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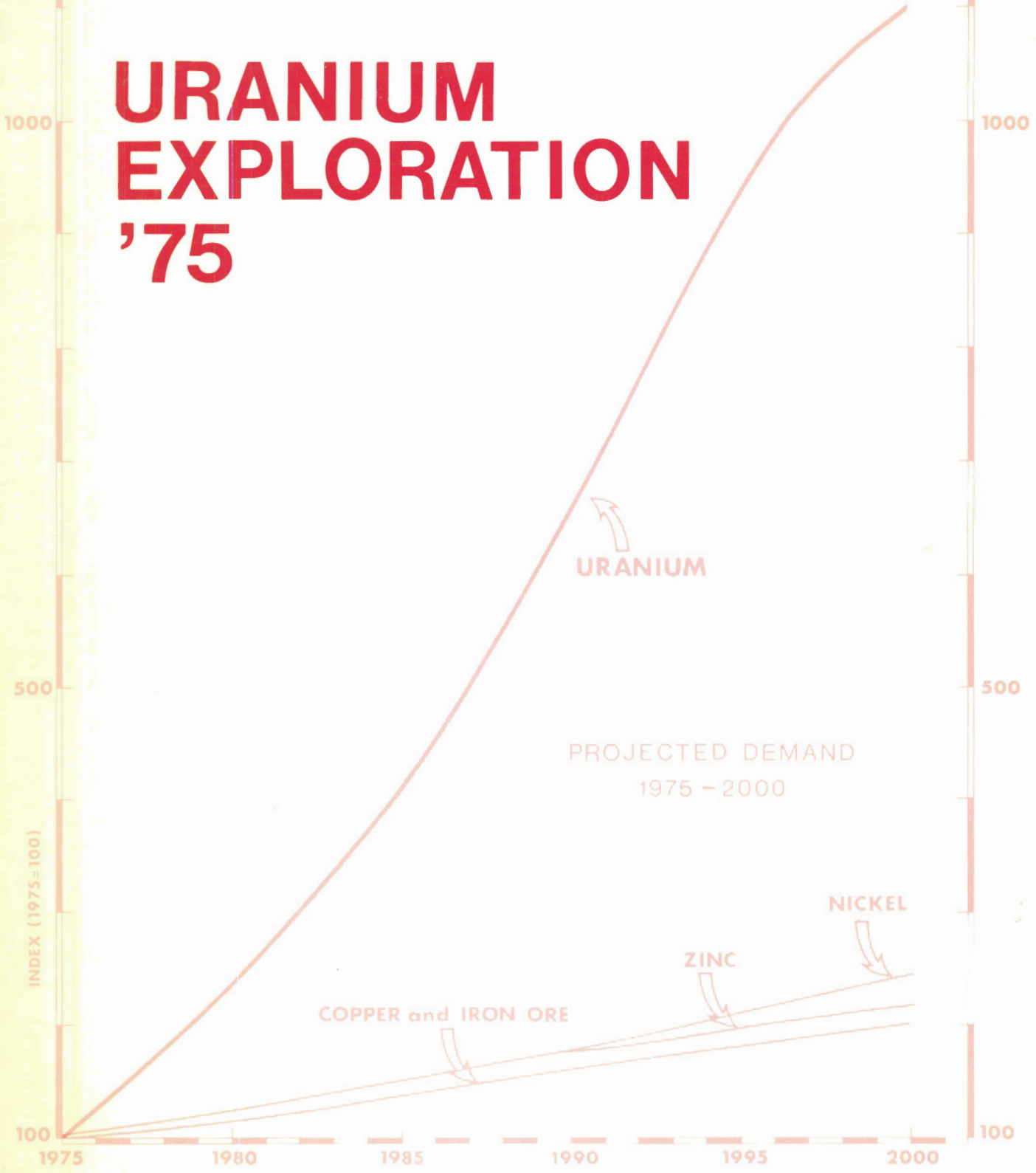
GEOLOGICAL SURVEY OF CANADA

DEPARTMENT OF ENERGY, MINES AND RESOURCES, OTTAWA

PAPER 75-26

URANIUM EXPLORATION '75



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GEOLOGICAL SURVEY
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URANIUM EXPLORATION '75

