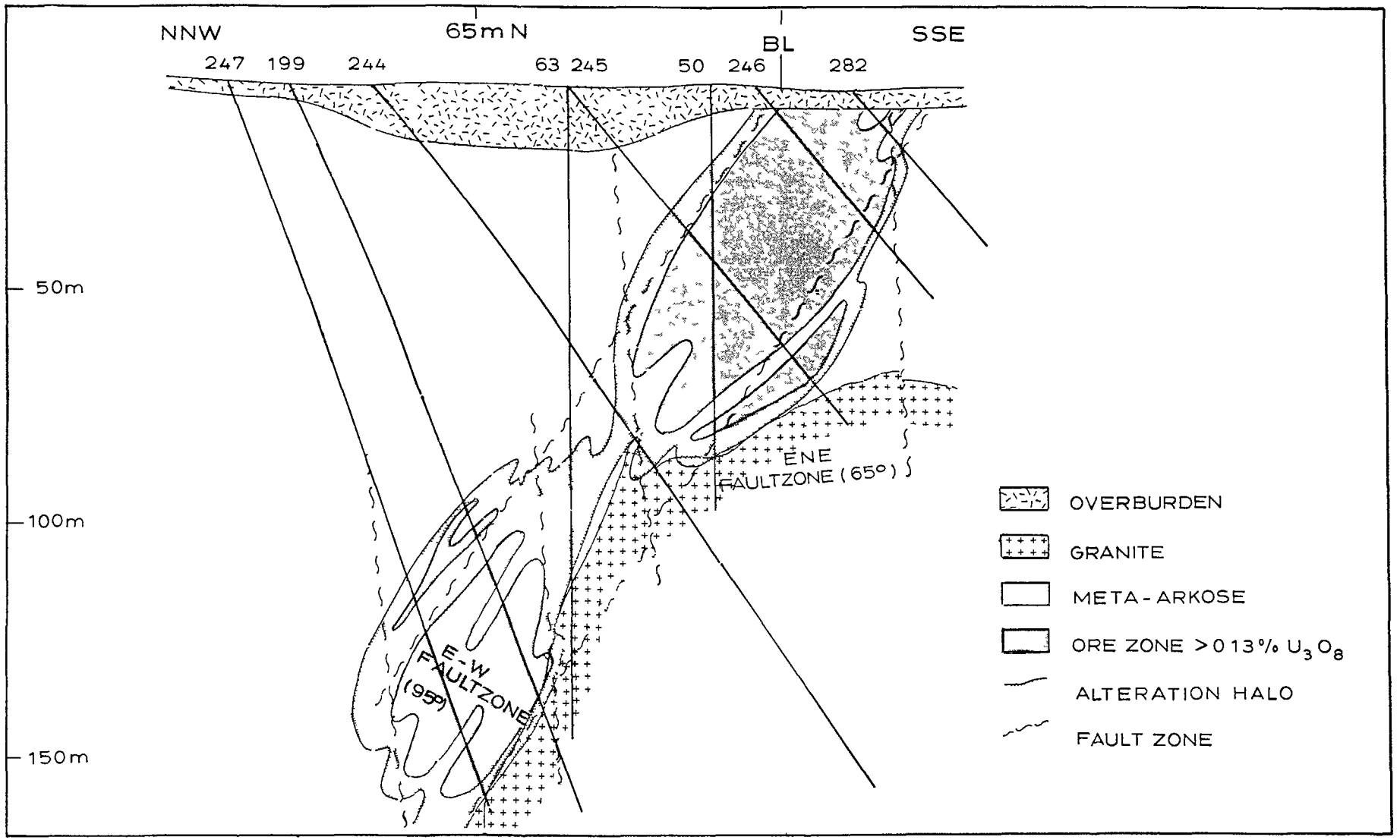

FIG 8 Kiggavik (Lone Gull) main zone, section O + OO (0 m W/E).

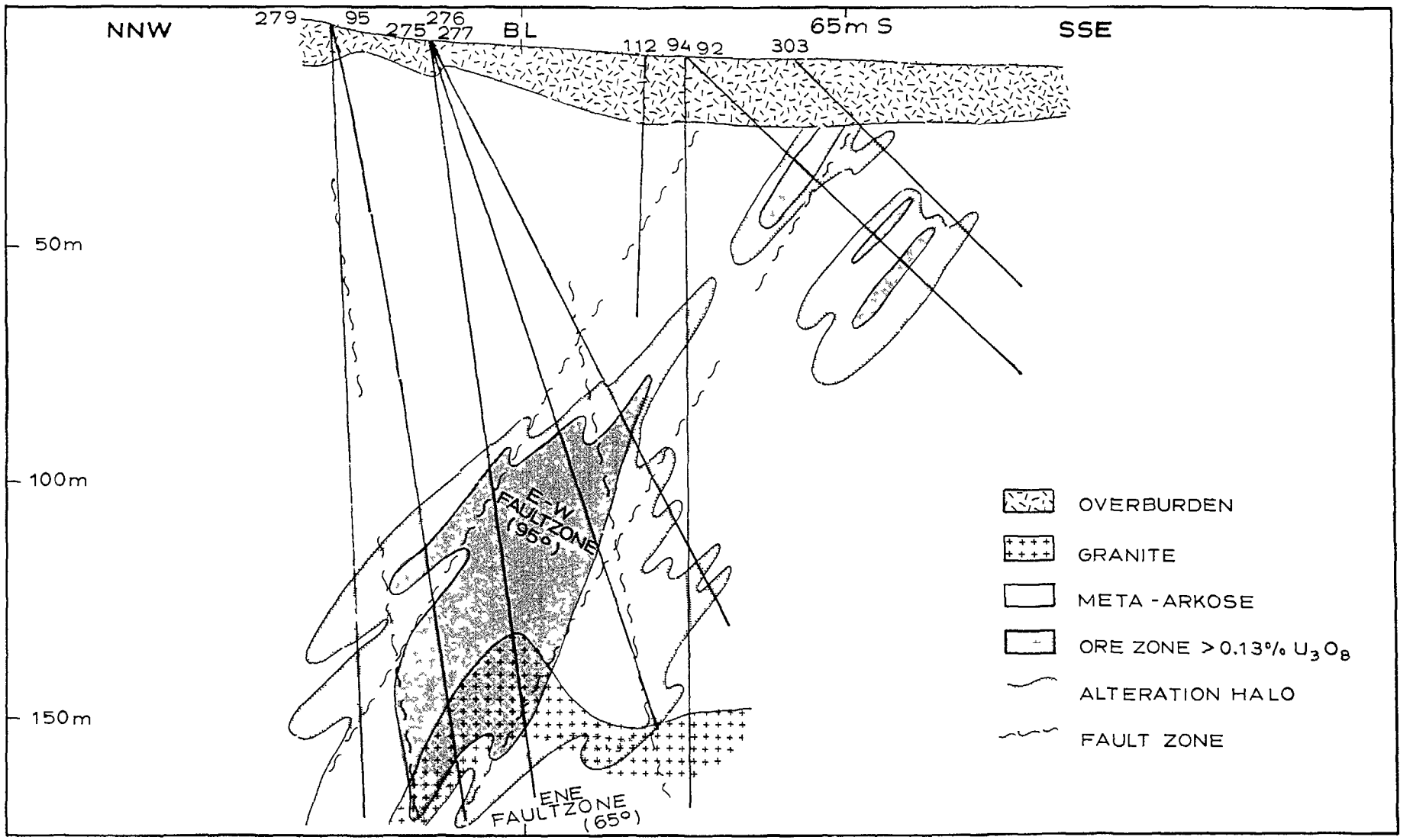

FIG.9. Kiggavik (Lone Gull)· main zone, section 5 + 50E (164 m E)

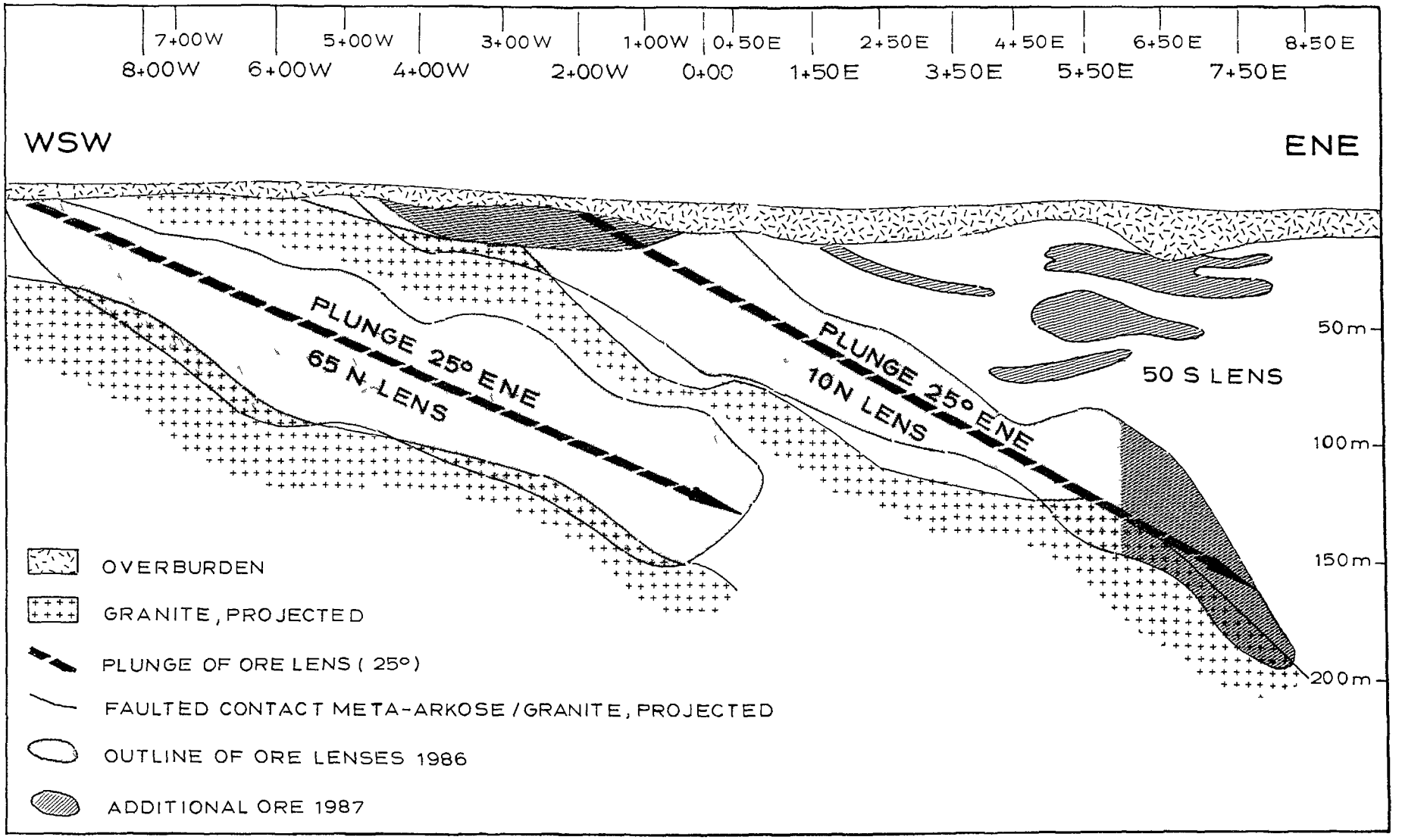

FIG 10 Kiggavik (Lone Gull) main zone, WSW–ENE — longitudinal section with projected ore lenses and granite contacts

Sections through the Centre Zone ore body show two well defined ore lenses, one below and one above an orthoquartzite horizon (Fig. 11, 12). The lenses follow closely the shallow dip of the orthoquartzite to the north. The mineralization reaches a thickness of 30 m in each of the lenses, the length of the ore zone is approximately 150 m and the maximum width about 100 m. Almost the total mineralization is found above a depth of 100 m in the Centre Zone.

RESERVES

There are several mineralized zones within Urangesellschaft's properties in and around Kiggavik, but only the Main and Centre Zones have been drilled in detail. The average drill pattern in both ore bodies is 30 x 15 m .

In the Main Zone there are two individual ore lenses, the 65N lens and 10N lens, each having a distinct average grade: 0.45 % U308 and 0.81 % U308 respectively. The combined geological reserves of the Main Zone amount to 2,425,000 t of ore averaging 0.58 % U308 in both lenses (Table I).

In the Centre Zone both ore zones have an average grade of 0.78 % U308 and contain 560,000 t of ore.

The total geological reserves for these two orebodies - up to the end of 1986 - are about 40 million pounds U308 of which about 75 % can be mined. The average grade of the ore is 0,6 % U308. An open pit operation is planned.

How the ore reserves in Kiggavik compare with major Athabasca deposits and some of their features are listed in Table II (compiled from various sources Wallis et al. 1985; Fogwill, 1985).

MINERALIZATION

Uranium is hosted for the greater part in altered metasediments, mainly metaarkose, metapelites and sericite schists and to a much smaller extent in altered granite and intrusive rocks, with the exception of the diabase. The mineralization occurs finely disseminated along foliation planes or in veinlets or seams parallel to the foliation. Also very common is mineralization filling fractures and forming coats on fracture walls crosscutting the foliation.

The two major uranium minerals are pitchblende and coffinite. Secondary uranium minerals are not very common. Fine grained uranophane occurs in weathered rocks at surface but also occasionally at greater depth.

Pitchblende and coffinite are often associated with marcasite and pyrite indicating replacement. Marcasite occures pseudomorph after pyrite and both are the most common sulfide minerals. Other sulfides or accessory metals are present only in minor amounts underlining the simple elemental composition characteristic of the Kiggavik ore zones.

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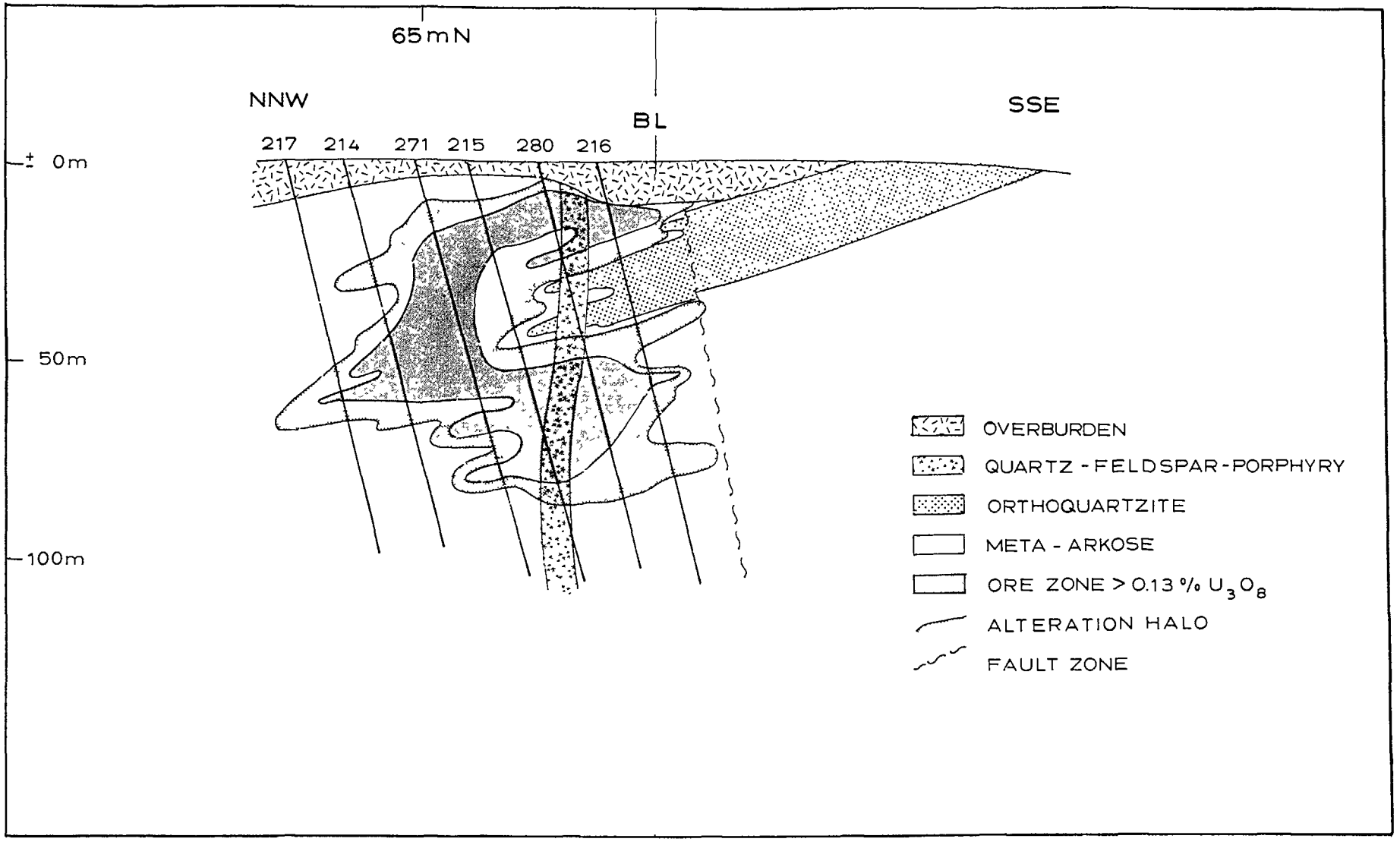

FIG.11. Kiggavik (Lone Gull): centre zone section 25 + 50E (818 m E).

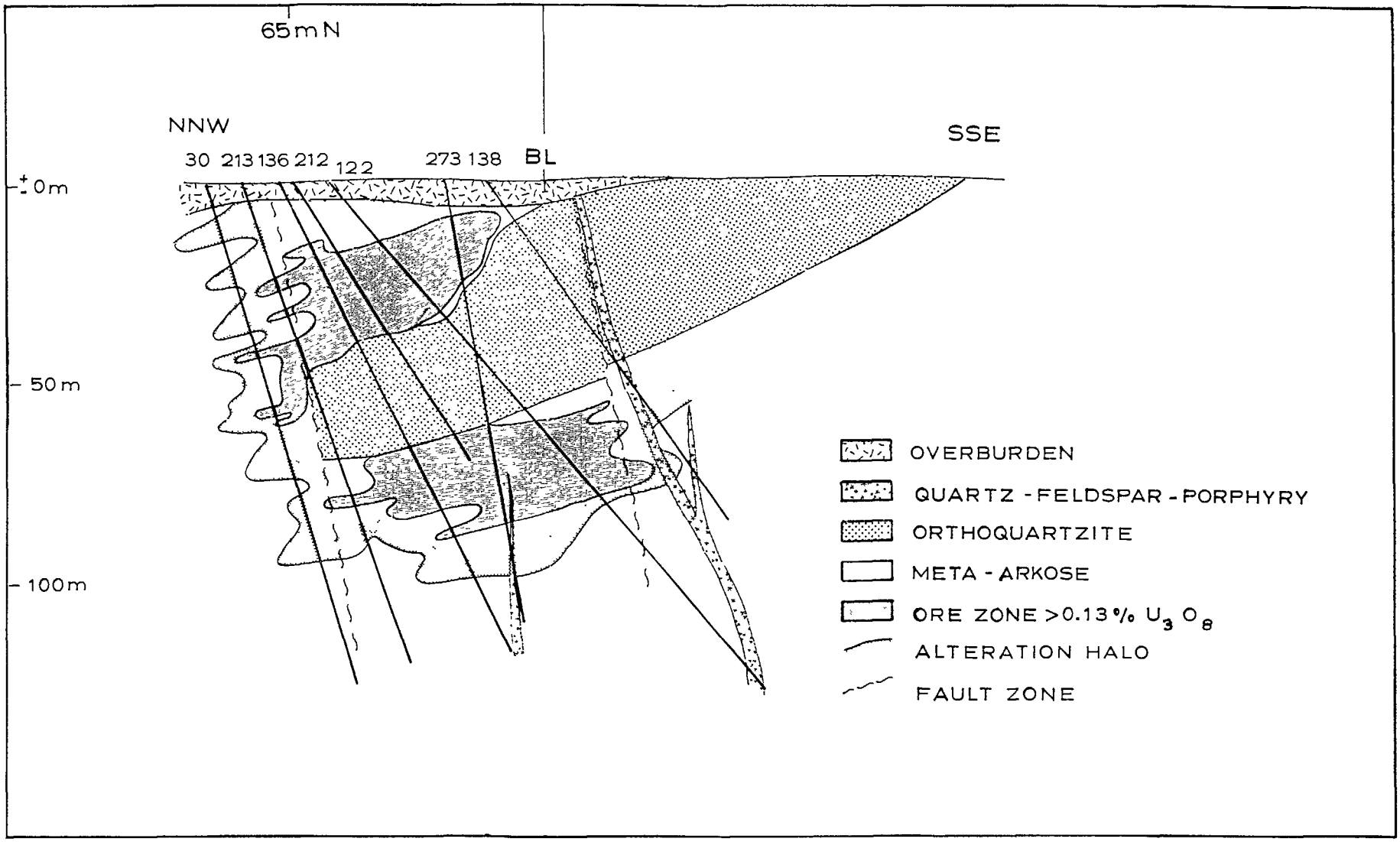

FIG.12. Kiggavik (Lone Gull): centre zone section 27 + OOE (818 m E).

TABLE I. KIGGAVIK (LONE GULL): SUMMARY OF GEOLOGICAL RESERVES (1986)

ORE ZONE	TONNES ORE ($t \times 10^3$)	GRADE $\%U_3O_8$	TONNES U_3O_8	POUNDS (lbs $U_3O_8 \times 10^6$)
Main Zone	2,425	0.58	13,978	30.7
Centre Zone	560	0.78	4,344	9.6
Total	2,985	0.61	18,322	40.3

TABLE II. SUMMARY DATA ON ATHABASCA URANIUM DEPOSITS AND KIGGAVIK

DEPOSIT	RESERVES lbs U_3O_8 x 1 million	GRADE $\%U_3O_8$	DEPTH TO TOP OF DEPOSIT (m)	HOST ROCK	ACCESSORY METALS (Ni, Cu, Co)	GRAPHITE
Cigar Lake	284	14.3	410	Sandstone Basement	yes	yes
Key Lake	198	2.4	15	Sandstone Basement	yes	yes
Eagle Point	140	1.7 - 2.3	15	Basement	no	yes
Midwest Lake	42	1.9	200	Sandstone Basement	yes	yes
Rabbit Lake	40	0.4	15	Basement	no	yes
Collins Bay B	25	0.4	18	Sandstone	yes	yes
Dawn Lake	22	1.0	90	Sandstone Basement	yes	yes
Mc Clean Lake	14	1.8	90 - 150	Sandstone Basement	yes	yes
Kiggavik *up to 1986	*40	0.6	0	Basement	no	no

ALTERATION

The uranium mineralization is intimately associated with an intensive alteration halo, underlining the close relationship between alteration and mineralization. The alteration is characterized by desilification, conversion of feldspar and mica to clay minerals and strong oxidizing and reducing features, especially in pyrite/marcasite rich rock units. Simplified, four different stages of alteration can be distinguished:

- light greenish grey coloured alteration
- light red to deep cherry red coloured hematitization
- light grey to buff coloured alteration, showing limonite staining outlining solution fronts
- chalk white, massive, extremely intensive alteration

The alteration follows a distinct structural pattern. The structures were preconditioned spacially and chemically by the Paleo-Helician laterization processes, opening the system for the later circulation of solutions. The later alteration processes were favoured by the existence of strongly hematized lateritic zones and by the abundant presence of pyrite/marcasite in the host rock. This geochemical environment was ideal for the development of the necessary redox conditions.

The alteration process has a pronounced effect on the specific gravity of the rock (Fig. 6). The decrease is dramatic from 2.7 for unaltered metaarkose to 2.1 and lower in highly altered, chalk white metasediments. The average specific gravity of altered rocks was determined as 2.3 for all Kiggavik host rocks (Miller et al.,1985). The contrast in specific gravity with granite and intrusive rocks is as big as with metasediments. Gravity surveys provide a sensitive tool to measure these contrasts and results contoured at 0.05 mgal intervals provide an interpretable picture of the alteration halo. The extent of the alteration found in drilling correlated well with the gravity results. The main structural controls of the ore lenses are visible and lithological units with higher specific gravity, such as the diabase, can be recognized.

The possible extent of the mineralization is defined by the extent of the alteration showing up as gravity lows. Drilling outside of gravity lows only seldom intersected mineralization which then was very weak or occurred at great depth.

STRUCTURAL CONTROL OF MINERALIZATION

Faults and their strike and dip direction can only be detected outside alteration zones. Results from diamond drilling revealed that similar to the Athabasca deposits, Kiggavik has linear-shaped ore lenses. The major part of the Main Zone ore is contained in two parallel cigar-shaped lenses striking 65° and plunging ENE at 25° (Fig. 6). Strike, plunge and the particular shape of the ore lenses is controlled by intersecting fault zones which were identified by drilling, geophyscial surveys and field

observations. One fault zone which controls both Main Zone ore lenses, is striking 95°E and dipping 60° to the north. This zone separates the granite from the metasediments and is characterized by a few metres wide breccia in part silicified, providing a strong VLF anomaly.

The second controlling factor for the location of the mineralization are two parallel fault zones striking 65° ENE dipping steeply south. The intersection of the 65°ENE fault zone with the 95°E fault zone is the locus for mineralization. The different strike and dip direction of the intersecting fault zones cause the plunge of the ore lenses at 25° to the ENE.

The 65°ENE direction coincides with the direction of the dirty quartzite/orthoquartzite contact and with the general strike direction of the metasediments. Significant faulting along the 65°ENE direction is also apparent in the field, as the major fault displacing the Thelon formation and several faults within the orthoquartzite follow this direction.

The recognition of this structural control of the mineralization was of great practical importance for the positioning of drill holes. Drilling followed in the early years the more prominent 95°E structural direction known from drill holes and geophysical surveys. The interpretation of the mineralization based on these data was discontinuous. Only a more detailed drill programme provided additional information so that the 65°ENE direction was recognized as the main strike direction of the ore. With this structural information the follow-up of the ore lenses became predictable with great accuracy in direction and plunge.

The mineralization of the Centre Zone is located 500 m east of the Main Zone in continuation of the 65°ENE fault direction. Faulting in this direction, visible in the field and in drill hole data, might have formed one control for the ore deposition in the Centre Zone. The second control is seen in structures, possible thrust faults, parallel to the shallow dipping orthoquartzite/metaarkose contact which provided channel ways for solutions. The ore was precipitated where the 65°ENE fault zone intersected the shallow dipping contact zone causing the characteristic shallow dip of the ore in the Centre Zone, which is quite different and steeper in the Main Zone. The centre of the mineralization of the upper lens of the Centre Zone is 40 m north of the base line while the centre for the lower lens is at 15 m N. This indicates that the 65°ENE fault zone dips 60° to 65° S. The host rocks of the lens above the orthoquartzite are feldspathic, sericitic metasandstones with interbedded sericite schist. They are different from the chloritic metaarkose which host the lower lens. Therefore, an interpretation that a mineralized horizon was tightly folded or the same horizon repeated by faulting is not conclusive to explain the two ore lenses from field observations.

For the area between Main and Centre Zone some alteration is indicated by gravity surveys but no significant mineralization was encountered in wide spaced drilling. This indicates that beside a structural system to control mineralizing fluids, uranium must be present and a lithology favourable to precipitate uranium, in order to form a deposit in a certain location.

Apart from the 95°E and 65°ENE fault zones, 350° NNW trending faults (which is also the strike direction of the diabase) and NNE faults cross cut the area. The ore lenses do not seem to be disrupted by this faulting They may, however, be responsible for minor changes in the plunge of the lenses.