GEOLOGICAL SURVEY OF CANADA
A.G. DARNLEY
V. RUZICKA
W. DYCK
E.M. CAMERON
K.A. RICHARDSON

MINERAL DEVELOPMENT SECTOR
R.M. WILLIAMS

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GEOCHEMISTRY APPLIED TO URANIUM EXPLORATION

Willy Dyck

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5. THE FEDERAL-PROVINCIAL URANIUM RECONNAISSANCE PROGRAM

A. G. Darnley, E. M. Cameron and K. A. Richardson

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FOREWORD

There is no need to emphasize to those who have followed recent international developments that in the medium and long term the World has a major energy problem and that Canada is inextricably involved. Although nuclear energy offers a viable solution to the problem not everyone is happy with the idea of proliferating nuclear power, but with a choice between nuclear sources of energy or freezing in the dark, the choice most people will make is quite clear.

The main emphasis of the session at which these papers were presented was on geoscience applied to uranium exploration thus the Geological Survey provided most of the material. However to set the stage for the magnitude of the exploration effort now required, the paper by R. M. Williams of the Mineral Development Sector provides an informed review of the latest information on the projected demand and thus the discovery requirements. The conclusion of his paper is that it is certain that presently known conventional types of uranium deposit will not be sufficient to supply future needs.

Dr. Ruzicka's paper reviews the geological features of some lesser known types of uranium deposit, in order to draw attention to the possibility of such deposits being found in Canada.

The organizers of the session had hoped to include a paper outlining the problems of extracting uranium from various low grade source materials. There is no point in seeking uraniferous shales if uraniferous granites are easier to process, or vice versa. Unfortunately, due to pressure of other commitments, the information necessary to prepare such a paper could not be gathered together in time.

The third and fourth papers cover various aspects of geophysics and geochemistry which can be applied to uranium exploration in 1975 and the final paper describes the new Federal-Provincial Uranium Reconnaissance Program, and the rationale behind it. The program, which begins this summer, represents the major development in the provision of systematic geoscience surveys by governments; it is interesting to note that a rather similar program is being launched simultaneously in the United States. Within the next few years we can expect a substantial leap forward in the quantity and quality of geoscience data publicly available relating to uranium, and if the past is any guide to the future, this will lead to many discoveries.

A. G. Darnley
Co-ordinator,
Geological Survey of Canada
Uranium Program

ABSTRACT

Nuclear energy offers a viable solution to the major energy problem that faces the world. This publication comprises five papers that were presented orally to the Prospectors and Developers Association in March 1975. The main emphasis is on geoscience applied to uranium exploration but one paper considers projected demand and the conclusion reached is that presently known conventional types of uranium deposit will not meet future needs.

The geological features of some lesser known types of deposits are considered and the various aspects of geophysics and geochemistry that can be applied to current uranium exploration programs are discussed. The concluding paper describes the Federal-Provincial Uranium Reconnaissance Program which begins in the summer of 1975.

RÉSUMÉ

L'énergie nucléaire constitue une solution valable à la crise mondiale de l'énergie. Cette publication réunit cinq communications qui ont été présentées oralement à l'Association des prospecteurs et des exploitants de mine en mars 1975. Les auteurs traitent principalement de l'application des sciences de la Terre à la recherche de l'uranium, sauf un, qui étudie la demande prévue et conclut que les gisements classiques d'uranium connus actuellement ne suffiront pas à satisfaire les besoins futurs.

Les auteurs traitent des caractéristiques géologiques de certains types de gisements moins connus et présentent diverses applications de la géophysique et de la géochimie qui peuvent servir dans les programmes actuels de recherche de l'uranium. La dernière communication donne une description du Programme fédéral-provincial de recherche préliminaire de l'uranium qui débute à l'été 1975.

Contributors

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R. M. Williams	- Mineral Development Sector

1. URANIUM TO 2000, AN EXPLORATION CHALLENGE

R. M. Williams

Abstract

World demand for uranium will grow at the unprecedented rate of some 15 to 20 per cent a year over the next ten to fifteen years. To meet this demand, it is estimated that the current level of world reserves of uranium must be increased by some 2. 6 million tons of U_3O_8, over the period from 1975 to 1990. By 1990 annual gross additions to reserves will have had to triple to something in the order of 270 000 tons of U_3O_8 per year. The total number of deposits and the total tonnage of U_3O_8 that needs to be discovered and developed, however, will vary widely depending on the order in which deposits of different sizes and grades will come on stream.