AGE OF MINERALIZATION

Six mineralized samples were used for U-Pb isotopic age dating. The results of these sparse data should be treated with some caution but they suggest several events. One older event at 1400 Ma and a later event at about 1000 Ma. Young resetting of the U-Pb system is indicated at about 10 Ma.

The oldest age was obtained from deep-seated fracture controlled pitchblende within the alteration zone in the granite.

The Thelon formation has, a minimum age of 1660 Ma (Miller et al., 1985) which, however, does not correspond with the age of the Athabasca sediments, being about 1450 Ma years. In any case the uranium mineralization is younger than the Thelon sedimentation and indicates that the precipitation of uranium took place after the sedimentation has been completed. This shows a relationship typical for unconformity related uranium deposits.

GENETIC MODEL FOR THE KIGGAVIK DEPOSIT

Only a limited amount of detailed research concerning the genetic development of the formation of this uranium deposit has been conducted. Thus the following description might be subject to future changes.

The Paleoaphebian sulfide-bearing metasediments of the Hurwitz Group are enriched in uranium (6-33 ppm). They were metamorphosed, only slightly deformed and later intruded by low granites. During the following late Aphebian Dubawnt event a period of tectonic rifting, continental sedimentation and mafic and felsic volcanism took place, strongly faulting and rifting the older rock units mainly in an ENE direction (Miller et al., 1986).

At the end of the Aphebian a lateritic weathering process with intensive desilification and associated limonitization or hematitization affected the rocks, preconditioning the older Dubawnt structures spacially and chemically for later solution movements.

After sedimentation of the Thelon sandstone, diagenetic processes developed at the base of the Thelon in the sediments. The weakly developed feature can only be seen where the regolithic unconformity is exposed, not far away from the ore zones. This process was later overprinted by an intensive hydrothermal event leading to a strong hydrothermal alteration within the remaining regolithic zone of the basement as well as in strongly oxidized shear zones. Migrating solutions, probably

mainly under reducing conditions altered the oxidized regolithic zone at the unconformity and in deeper-reaching fault zones.

This process was characterized by hydrolysis of feldspar and mica, remobilization of iron, chloritization of biotite and development of sericite, hematite, and illite. Uranium-bearing solutions oscillated through the regolith and hydrothermal altered metasediments preferably in intensely sheared zones and precipitated where redox interfaces were developed. The iron-sulfide-bearing host rock and in lesser amounts carbonaceous matter may have provided reducing conditions for the precipitation of uranium.

The source of uranium for the deposits is not yet known but at least from the theoretical point of view there is above background uranium in the sediments and the granite directly in the vicinity of the deposit and further away there are increased uranium values in the acid volcanics of the Dubawnt Group. If there is an additional source, maybe in the Helikian sediments, it cannot be answered.

COMPARISON OF COMMON FEATURES IN KIGGAVIK AND IN DEPOSITS OF THE ATHABASCA URANIUM DISTRICT

The most common features among deposits of the Athabasca uranium district are their close relationship with the Helician unconformity, their association with graphitic sequences and that their mineralization is contained within a distinct alteration envelope (Table III, various sources and Fogwill, 1985).

The first two features, the relationship with the unconformity and the presence of graphite, are not observed in the Kiggavik deposit. The geological evidence supports the expectation, however, that paleoweathered rocks formed at the unconformity were once present over the deposit although the level of today's erosion left no evidence of a regolith in the immediate vicinity of the deposit.

The absence of graphitic sequences make Kiggavik outstanding among the unconformity related deposits and it can be speculated that this specific type of deposit has been overlooked due to the greater difficulty to detect these deposits under sandstone cover.

Also unlike most Athabasca sandstone deposits Kiggavik uranium mineralization is not associated with significant amounts of accessory metals and is in this respect similar to the basement-hosted deposits Eagle Point and Rabbit Lake and dissimliar to hydrothermal vein deposits with gangue minerals. Despite these specific differences there is a long list of similar features:

- Kiggavik exhibits an alteration envelope very similar to the Athabasca deposits

- The ore only occurs within the alteration envelope

- The ore occurs in Lower Proterozoic metasediments
- The ore postdates the development of continental basins
- Crosscutting diabase dykes are part of the sequence in both districts
- The age of the mineralization is similar
- The ore zones exhibit linear features contrary to vein type features

CONCLUSION

Based on the geological model known from Rabbit Lake just east of the Athabasca Basin, the rim of the Thelon Basin had been selected for grass roots exploration. The aim was to locate a uranium deposit of similar quality.

The results prove that the approach was correct and we may speculate now that some areas around and even below the Thelon sandstone cover are containing similar unconformity-related uranium deposits not yet discovered.

TABLE III. FEATURES OF KIGGAVIK AND UNCONFORMITY RELATED DEPOSITS OF THE ATHABASCA URANIUM DISTRICT

FEATURE	KIGGAVIK	ATHABASCA URANIUM DISTRICT
Location of ore body in relationship to basin:	2000 m south of the rim of the Thelon Basin	close to the rim or within the Athabasca Basin
Regolith and unconformity:	developed 1800 m north of the deposit, probably eroded over deposit	developed
Host rocks:	Aphebian meta-arkose, meta-pelites, granite and associated intrusive rocks	Helikian sandstones Aphebian meta-arkose and meta-pelites
Graphite:	absent	present with deposits
Carbonaceous matter:	present in minor amounts	frequently present
Diabase:	crosscuts ore zone	present or part of regional geology
Temperature of ore precipitation:	<300°C indicated by marcasite	150° - 250°C
Alteration:	strong host rock alteration, depletion of quartz, hematization and limonitization, illite and chlorite as main clay minerals	similar alteration

TABLE III (cont.)

FEATURE	KIGGAVIK	ATHABASCA URANIUM DISTRICT
Form and control of ore zones:	– linear features with well defined plunge – structural control by intersecting Az 65° and Az 95° fault zones – ore only within alteration zone	– linear features – structural control by fault zones and unconformity – ore only within alteration zone
Accessory metals (Ni,Cu,Co):	none	– basement deposits like Rabbit Lake and Eagle Point have no accessory metals – deposits with sandstone, unconformity and basement ore usually have significant accessory metal concentrations
Age of mineralization:	postdates Thelon Basin ~1400 ma	postdates Athabasca Basin ~1350 ma
Remobilization event:	1000 ma	1000 ma
Feature of deposit used prominently for exploration:	alteration zones reflected as lows in gravity surveys	graphitic conductors detected by EM surveys

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THE EAGLE POINT URANIUM DEPOSITS, NORTHERN SASKATCHEWAN, CANADA

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Abstract

The Eagle Point uranium deposits are located on the eastern edge of the Athabasca Basin, about twelve kilometres north-northeast of the Rabbit Lake mill complex in northern Saskatchewan.

These deposits were discovered in 1980 during systematic drill testing of geophysical and uranium-in-till anomalies associated with the Collins Bay Fault, in the area northeast along strike from the Collins Bay B-Zone, D-Zone, and A-Zone uranium deposits.

The Eagle Point deposits consist of a series of moderately steeply dipping tabular veins and lenses which are both concordant and discordant to, and wholly within, Aphebian metasedimentary rocks. The mineralization outlined to date occurs entirely within the hanging wall of the Collins Bay Fault.

The deposits occur within the variably graphitic lowest unit of the Aphebian Wollaston Group, and within 1.5 metres to 365 metres of the underlying, possibly Archean granitoid basement.

Mineralization is considered to be primarily structurally controlled. This conclusion is based on the discordant nature of the veins, the presence of microstructures within the veins, and the lack of any consistent association between mineralization and lithology.

Mineralization consists of uraninite and pitchblende, and has been dated at 1400±25 Ma, with younger generations recognized. Only minor amounts of some other metals are present.

The alteration associated with the mineralization is moderately to strongly developed, and consists mainly of illitization. Zones of intense alteration extend less than one metre from mineralization. Hematite is spatially associated with much of the mineralization.

The combined deposits are currently estimated to contain geological reserves of about 51200 tonnes U. The origin of the deposits remains speculative at this time.

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1. INTRODUCTION

The Eagle Point uranium deposits are situated on the eastern edge of the Athabasca Basin, about twelve kilometres north-northeast of the Rabbit Lake mill complex in northern Saskatchewan, at about latitude 58°17.5' north and longitude 103°36.5' west (Fig. 1). They consist of the Eagle North deposit (held by an equal share joint venture of Eldorado Resources Limited, Noranda Exploration Company Ltd., and the Saskatchewan Mining Development Corporation) and the Eagle South deposit (held wholly by Eldorado Resources Limited).

The Eagle Point deposits are in close proximity to the Rabbit Lake and Collins Bay B-Zone Mines and the D- and A-Zone deposits. Located on the northwest shore of Harrison Peninsula, the Eagle North deposit lies entirely under the waters of Collins Bay; the Eagle South deposit straddles the shoreline of Collins Bay.

The geological interpretation presented here is based on drill hole information as no outcrops exist in the Eagle Point area.

The regional geological setting and exploration history are first described. The deposits' geology and their structural and alteration aspects, are discussed next. The paper ends with a summary of the mineralization and reserves.

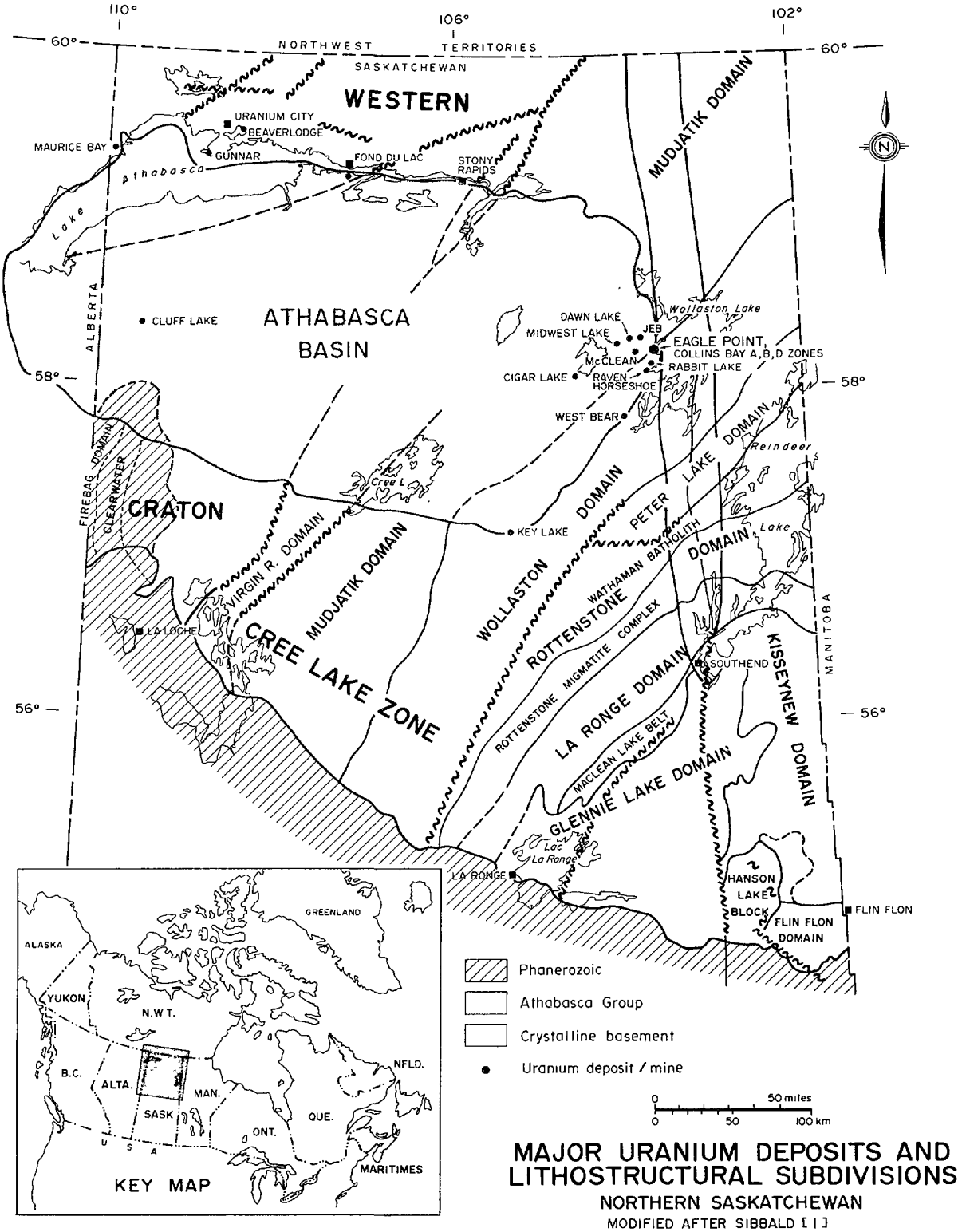
2. GEOLOGY OF THE RABBIT LAKE-COLLINS BAY AREA

The deposits occur within the Wollaston Group of Aphebian age, which lies within the lithostructurally defined Wollaston Domain of the Churchill Province (Fig. 1) [1]. The Wollaston Group overlies a presumed Archean (?) granitoid basement.

A regionally consistent stratigraphy has been established for the Wollaston Domain. It has been recognized in the Rabbit Lake area (Figs. 2 and 3) by Ray [2], Thomas [3], Sibbald [1], and others. The geology of the Rabbit Lake-Collins Bay area is summarized as follows.

2.1. Stratigraphy

Archean basement in the Wollaston Lake area may be represented by the Trout Narrows and Berman Island Granites at the south end of Wollaston Lake, and by the Shaganappie Island Granite in the northeast corner of the lake [1]. In the Rabbit Lake area, a medium- to coarse-grained foliated to gneissic granitoid unit occurs in a stratigraphic position which is apparently analagous to that of these possibly Archean granites. In places, it underlies, in partial fault contact, variably graphitic Aphebian paragneiss; in other places, it is unconformably overlain by Athabasca sandstone and conglomerate in the footwall of the Collins Bay Fault.

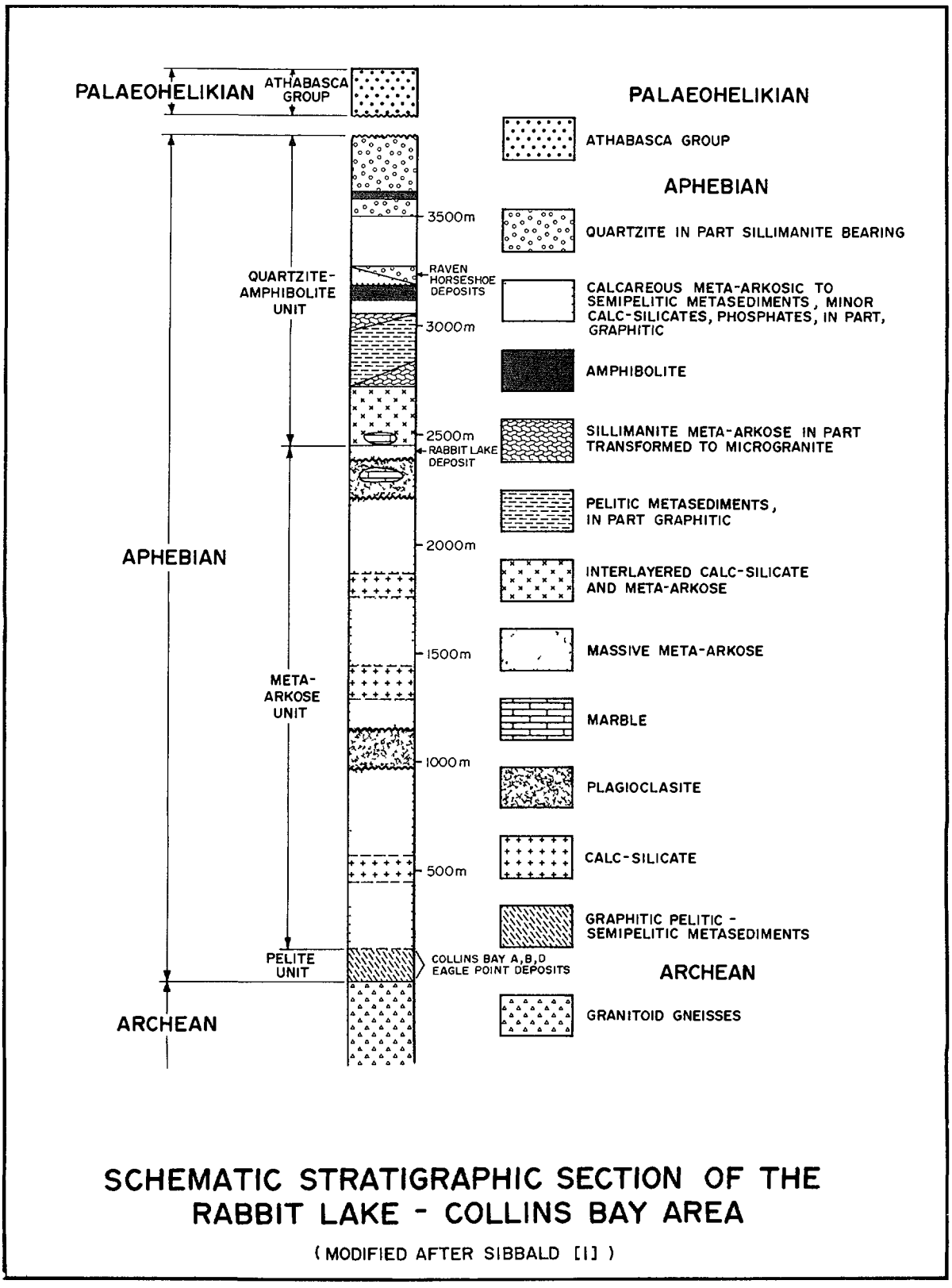


MAJOR URANIUM DEPOSITS AND LITHOSTRUCTURAL SUBDIVISIONS

NORTHERN SASKATCHEWAN

MODIFIED AFTER SIBBALD [1]

FIGURE 1.



SCHEMATIC STRATIGRAPHIC SECTION OF THE RABBIT LAKE - COLLINS BAY AREA

(MODIFIED AFTER SIBBALD [1])

FIGURE 2.

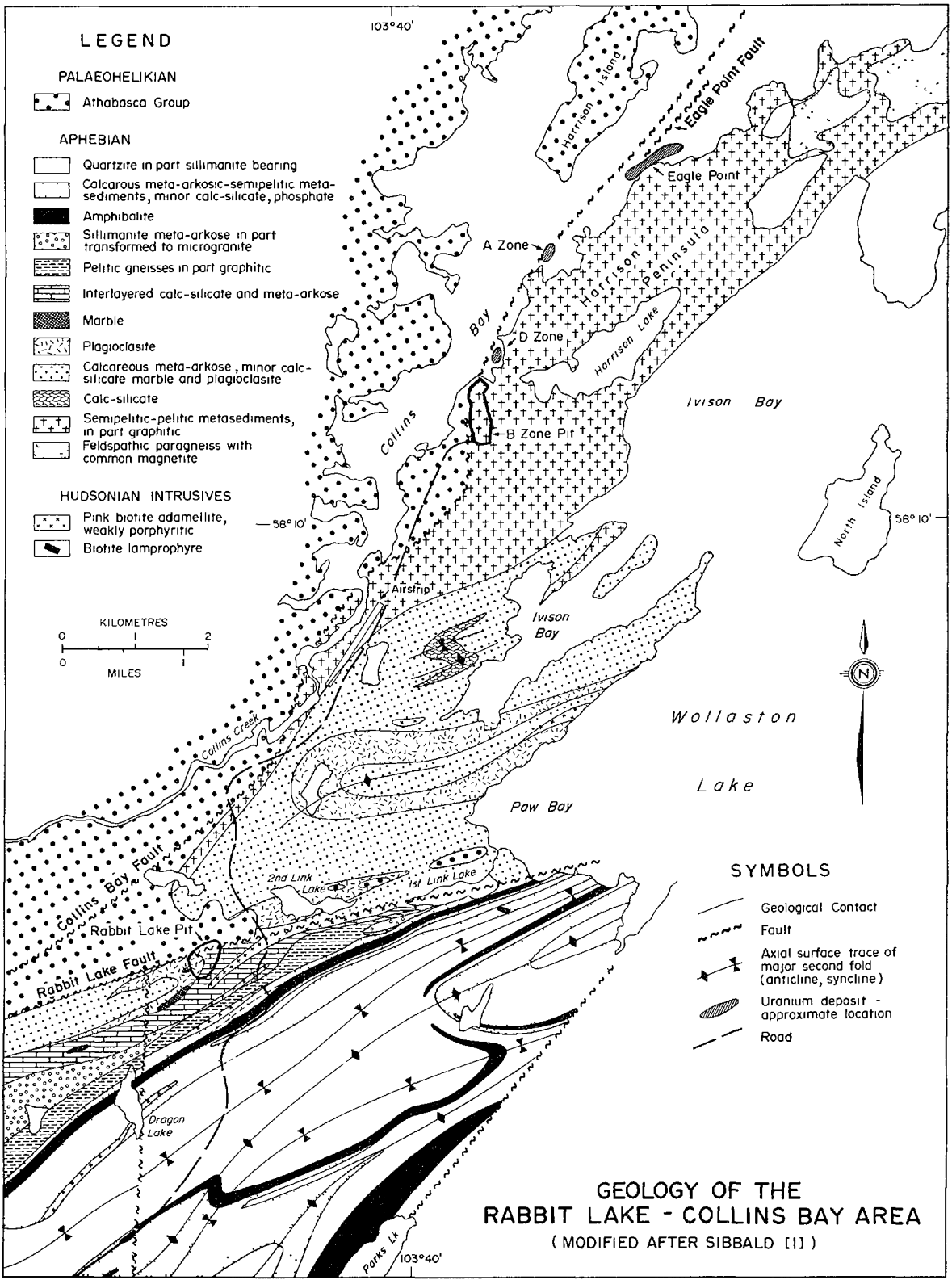

LEGEND
PALAEOHELIKIAN
Athabasca Group
APHEBIAN
Quartzite in part sillimanite bearing
Calcarous meta-arkosic-semipelitic meta-sediments, minor calc-silicate, phosphate
Amphibolite
Sillimanite meta-arkose in part transformed to microgranite
Pelitic gneisses in part graphitic
Interlayered calc-silicate and meta-arkose
Marble
Plagioclasite
Calcareous meta-arkose, minor calc-silicate marble and plagioclasite
Calc-silicate
Semipelitic-pelitic metasediments, in part graphitic
Feldspathic paragneiss with common magnetite
HUDSONIAN INTRUSIVES
Pink biotite adamellite, weakly porphyritic
Biotite lamprophyre
KILOMETRES
0 1 2
0 1
MILES
103°40'
58° 10'
Harrison Island
Eagle Point Fault
Eagle Point
A Zone
Harrison Peninsula
Harrison Lake
D Zone
Collins Bay
B Zone Pit
Ivison Bay
North Island
Airstrip
Collins Creek
Wollaston Lake
Paw Bay
2nd Link Lake
1st Link Lake
Collins Bay Fault
Rabbit Lake Pit
Rabbit Lake Fault
Dragon Lake
Parks Lk
SYMBOLS
Geological Contact
Fault
Axial surface trace of major second fold (anticline, syncline)
Uranium deposit - approximate location
Road
GEOLOGY OF THE
RABBIT LAKE - COLLINS BAY AREA
(MODIFIED AFTER SIBBALD [1])

FIGURE 3.

The lowermost unit of the Wollaston Group consists of a variably graphitic ferromagnesian-mineral-rich (generally biotite and cordierite) unit, with discontinuous quartzo-feldspathic, quartzitic, and/or calc-silicate-bearing interbeds and lenses.

This basal unit hosts the Collins Bay A-, B-, and D-Zone deposits, as well as the Eagle Point deposits. It is overlain by a series of calcareous and non-calcareous metasediments, interlayered with less extensive calc-silicates, plagioclase-rich rocks, and biotitic paragneisses. This succession is marked in its upper part by the appearance of massive carbonate, which was the host for the Rabbit Lake deposit [4, 5]. It is, in turn, overlain by an assemblage of interlayered feldspathic paragneisses, amphibolites, quartzites, and ferromagnesian-mineral-rich metasediments -- the Hidden Bay assemblage of Wallis [6], stratigraphically the highest rocks yet recognized in the Wollaston Group in Saskatchewan.

The Wollaston Group represents sediments which were deposited in a shallow, marine, near-shore and possibly restricted environment. The carbonates may represent algal-bank type accumulations, with graphite in some of the units derived from organic debris. The unusual chemistry of the albite-rich metasediments (plagioclasites) suggests that these rocks were derived from saliferous pelites [7].

The Hudsonian Orogeny (dated at about 1850 to 1700 Ma) was followed by a long period of erosion of the Aphebian rocks. This conclusion is supported by the presence of a regionally developed paleoweathering zone, well preserved under the Athabasca Group [8]. Macdonald [8] has stated that, depending on the host lithology and local dilatency, the thickness of the altered zone ranges from about five m to more than 220 m and averages about 30 m. This paleoweathering zone is well exposed in the Rabbit Lake pit, in the footwall of the Rabbit Lake Fault.

The Helikian Athabasca Group, deposited between 1430 to 1550 Ma [9], occurs only in the footwall of the Rabbit Lake Fault in the Rabbit Lake area, and mainly (but not exclusively) in the footwall of the Collins Bay Fault. Only the Manitou Falls Formation B member [10], consisting of interbedded fluviatile conglomerate and sandstone, is present in the Rabbit Lake-Collins Bay area.

These sediments are generally well layered at a scale of centimetres to metres, and consist dominantly of quartz and quartzite grains and pebbles. The layering has a planar character, but small-scale (centimetres to decimetres) crossbeds occur. The coarser grained, conglomeratic layers are typically hematitic, and thin bands of heavy minerals are common.

The Athabasca Group in the Rabbit Lake map area (Fig. 3) is about 100 m thick near Collins Creek, west of the Rabbit Lake pit.

Post-Athabasca mafic dykes are known in the area from at least three localities: south of Rabbit Lake, the B-Zone area, and on Harrison Peninsula.

2.2. Structure

Two major regional deformational events are recognized in the Rabbit Lake-Collins Bay area [1]. The earliest phase of folding developed a prominent foliation (both in the basement and Wollaston Group rocks) which is generally parallel to the original layering in the sediments. Second event folds are steeply inclined to upright, close to tight structures plunging gently to the northeast or southwest along northeasterly trending fold axes. This latter deformational event defines the strongly linear character of the Wollaston Domain. An example of this fold style is well exposed in the area south and southeast of the Rabbit Lake pit (Fig. 3). Folding of this character also appears to be developed on Harrison Peninsula and in the Collins Bay-Seal Lake area. The A-, B-, and D-Zone deposits, as well as the Eagle Point deposits, occur on the southeast limb of an overturned, tight to close anticline with a one-half wavelength of about four to five kilometres. Archean granitoid rocks in the core of the anticline exhibit a high magnetic relief, and the conductive lower Aphebian graphitic rocks define closure of this anticline to the northeast.

Two additional minor fold events were identified by Hoeve and Sibbald [5] in the Rabbit Lake pit.

Two important fault directions are present in the map area: northeasterly and northerly.

The Rabbit Lake and Collins Bay Faults are northeasterly trending reverse faults of post-Athabasca and, probably, pre-Athabasca age. They tend to be localized within graphitic horizons, wherein numerous planes of slippage are typically developed, and generally exhibit breccia-, shear-, and crackle-zones which are from five to 100 or more metres wide. Apparent vertical offset along these faults is in the order of about 100 m; dips range from 30° to 60° southeasterly.