If uranium is to be discovered and developed for production at a rate sufficient to meet demand, there must be a rapid and accelerating expansion of exploration effort. However, this alone will not be enough! Exploration philosophies must be re-examined and, perhaps, modified; and a more effective and systematic use of all available exploration technology must be a prerequisite. Even more important, new methods of financing these efforts must be developed, that will satisfy the growing aspirations of governments and, at the same time, provide the needed financial incentive to industry, as well as an assurance of supply to participating consumers.

Introduction

The paper reviews the current status of the supply-demand situation for uranium, and attempts to cover the subject with the objective of illustrating the size of the uranium exploration challenge for the remainder of the century in terms of the quantity of uranium that must be discovered and the rate at which the discoveries must be developed.

Some significant factors which may be inhibiting the industry's response to the challenge to discover more uranium are also reviewed, with the objective of generating some discussion and, hopefully, some constructive ideas.

Uranium Demand

Forecasting future requirements for any commodity is a notoriously difficult exercise. In the case of uranium, however, the exercise is made marginally easier in that its future use is almost entirely related to the generation of electricity. An estimate of the future demand for electricity, in turn, is dependent on the expected growth, in consumption of total energy, on forecasts of future economic growth, and ultimately on forecasts of future population growth. Although there are uncertainties associated with all of these factors, the uncertainties are related largely to the long term. Expectations for the next ten years tend to be relatively firm.

One of the most recent forecasts of nuclear power growth is that published by the United States Atomic Energy Commission (USAEC) in early 1974. This study projected that installed world nuclear capacity will increase from some 50 000 MW in 1974 to between 2. 5 and 4. 0 million MW in the year 2000, when more than half of all electricity will be generated by nuclear power. It is pertinent to note that at the end of 1974, 350 000 MW of nuclear capacity was either operating, under construction, or ordered, virtually confirming predictions for the early 1980's. To put this in perspective, this represents forward construction commitments on the part of electrical utilities of some 150 or 200 billion dollars.

These projections of installed nuclear capacity translate into requirements for uranium as shown in Figure 1. 1. The middle range of these projections