Northerly striking, subvertically dipping normal and/or wrench faults exhibit both pre-Athabasca and, post-Athabasca movement. They tend to occur in locally alternating, sinistrally and dextrally displaced sets. Horizontal displacements along these faults are typically hundreds, and occasionally thousands, of metres.

2.3. Metamorphism

Upper-amphibolite-grade mineral assemblages typify most of the Wollaston Domain. Coarse-grained to pegmatitic felsic segregations commonly occur within most lithologies, representing anatectic differentiates derived from the surrounding lithologies.

2.4. Uranium Deposits

Uranium deposits in the Rabbit Lake-Collins Bay area include the Rabbit Lake Mine (now exhausted), the Collins Bay A-, B-, and D-Zones, and Eagle Point. The B-Zone mine is currently in production.

The Rabbit Lake deposit has been discussed by Knipping ([1], Hoeve and Sibbald [5], and most recently by Heine [4]. The A- and B-Zones have been discussed by Jones [12]. Some aspects of the Eagle Point deposits have previously been discussed by Sopuck et al [13].

3. EXPLORATION HISTORY

The discovery in 1968 of the Rabbit Lake deposit in the Wollaston Lake area by Gulf Minerals Canada Ltd. (GMCL) established the potential of the Athabasca Basin as a host for uranium deposits. In the Collins Bay-Rabbit Lake area, this was followed by the subsequent discoveries of the Collins Bay A-Zone in 1971, the B-Zone in 1977, and the D-Zone in 1979 (Fig. 3).

The Eagle Point deposits were discovered by Gulf in 1980 through systematic exploration of the electromagnetic conductors asssociated with the Collins Bay Fault, in a northeasterly direction along strike from the A-Zone (Fig. 4). These conductors were first identified by a 1975 airborne Tridem survey and later by an INPUT survey flown in 1979.

In 1978, ground EM surveys were undertaken in the Eagle Point area to locate the airborne conductors.

Diamond drilling began to test these conductors in 1978, and the discovery holes for both Eagle North and Eagle South were drilled in February, 1980. The discovery hole was number 38 on Eagle North. At Eagle South, significant uranium in bedrock was located by a reverse circulation drilling program (hole number 28) that was following up uranium-in-basal till anomalies located by this method in 1979.

Additional ground EM and magnetic surveys were undertaken in 1981 to define conductors and structures in more detail.

Drilling continued each year until 1982. After the completion of drilling in 1981, the mineralization at Eagle North was recognized to occur in three main zones (Fig. 5). At Eagle South, drilling had failed to define any significant mineralized zones comparable in grade or thickness with those at Eagle North.

In 1985, a joint-venture decision was taken to continue to drill the main zone (the 02 Zone) at Eagle North at 50-foot (15.2 m) grid centres, and to define the limits of mineralization along strike and down-dip and -plunge at the same drill-hole spacing. At Eagle South, drilling resumed at 100-foot (30.5 m) grid centres to test along strike and down dip. Drill hole 144 at Eagle South intersected the first

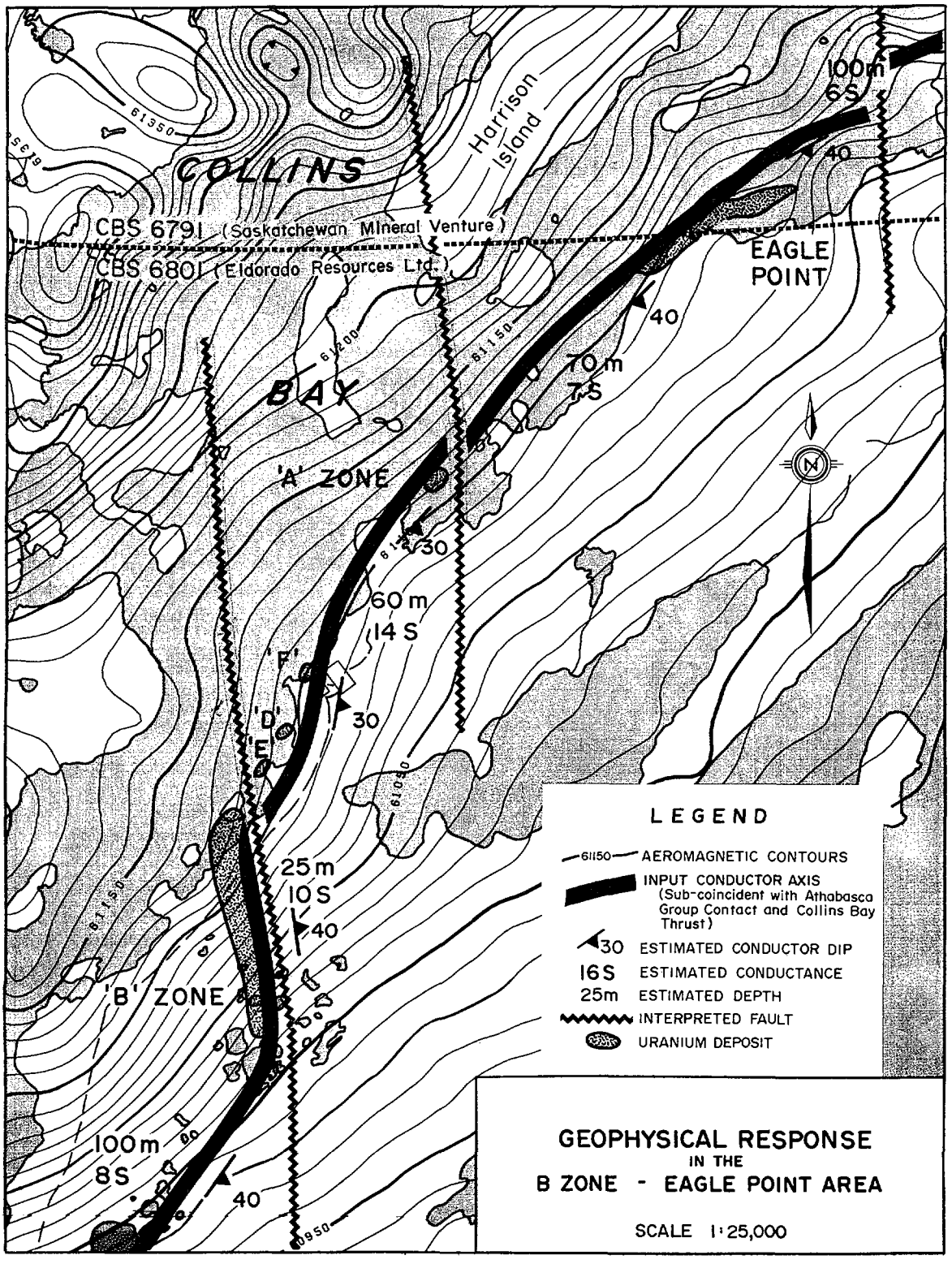

COLLINS
BAY
Harrison Island
CBS 6791 (Saskatchewan Mineral Venture)
CBS 6801 (Eldorado Resources Ltd.)
EAGLE POINT
'A' ZONE
'B' ZONE
'D'
'E'
'F'
100m 6S
40
70m 7S
30
60m 14S
25m 10S
100m 8S
61350
61200
61150
61100
61050
LEGEND
AEROMAGNETIC CONTOURS
INPUT CONDUCTOR AXIS (Sub-coincident with Athabasca Group Contact and Collins Bay Thrust)
30 ESTIMATED CONDUCTOR DIP
16S ESTIMATED CONDUCTANCE
25m ESTIMATED DEPTH
INTERPRETED FAULT
URANIUM DEPOSIT
GEOPHYSICAL RESPONSE
IN THE
B ZONE - EAGLE POINT AREA
SCALE 1:25,000

FIGURE 4.

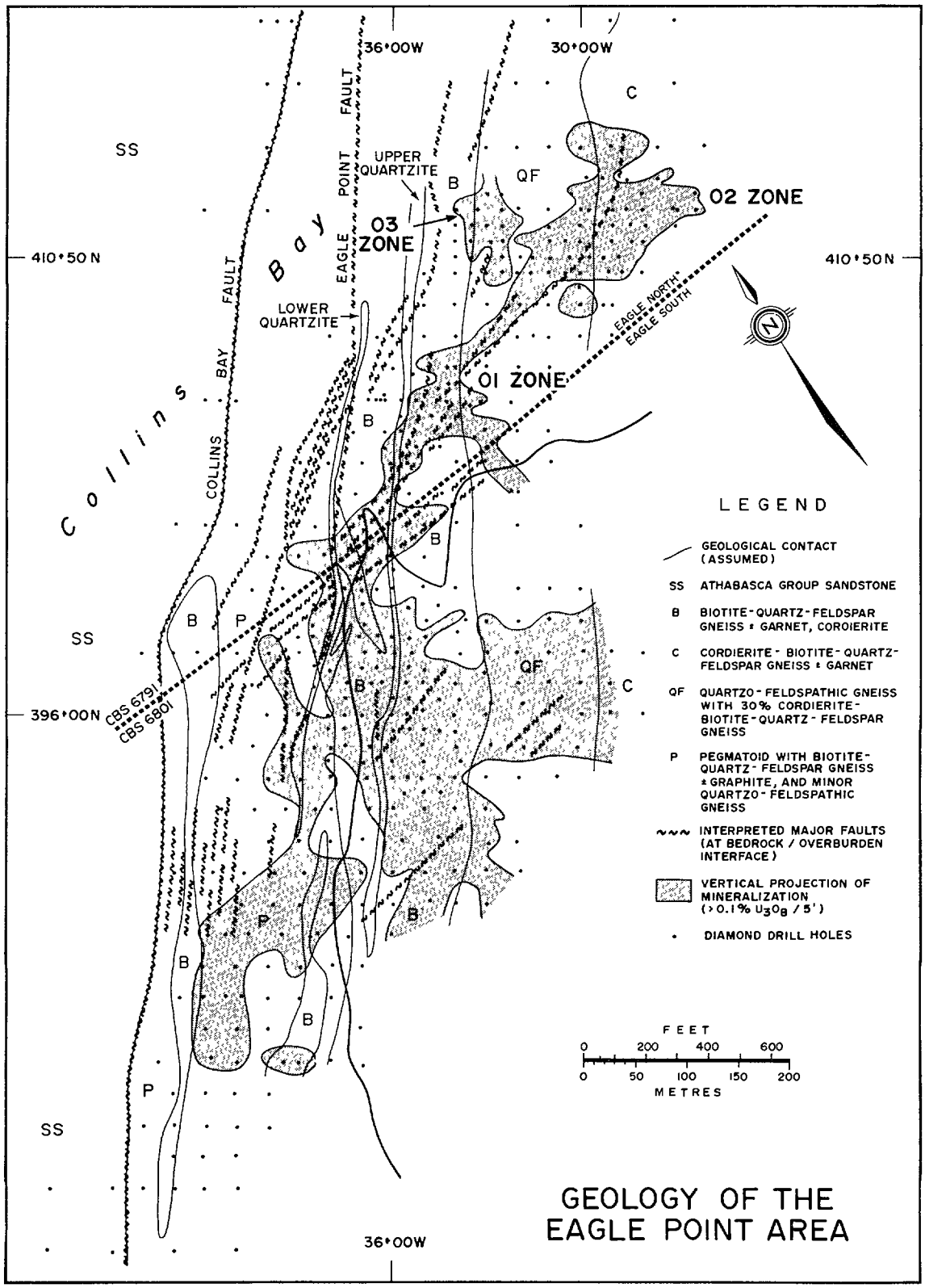

36°00W
30°00W
410°50N
396°00N
SS
C
QF
B
P
UPPER QUARTZITE
LOWER QUARTZITE
POINT FAULT
EAGLE BAY FAULT
COLLINS BAY FAULT
Collins Bay
03 ZONE
02 ZONE
01 ZONE
EAGLE NORTH
EAGLE SOUTH
CBS 6791
CBS 6801
N
LEGEND
GEOLOGICAL CONTACT (ASSUMED)
SS ATHABASCA GROUP SANDSTONE
B BIOTITE-QUARTZ-FELDSPAR GNEISS ± GARNET, CORDIERITE
C CORDIERITE-BIOTITE-QUARTZ-FELDSPAR GNEISS ± GARNET
QF QUARTZO-FELDSPATHIC GNEISS WITH 30% CORDIERITE-BIOTITE-QUARTZ-FELDSPAR GNEISS
P PEGMATOID WITH BIOTITE-QUARTZ-FELDSPAR GNEISS ± GRAPHITE, AND MINOR QUARTZO-FELDSPATHIC GNEISS
INTERPRETED MAJOR FAULTS (AT BEDROCK / OVERBURDEN INTERFACE)
VERTICAL PROJECTION OF MINERALIZATION (>0.1% U_3O_8 / 5')
DIAMOND DRILL HOLES
FEET
0 200 400 600
0 50 100 150 200
METRES
GEOLOGY OF THE EAGLE POINT AREA

FIGURE 5.

concentration of uranium (3.75% U_3O_8 over 30.0 m) at Eagle South which resembled the grades and thickness found at Eagle North.

In 1986, drilling further tested two zones (the 02 and 03 Zones) at Eagle North and the largest zone (144 Zone) at Eagle South at 50-foot (15.2 m) centres, and tested the Eagle South mineralization along strike and down dip at 100-foot (30.5 m) centres.

To date, drilling at Eagle South totals 66,252.0 m in 284 holes, and at Eagle North, 47,259 m in 245 holes, for a total of 113,512.0 m in 529 holes (Table I).

TABLE I

EAGLE POINT

DIAMOND DRILLING HISTORY

Year	Eagle South			Eagle North			Total		
	Holes	Total metreage	Cumulative metreage	Holes	Total metreage	Cumulative metreage	Holes	Total metreage	Cumulative metreage
1978	-	-	-	14	948	948	14	948	948
1979	-	-	-	12	752	1,700	12	752	1,700
1980	38	7,140	7,140	71	10,604	12,304	109	17,745	19,445
1981	86	12,467	19,607	85	16,942	29,246	171	29,409	48,854
1982	-	-	-	26	3,610	32,856	26	3,610	52,464
1983	-	-	-	-	-	-	-	-	
1984	-	-	-	-	-	-	-	-	
1985	56	18,347	37,954	14	4,824	37,680	70	23,171	75,635
1986	104	28,298	66,252	23	9,579	47,259	127	37,877	113,512
	284	66,252		245	47,259		529	113,512	

Three main zones of uranium mineralization have been identified at Eagle North (the 01, 02 and 03 Zones) and two large and several smaller zones at Eagle South. The 02 and 03 Zones at Eagle North and about 50% of the two largest zones at Eagle South have been defined by drilling at 50-foot (15.2 m) centres. Further definition and close-off surface drilling is required. However, because of the nature of the deposits, future exploration drilling of the down-dip extention of the mineralization will be more efficiently carried out from underground.

4. DEPOSIT GEOLOGY

The deposit area is underlain by paragneisses of the Wollaston Group and related Hudsonian anatexites, and by Lower Aphebian, or possibly Archean, granitoid gneiss. Fluviatile sandstone and conglomerate of the Manitou Falls Formation of the Helikian Athabasca Group occur immediately to the west of the Collins Bay Fault, and unconformably overlie the older gneisses. Two major reverse faults transect the deposit area and are more-or-less conformable with the stratigraphy. The upper fault, termed the Eagle Point Fault (EPF), is well developed at Eagle North and appears to dissipate in the Eagle South deposit area. The lower fault, termed the Collins Bay Fault (CBF), is a major regional feature, occurring near the base of the Aphebian section and very near the top of the Archean(?) granitoid basement. Both of these faults are discussed in detail later.

The surface projection of the geology and structure relative to the drill-hole collar locations is presented in Figure 5.

A comparative stratigraphic column for the Eagle Point deposits is shown in Figure 6.

A typical cross section illustrating the main geological elements of each of the Eagle South and Eagle North deposits is presented as Figures 7 and 8 respectively.

4.1. Quaternary

The Eagle North deposit is situated beneath Wollaston Lake near the east shore of Collins Bay. Water depths range up to approximately 12 m at the extreme northern and western limits of the deposit area. The Eagle South deposit straddles the shoreline of Collins Bay, extending offshore where the water cover is up to 8 m deep. Bedrock is covered by 8 to 9 m of bouldery glacial till, with minor lacustrine sediments.

4.2. Helikian

The Helikian Athabasca Group is confined to the west side of the Eagle Point drilling area, on the footwall side of the Collins Bay Fault. It consists of sandstones and conglomerates of the Manitou Falls Formation and directly overlies the Archean (?) granitoid.

4.3. Hudsonian Pegmatoid

Potassium feldspar, plagioclase, and quartz are the major constituents of this rock type, the dominant features of which are its coarse texture and felsic composition. Myrmekitic intergrowths of quartz and feldspar are common. Variable but minor quantities of biotite, garnet, sillimanite, tourmaline, and cordierite are frequently present. This

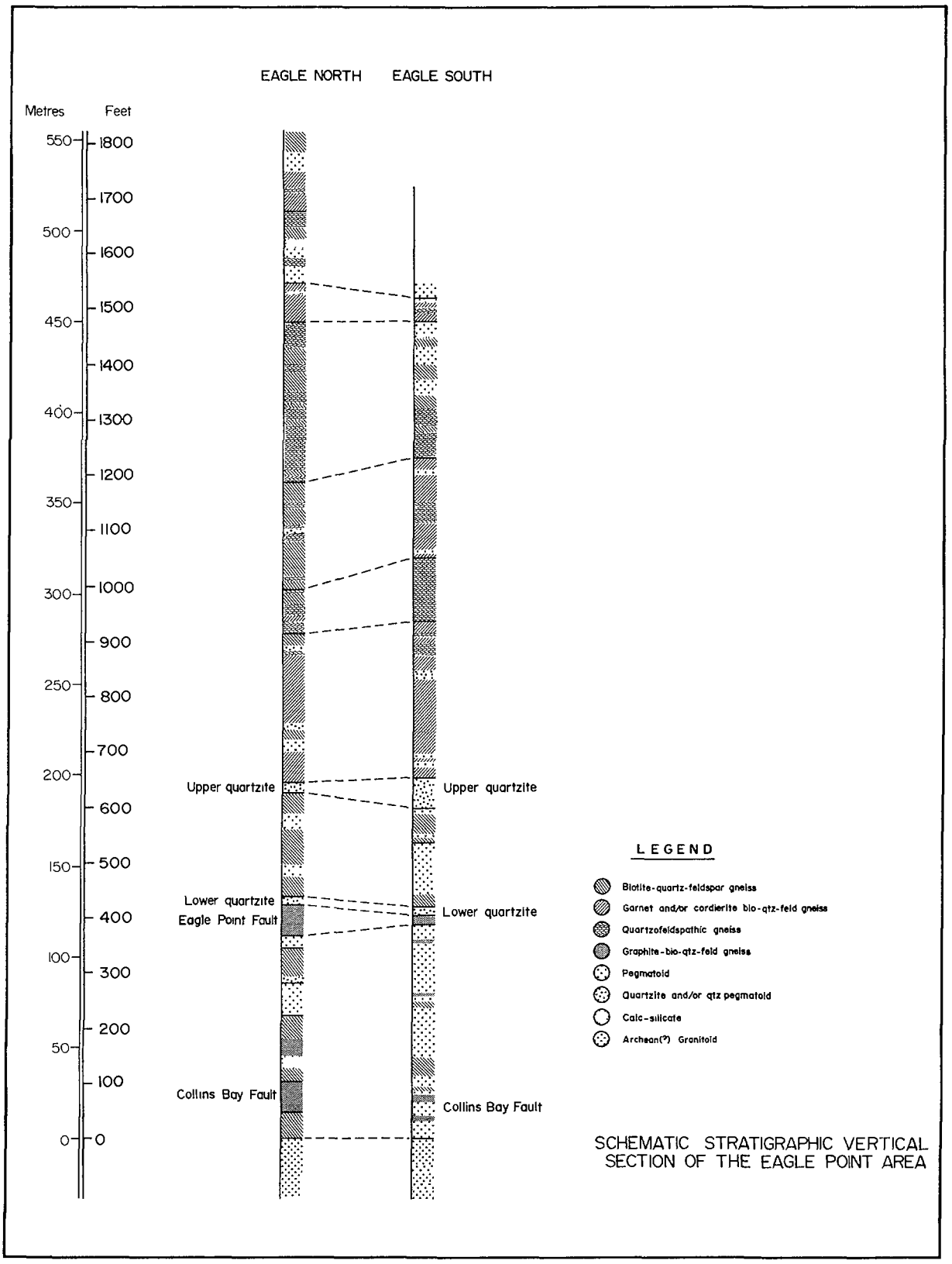

EAGLE NORTH
EAGLE SOUTH
Metres
Feet
550
1800
1700
500
1600
450
1500
1400
400
1300
350
1200
1100
300
1000
900
250
800
700
200
600
150
500
400
100
300
200
50
100
0
0
Upper quartzite
Upper quartzite
Lower quartzite
Eagle Point Fault
Lower quartzite
Collins Bay Fault
Collins Bay Fault
LEGEND
Biotite-quartz-feldspar gneiss
Garnet and/or cordierite bio-qtz-feld gneiss
Quartzofeldspathic gneiss
Graphite-bio-qtz-feld gneiss
Pegmatoid
Quartzite and/or qtz pegmatoid
Calc-silicate
Archean(?) Granitoid
SCHEMATIC STRATIGRAPHIC VERTICAL SECTION OF THE EAGLE POINT AREA

FIGURE 6.

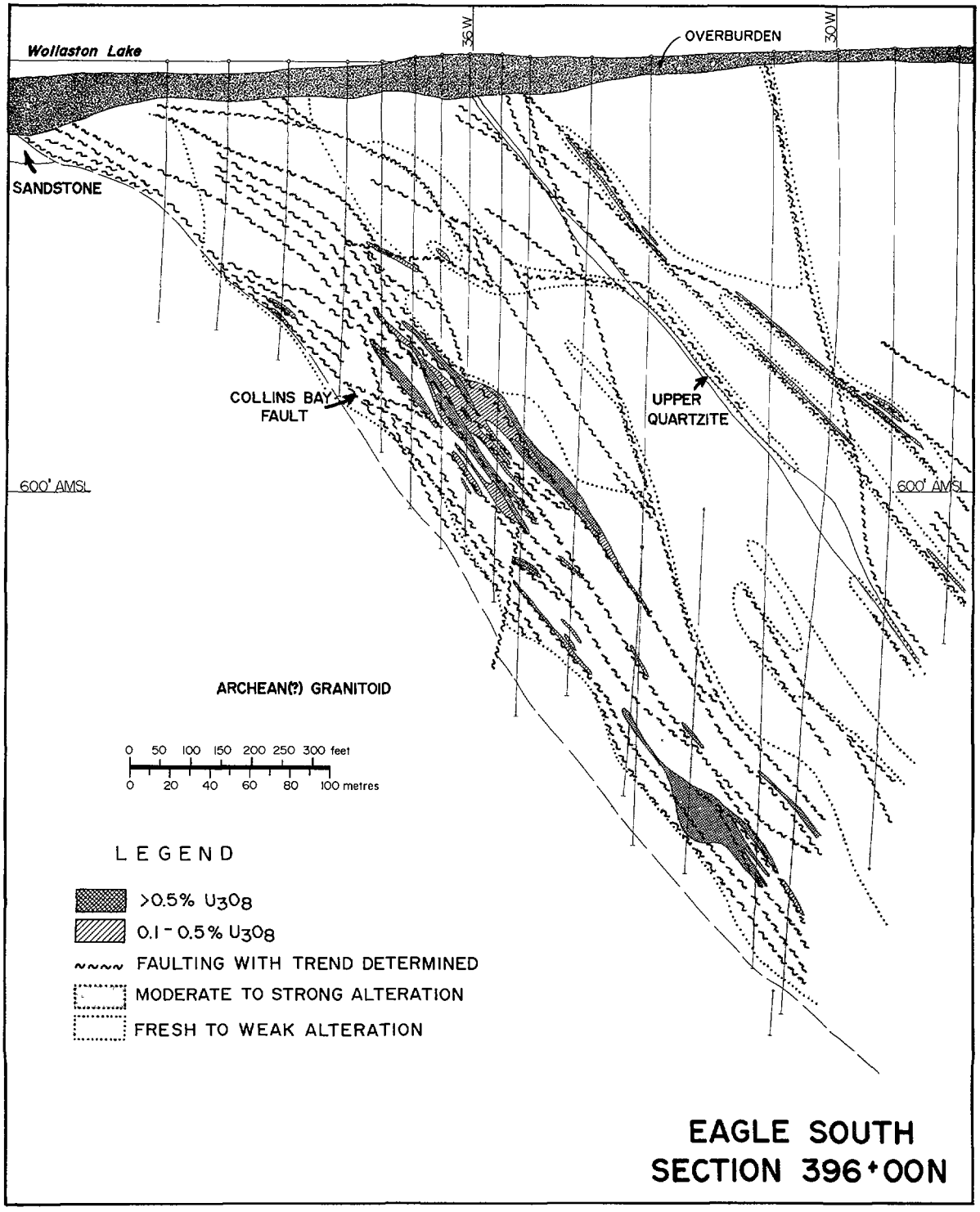

Wollaston Lake
36W
OVERBURDEN
30W
SANDSTONE
COLLINS BAY FAULT
UPPER QUARTZITE
600' AMSL
600' AMSL
ARCHEAN(?) GRANITOID
0 50 100 150 200 250 300 feet
0 20 40 60 80 100 metres
LEGEND
>0.5% U3O8
0.1 - 0.5% U3O8
FAULTING WITH TREND DETERMINED
MODERATE TO STRONG ALTERATION
FRESH TO WEAK ALTERATION
EAGLE SOUTH
SECTION 396+00N

FIGURE 7.

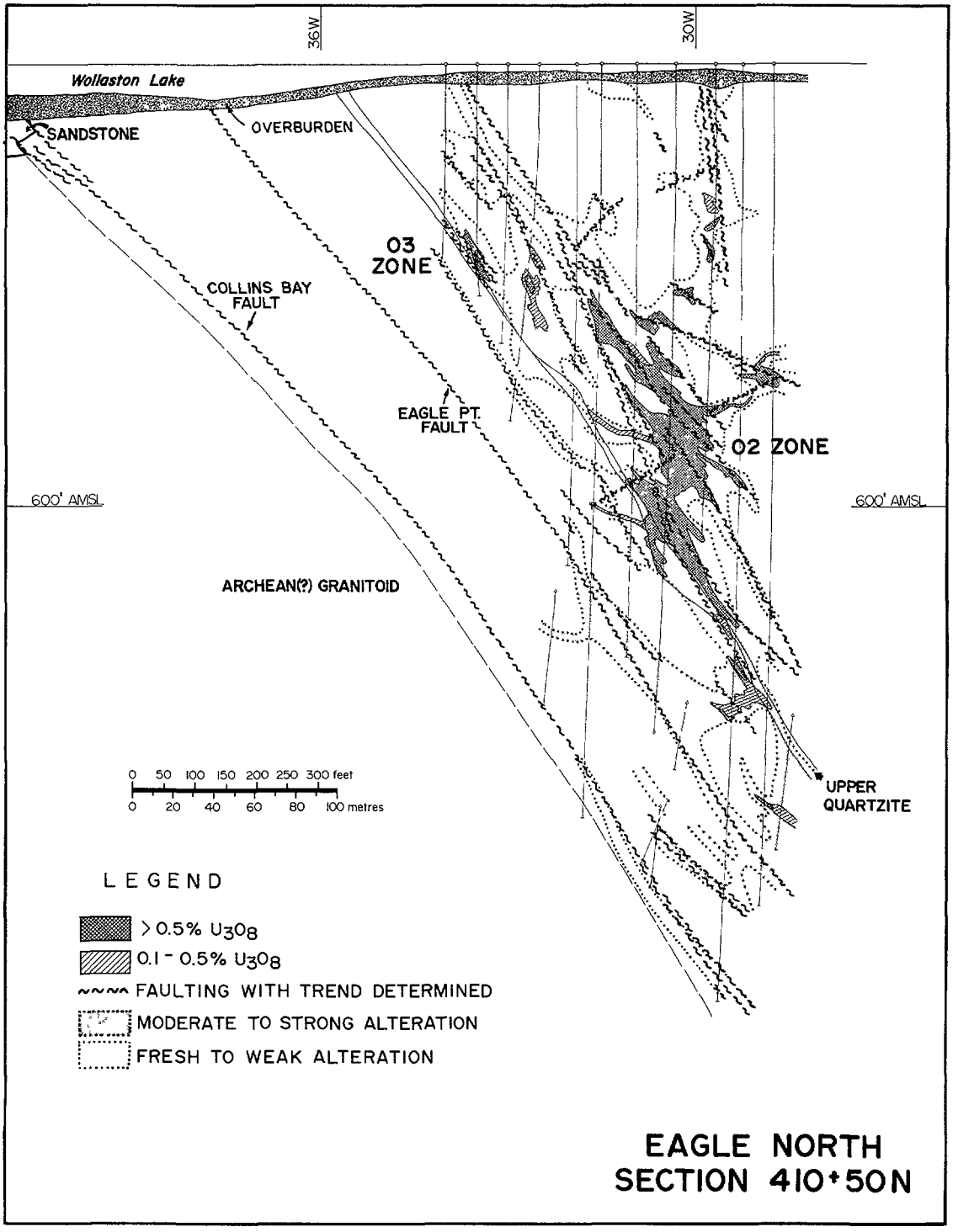

36W
30W
Wollaston Lake
SANDSTONE
OVERBURDEN
03 ZONE
COLLINS BAY FAULT
EAGLE PT. FAULT
02 ZONE
600' AMSL
600' AMSL
ARCHEAN(?) GRANITOID
0 50 100 150 200 250 300 feet
0 20 40 60 80 100 metres
UPPER QUARTZITE
LEGEND
> 0.5% U3O8
0.1 - 0.5% U3O8
FAULTING WITH TREND DETERMINED
MODERATE TO STRONG ALTERATION
FRESH TO WEAK ALTERATION
EAGLE NORTH
SECTION 410+50N

FIGURE 8.

lithology represents an anatectic segregation rather than a true magmatic pegmatite. Its mineralogical composition, therefore, depends to some extent on the rock type(s) immediately adjacent to it.

This unit occurs throughout the Aphebian sequence and to a lesser extent in the Archean(?) granitoid gneiss. It generally forms narrow discontinuous zones. However, thicker, more continuous zones occur near the base of the Aphebian section, close to the Collins Bay and Eagle Point Faults. This unit is estimated to make up 15 to 20 per cent of the Aphebian sequence in the deposit area.

4.4. Aphebian

A 450 m thick sequence of Aphebian rocks hosts the Eagle Point deposits (Fig. 6). These rocks form a northeasterly striking (035°), southeasterly dipping (40-55°), lithologically variable metasedimentary sequence, which probably represents a shallow-marine, near-shore, and, in part, restricted depositional environment. Mudstones with some organic debris are believed to have been intercalated with fine-grained detrital rocks (arkose and minor quartzite). Minor iron-rich sedimentary rocks may have volcanic (basaltic) affinities. Calcium-rich mudstones suggest that evaporitic conditions may, at times, have prevailed locally.

This sequence was subsequently metamorphosed to the amphibolite facies.

Several rock types have been defined during drill core logging; they commonly grade into one another along strike and across contacts.

Biotite-quartz-feldspar gneiss contains abundant quartz and plagioclase, and variable amounts of biotite -- in excess of 10 per cent, and generally close to 20 to 25 per cent. Other minerals present include potassium feldspar, garnet, cordierite, sillimanite, pyrite and graphite, along with minor quantities of apatite, tourmaline, sphene and zircon.

Texturally, the gneiss is fine- to medium-grained, moderately to well foliated and, in most places, well banded. When fresh, it is medium to dark grey in colour.

Biotite-quartz-feldspar gneiss is the dominant rock type in the deposit area, and comprises 30 to 40 per cent of the Aphebian sequence (Fig. 6).

Cordierite-biotite-quartz-feldspar gneiss is similar in composition to the biotite-quartz-feldspar gneiss, but contains more than ten per cent cordierite as pinitized, blue-green, small- to medium-sized grains which often occur as augen near fault zones. This unit makes up from five to ten per cent of the stratigraphic sequence (Fig. 6).

Garnet-biotite-quartz-feldspar gneiss is also similar in composition to the biotite-quartz-feldspar gneiss, but has more than five per cent garnet, which forms idioblastic to subidioblastic, small to large porphyroblasts. In places, garnet is massive over narrow intervals. Garnet is generally pink to mauve when fresh, but is usually altered to chlorite. It has been identified as pyrope.

This unit comprises approximately five per cent of the Aphebian stratigraphy (Fig. 6).

Garnet-cordierite-biotite-quartz-feldspar gneiss texturally and compositionally resembles biotite-quartz-feldspar gneiss but contains more than five per cent garnet and ten per cent cordierite. When highly altered, it is indistinguishable from other similarly altered Aphebian paragneisses as both garnet and cordierite are altered to chlorite, pinite and similar alteration minerals.

Garnet-cordierite-biotite-quartz-feldspar gneiss comprises less than five per cent of the Aphebian stratigraphy (Fig. 6).

Graphite-biotite-quartz-feldspar gneiss contains in excess of five per cent graphite as grains along foliation planes, as disseminated flakes, and in massive form. From one to five per cent pyrite is typically present. One band of this rock type occurs near the base of the Aphebian sequence, where it is a locus for major faulting. In the deposit area, both the Collins Bay and the Eagle Point reverse faults are developed almost entirely within this lithology. Graphite has been mobilized along the fault planes, and forms concentrations which make up to 50 per cent of the rock.

This unit comprises five per cent or less of the stratigraphic sequence, but is important in relation to the mineralization process in that it provides a locus for faulting.

Quartz-feldspar gneiss dominates the upper portion of the Aphebian sequence. It contains mostly plagioclase, 10 to 25 per cent quartz and less than 10 per cent biotite. Accessory garnet, sillimanite, potassium feldspar, graphite, apatite, tourmaline, zircon and pyrite may be present. Where sillimanite forms more than five per cent of the rock, a separate unit has been distinguished. The quartz-feldspar gneiss is weakly foliated to massive and medium to coarse-grained. In places, it looks granitic. It contains numerous anatectic pegmatoids similar in composition to the host rock. Its poorly foliated to massive appearance is primarily due to the paucity of biotite.

This rock type comprises 15 to 20 per cent of the Aphebian sequence in the deposit area (Fig. 6).

Sillimanite-quartz-feldspar gneiss is mineralogically similar to quartz-feldspar gneiss, but contains more than five per cent sillimanite and minor amounts of garnet. The sillimanite occurs as aggregates of fibrous crystals which together with the biotite, give the rock a weakly foliated

texture. The outer margins of the sillimanite are typically hematite-stained, imparting a pink or red colour to the rock.

Quartzite contains more than 75 per cent quartz, up to 25 per cent plagioclase, and accessory sillimanite, garnet, biotite, and sphene. Massive, coarse-grained to pegmatitic quartzite and foliated medium- to coarse-grained quartzite occur within the sequence, often together, and are interbanded with impure quartzite containing more than 25 per cent feldspar. Some of these rocks are not true quartzites but are probably anatectic derivatives of quartz-rich metasediments.

Quartzite units are common throughout the stratigraphic column, and range in thickness from 10 cm to more than 15 metres. They usually form discontinuous lenses, but two fairly continuous units have been recognized which, where present, serve as excellent marker horizons termed the upper and lower quartzites.

The lower quartzite is generally narrower and less continuous than the upper unit, and occurs about a metre above the Eagle Point Fault. The main marker horizon, the upper quartzite, is situated approximately 40 m above the lower unit, and is up to 18 m thick. A conformable and, in places, mineralized, fault system occurs immediately above this unit.

The quartzites are volumetrically insignificant, comprising only one to two per cent of the Aphebian sequence.

Calc-silicate rocks also form only a small portion of the Aphebian metasediments. They occur as 0.2 to five m thick layers which, although noted throughout the Aphebian sequence, are generally associated with quartzites and mafic gneisses. The layers are discontinuous and rarely traceable for more than 30 m along strike. They probably represent calcareous mudstones.

Calc-silicates contain clinopyroxene (diopside), amphibole and garnet as major constituents, and quartz, calcite and plagioclase as subordinate minerals.

Marble is rare, generally occurring as narrow bands within calc-silicate rock. It is made up mostly of dolomite and/or calcite.

Amphibolite comprises a minor part of the stratigraphic sequence in the Eagle Point area, and consists of garnet, diopside, amphibole, cordierite, biotite and pyrite with minor amounts of plagioclase. The unit is quite continuous from hole to hole, and may contain sections carrying up to 50 per cent massive garnet over several metres. Generally, this unit is weakly to moderately magnetic. It is probably metamorphosed iron formation.

4.5. Lower Aphebian (Archean?) Granitoid

This unit is weakly foliated, medium- to coarse-grained, crystalline, and equigranular. It underlies the Aphebian gneissic sequence in the hanging wall of the Collins Bay Fault, and the Athabasca Group rocks in the footwall of the Collins Bay Fault. It consists of quartz (30-40%), potassium feldspar and, plagioclase (40-50%), five to ten per cent biotite, and minor garnet and sillimanite. It is distinguishable from the Aphebian biotite-quartz-feldspar gneiss by the absence of coarse banding, generally coarser grain size, and by the absence of graphite.

This granitoid unit probably represents basement to the Wollaston Group. At Eagle Point, Pb/Pb ratios suggest that the age of the granitoid is at least 2000-2100 Ma and that the U/Pb system in the granitoid was extensively modified at about 1305 Ma.

5. STRUCTURAL GEOLOGY

5.1. General

The Eagle Point deposits are hosted by a sequence of Aphebian paragneisses which overlies an older (Archean?) granitoid basement. The rocks occur in a homocline which strikes northeasterly and dips at about 45° to the southeast. Reverse faulting within the Aphebian metasediments is the dominant structural feature of the area, and the mineralization is controlled either by reverse faults, or by secondary faults and breccia zones.

Broad, open folding occurs on a regional scale. Very small scale folding is evident in the deposit area.

5.2. Faulting

Introduction. The localization of uranium mineralization at Eagle Point is entirely controlled by faults and their attendant breccias. The character of these faults has been influenced by the layered nature and marked contrasts in competency of the units within the paragneiss sequence, by the configuration of the Archean(?) - Aphebian unconformity surface, and probably by regional and local folding. Because the major reverse faults tend to follow less competent, more fissile stratigraphic units (usually graphitic paragneiss), parts of the mineralized zones controlled by these faults appear to be "stratabound". However, significant portions of the mineralized zones also occur in structures which clearly crosscut the stratigraphy, particularly at Eagle North.

At least three sets of faulted and brecciated structures are known to control the location of mineralization:

1) reverse faults
2) steeply dipping faults and breccias, and
3) north-dipping faults.

Reverse faults. Two principal zones of reverse faulting, the Collins Bay Fault (CBF) and the Eagle Point Fault (EPF), are present in the Eagle Point area.

The EPF and CBF are zones of brittle deformation, with intervals of graphitic breccia (both healed and unhealed), slips, shears and gouge, localized within graphitic paragneiss and pegmatoid units. Strong evidence exists for multiple periods of movement with, for example, zones of unconsolidated breccia and gouge in sharp contact with healed, often silicified, breccia. The presence of graphitic breccias within otherwise non-graphitic pegmatoid rocks indicates that graphite has been mechanically introduced and mobilized.

The variable width of the Eagle Point and Collins Bay Faults is approximately 9 to 18 m at Eagle Point. The stratigraphic separation between the two reverse faults is about 50 to 60 m. Their strikes of about 035°, consistently coincide with the strike of the enclosing paragneisses; dips range from 40° to 55° southeast. Both faults tend to flatten in the up-dip direction. This curvature of the fault zones may reflect warping of the enclosing gneisses or irregularities in the surface of the underlying granitoid.

Reverse movement on the Collins Bay Fault has pushed the Aphebian gneisses over basal units of the Athabasca Group and over the sub-Athabasca paleoweathered zone. Since the unconformity surface in the hanging wall has been eroded, the amount of vertical movement on the Collins Bay Fault at Eagle Point is unknown. However, in the Rabbit Lake area and in areas further southwest along strike, reverse vertical displacement is about 100 m. At the B-Zone Mine, movement is also known to be reverse.

In the Eagle North deposit, the EPF is observed in drill core to be a much wider zone than the CBF. It shows more evidence of "late" movement such as gouge, clay, and breccia. This suggests that the EPF took up more of the late stress than did the CBF and possibly explains the lack of significant uranium mineralization below the EPF at Eagle North due to the absence of sufficient dilatancy.

In the Eagle South deposit, the CBF is observed in drill core to consist of a broad zone of anastomosing faults and breccias with a true thickness of about 55 to 70 m. It occurs within the lower graphitic horizon and an overlying pegmatoid unit. The higher graphitic unit which hosts the EPF at Eagle North is not strongly faulted at Eagle South. The faulting associated with this horizon at Eagle South is minor, discontinuous, and generally unmineralized.

Less well developed conformable faults are present in the area, in the zone above the EPF. These are probably coeval with the major reverse faults.

Steeply dipping faults and breccias. Steeply dipping breccia zones host a significant proportion of the mineralization at Eagle North, for example in the 01 and 02

Zones which are probably located on different parts of the same structure. They strike at about 080°, with dips ranging from, most commonly, 80° north to 80° south. Subvertical faults and fractures are commonly observed in core in the vicinity of mineralization, and their presence is deducible from the distribution of mineralization in drill sections. They are restricted to structurally high portions of the Wollaston Group, and do not appear to extend much below the level of the Eagle Point Fault. They do not appear to offset or otherwise disrupt the EPF.

North-dipping faults. A number of north-dipping faults appear to be present. Most of these faults are inferred from the interpretation of the mineralized veins, some of which appear to strike easterly and dip moderately northerly.

Relationship of mineralization to faulting. The three fault sets mentioned above are the only ones currently recognized to contain mineralization. In any given zone, mineralization is typically present in structures of more than one orientation. Faults that cut across the stratigraphy have provided conduits to link stratabound veins at different stratigraphic levels. Hydrothermal solutions moving through cross-cutting structures were offered egress to stratabound reverse fault zones, or to stratigraphic horizons with favourable permeability. A ladder-like pattern of mineralization is likely, and appears to have developed, particularly at Eagle North.

Other fracture systems and orientations. Structural trends other than those described above are less well understood. Other possible trends include:

a) Northwesterly striking faulting: whereas the major fault trends are well documented, most healed fractures (forming veinlets of quartz $\pm$ calcite $\pm$ pyrite $\pm$ pitchblende, and considered "minor" in nature with respect to uranium mineralization) have not yet been systematically analysed as to location and orientation with respect to core angles and foliations. Partial documentation of the attitude of these veinlets indicates that more than 90 per cent of them strike approximately normal to the foliation and have a dip of greater than 70°, both northeasterly and southwesterly.

b) Northerly striking faults: the existence of such faults on a regional scale is well established. They are probably subvertically dipping wrench faults and are known from work by various groups in many areas both to predate and postdate the deposition of the Athabasca Group. They probably date from at least the late Hudsonian, and possibly reflect large scale faulting from much earlier time. Faults of this set have been suggested to cut across the Eagle North deposit area, and to have dispersed the uranium mineralization both upwards and downwards in the stratigraphy. These northerly striking faults have been interpreted from magnetic and VLF-EM data, but have not yet been confirmed in drill core in the deposit area.

5.3. Folding

Regional scale folding is interpreted to occur on Harrison Peninsula and in the Collins Bay-Seal Lake area just north of the area in Figure 3.

Smaller scale folding has deformed Aphebian rocks in the Eagle Point area, and, in some cases, may have indirectly influenced the location of mineralization.

Hinges of minor folds are commonly seen in drill core, and the orientation of foliations in any given section of core is found to change from place to place. These two observations clearly indicate that paragneisses at Eagle Point have been folded, perhaps extensively.

6. ALTERATION

Petrographic and analytical studies of host-rock alteration at Eagle Point have been done by GMCL, by Sopuck et al [13] and -- most recently -- by Eldorado. The interpretation of the alteration pattern presented here is based on 'macroscopic' observations made during routine core logging supplemented by limited analytical work. Further detailed work is required to document adequately the chemistry, mineralogy and other features related to the several alteration events that have affected the area.

At present, most Aphebian rocks intersected in drilling at Eagle Point are recognizably altered to some degree. In general, the freshest rocks in the area occur at the greatest distances from mineralization. Also, the degree and extent of alteration tends to decrease with depth below the main mineralized zones, both vertically and down the stratigraphic dip.

For the most part, all silicates except quartz are replaced to varying degrees by hydrated phyllosilicates. Amphibole and cordierite are the most readily altered minerals. Garnet, plagioclase, biotite and potassium feldspar are more stable.

Alteration products have been identified using X-ray-diffraction and electron-microprobe methods. Amphibole and garnet appear to be replaced mainly by chlorite; cordierite by illite and chlorite; biotite by clay minerals, chlorite, and Fe-hydroxide, with leucoxenic Fe-Ti oxides along cleavages; and plagioclase by illite, other clay minerals and carbonate.

The phyllosilicate mineralogy and the spatial distribution of these minerals have not yet been systematically studied, but work to date [14] suggests that the magnesian chlorite (Mg/Fe ratio from 7 to 20) predominates down to depths of about 75 m below bedrock surface, and that magnesium-iron chlorite (Mg/Fe ratio of about one) predominates below about 75 m.

At least four types of alteration have been postulated and/or recognized:

1) paleoweathering of pre-Athabasca age;
2) retrograde alteration associated with faulting of both pre- and post-Athabasca age;
3) possible magnesium metasomatism caused by diagenetic-hydrothermal fluids circulating through the Athabasca Basin during and after deposition of the Athabasca Group rocks; and
4) alteration spatially related to mineralization, of which at least three generations have been identified.

Typically, however, the chemical inhomogeneity of the metasedimentary units tends to mask all but the most prominent aspects of the lithogeochemical character and pattern of the several alteration types.

Lateritic paleoweathering -- typified by its characteristic red, oxidized zone overlying a reduced, green zone -- occurs beneath the Athabasca Group throughout the Athabasca Basin. It is present in the deposit area in the footwall of the Collins Bay Fault, where Archean(?) granitoid rocks occur directly beneath the Athabasca cover.

Hematitic alteration also occurs in the hanging wall of the Collins Bay Fault at the bedrock surface in scattered pockets and areas, possibly as remnants of the oxidized paleoweathering profile. However, the distribution of these areas and the nature of the alteration have not yet been well documented.

Retrograde alteration genetically related to late faulting, typified generally by variable degrees of chloritization of mafic minerals and clay alteration of feldspar, has not been conclusively documented as a uniquely separate event. Observation and limited analytical work to date have indicated that the chloritization of mafic minerals, particularly cordierite, and the illitization and sericitization of plagioclase, are at least incipiently developed throughout the deposit area in the hanging wall of the Collins Bay Fault. These effects are accompanied by soda (Na_2O) depletion [13]. Visually, these altered rocks resemble the "green zone" rocks in the typical paleoweathering profile, and mineralogically, they appear indistinguishable from green zone rocks [13]. At Rabbit Lake, Hoeve and Sibbald [5] recognized an early alteration event typified by dark green chloritization in rocks hosting the orebody, and postulated (p. 1461) that this chloritization "...may have been derived from the late Hudsonian retrogression."

Thus, the widespread incipient to weakly developed chloritization may be of at least two different ages -- late Hudsonian and Helikian -- or may more likely be of both ages, with the Helikian event overprinting the late Hudsonian.

Fischer [14] speculated that a muscovite/illite -- chlorite assemblage (with this chlorite having a high Mg/Fe ratio), which is widely distributed at shallow depths in both barren and mineralized sections, may indicate Mg-metasomatism caused

by solutions that prevailed in the Athabasca Basin after the deposition of the Athabasca Group. He interpreted this event to be separate from, and later than, the first mineralization event.

Alteration spatially related to mineralization is characterized by bleaching of the mafic minerals, chloritization and illitization of feldspar, and hematitization. It is generally moderately to strongly developed. All silicates except quartz, which is usually preserved except in completely altered "clay rock," are replaced to varying degrees by hydrated phyllosilicates. In the highest grade parts of the mineralized zones, illite is the dominant phyllosilicate with little to no chlorite; in lower grade material, chlorite and illite are present in about equal proportions.

Paragenetically, hematitization directly associated with mineralization clearly forms one of the latest alteration events.

Silicification is spatially related to mineralization to only a minor extent. Healed breccia zones well removed from mineralization are typically silicified. Silicification occurs within and very close to, the quartzitic metasedimentary units, and invades adjacent units as quartz veins and silicified zones of limited extent. Silica $\pm$ carbonate $\pm$ pyrite veinlets are common throughout the deposit area, but their distribution and frequency have not yet been systematically documented.

At Key Lake, Sopuck et al [13] recognized that, in the basement funnel zone of alteration below the Deilmann deposit, the green alteration is texturally, mineralogically, and chemically similar to alteration found in the lower green layer of the regolith in regional holes. They noted, however, that intense silicification, tourmalinization (dravite), and chloritization are characteristic of the centre portion of the hydrothermal root zone. At Eagle Point, boron enrichment appears to be associated with, and limited to, the bleached zones within a few metres from mineralization and along the graphitic conductive zones [13]. Silicification is only a minor feature related to mineralization.

Limited work to date suggests that uranium in the alteration halos around the mineralized lenses is enriched by a factor of up to ten over background values.

At Eagle North, alteration associated with mineralization is restricted to relatively narrow zones around and along both mineralized and unmineralized faults and fracture systems. Here, within a few metres of mineralization, the host rock is fresh-looking or is only weakly altered. At Eagle South, the alteration is more extensive and pervasive because of the apparent greater density of faulting. In general, however, mineralization-associated alteration, which is of restricted distribution compared to the clay alteration in the Athabasca Group around the typical unconformity-type deposits, does not significantly enlarge the Eagle Point-type exploration target.

7. MINERALIZATION

Uranium mineralization at Eagle Point occurs in lenses, pods, and veins which are both concordant and discordant to the metamorphic stratigraphy, and are distributed through a stratigraphic thickness of at least 300 m.

The mineralization at Eagle Point is structurally controlled, occurring as fault- or fracture-fillings and as impregnations into altered paragneisses and pegmatoid rocks.

The total strike length of mineralized rock is about 1000 m (Fig. 5). The main mineralized zones generally have a total vertical width of approximately 90 m, in places ranging up to about 250 m. Mineralization extends to a vertical depth of at least 360 m below the present bedrock surface.

At Eagle South, five distinct zones have so far been identified. The two largest of these zones occur as concordant, tabular lenses which dip about 45° towards the southeast; they are subparallel to, and occur immediately above, the Collins Bay Fault (Fig. 7). In section, these zones are from 90 to 120 m long and 15 to 40 m thick. They occur entirely within sheared and faulted pegmatoid rock.

At Eagle North, most of the mineralization occurs in three distinct zones, the largest of which is the 02 Zone (Fig. 8). In plan, the 01 Zone is about 125 m by 30 m, the 02 Zone 210 by 75 m, and the 03 Zone about 60 by 30 m. In cross-section, these three zones are very ragged, with a depth-to-width ratio of approximately 1:1 to 2:1. These zones are, in part, elongated subparallel to the foliation in cross-section, but clearly transect several lithological units. The long axes of the 01 and 02 Zones plunge at about 40° towards 080°. The lensoid 03 Zone has no obvious strike or dip direction. Other, less significant zones occur in northeasterly striking, northwesterly dipping faults.

At Eagle South, the majority of the mineralized lenses are confined within about 150 m of the Archean (?) granitoid surface (measured perpendicular to this surface). Here, the EPF and CBF appear to converge into an anastomosing series of breccias and fault zones. The mineralization occurs within this zone and has not been found below the CBF.

At Eagle North, uranium mineralization occurs mainly above the Eagle Point Fault, with only weak mineralization in the fault itself. This mineralized section begins about 60 m above the Archean (?) granitoid surface (measured perpendicular to this surface).

7.1. Uranium Mineralization

The Eagle Point deposits are mineralogically simple, consisting of several generations of uraninite and pitchblende. All other metals (particulary impurities such as As, Ni, and Mo) are present in trace amounts only (Table II).

TABLE II

URANIUM AND MINOR ELEMENT CONCENTRATION
OF A COMPOSITE SAMPLE FROM THE
02 ZONE, EAGLE NORTH

Ag (oz/t)		0.16
As		60
Au (oz/t)		0.002
Bi		60
Ca		3300
Cd	less than	10
Co		60
$(CO_3)^{-2}$		4400
Cr		120
Cu		370
Fe (total) (per cent)		1.22
Mn		750
Mo		620
Ni		90
P		200
Pb		1570
Pt(oz/t)	less than	0.001
Sb	less than	10
Se	less than	20
Sn	less than	10
Te		2.2
U (per cent)		1.865
V		400
Zn	less than	50
Zr		270

This is one of the notable differences of the Eagle Point mineralization and that of other unconformity-type deposits, such as Key Lake, Cigar Lake, and the Collins Bay B-Zone, where Ni and As are present as major constituents.

Several forms of uranium mineralization have been identified at Eagle Point.

1) Generation I uraninite, highly reflective in polished sections and consisting of well formed cubes, represents the oldest generation of uranium mineralization preserved in the deposit; the cubes commonly show incipient cataclastic deformation (Fig. 9);

2) Generation II uraninite is formed by the oxidation of Generation I uraninite and is pseudomorphous after it (Fig. 10); Generation II crystal development was commonly followed by reaction of these crystals with pore fluids, resulting in their removal by dissolution and replacement by siliceous material;

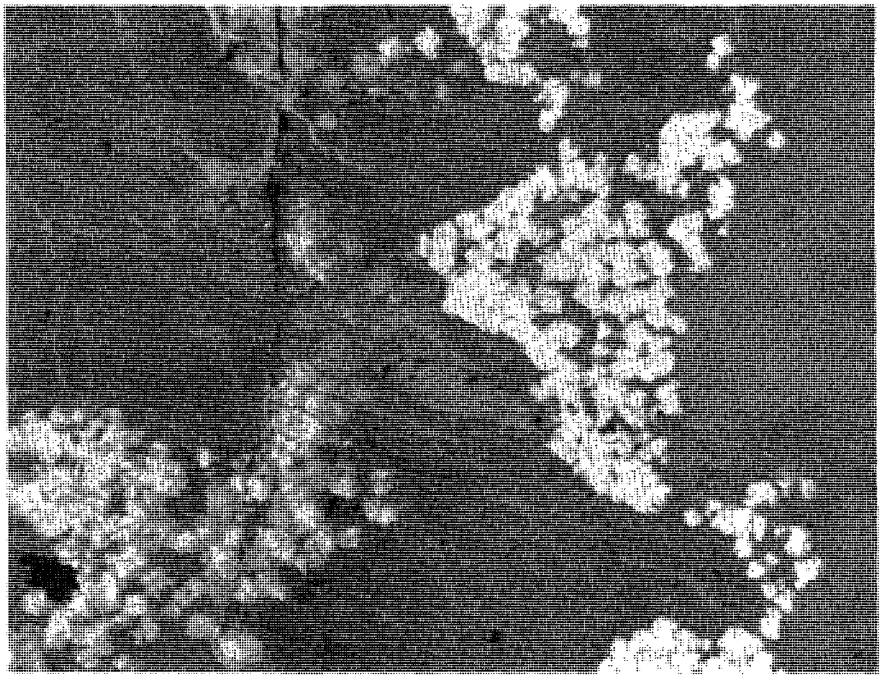


FIGURE 9.