Figure 1·1

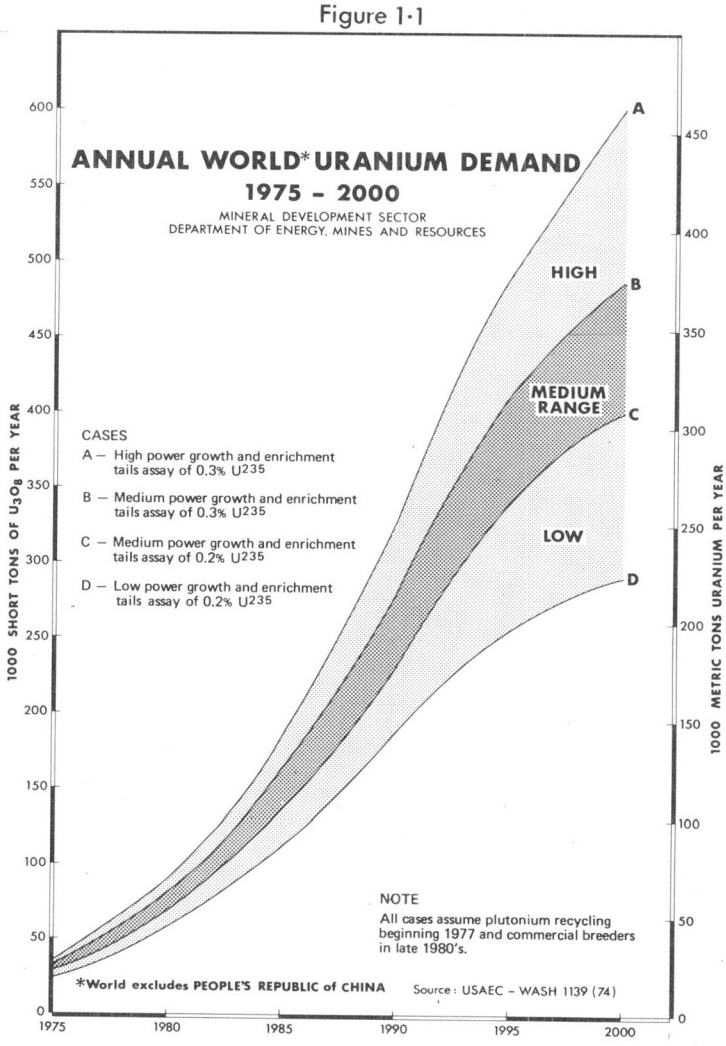


TABLE 1.1

Forecast of world* nuclear power capacity, 1980 to 2000

(MW x 1000)

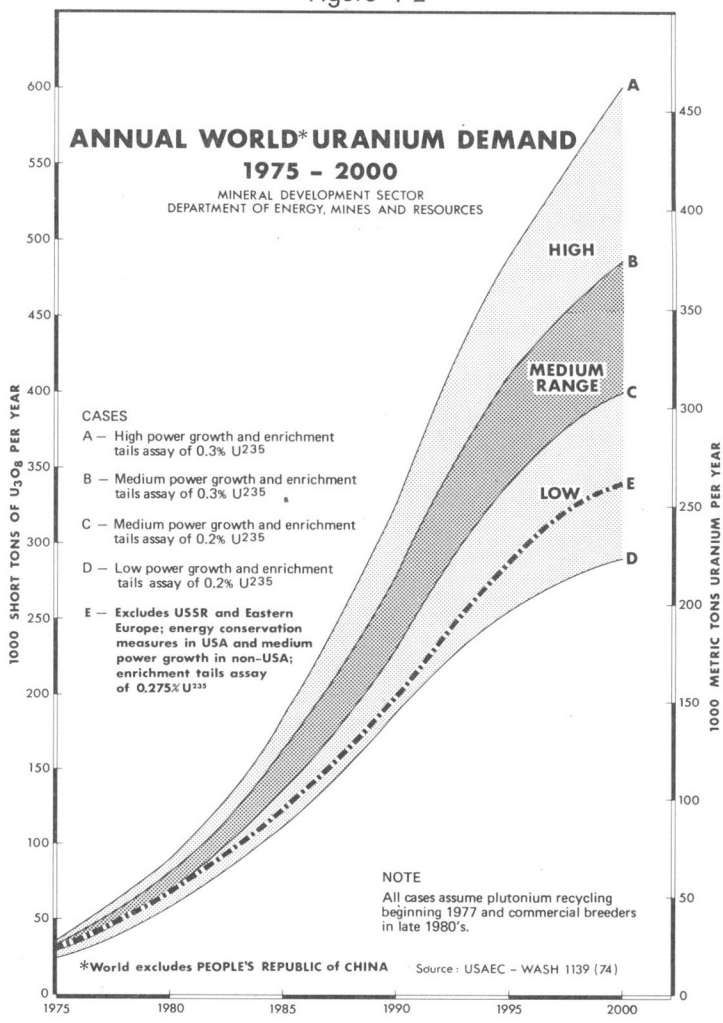
Year-End	Low	Medium	High
1980	198	242	279
1985	521	647	695
1990	1 050	1 280	1 475
1995	1 700	2 187	2 560
2000	2 450	3 330	3 950

* World excludes People's Republic of China.
Source: USAEC, Wash. – 1139(74)

grows from some 30 000 tons of uranium oxide (U_3O_8)[1] a year in 1975, to between 70 000 and 80 000 tons in 1980, and 400 000 to 490 000 tons a year in the year 2000. For the post-1980 period, however, it is more important to look at the range of the projections and the major factors that contribute to this uncertainty range than at the particular forecast numbers themselves. The principal factors include the timing and rate of introduction of commercial breeder reactors, the timing and rate of introduction of plutonium recycling in light-water reactors, the assay of the tails stream from uranium enrichment plants, the particular reactor strategy or reactor-mix chosen for individual countries, and perhaps most important of all, the rate of nuclear power growth.