Generation I uraninite cubes; scale: 1 cm = 0.14 mm

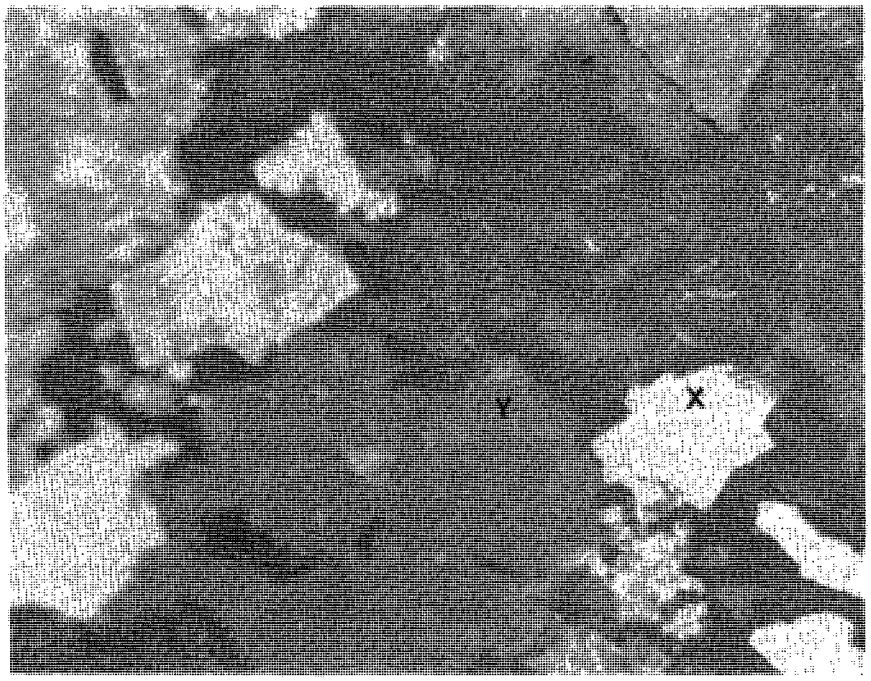


FIGURE 10.

Generation I and II uraninite; cubes of Generation I uraninite (X) with high reflectivity are adjacent to cubes of Generation II uraninite with low reflectivity (Y); scale: 1 cm = 0.028 mm.

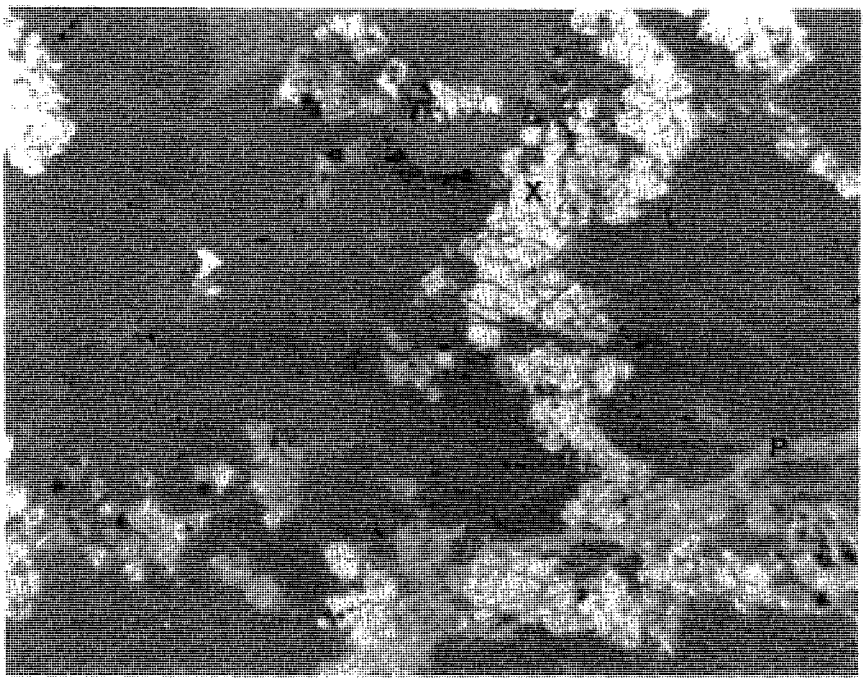


FIGURE 11.

Generation I uraninite (X) cut by a vein of pitchblende (P); scale: 1 cm = 0.14 mm

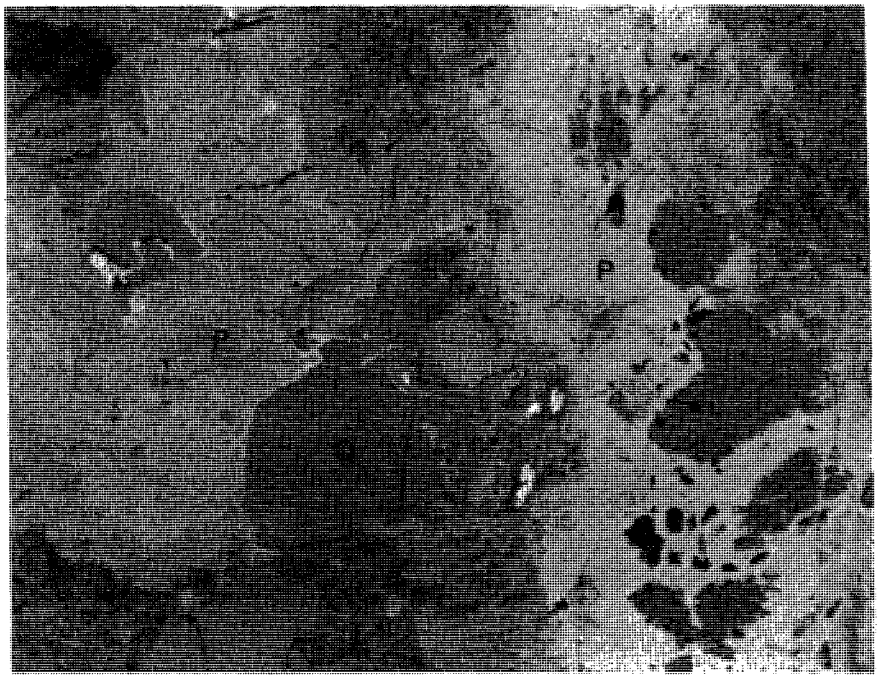


FIGURE 12.

Altered paragneiss containing massive pitchblende (P) indurating an illite-rich matrix (I) and rimming quartz grains (Q); scale 1 cm = 0.14 mm.

3) pitchblende occurring as veins crosscuts both generations of uraninite, which it therefore postdates; it probably represents redeposition of UO_2 removed from Generation I and II uraninite (Fig. 11);

4) pitchblende rimming and filling fractures in quartz grains occurs in areas of porous rock; here, the quartz grains, being impermeable and generally non-reactive, acted as barriers to circulating mineralizing solutions which "welled up" against them to form rims and fill fractures (Fig. 12).

5) pitchblende in biotite commonly occurs as oriented inclusions along cleavage planes.

6) boltwoodite $[K_2(UO_2)_2(SiO_3)_2(OH)_2.5H_2O]$ has been identified by X-ray diffraction; this secondary uranium mineral represents the youngest stage of uranium mineralization, and is common in rocks which contain altered biotite, suggesting that the potassium it contains was derived from the biotite; in many places, boltwoodite cements fractured areas; and

7) coffinite $[U(SiO_4)_{1-x}(OH)_{4x}]$ has been positively identified by X-ray diffraction in only one specimen in which it occurs only in trace amounts.

Notably, boltwoodite and coffinite account for less than one per cent of the total uranium species. The major species are uraninite and pitchblende.

7.2. Base Metal Sulphides and Arsenides

Base metal sulphides, mainly pyrite (FeS_2), galena (PbS), and chalcopyrite ($CuFeS_2$) are present only in trace amounts (Table II), and generally constitute less than one per cent of the total mineralization.

Pyrite is the most abundant of these, and locally makes up to several per cent of the rock. At least two generations have been recognized. The older pre-dates Generation I uraninite, occurring in fresh biotite gneiss as roundish-to-subidioblastic, large grains which are part of the metamorphic fabric; it forms 0.05 to 2 per cent of the rock on average. The younger generation of pyrite occurs in narrow fractures with carbonate and/or quartz. Its age relative to uranium mineralization is uncertain, but, in part, it postdates alteration associated with mineralization.

Galena variably occurs as specks in uraninite and pitchblende formed by the reaction of radiogenic lead with sulphur, as well shaped grains (cubes) in places associated with cubes of uraninite, as oriented inclusions in cleavage planes of biotite, as fracture fillings in barren rocks, and as dendritic veinlets associated with pitchblende.

Chalcopyrite is rare, being generally associated with high-grade mineralization as well shaped specks. Rare globules of native copper occur within and adjacent to the uranium mineralization, as cubes replacing uraninite I, as veins in fractures, and along cleavage planes in biotite.

No arsenides have been identified to date.

7.3. Carbonaceous Matter

Carbonaceous material with a characteristic odour is commonly associated with higher grade mineralization. It generally occurs in very low concentrations as small sooty blebs and buttons, resembling material from Cluff Lake described by Landais and Dereppe [15]. These authors identified it as bitumen, containing 60 to 80 per cent carbon, 3.5 to 4.5 per cent hydrogen, and 6 to 13 per cent oxygen.

8. PROCESSING CHARACTERISTICS AND MINEABILITY

Although work on the processing characteristics of the Eagle Point ore is in progress, several points are noteworthy at the present time.

The Eagle Point deposits are essentially monomineralic uranium occurrences with few impurities which will affect the amenability of mineralization to processing. They differ significantly from typical unconformity-type deposits in that nickel and arsenic are virtually absent. As well, negligible other chemical variation exists within the deposits, such that blending of ore will not be required prior to processing except to maintain a uniform mill grade.

This contrasts with some of the other unconformity-type deposits which contain significant chemical zonation necessitating complex grade control, blending, and extraction procedures which add to overall production costs.

Hydrothermal alteration at Eagle Point is generally narrowly restricted to mineralized zones, such that the host rocks are relatively competent. The exploitation of the deposit is likely to utilize, for the most part, conventional underground mining techniques. This situation is most fortuitous in that, while alteration and fracturing are of considerable benefit in open-pit mining situations, they are disadvantageous in underground operations where specialized mining methods would probably be required, increasing operating costs (deeply buried unconformity-type deposits, such as Cigar Lake, Midwest and McClean Lake, fall into this latter category).

The absence of extensive significant clay alteration at Eagle Point should result in an easily handled and easily processed ore.

9. RESERVES

The total geological reserves of the combined Eagle Point deposits are approximately 133 million pounds U_3O_8 (51,200 tonnes U), at an average grade of about 1.80 per cent U_3O_8. Some potential exists for adding to the Eagle North reserves, and the Eagle South deposit is not closed off down dip, so that the total reserves are potentially larger than those so-far proven, and might approach the size of Key Lake. Three-dimensional geostatistical reserve estimations have been completed on Eagle North and are in progress on Eagle South.

10. GEOCHRONOLOGY

U/Pb age determinations on five high grade uranium samples were commissioned by GMCL in 1981. Fischer [14] has interpreted the results as follows:

- the two generations of uraninite are dated at 1000 to 1400 Ma and at 450 to 700 Ma, with the older probably 1400±25 Ma; and

- two generations of pitchblende are dated at 500 to 700 Ma and 5 to 20 Ma.

No further work has been done on the ages of the mineralization. The uranium in some zones and certain fracture orientations may be of a different age than that in the main zones, but this has not yet been established.

11. CLASSIFICATION AND ORIGIN OF THE DEPOSIT

The Eagle Point uranium deposits have many features in common with the well known "unconformity-type" deposits in the Athabasca Basin such as Cigar Lake, Key Lake, Collins Bay B-Zone, and others. In varying degrees of similarity, these features include:

1) the ages of the several generations of uranium oxide;

2) the age and stratigraphic relationships of the metasedimentary rocks in the deposit area;

3) relative proximity to the inferred position of the Helikian paleosurface;

4) the grades of the mineralization; and

5) the mineralogy and chemistry of the alteration directly related to mineralization.

Eagle Point is therefore interpreted to be a variant of the unconformity-type deposit, with the following significant differences:

1) the deposit is hosted entirely by Aphebian rocks;

2) the mineralization is simple, with no significant quantities of other metals;

3) the mineralization extends for a considerable distance down dip from the inferred position of the Helikian paleosurface; and

4) the shapes of the main zones are much more tabular and/or equidimensional than pencil-like (as at Cigar Lake, for example).

Three principal models of the origin of the Athabasca Basin unconformity-type uranium deposits are currently postulated. These models, which differ in their concepts of the time and mechanism of primary uranium deposition or pre-concentration, the source of the uranium, and the degree and timing of later modification, are:

1) the supergene model, first outlined by Knipping [11];

2) the diagenetic-hydrothermal model, first formulated in print by Hoeve and Sibbald [5]; and

3) a syngenetic model of primary accumulation, incorporating significant metamorphic-hydrothermal upgrading and some aspects of the first two models.

The supergene model suggests that the deposits were created primarily by surficial processes at or near the subaerial paleosurface during Helikian weathering and/or during deposition of the Athabasca Group sediments. Uranium was mobilized by oxidizing ground water during the weathering of (U-enriched?) metasediments and/or granitic rocks, and was deposited in permeable fault zones and/or karsted topographic sinks. Uranium was deposited by reducing conditions created by graphitic, sulphidic host rock or by electrolysis, in part generated by a conductive host rock [16]. In this model, the Athabasca cover served primarily as a protective cap to preserve the deposit from erosion. The model advocates allow that post-Athabasca faulting, burial metamorphism, mafic intrusives, and diagenesis may all have modified the pre-existing deposits to present ore grades and metal accumulations. This mechanism of deposit formation is invoked for Rabbit Lake by Heine [4] and Knipping [11].

The diagenetic-hydrothermal model, emphasizes the role of oxidizing, uranium-bearing, diagenetic solutions from the Athabasca Group interacting with, at or near the Helikian unconformity, reductant-bearing solutions migrating upward through fracture systems in the Aphebian rocks. This model of deposit formation is invoked by Jones [12] for the Collins Bay A- and B-Zones, by Hoeve & Quirt [17] for Midwest; with some modification, by Wallis et al. [18] for the McClean deposits; by Laine [19] for the deposits of the Carswell Structure; by Harper et al [20] for the Maurice Bay deposit, and by Hoeve and Sibbald [5] for Rabbit Lake.

The third model invokes syngenetic accumulation during Aphebian sedimentation and probable upgrading during the Hudsonian Orogeny, followed by important episodes of supergene and/or diagenetic upgrading. De Carle [21] and Clark and Fogwill [22] propose this type of complex history for Key Lake and Dawn Lake respectively.

Each of these theories of origin has been considered for the Eagle Point deposits, but insufficient diagnostic data exist at this time to permit any definitive conclusion.

12. CONCLUSIONS

The Eagle Point deposits occur entirely within Wollaston Group rocks of Aphebian age. They are essentially structurally controlled, and are remarkably similar to each other in their simple mineralogy, consisting essentially of uranium oxide. Nickel, arsenic, cobalt, boron and other metals, which are characteristically present in typical unconformity-type deposits and which are contaminants as far as processing is concerned, are essentially absent.

At Eagle South, the mineralized zones are hosted by a complex structural system of anastomosing faults located above the Collins Bay Fault. The Eagle Point Fault is not well defined at this deposit.

At Eagle North, mineralization occurs in three main zones, located above the Eagle Point Fault in near-vertical structures which strike at about 080°. The 02 Zone contains the largest portion of the reserves at about 16,400 tonnes U.

Phyllosilicate alteration is characteristic of the mineralized zones, but is strongly developed only in close proximity to the mineralization. Alteration is, therefore, not very useful as an exploration tool.

The hosting units are relatively competent. The deposits are therefore likely to be successfully exploited utilizing conventional mining techniques.

The total geological reserves as determined by geostatistical methods for Eagle Point are about 51,200 tonnes U at a grade of about 1.53 percent U. Considerable potential exists for enlarging the Eagle South deposit as the main zones remain open down dip where they have been drill tested only to a depth of about 300 m. Smaller zones, stratigraphically higher, also remain open.

Less potential for significantly increasing reserves exists at Eagle North, where more drilling has been carried out.

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ALBITITE-TYPE URANIUM MINERALIZATION IN THE NONACHO BASIN AREA, NORTHWEST TERRITORIES, CANADA

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Abstract

The Proterozoic Nonacho Basin extends along the 110°W meridian between Lake Athabasca and the East Arm of Great Slave Lake, NWT, Canada. This basin overlies a sinistral shear zone developed in the Archean (+ 2.5 Ga) basement of the Keewatin Block at its transition to the 2.0 - 1.9 Ga-reactivated Taltson Magmatic Zone in the westernmost part of the Churchill Province. The age of this basin's Proterozoic supracrustals is constrained by the traversing Sparrow diabase dykes for which a minimum age of 1.7 Ga has been interpreted.

During the period 1977 to 1984, Uranerz in partnership with Alberta Energy Company carried out a major uranium exploration program within the Nonacho Basin area initially in the search for unconformity-related deposits. In the southeastern portion of the basin the Archean and Aphebian rocks show strong and extensive post-metamorphic cataclastic deformation, sodium metasomatism and diaphthoresis. These features appear to be controlled by regional N- and NE-striking fault zones, which are partly developed as thrust faults along Nonacho Group sediment/basement contacts. Several hundred uranium occurrences were located in the course of exploration within cataclastic albitite zones. Five of the most important occurrences were investigated in detail by trenching, diamond drilling and metallurgical testing.

At Mosquito Gulch, one of the five occurrences, a uranium mineralized zone with an E-W strike extent of more than 500 m and a width of 20 to 50 m was outlined by drilling to a depth of 200 m. The mineralized zone dips at an angle of 45° to the south and plunges 10 to 20 degrees to the southeast. The host rocks are chloritic albitite microbreccias with epidote, sericite, quartz, and calcite as accessories. Uraninite occurs mainly within the chloritic matrix of the cataclasites, either in disseminations or in stringers and veinlets along shear and fracture planes.

The Mosquito Gulch mineralization is monometallic and geochemically characterized by very low Th and enhanced Ti, Zr, P, and Y values. From results of U/Pb isotope analyses a maximum age of primary uranium mineralization of 2.2 Ga is interpreted. Grades and thicknesses of the Mosquito Gulch mineralization show little continuity. The overall grade of the mineralized zone is about 1 lb U_3O_8 per tonne. The metal content of the deposit is drastically reduced if the cut-off is raised.

The potential feasibility of a mining project was evaluated for the area within an orientation study. The Gunnar deposit south of Uranium City, Saskatchewan, was used as the base for the model. The study showed that average grades for a medium size deposit with combined open pit and underground mining have to be well in excess of 0.2 % U_3O_8 to make the project economic at a sales price of US$ 30 per lb U_3O_8. This negative result is partly caused by high capital investment due to the non-existent infracture of the area and also partly by relatively high mining costs due to the discontinuous vein-like geometry of the ore.

Other occurrences investigated in the area differ from the Mosquito Gulch prospect with respect to setting and characteristics of metasomatism and mineralization.

The economic significance of the albitite-type occurrences in the Nonacho area specifically and of albitite-type deposits in other parts of the Western World at uranium prices below US$ 30 per lb U_3O_8 is rather limited. The irregular vein-type nature of these deposits combined with low to medium average grades cause high average production costs. These can hardly be balanced by major depth extension and ease of metallurgical processing, which are also characteristic of this deposit type.

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1. INTRODUCTION

The Nonacho Basin is located about halfway between Lake Athabasca and the East Arm of Great Slave Lake, NWT, Canada (Fig. 1). The first geological record of the area is only about 70 years old and stems from Charles Camsell [1], who explored during the time of World War I along the Tazin and Taltson Rivers. Uranerz geologists arrived in the area in 1977 in the search for Key Lake-type deposits. Follow-up work of a regional airborne radiometric survey and a geochemical survey resulted in the discovery of a large number of radioactive occurrences, which clustered at the southeastern margin of the Nonacho Basin. Competitors activities in 1977 and 1978 caused a staking rush in the area and made a regional exploration approach more difficult. In 1979, when the uranium prices reached their historic peak, the first drilling program on the Mosquito Gulch prospect yielded encouraging results. One of the first holes intersected 0.35 % U_3O_8 over 7.3 meters. In 1980 a second drilling program was carried out to test three additional prospects. Several others were investigated by trenching and sampling. Petrological and mineralogical studies established in 1978/79 that the granitic gneisses of the basement in large parts showed strong tectonization, diaphthoresis, and sodium metasomatism. Most of the uranium occurrences discovered were related to these features. Then, similarities to the Beaverlodge and Gunnar uranium deposits became apparent. From 1981 onward the momentum of

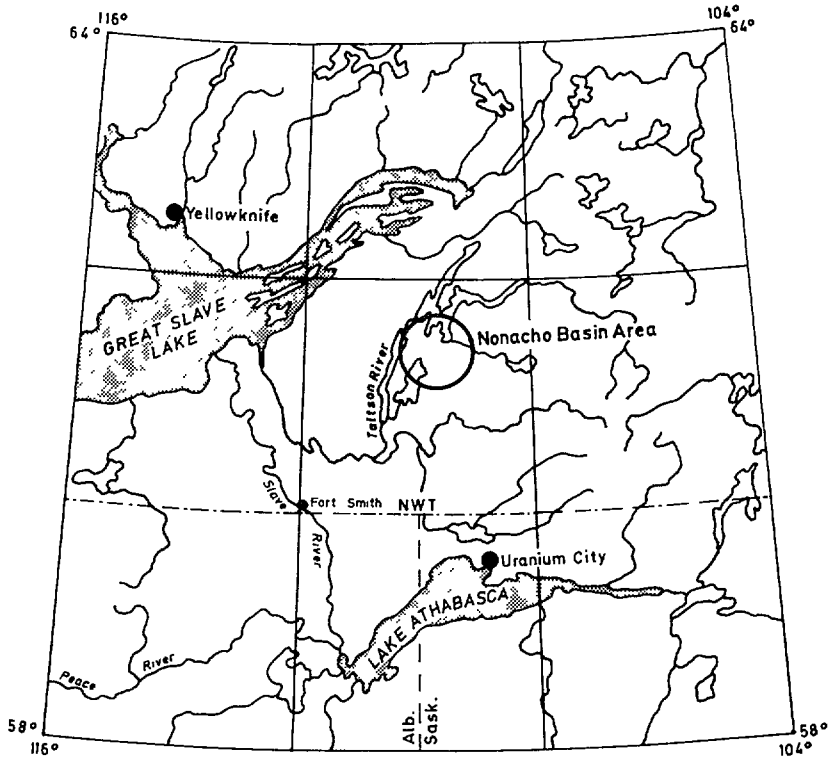

FIG. 1 Location of the Nonacho Basin area

exploration in the Nonacho area steadily diminished due to the drastic change in the uranium market and the lack of success in discovering ore zones with substantial tonnage and medium to high grades. Furthermore, an economic orientation study of the project showed that the economic target in this remote area necessitates substantially higher grades than could be reasonably expected from exploration results. Also the rapidly increasing knowledge on albitite-type uranium deposits from other parts of the world did not provide sufficient stimulation for a continuation of the search.

This paper gives a broad overview of results of field and laboratory work carried out so far. The lack of economic success is to be made responsible for the fact that only very limited scientific investigations of the discovered uranium occurrences were carried out. Some further work is in progress but much more needs to be done to clarify the metallogenesis of albitite-type uranium mineralization in the Nonacho Basin area.

2. REGIONAL GEOLOGY

The Proterozoic Nonacho Basin traverses the northwesternmost part of the outcropping Churchill Structural Province (Fig. 2). The basement of this region is subdivided into the Taltson Magmatic Zone (TMZ) on the west

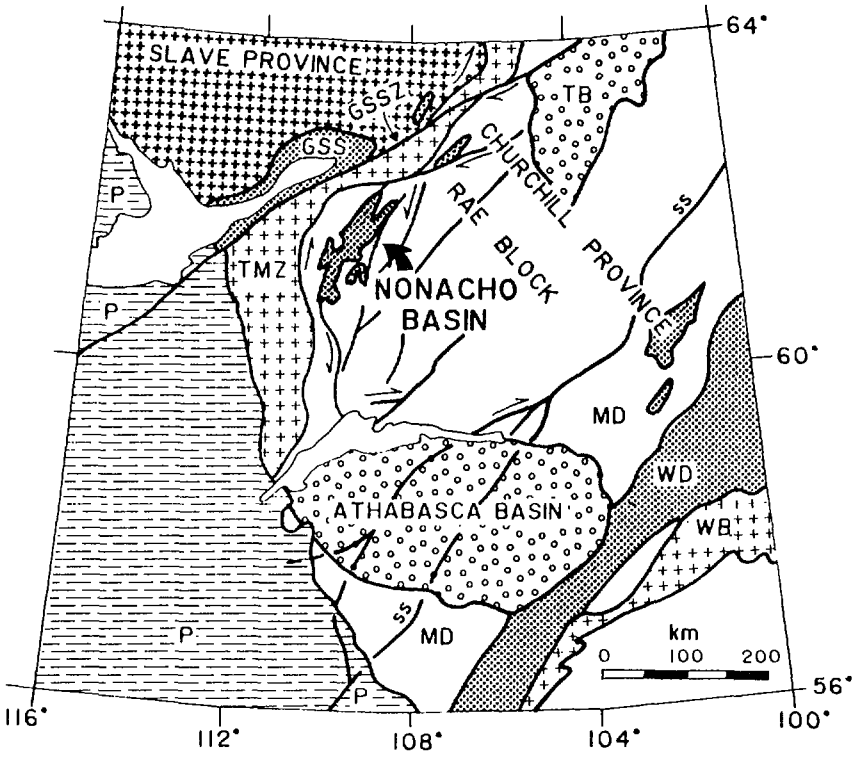

FIG. 2 Regional geological setting of the Nonacho Basin area

side dominated by 2.0 to 1.9 Ma granitoid plutonism and the Rae Block to the east, which predominantly comprises Archean rocks [2] . Major north- and northeast-striking fault zones occur at the western margin of the Rae Block, which appear to be connected with the evolution of the Great Slave Shear Zone. They represent zones of major ductile and brittle sinistral tectonics [2] .

Aspler and Donaldson [3] have presented stratigraphic, sedimentologic and structural data, which indicate that the evolution of the Nonacho Basin was controlled by sinistral strike-slip faults at its western margin (Fig. 3). The 200 km long and 60 km wide basin comprises several rhomb, wedge, and rectangular shaped sub-basins, which were separated during and after the sedimentation by basement uplifts and thrusting.