A number of developments have occurred since these projections were made which, taken individually, could alter this outlook one way or another. Factors that would raise the projections include plans by several countries, particularly France and Japan, to accelerate their nuclear power programs in the wake of the dramatic increase in the cost of fossil fuels; a deteriorating outlook for early solutions to problems besetting the nuclear fuel reprocessing industry and thus a continued postponement of large scale recycling of plutonium; lower than expected fuel-burnup experience with presently operating light water reactors; and the recent decision by the United States' Energy Research and Development Agency (ERDA)[2] to increase its transaction enrichment tails assay from 0.2 to 0.275 per cent U^{235} beginning July 1, 1976 and possibly to 0.30 per cent beginning July 1, 1981. Counteracting

Figure 1·2



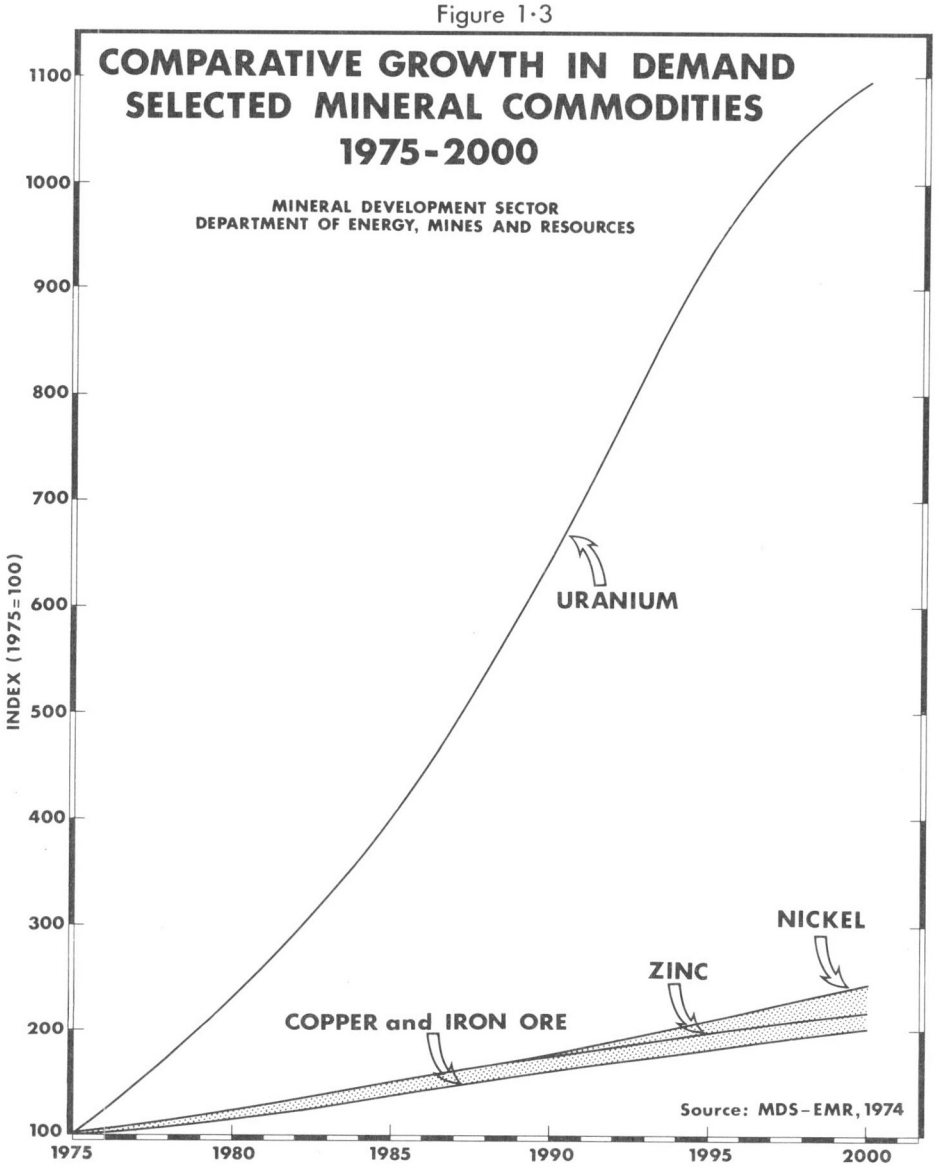
factors include the continued gloomy outlook for public understanding of the environmental impact of nuclear power; continued delays in construction due to the regulatory and licensing process but due also to increased incidents of shortages in equipment and supplies; and finally, the cancellation or postponement of nuclear power projects, particularly in the United States, due largely to the inability of utilities to raise the large amounts of required capital. The net effect of all of these factors on the projections shown in Figure 1.1, however, is likely small.