The depositional age of the Nonacho Group is more clearly constrained by its maximum age (Fig. 4). Bostock [4] has found cobbles of a granite which he assumes to be younger then the Konth Syenogranite in the basal conglomerate of the Nonacho Group. The Konth Syenogranite has recently been dated at 1922 Ma (U-Pb monazite) [5] . The minimum age of the Nonacho Group is constrained by the 1700 Ma dated [6] Sparrow diabase dykes, which intrude

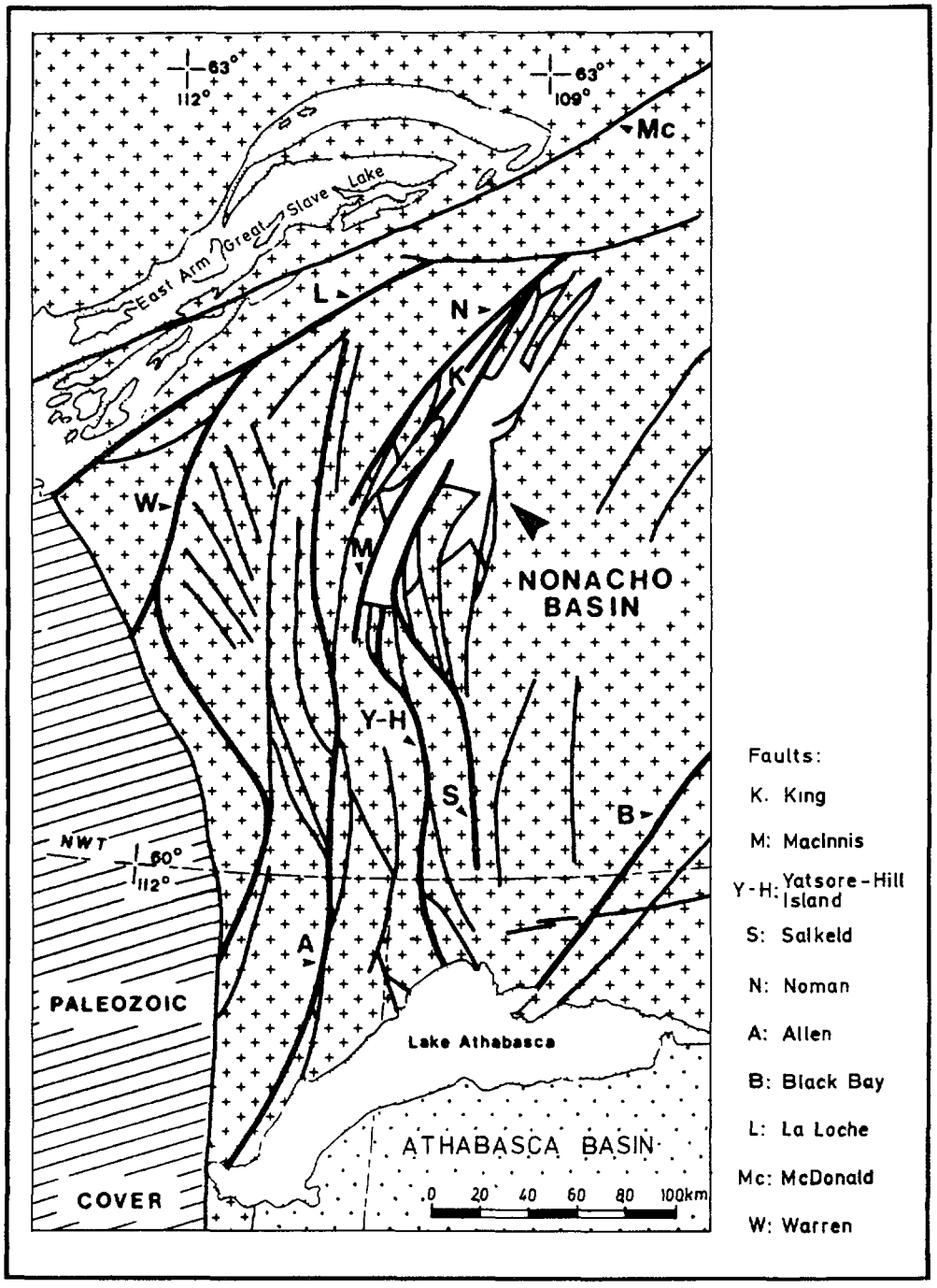

FIG. 3 Regional faults in the Nonacho Basin area, north-western Churchill Province (modified from Aspler and Donaldson [3])

the Nonacho Group and the Konth Syenogranite (H.H. Bostock, personal communication, 1987). Therefore, the sedimentation of the Nonacho Group is likely to be of late Aphebian age. The sediments are folded about NNE-trending axes plunging to the north but they have escaped major thermal metamorphism.

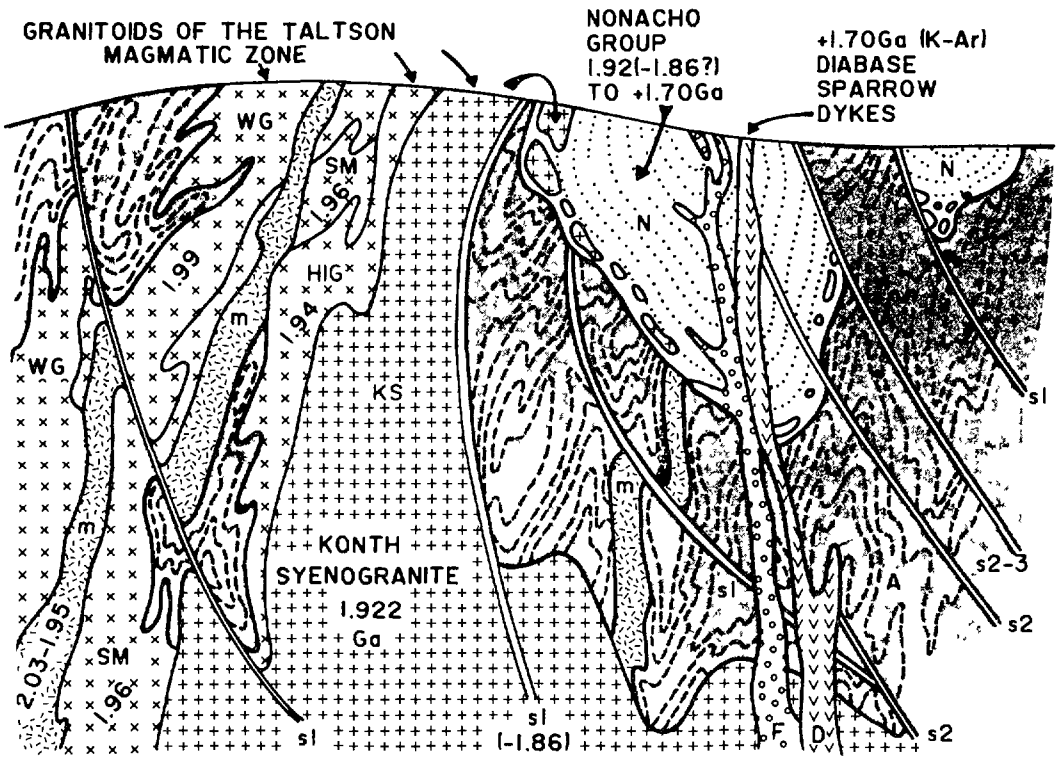

FIG. 4 Stratigraphic relationship of the Nonacho Basin within the surrounding basement (looking North). Left side shows the Taltson Magmatic Zone, right side the Rae Block with the Nonacho Basin.
A - Archean and possibly some early Aphebian sequences; granitoids of the Taltson Magmatic Zone: WG - Western granodiorite, SM - Slave monzogranite, HIG - Hill Island muscovite granite, KS - Konth syenogranite and other undated younger derivates which provided clasts for the basal Nonacho Group sediments; post-Nonacho lithologies: F - flinty aphanitic felsite and possibly also diorite-granodiorite dykes and quartz latite dykes of Bostock (4), D - diabase Sparrow dykes (+ 1.7 Ga); structures: m - syn-Hudsonian = pre-Nonacho mylonites (2.03 - 1.95 Ga), s - brittle deformation: s-1 - older suite of shears (about 1.86 Ga), which uplifted the granitized basement prior and during the Nonacho deposition, s-2 - younger suite of post-Nonacho shears, possibly used by F, S-2-3 - youngest shears.

Aspler and Donaldson [3] observed a regionally penetrative D_3 cleavage (Fig. 5). They postulate that the angular relationship between faults and this cleavage indicates postdepositional heterogeneous sinistral shearing.

3. AREA OF INVESTIGATION, GEOLOGY

The Uranerz exploration activities were concentrated within the area outlined in Fig. 5. Several smaller sub-basins occur in this area of which the southernmost are not shown on the regional map by Aspler and Donaldson [3] . These sub-basins are mostly controlled by N- and NE-trending faults. A broad zone along these faults within the basement shows extensive tectonization and strong influence of diaphthoresis and sodium metasomatism.

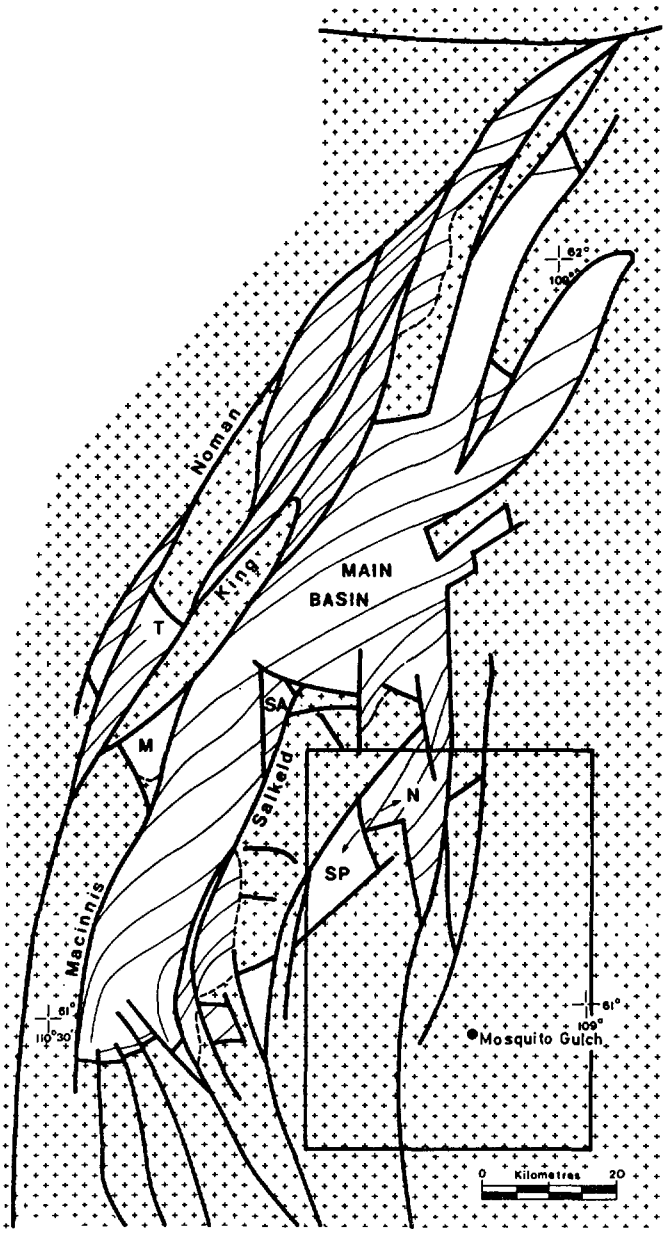

FIG. 5 Nonacho Basin, faults (bold lines), cleavage (fine lines), sub-basins: M - McInnis, SA - Salkeld, SP-N - Sparks-Naskethey, T - Taltson, (modified from Aspler and Donaldson [3]); and area of main exploration activities by Uranerz.

Fig. 6 shows the location of five more important uranium occurrences of a total of about 300, which were located in the course of exploration within this area.

4. MOSQUITO GULCH PROSPECT

4.1 Geological frame and petrology of country and host rocks

The Mosquito Gulch prospect (Fig. 7) is located immediately east of the N-trending faulted contact between Nonacho Group sediments and cataclastic to mylonitic basement rocks where a thrust fault dips 45 to 60 degrees east,

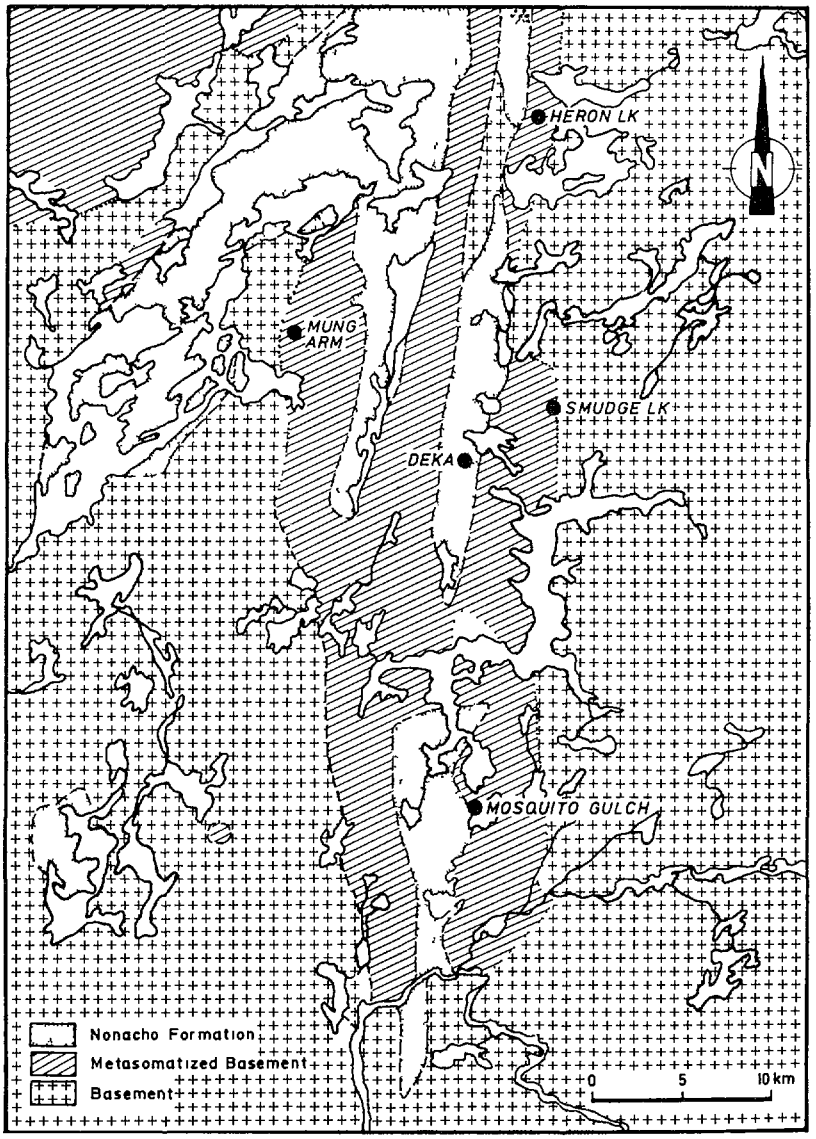

FIG. 6 Southeastern margin of Nonacho Basin showing N/S elongated sub-basins, metasomatized Archean basement and main uranium occurrences.

i. e. the basement is thrusted over the sediments. South of the prospect the N-trending fault has probably been offset to the east. At the contact zone the Nonacho Group sediments have been strongly silicified and appear macroscopically dark grey. Microscopically they can be classified as arkoses. The matrix consists predominantly of quartz with minor chlorite, sericite and opaque minerals. It is uncertain whether the massive invasion of quartz along the thrust is related to post-Nonacho metasomatic processes in the basement. Up to 3 km east of the sediment/basement contact, the basement is represented by partly to totally albitized mylonitic, blastomylonitic, and cataclastic rocks (which were initially mapped as tectonized granodioritic gneisses). The composition of these rocks comprises quartz (3 to 30 vol.%), chlorite (10 to 20 vol.%), and albite (50 to 80 vol.%) with minor K-feldspar,

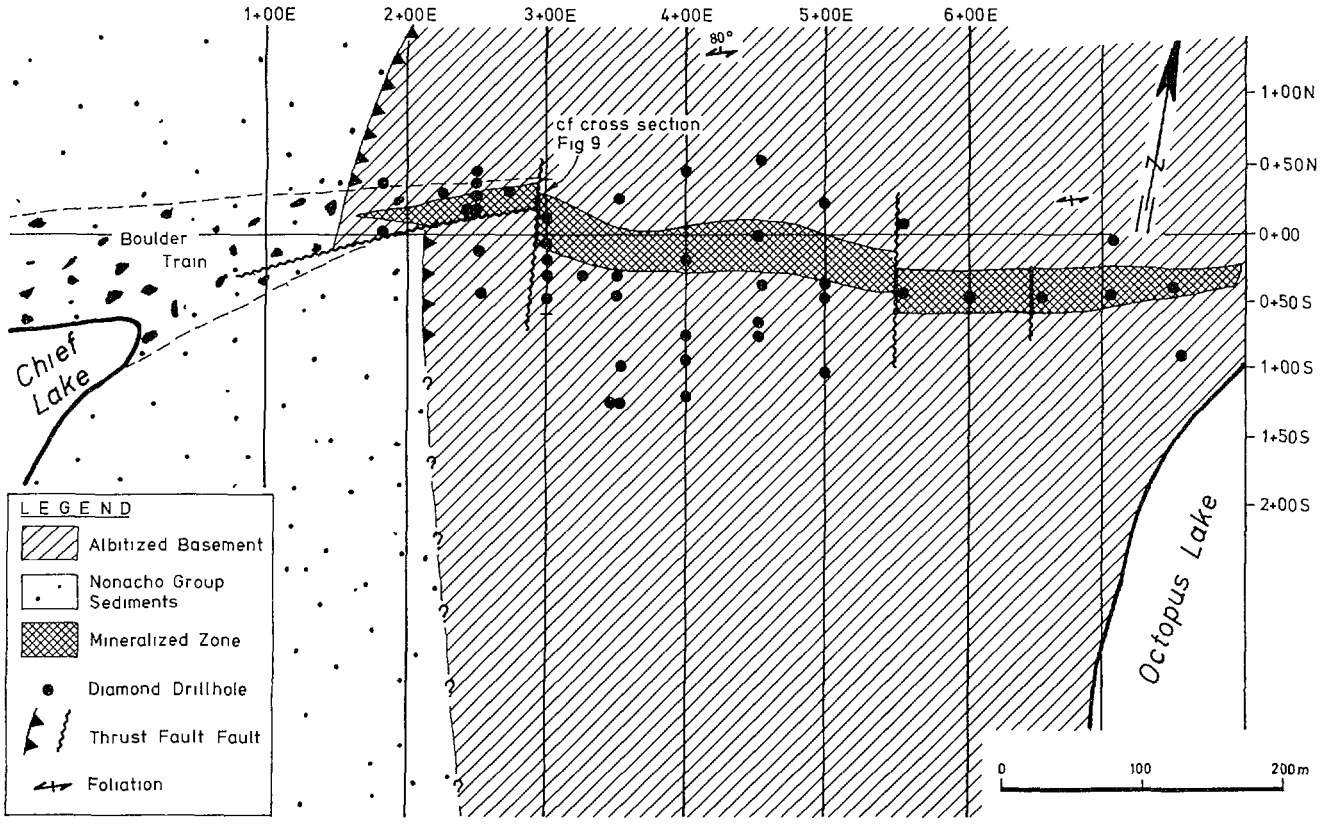

FIG. 7 Mosquito Gulch Prospect, plan showing surface projection of mineralized zone, grid, drillholes, position of section (cf. Fig. 9) and thrust fault at contact between albitized basement and Nonacho Group sediments. The mineralized zone subcrops at the western end where glacial erosion occurred (cf. boulder train at Chief Lake).

epidote, calcite, sericite, and opaque minerals. Away from the contact the basement rocks become progressively less cataclastic. All transitions from the hypidiomorphic granular textured biotite granite or biotite hornblende gneiss to mylonitic chloritic albitite can be observed.

Chemically (cf. Table I), albitization and chloritization are expressed in Na_2O contents of 6 to 10 weight %, increased Al_2O_3, Fe_2O_3, MgO and CaO contents, and elevated TiO_2, Zr and P_2O_5 contents. Furthermore, significantly reduced SiO_2 and K_2O contents prevail in the albitized rocks as compared to the unmetasomatized country rocks. On the other hand, there is no apparent chemical difference between uranium mineralized and barren albitites.

The albitization developed in several stages (cf. Fig. 8). Initially cloudy albite replaced sericitized plagioclase (cf. No. 2 Fig. 8), while the K-feldspar remains largely fresh. A second stage, checkerboard patterned

Table I. Chemical analyses (in weight-%, unless otherwise noted) of albitized (CN 9722 - CN 9730) and non-albitized (CN 9741 - CN 9743) granodioritic rocks from the Mosquito Gulch area. Sample CN 9720 represents a partly albitized granodiorite. Samples CN 9706 to CN 9730 represent uranium mineralized albitites.

	CN 9741	CN 9742	CN 9743	CN 9720	CN 9722	CN 9706	CN 9707	CN 9717	CN 9728	CN 9730
SiO_2	75.48	72.97	77.09	73.55	61.16	52.26	64.65	62.38	63.10	61.07
TiO_2	0.12	0.18	0.22	0.16	0.62	0.67	0.44	0.40	0.38	0.36
Al_2O_3	9.86	10.35	9.39	12.11	21.84	23.14	20.31	19.09	20.83	22.12
Fe_2O_3 tot.	1.75	2.07	1.50	2.38	4.68	8.66	2.82	3.72	2.78	3.93
MnO	0.01	0.01	0.00	-	0.02	0.08	0.00	0.03	0.02	0.02
MgO	0.35	0.42	0.31	1.85	0.61	7.38	1.54	1.93	1.94	2.79
CaO	0.32	0.67	0.70	2.64	1.13	0.78	0.45	2.59	1.16	0.53
Na_2O	2.83	2.79	2.69	5.00	8.67	6.18	9.69	8.80	9.14	8.82
K_2O	5.98	6.73	6.54	0.37	1.79	1.00	0.50	0.19	0.43	0.71
P_2O_5	0.02	0.25	0.33	0.20	0.22	0.42	0.13	0.53	0.57	0.21
Sa	96.72	96.44	98.77	98.36	100.74	100.57	100.53	99.66	100.35	100.57
U_3O_8	-	-	-	-	4 ppm	0.16	0.08	0.03	0.24	0.14

twinned albite (cf. No. 3 and 6 Fig. 8) is found in more intensely albitized rocks, where quartz disappears and is replaced by carbonate and albite and carbonate in turn is replaced by chlorite. Chlorite initially replaced biotite and later, a second hydrothermal chlorite phase filled veinlets and fractures (cf. No. 4 and 5, Fig. 8). Cataclasis postdates the sodium metasomatism and only minor post-cataclasis recrystallization of albite is observed.

4.2 The mineralized zone

The uranium mineralized zone at Mosquito Gulch (cf. Fig. 7) has an E-W strike extent of more than 500 m, which follows a topographic depression. A mineralized boulder train originated at the western end of the zone, where it subcrops. The mineralized zone has a width of 20 to 50 m and was outlined to a depth of 200 m by drilling. It dips at an angle of 45 degrees to the south and plunges 10 to 20 degrees to the southeast. Fig. 9 shows a schematic cross section along line 3+00 E. Diamond-drill intersections of up to 0.35 % U_3O_8 over 7.3 m and 0.1 % over 27 m were obtained, however, grades and thicknesses show little continuity and the overall grade of the mineralized zone

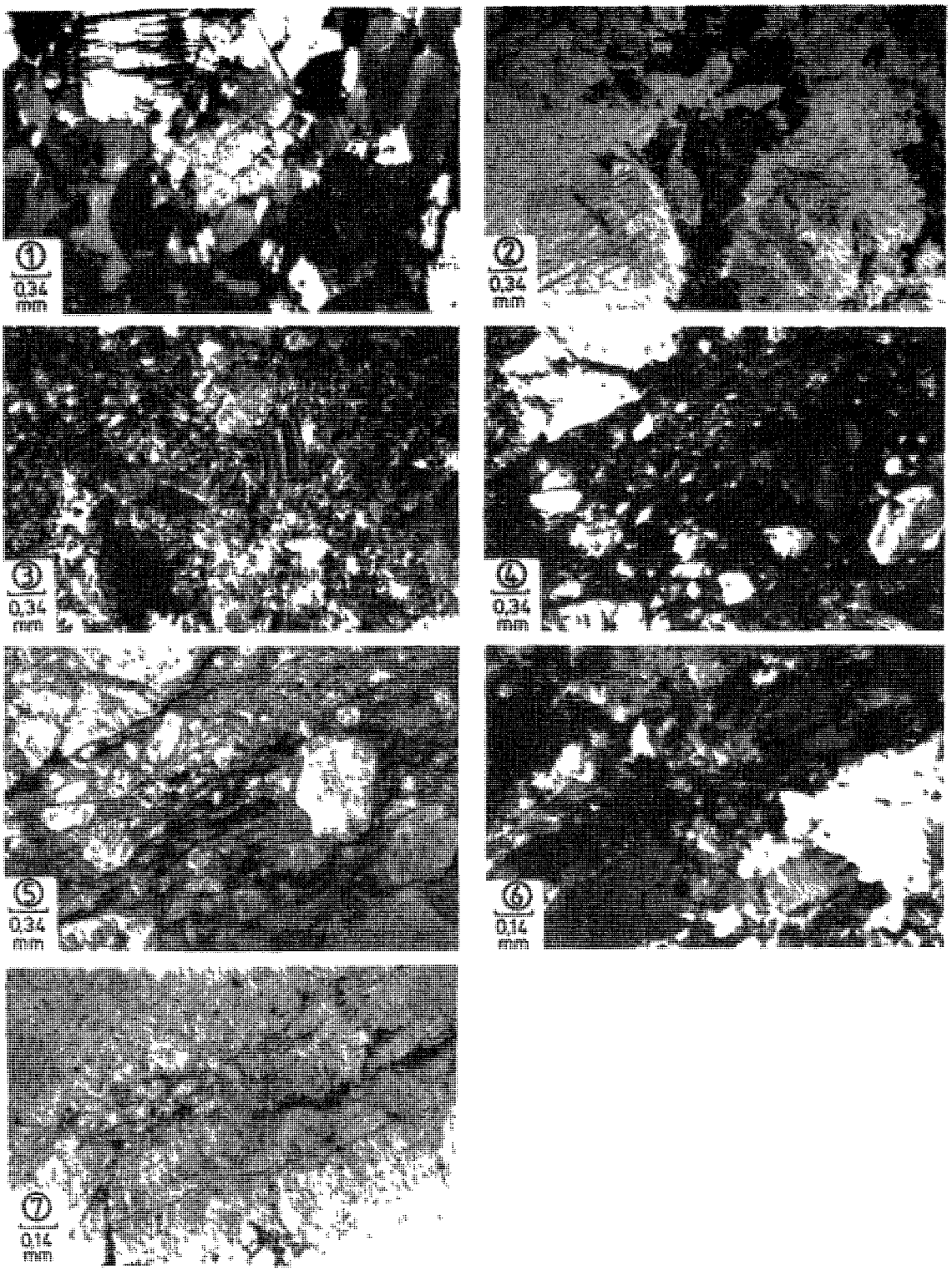

FIG. 8 Photomicrographs of thin sections of non-albitized and albitized granitoid rocks of the Mosquito Gulch area: 1 - non-albitized granite, large microcline at upper left, CN 9742, + nc; 2 - albitized granite, large cloudy albite is partly replaced by clear albite, chlorite and epidote form matrix, CN 9722, // nc; 3 - cataclastic albitite, deformed larger albite crystals are replaced by matrix of checker-board albite, sericite and carbonate, CN 9726, + nc; 4 - albitite breccia, broken albite in matrix of chlorite, CN 9718, + nc; 5 - same as 4 but // nc, protomylonitic texture, chlorite replaces albite; 6 - albitite, checker-board albite replaces initial stage albite, CN 9705, + nc; 7 - same as 6 but // nc, opaque minerals including uranium mineralization occur mainly along grain boundaries preferably at boundaries of finer to coarser grains.