Before comparing these projections of demand to the supply side of our equation, we must first exclude that part of the world for which we lack supply information. Figure 1.2 illustrates a case (Case E) which excludes the U.S.S.R., Eastern Europe and the People's Republic of China. It also assumes an operating enrichment tails assay of 0.275 per cent U^{235}, a nuclear power growth rate in the United States moderated by energy conservation measures, and a moderate rate of nuclear power growth for the rest of the world. Using these assumptions, annual world requirements are expected to grow from 30 000 tons U_3O_8 in 1975, to 124 000 tons in 1985 and 338 000 tons in the year 2000. This projection is not radically different from that made by the

[1] Short tons used throughout; 1 short ton U_3O_8 equals 769.3 kgm uranium metal.

[2] As of January 21, 1975 the USAEC ceased to exist and two new agencies were created, ERDA and the Nuclear Regulatory Commission (NRC).

Figure 1·3



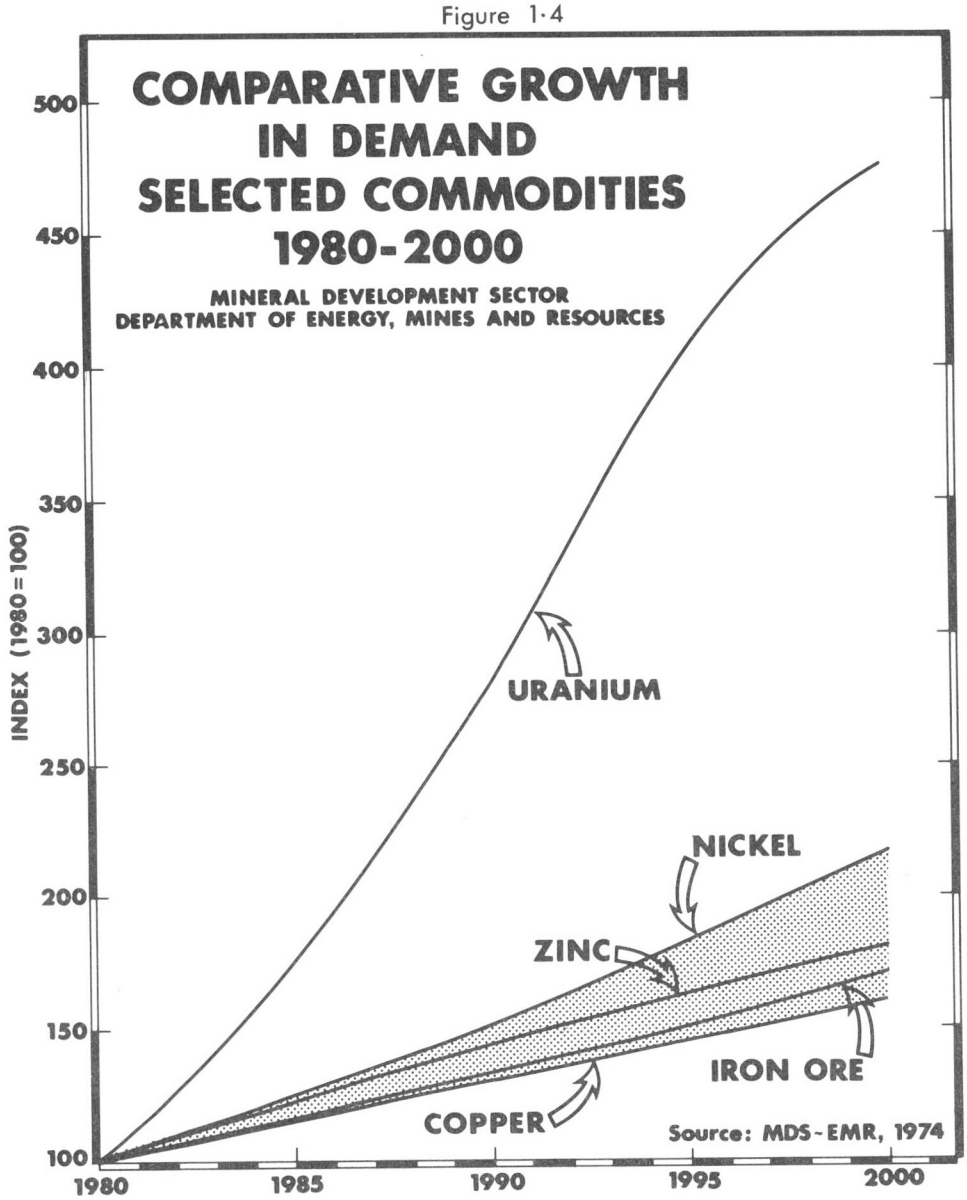
Nuclear Energy Agency of Organization for Economic Co-operation and Development (OECD) and the International Atomic Energy in their study of August 1973 (Lane, *et al.*, 1974; Anonymous, 1973).

It has been stated that the rate of growth in uranium demand is unprecedented at something in the order of 15 to 20 per cent a year over the next ten to fifteen years. Figure 1. 3 illustrates this growth rather dramatically in relation to the expected demand for copper, zinc, nickel and iron ore for the period 1975 to 2000. For uranium, we see a ten-fold increase in annual demand over the next 25 years compared with a mere doubling in demand for the other commodities during the same period. Even when compared with a base year of 1980, the difference in growth rates is startling (Fig. 1. 4).

Exploration and Development Requirements

Given these projections of uranium demand, it is possible to illustrate the requirements for new reserves that must be developed both from known deposits and from deposits yet to be found. Figure 1. 5 illustrates two curves related to Case E as depicted in Figure 1. 2 for the world, excluding the U. S. S. R., Eastern Europe and the People's Republic of China. The lower curve represents the cumulative requirements from 1975 to 1990. However, this curve understates the question of how large our developed reserves need be at any point in time. Because of the time required to replace reserves that are being produced, a viable industry must at all times maintain reserves sufficient to meet an

Figure 1·4



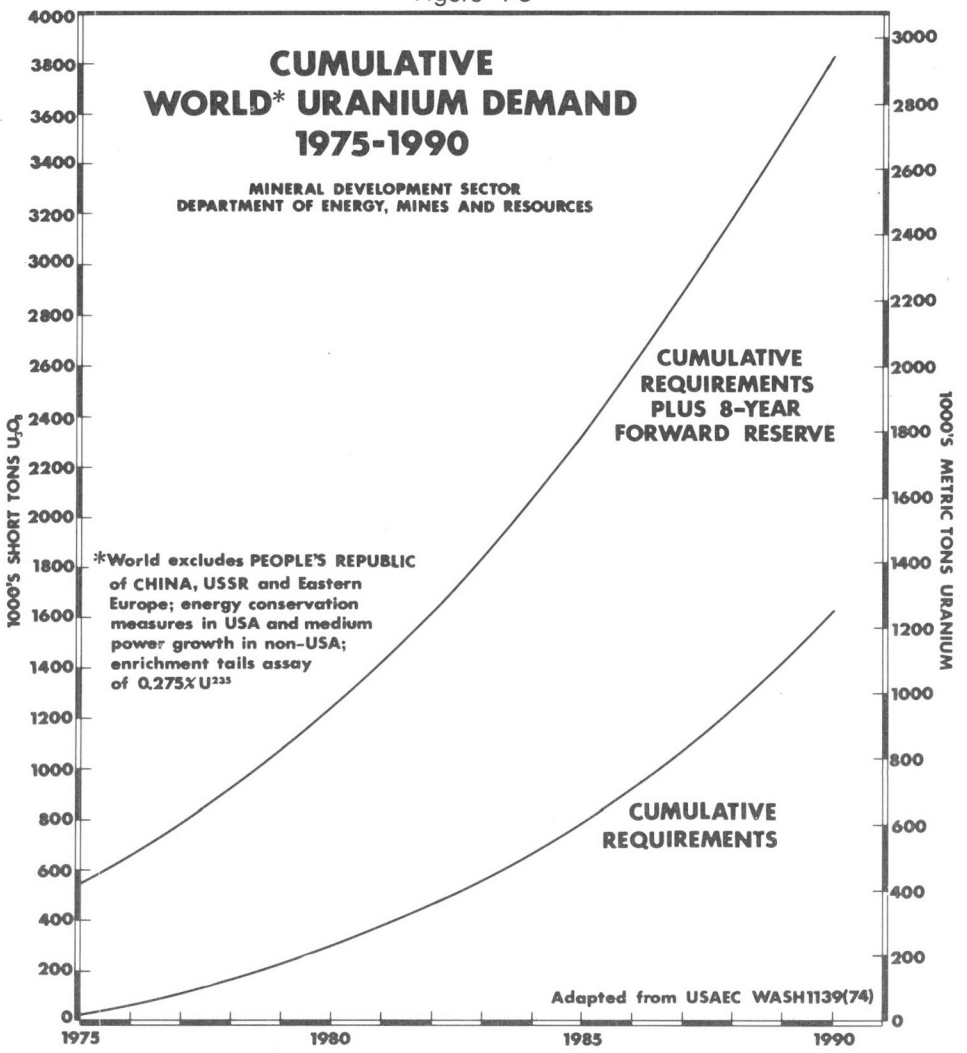
appropriate period of forward requirements. The upper curve is intended to illustrate the reserve position necessary to meet eight years of forward requirements. This curve is derived simply by shifting the cumulative requirements curve eight years backward in time (to the left).