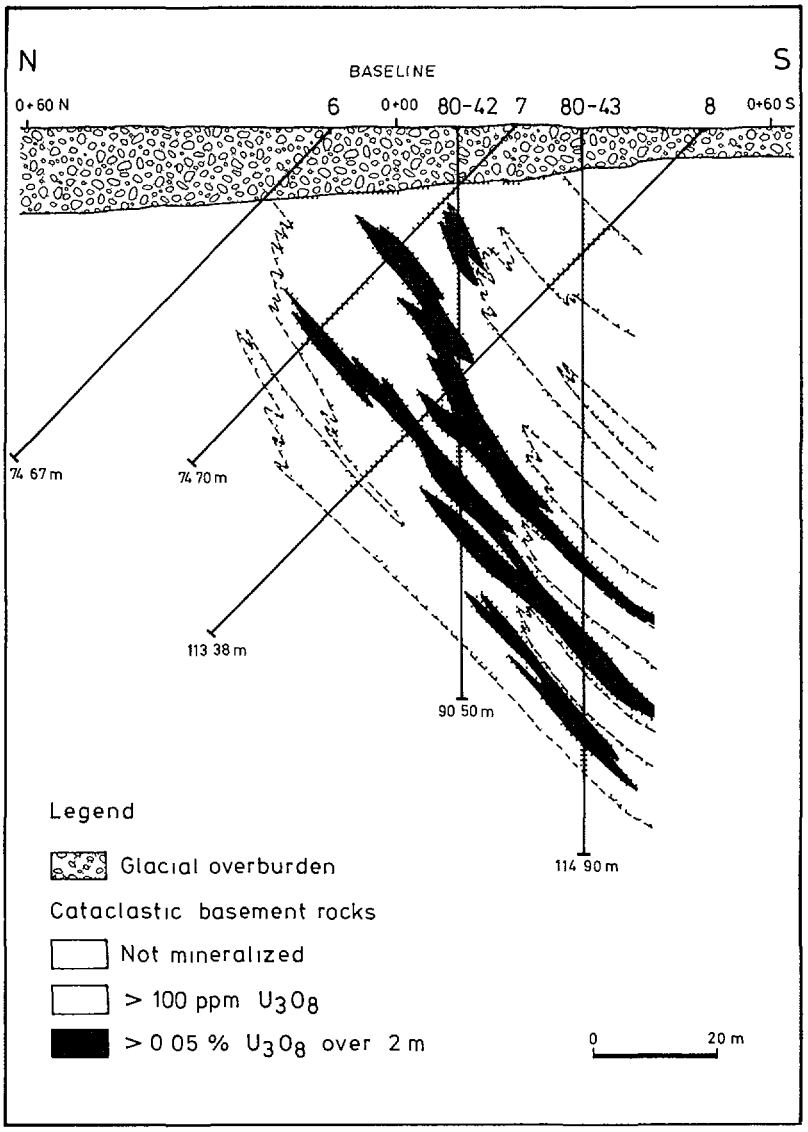

FIG. 9 Mosquito Gulch, schematic cross section along line 3+00E showing distribution of uranium mineralization at different cut-offs, cf. Fig. 7 for position of section.

at a cut-off grade of 100 ppm U_3O_8 is about 1 lb U_3O_8 per tonne. Grade distribution follows an almost lognormal pattern. Only less than 5 % of the total population indicates a separate population of higher grades. This is in accordance with the observation that the metal content of the deposit is drastically reduced if the cut-off is raised, for example, to 0.05 % U_3O_8 over 2 m. Higher grade sections are very discontinuous.

4.3 Host rocks

The host rocks of the uranium mineralization are chloritic albitite microbreccias. Macroscopically it is difficult to distinguish between mineralized and non-mineralized rocks since no distinct fabric or colour is associated exclusively with the ore though often a layering and increase in hematite

can be observed in mineralized albitite. Microscopically epidote, sericite, quartz, calcite, apatite, sphene, leucoxene, and zircon are observed as accessories in thin sections. In polished sections besides uranium minerals minor galena, hematite (partly as specularite), magnetite, and pyrite were identified. Whereby magnetite is usually replaced by hematite, galena occurs mainly intergrown with uranium minerals and cataclastic pyrite is partly recrystallized.

4.4 Uranium mineralization

Uranium mineralization occurs either disseminated and in streaks parallel to the layering of the host rock or in veinlets (cf. Figs. 10a, b and 11a, b). It comprises uranium oxides, which exhibit partly idiomorphic but predominantly a collomorphic and xenomorphic habit (cf. Figs. 12, 13 and 14). Minute spherules measure only a few microns in diameter whereas irregular shaped ragged aggregates reach a grain size of 0.1 mm. A relatively high reflectance (16.7 % at 546 nm) [7] and a lattice constant (a_o) of 5.468 Å calculated from X-ray diffractometry tentatively indicate a low oxidation stage (UO 2.03) for one of at least two different uranium oxide phases. This corresponds with data of Cathelineau et al. [8] for Proterozoic pitchblendes. Results of electron microprobe analysis of two uranium oxide phases with different reflectivity values and textures are listed in Table II.

The Mosquito Gulch uranium mineralization is essentially monometallic. Geochemically it is characterized by very low Th and slightly enhanced Ti, Zr, P, REE, Pb, Zn, and V levels (cf. Table III). Höhndorf [9] carried out U/Pb isotopic analyses on 5 uranium mineralized albitites and interpreted an age of primary uranium mineralization of 2.2 Ga and an age for remobilization of 0.65 Ga. Rb/Sr whole rock analysis data of albitites and partly albitized basement rocks scatter widely and do not define an isochron.

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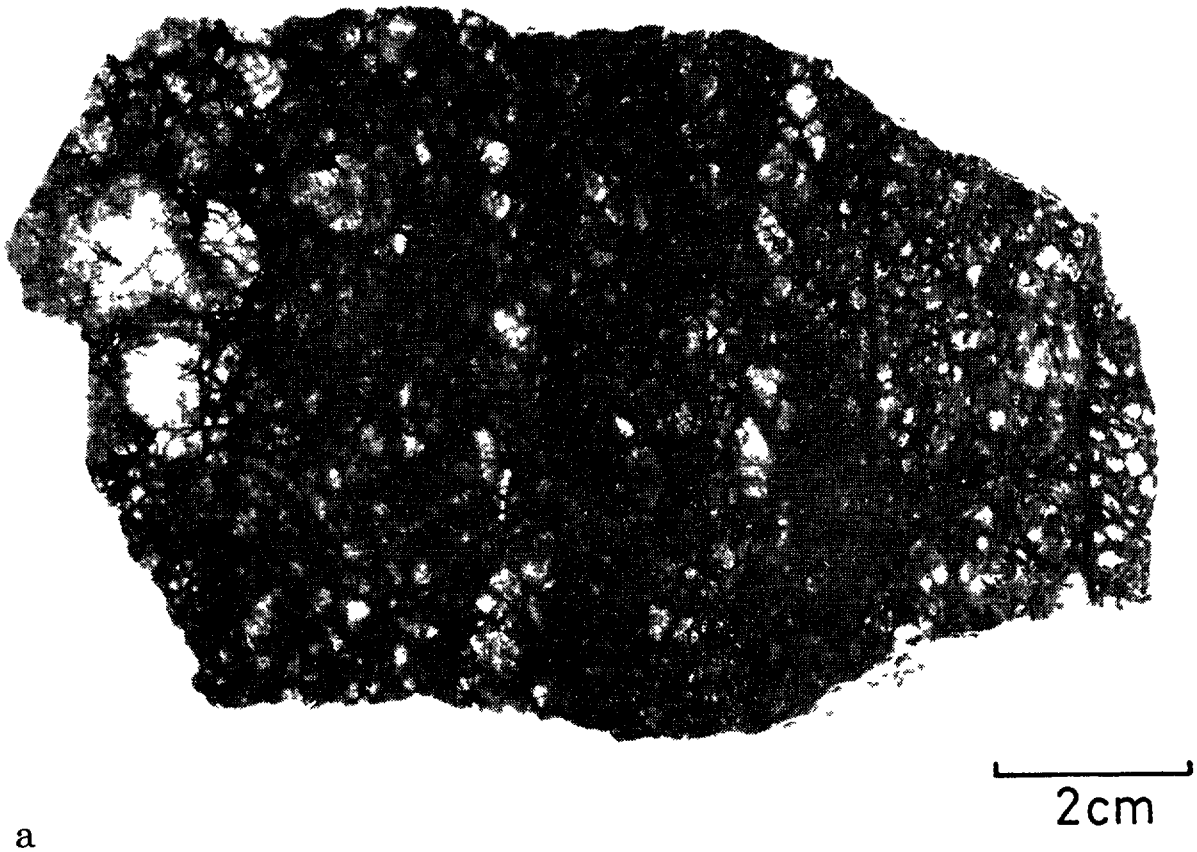
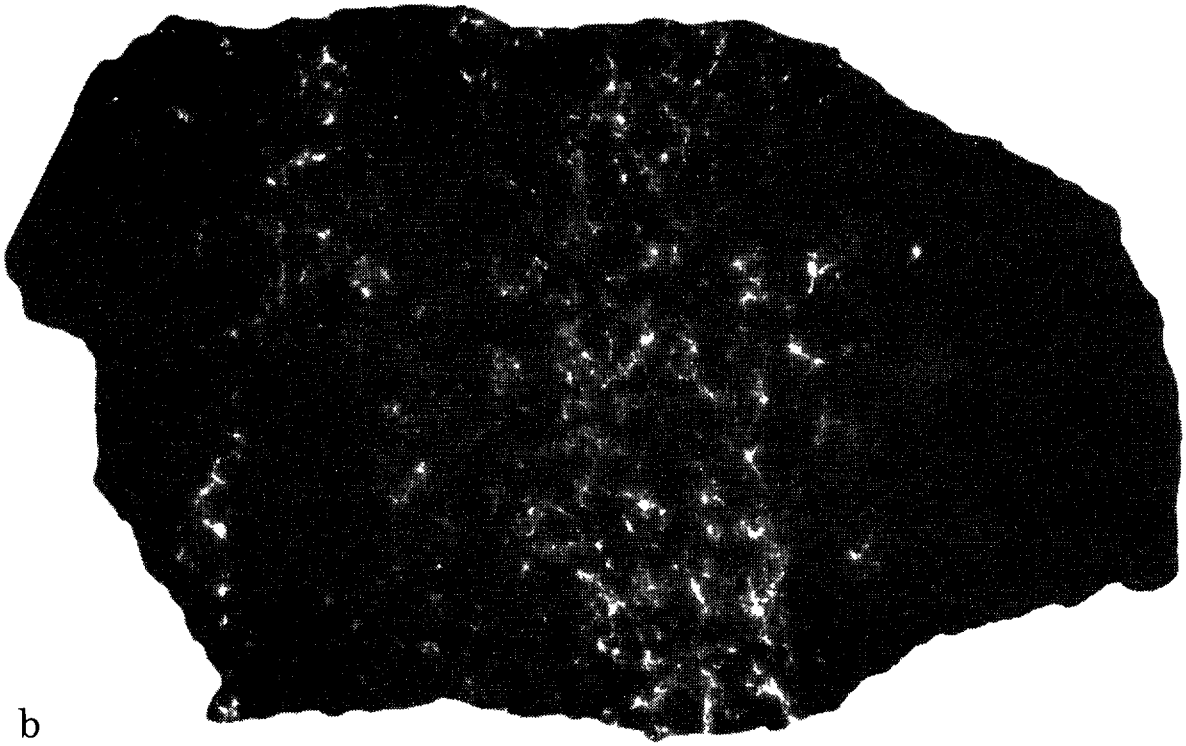


a



b

FIG. 10 a) Photograph of handspecimen (CN 10837) of uranium mineralized albitite with layered texture. b) The autoradiograph shows a disseminated distribution of uranium mineralization enriched in certain layers.

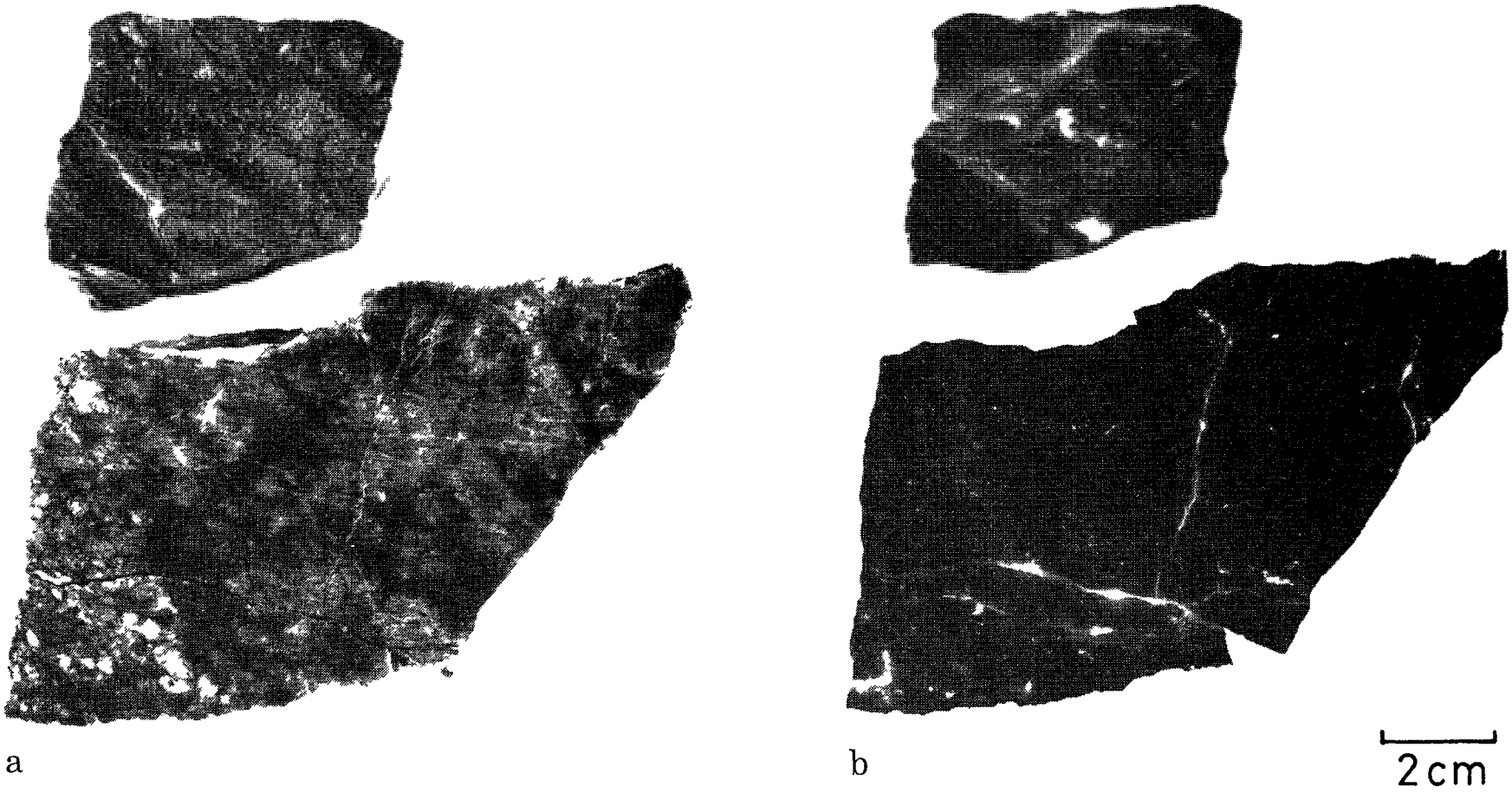


FIG. 11 a) Two hand specimens of uranium mineralized albitite. The smaller specimen has a gneissic texture and contains substantial amounts of chlorite, whereas the larger specimen has an irregular massive texture and contains very little mafics.
b) The autoradiographs show a streaky distribution of uranium mineralization within the small, and veinlets in the larger specimen.

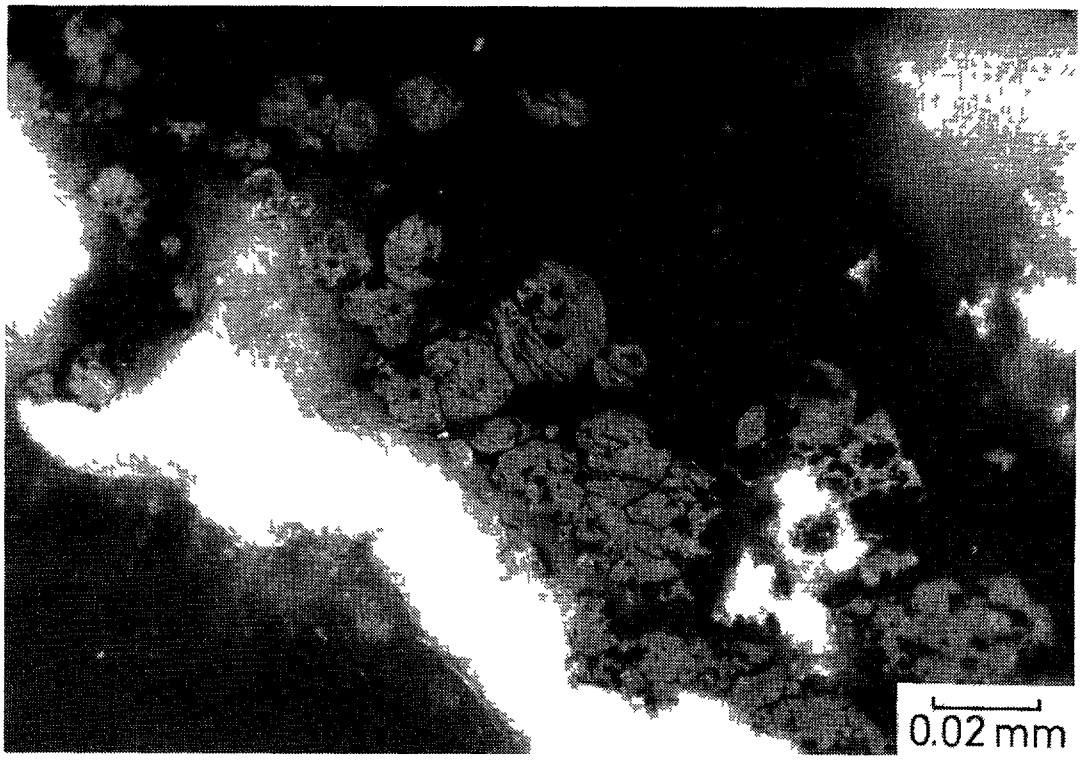


Fig. 12 Photomicrograph, polished section CN 9728 A1, obj. 50 x imm., 1 nic.:subhedral to roundish uraninite grains (grey) aside a veinlet of anatase (white).

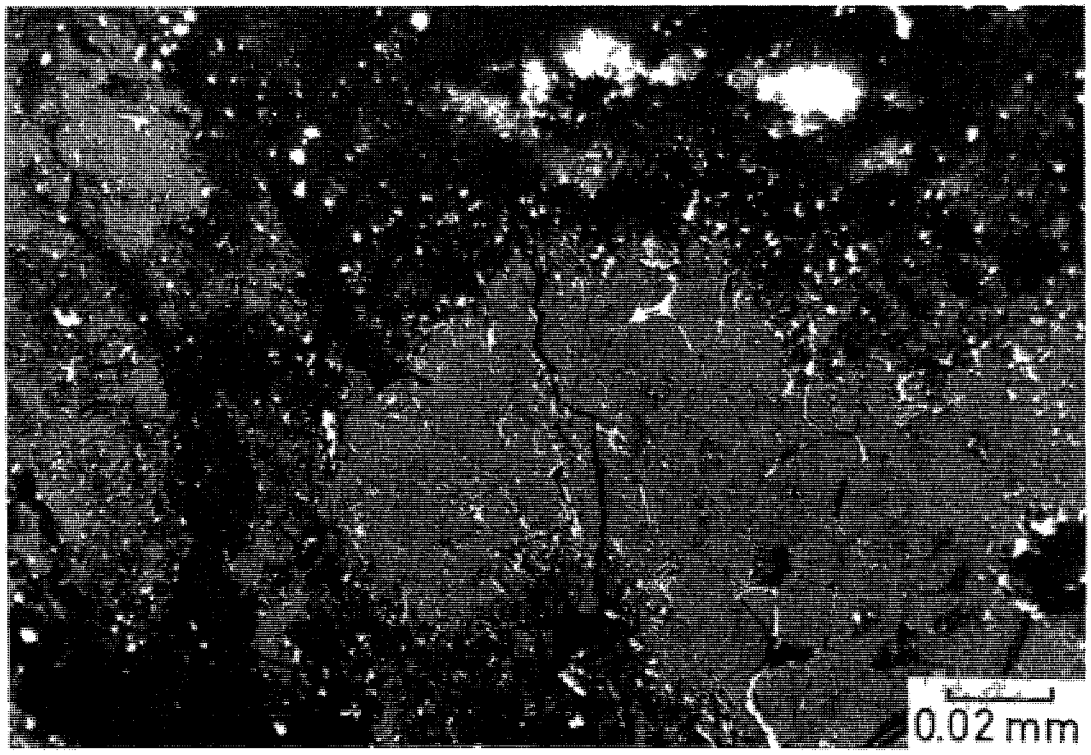


Fig. 13 Photomicrograph, polished section CN 6216, obj. 50 x imm., 1 nic.: Aggregate of subhedral grains of uraninite (grey) with galena (white) along grain bounderies, and in matrix.

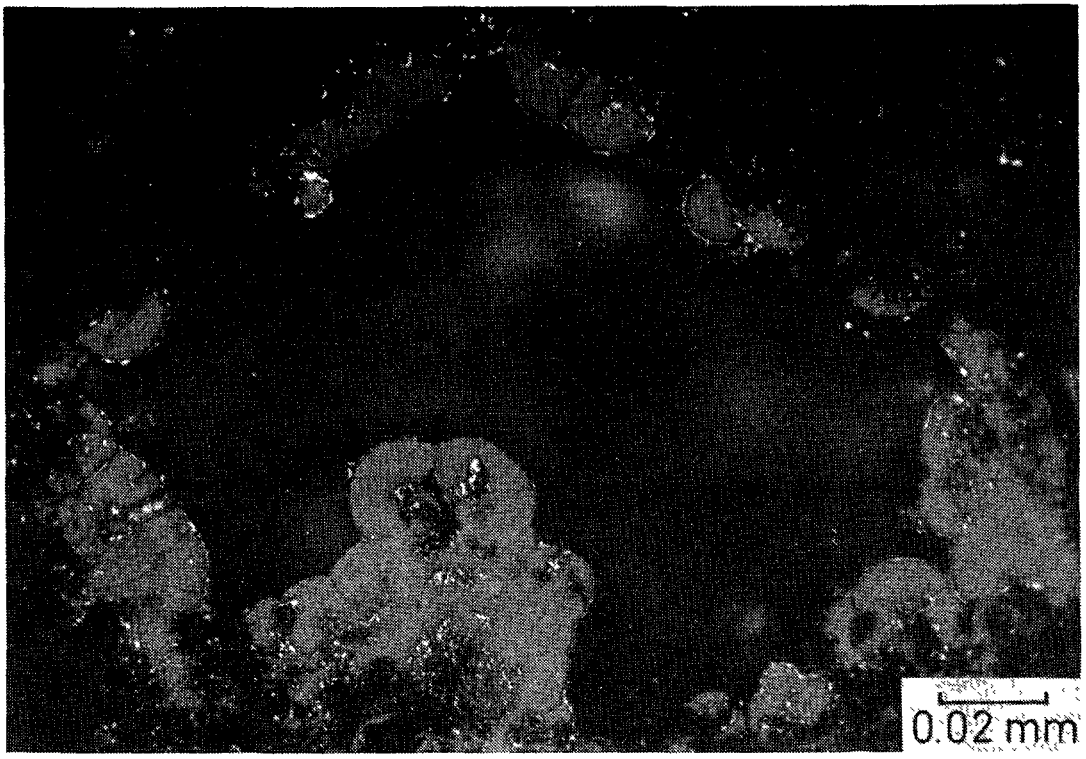


Fig. 14 Photomicrograph, polished section CN6216, obj. 50 x imm., 1 nic.: Colloform uraninite (grey) coating a vug, minor galena (white) associated.

Table II. Electron microprobe analyses of uranium oxides; CN 9728 (average of 15 measurements), veinlet with reflectivity value of 16.7 % at 546 nm; CN 9547 (average of 9 measurements), euhedral partly corroded uraninite with reflectivity value of 12.2 % at 546 nm.

Sample No.	CN 9728	CN 9547
UO_2	73.07	85.56
PbO	18.37	4.10
CaO	2.66	2.33
SiO_2	0.42	3.81
Ce_2O_3	0.28	0.08
ThO_2	0.08	0.21
TiO_2	0.06	0.02
FeO	0.03	0.02
Al_2O_3	0.03	0.09
Total:	95.00	96.22

Table III. Chemical analysis of a composite drill core sample, Mosquito Gulch mineralization.

Sample	%		ppm
SiO_2	56.10	Zr	500
TiO_2	0.49	Pb	170
Al_2O_3	19.04	V	110
Fe_2O_3	6.87	Ni	98
MgO	5.38	Ce	98
MnO	0.10	Zn	90
CaO	2.42	Cu	10
Na_2O	5.96	Ta	10
K_2O	0.21	As	< 10
P_2O_5	0.46	Mo	< 10
CO_2	0.65	Nb	< 10
U_3O_8	0.08	Ag	< 5
		Au	<< 0.50
Total	97.76		

4.5 Metallurgy

Metallurgical laboratory scale tests on a sample of uranium mineralized albitite (cf. Table III) ground to minus 500 microns yielded good recoveries (95 %) and low acid consumption (about 45 kg/t). The mineralized rock is also amenable to radiometric ore sorting. A test resulted in an "accept" of 46 weight % with a metal recovery of 81 weight %.

4.6 Economic orientation model

The potential feasibility of a mining project was evaluated for the area within an orientation study. The Gunnar deposit south of Uranium City, Saskatchewan, was used as the base for the model. The study showed that average grades for a medium size deposit with combined open pit and underground mining have to be in excess of 0.2 % U_3O_8 to make the project economic at a sales price of US$ 30 per lb U_3O_8. This negative result is partly caused

by high capital investment due to the lack of infrastrucure of the area and also partly by relatively high mining costs due to the discontinuous vein-like geometry of the ore.

5. HERON LAKE, MUNG ARM, SMUDGE AND DEKA PROSPECTS

Other uranium occurrences which were investigated in the area by Uranerz differ from the Mosquito Gulch prospect with respect to setting and characteristics of metasomatism and mineralization.

At Heron Lake, a 400 m-long, 15 to 20 m-wide mineralized shear zone, which has been drill-tested to a vertical depth of 150 m, is spatially related to a diabase dyke, which is post-mineralization in age. Similar to Mosquito Gulch the foliation of the country rocks, which comprise albitized and chloritized mylonitic and brecciated paragneiss and granite, runs almost perpendicular to the 315 degrees trend of the mineralized shear zone, which dips steeply to the SW. The shear zone is comprised of strongly hematized quartz breccias. The uranium mineralization is characterized by a higher carbonate content compared with the mineralization at Mosquito Gulch. The best drill intersection is 0.21 % over 5 m but this is vertically and laterally discontinuous.

At Mung Arm, at least twelve mineralized outcrops, each 10 to 15 m long occur within an E-W trending, 1 km long and 250 m wide zone. Multiple mineralized sheet-type bodies dip 35 to 50 degrees south. The host rocks are fine- to medium-grained albitized metasediments. Higher grade uranium mineralization comprises pitchblende veinlets associated with chlorite and carbonate.

At Smudge coarse-grained hematized feldspathites predominate as hosts. Locally, indications for a potassium metasomatic phase were observed. The uranium mineralization comprises besides uraninite/pitchblende, coffinite/nenadkevite* and uranium titanium phases (cf. Fig. 15 and 16).

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* According to Nickel, E.H. and Mandarino, J.A. [10] the name has been discredited.

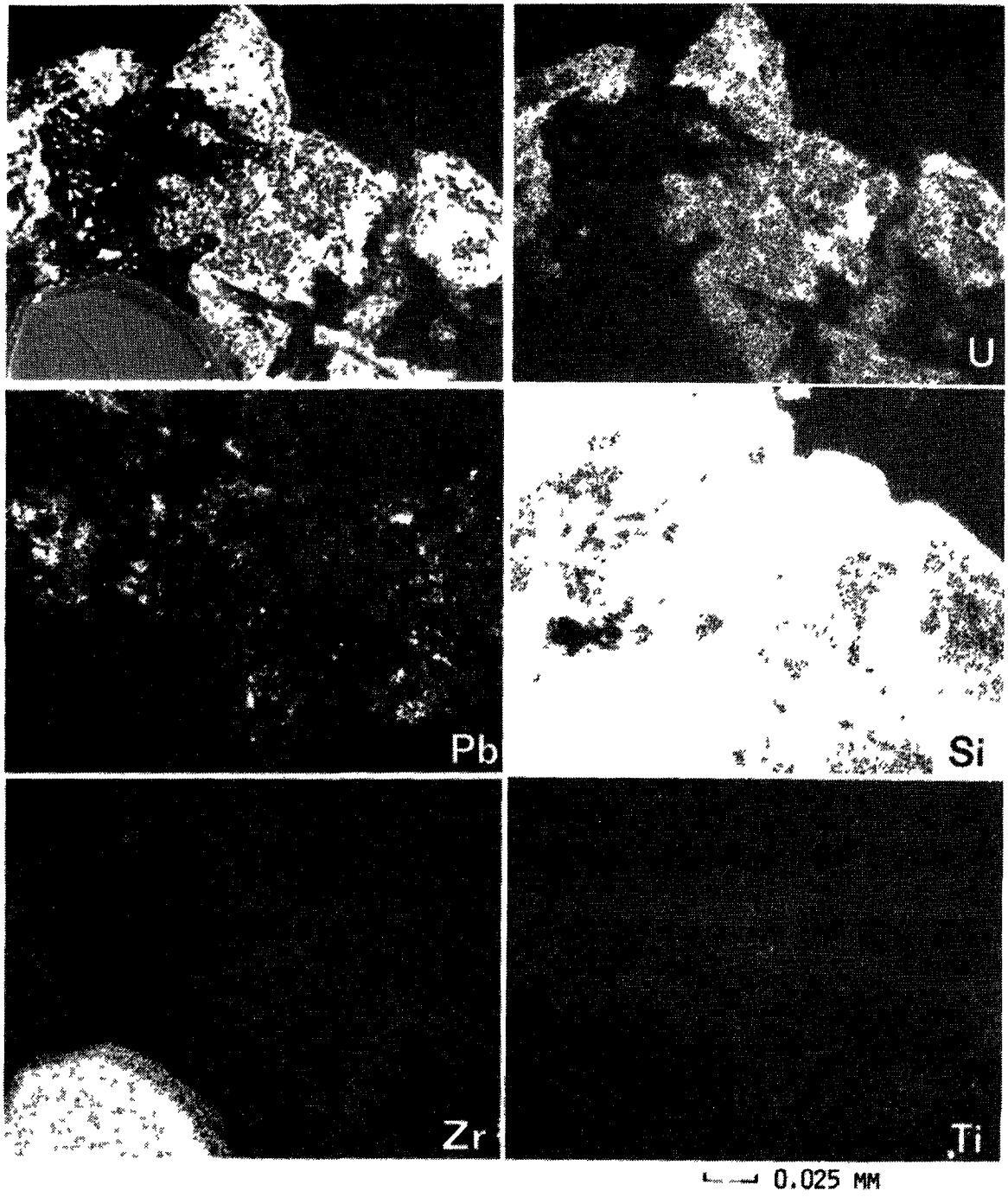


FIG. 15 Smudge, CN 10618; image of back scattered electrons (top left) of ragged aggregate of a uranium phase with subhedral grains intergrown with a euhedral zircon grain. WDS electron microprobe scanning photographs show the element distributions of U, Si, Ti, Pb, and Zr from which the presence of coffinite (nenadkevite) - $USiO_4$ - is inferred. In addition galena - PbS - and zircon - $ZrSiO_4$ (bottom left) occur; Ti and Zr are incorporated in the U-phase.

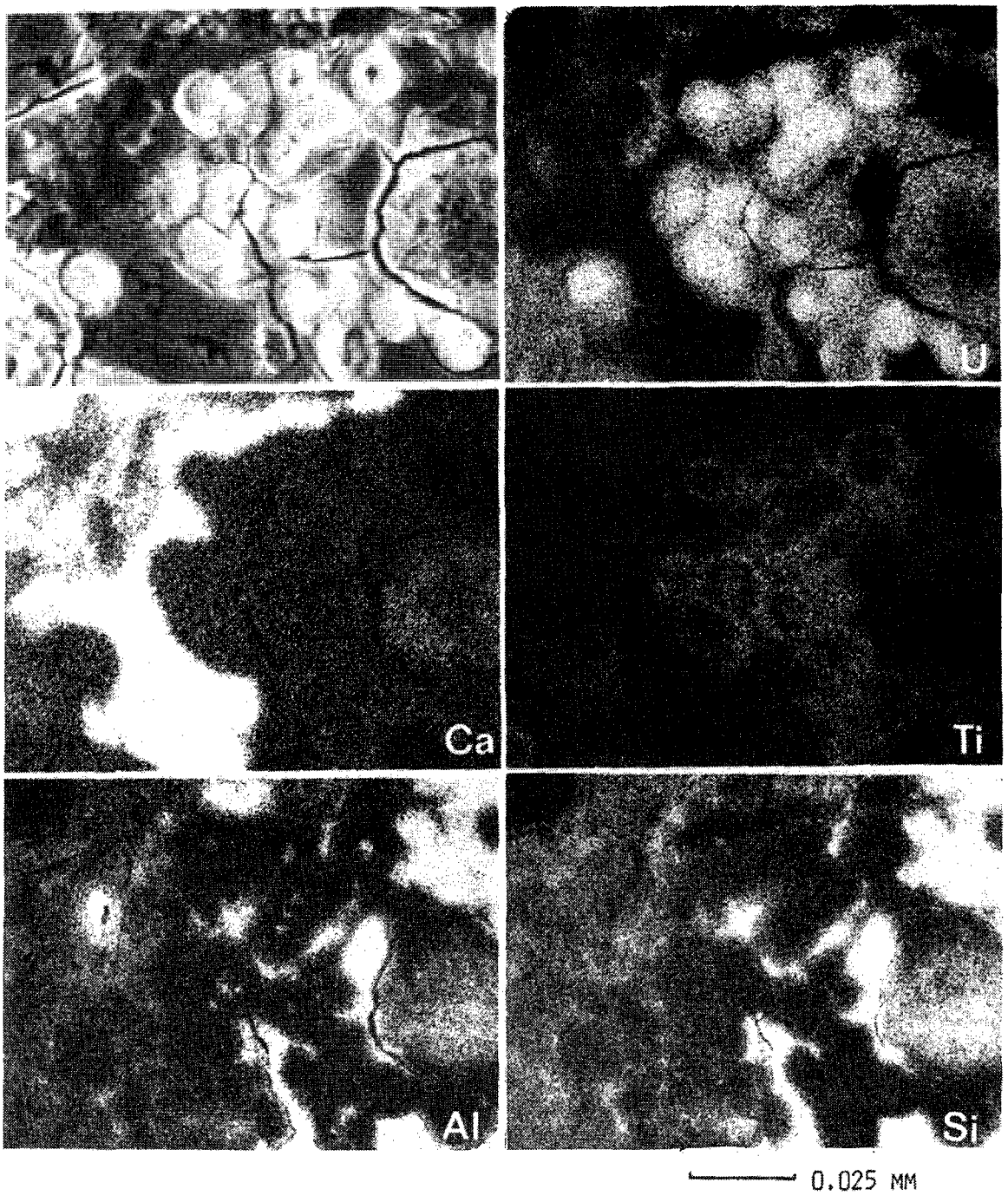


FIG. 16 Smudge, CN 10621; image of back scattered electrons (top left) of an aggregate of a globular textured uranium phase. WDS electron microprobe scanning images show the element distributions of U, Ti, Si, Al, and Ca from which the presence of a Ti-bearing U-phase is inferred, in a matrix with the element combination Al, Ca, and Si.

Finally, at the Deka prospect, which is located about 600 m west of the Nonacho/basement contact within Nonacho Group quartzites, a 150 m long and 50 to 80 m wide alteration zone was outlined by lithogeochemical sampling. The Nonacho quartzite is fractured, quartz-veined and strongly albitized (max. Na_2O = 9.65 %). Radioactive fractures occur within the alteration halo. Geochemically this uranium mineralization is characterized by high (max. values in brackets) Fe_2O_3 (25.7 %), Mg (3.9 %), TiO_2 (2.6 %), CaO (0.8 %), Cr (622 ppm), V (401 ppm), and Ba (318 ppm). Post-Nonacho Group albitization has only been observed at this prospect.

6. SIMILAR OCCURRENCES IN THE REGION

Yusa et al. [11] have recently published data on exploration results of PNC Exploration (Canada) Co. Ltd. in the Thekulthili Lake area at the southwestern end of the Nonacho Basin, about 50 km west of Mosquito Gulch. Three major types of uranium occurrences are described, of which the "mylonite type" shows very strong similarities with the mineralization associated with albitites in the area described in this paper. Also the structural position of the "mylonite type" uranium mineralization as shown in a schematic cross section (Yusa et al., Fig. 3) suggests the presence of sodium metasomatites. A minimum Pb/Pb isotope age of 1.9 $\pm$ 0.04 Ga is recorded for pitchblende. K-Ar dates of chlorite associated with mylonites are determined as 1.77 to 1.84 Ga. Alkali metasomatism is described only as associated with uranium mineralization in andesitic dykes, which cut the Nonacho Group sediments ("dyke type").

Radioactive "diorite boulders" near Hjalmar Lake were investigated by Maurice and Plant [12] . The composition of these boulders is essentially albite, chlorite, epidote, and secondary amphibole. The reported Na_2O content of 8.8 % and high REE and Zr values indicate an albitite-type mineralization possibly associated with sodic hornblende (arfvedsonite, riebeckite).

Belevtsev [13] was presumably the first author to classify the uranium deposits of the neighbouring Beaverlodge district as belonging to the albitite--type. This denomination particularly applies to the Gunnar deposit which has recently been documented by Evoy [14] .

7. DISCUSSION OF RESULTS AND CONCLUSIONS

The described uranium occurrences within the Nonacho Lake area are classified as albitite-type. This denomination was first introduced by Russian authors, where this type of deposit contributes substantially to the uranium resources of the USSR and consequently has been studied there in great detail, e. g.: [15] , [16] , and [17] . Avrashov [18] translated some of the respective pre-1980 Russian literature and compared the literature data with field data from the Nonacho occurrences [19] . Barthel [20] recently compiled the major characteristics of albitite-type uranium deposits by including the available data from deposits and occurrences of Western World Countries, i. e. Sweden [21] , [22] ; Brazil [23] ; Cameroons [24] , [25] and Canada.

The Nonacho occurrences share in fact the major characteristics of this type:

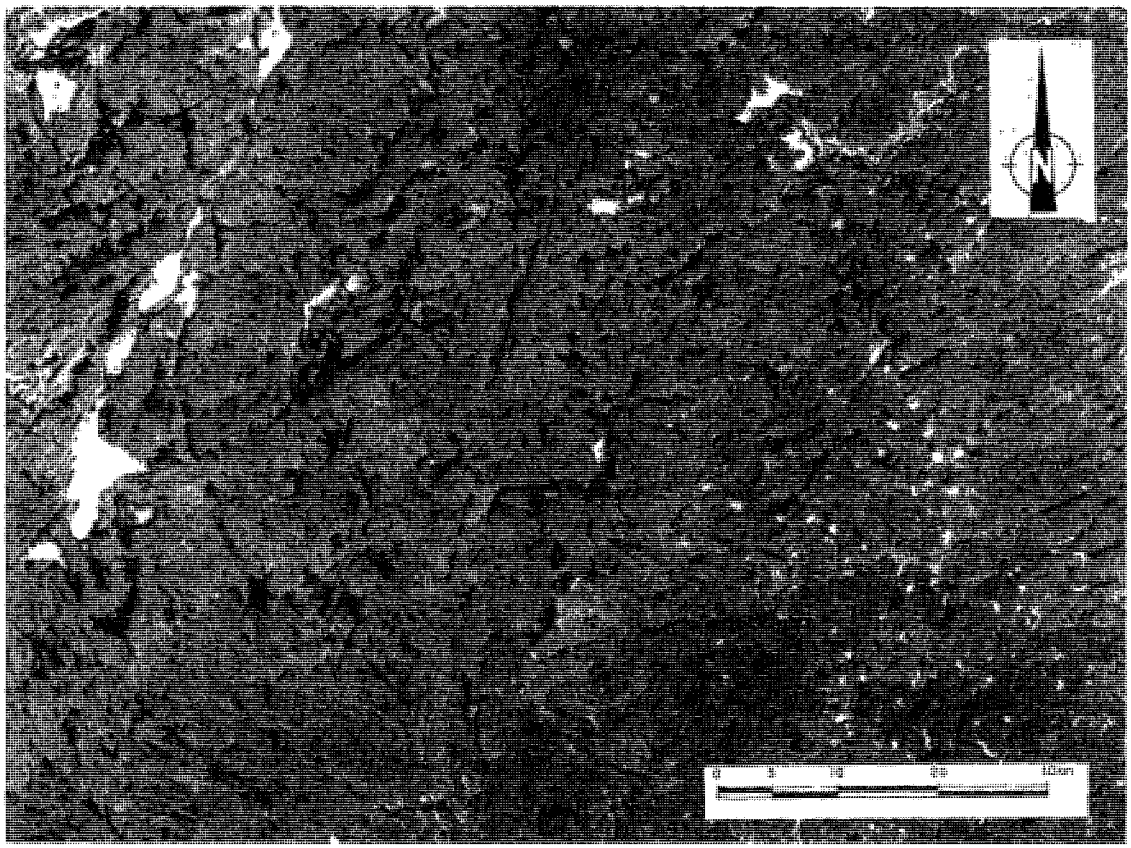
- they are located in a marginal part of an Archean platform region,
- they are related to deep-seated regional faulting which controls widespread sodium metasomatism,
- they are hosted by cataclastic to mylonitic albitites.

Furthermore the paragenesis and geochemistry of the mineralization compares favorably with the respective literature data.

The Mosquito Gulch mineralization could possibly be classified as what has been denominated by Russian authors [18] the medium to lower temperature albite-epidote- chlorite-calcite sub-type.

Polyphase development of the mineralization in the Nonacho Basin area is indicated by various uranium phases, various textural distribution patterns (i. e. disseminations and veinlets) and the fact that the albitizing and mineralizing episodes stretch over a period of more than 0.3 Ga, i. e. from 2.2 Ga, dated as the age of primary mineralization at Mosquito Gulch to post-Nonacho time, the latter being represented by the Deka mineralization. The polyphase development is most likely related to various pulses of metasomatism and hydrothermal alterations.

a



b

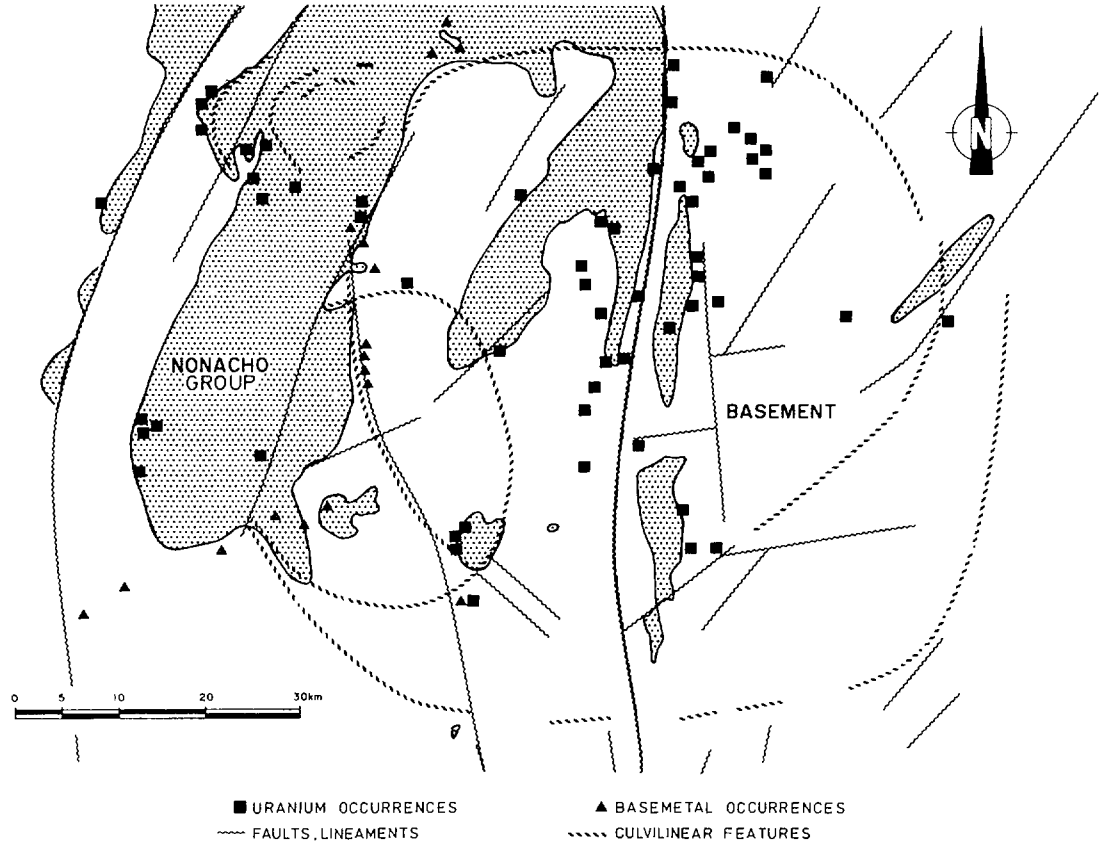


FIG. 17 a) Edge-enhanced Band 5 Landsat scene centered on Powder Lake, Northwest Territories (Landsat 2, Path 46, Row 17, image date May 30, 1981) b) Structural interpretation based on Landsat 2 image (cf. Fig. 17a). Geological data and radioactive occurrences compiled from geological mapping and radiometric prospecting.

A zonation of metasomatized bodies and mineralization has not been confirmed so far.

Though there is no direct relation between the formation of the Nonacho Basin and the development of sodium metasomatism and albitite-type uranium mineralization there is obviously a structural link. It is noteworthy that the structural trend of most of the described occurrences is E/W, i.e. at right angle to the structural setting of faults controlling the Nonacho Basin. The structures which control the 2.2 Ga albitites represent a system of re-activated Archean structures, and preceding the earliest dated mylonites of 2.0 Ga associated with the formation of the Great Slave Tectonic Zone. The ancient age of the Nonacho albitites is likely associated with a distinct period within the Blezardian orogenic cycle. However, the Rae Block - according to our knowledge - in the local environment east of the Taltson Magmatic Zone does not comprise any magmatic rocks younger than Archean. In the Beaverlodge (and also Cluff Lake) area, however, granitoid intrusions with ages of around 2.2 Ga exist. Furthermore, galena from the Beaverlodge uranium veins gave a Pb/Pb model age of 2.34 Ga in contrast to U-Pb pitchblende ages of 1.75 Ga [26] .

A regional structural interpretation from satellite images carried out by R. Loewer [27] identified a large circular structure (cf. Fig. 17) which encompasses the area of widespread sodium metasomatism. A linear structure with which most of the uranium occurrences are spatially associated runs across the centre of this circular feature. It could be speculated that the circular feature represents a domal structure related to a deeper seated intrusion. A direct genetic relation between the albitites and the intrusion of a granite is however unlikely. Therefore the association of the uranium bearing albitites and the circular feature remains rather unclear.

8. ECONOMIC SIGNIFICANCE OF ALBITITE-TYPE URANIUM DEPOSITS

The economic significance of the albitite-type occurrences in the Nonacho Basin area specifically and of albitite-type deposits in other parts of the Western World at uranium prices below US$ 30 per lb U_3O_8 is rather limited. The irregular vein-type nature of these deposits combined with low to medium average grades result in high production costs. These can hardly be balanced by major depth extensions and ease of metallurgical processing, which are also characteristic of this deposit type. Albitite-type uranium mineralization,

however, represents one of the earliest uranium enrichments in the development of the earth's crust. It has therefore been considered as a potential precursor of younger more enriched uranium mineralization particularly for Proterozoic unconformity-related deposits [28] .

ACKNOWLEDGEMENTS

The authors wish to acknowledge the enthusiasm and the work of all Uranerz exploration staff involved in the project. They further wish to thank the Management of Uranerzbergbau GmbH, Bonn, FRG and Uranerz Exploration and Mining Ltd., Saskatoon, Canada, for the permission to publish this paper. The careful editing and clarifying discussions with our colleague F. Bianconi is highly appreciated. Microprobe analyses were partly carried out with the financial support of the Deutsche Forschungsgemeinschaft (project AM 23/65). Last not least the financial support which the Ministry of Economics, FRG, granted to Uranerzbergbau for exploration work within the Nonacho project is acknowledged.

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THE SWANSON URANIUM DEPOSIT, VIRGINIA: A STRUCTURALLY CONTROLLED, U-P ALBITITE DEPOSIT

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Abstract

In 1977, Marline initiated ground and airborne radiometric reconnaissance surveys in several states immediately east of the Appalachian Mountains. Exploration focused on contacts between sedimentary rocks of Mesozoic basins and older basement rocks, and lead to the discovery of several anomalies along the western border fault of the Danville Triassic basin in southern Virginia. Detailed drilling at one anomaly delineated two large, nearly contiguous, uranium orebodies in metamorphic rock: Coles Hill South (the Swanson deposit) and Coles Hill North. Uranium mineralization occurs primarily within cataclastic zones in augen gneisses and amphibolites. Fine-grained coffinite/uraninite, associated with fluorapatite and chlorite, occurs as disseminations and in narrow healed fractures. Pervasive sodium metasomatism has resulted in albitization, quartz dissolution, and local development of sodium amphiboles. There is evidence of multiple stages of cataclasis, albitization, chloritization and hematitization.

Geological reserves for both deposits were initially estimated on the basis of vertical sections. The Swanson deposit was determined to contain 49 million lbs. U_3O_8 at an average grade of 0.113%, above a cutoff of 0.05%. The North deposit has similar total reserves but a lower average grade. Swanson deposit reserves were subsequently verified by use of polygonal and kriged block model methods. Mineable reserves within a proposed 110-acre, 880-foot deep pit were calculated to be 16.2 million tons of ore containing 34 million lbs. U_3O_8. The ore is amenable to an alkaline leach, with 85% recovery. Financial analyses have confirmed the economic feasibility of developing the Swanson deposit. Other anomalies along the border fault which have not yet been thoroughly evaluated may represent additional significant uranium reserves.

THE SWANSON URANIUM DEPOSIT, PITTSYLVANIA COUNTY, VIRGINIA, USA: STRATIGRAPHY, PETROLOGY AND ORE MINERALOGY

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Abstract

The Swanson uranium deposit (Coles Hill south orebody) is located within an approximately 450 m-thick wedge of cataclastic and protomylonitic gneisses related to the Chatam Fault zone (CFZ) in southern Virginia, U.S.A. The CFZ is a southeasterly dipping normal fault juxtaposing quartz-biotite-muscovite ± garnet schist of the Fork Mountain Formation in the footwall (minimum age 450 m.y.) against Triassic red beds in the hangingwall. Stratigraphy within the wedge of cataclastic rocks has been defined by exploration and development drilling. The section comprises five units: a Lower Augen Gneiss (dark-green to black feldspar-quartz-biotite gneiss containing ~4 mm plagioclase or K-feldspar augen), a Monzonite Augen Gneiss (a distinctive biotite-feldspar gneiss containing ~2 cm feldspar augen), an Upper Augen Gneiss (the main ore-bearing unit, a biotite-feldspar ± quartz gneiss with a mylonitic fabric containing ~1 cm and smaller feldspar augen), an Amphibolite (predominantly fine-grained amphibole-feldspar gneiss), and a Mylonitic Granite Gneiss (lenses of quartz in a matrix of crushed pink feldspar). These gneisses are separated from the Triassic red beds by ~5 m of fault gouge of the CFZ; no ore occurs in the Triassic sediments.

All of the units have been altered. Alteration includes chloritization, sericitization, hematitization, and a subtle but significant episode of sodium metasomatism. This latter event consumed quartz, formed albite, and increased porosity.

Coffinite is the most common ore mineral and occurs with subordinate amounts of uraninite, uranium-rich apatite, and an incompletely characterized U± Si± Ti phase of variable composition. Pyrite is the only sulfide present; it is quite rare. Alpha-track maps show that most of the ore is in veinlets and along fractures, although disseminated ore does exist. In gross aspect, much of the ore is essentially a stockwork of U-bearing veinlets localized within the fault zone.

The Swanson deposit appears to share a number of features with classical vein deposits of simple mineralogy, and the sodium metasomatism is reminiscent of the alteration accompanying uranium deposits in episyenites (e.g. the Gunnar deposit, Saskatchewan). We believe the deposit is of epigenetic hydrothermal origin, but the source of the uranium and the specific mechanisms that caused ore deposition are still obscure.

DETAILED MINERALOGY AND ALTERATION OF THE SWANSON URANIUM DEPOSIT, SOUTHERN VIRGINIA, USA

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The Swanson Uranium Deposit is hosted in augen gneisses and is strongly affected by mylonitic and cataclastic events. Overall, mineralization appears to be subparallel to the intersection of mylonitic foliation and an en echelon set of planar cataclastic zones. The deposit was most likely formed as a result of the regional tectonic events which developed this zone of mylonitisation adjacent to the Triassic graben basin.

The principal ore assemblage is a very fine grained mixture of coffinite - chlorite - fluroapatite and associated anatase and calcite. Pitchblende is present in only minor amounts and monazite (U, Th poor) is a trace accessory. An estimated 10-15% of the total ore-stage uranium is found in the aratite. The uranium content of pre-ore anatite averages 0.02% UO_2, whereas ore stage apatite averages 0.5% UO_2. Some euhedral, optically clear apatite contains over 3.5% UO_2.

Petrologic studies and whole rock analyses show the most significant alteration to be a multistage Na metasomatism process. This is characterized by quartz removal and a minor bulk density decrease and porosity increase. Mineralogically this is evidenced by alteration of oligoclase and potassium feldspart to albite, development of euhedral albite overgrowths on feldspar and quartz, and albite inclusions in zoned apatites. Further evidence of Na metasomatism is the development of the sodium amphibole riebeckite from prexisting amphiholes and chlorite. Riebeckite also develops on voids and along open fractures. Some dark blue faults (ultra cataclasites) further suggest the interrelationship of Na alteration and the most intense deformational events.

Aside from the U and phosphorous, the deposit is notable for its lack of geochemical enrichment in other metals commonly associated with many U deposits.

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