The world's currently delineated low-cost reserves, which we estimate to be in the order of 1.2 million tons of U_3O_8, are sufficient to meet requirements for the next 14 years. Figure 1.5, therefore, can be modified to illustrate the desirable growth in the reserve level as shown by curve A-C in Figure 1.6. (An alternate but less likely growth curve would be A-B-C). From this we can see, in gross cumulative terms, that over the next fifteen year period, we must develop new reserves totalling some 2.6 million tons of U_3O_8.

Required gross annual additions to reserves can be calculated as illustrated in the upper curve of Figure 1.7. However, again we must adjust for our present surplus reserve position and construct a modified curve (lower) beginning at a point equivalent to recent average annual additions to reserves, which we estimate to be in the order of 90 000 tons of U_3O_8 a year. The rate of growth of reserve additions would likely be moderate at first then accelerate in the early 1980's. Our conclusion is that, in the world context, annual gross additions to reserves must triple to something like 270 000 tons of U_3O_8 a year by 1990. If all additions to reserves were to come from new discoveries alone*, it has been estimated that annual world

*Reserve additions can also come from presently known sub-economic resources, as a result of changes (largely through research and development) that lower exploitation costs relative to uranium prices.

Figure 1·5



exploration expenditures would have to grow to between $500 and $600 million by 1990 (Williams, 1973).

These kinds of projections are useful for illustrating qualitatively the supply-demand situation on a world basis or for countries like the United States that have a very large production base. For a more comprehensive assessment it is necessary to examine the supply situation in much more detail, indeed on a mine by mine basis. Figure 1. 8* illustrates, for Canada, the future level of production that must be achieved, if Canada is to continue to supply roughly 20 per cent of world requirements. The relative proportion of domestic requirements is shown by the lower curve.

A detailed examination of Canada's known uranium reserves and resources (Fig. 1. 9*) shows that existing mines and known deposits whose future development is almost certain, can supply an appreciable portion of Canada's total requirements (export and domestic). Production levels from these sources will peak in the early 1980's at about 15 000 tons of U_3O_8 a year, then decrease as some deposits are depleted and as average grades of others decline. The effect of the very large deposits at Elliot Lake is very noticeable, in that significant production levels will be maintained in this area well into the next century. Clearly, additional production will be required from 'new sources', and the reserves to support this new production must be discovered with sufficient lead-time to allow for development of the deposits and construction of the plants.

When considering these new sources, it is possible to improve on a simple eight-year forward reserve formula by considering the types of deposits, in terms of size and grade, that may be discovered during the period. An internal study which is underway in the Mineral Development Sector, Department of Energy, Mines and Resources (EMR), is examining this question in detail for a number of commodities, working out illustrative examples based on models taken from past production history. A typical relationship between metal production capacity and reserves is shown in Table 1. 2 for three types of copper mines. The table

* Figures 1. 8 and 1. 9 are based on 1972 data. New data would not radically change the shape of the curves.

Figure 1·6

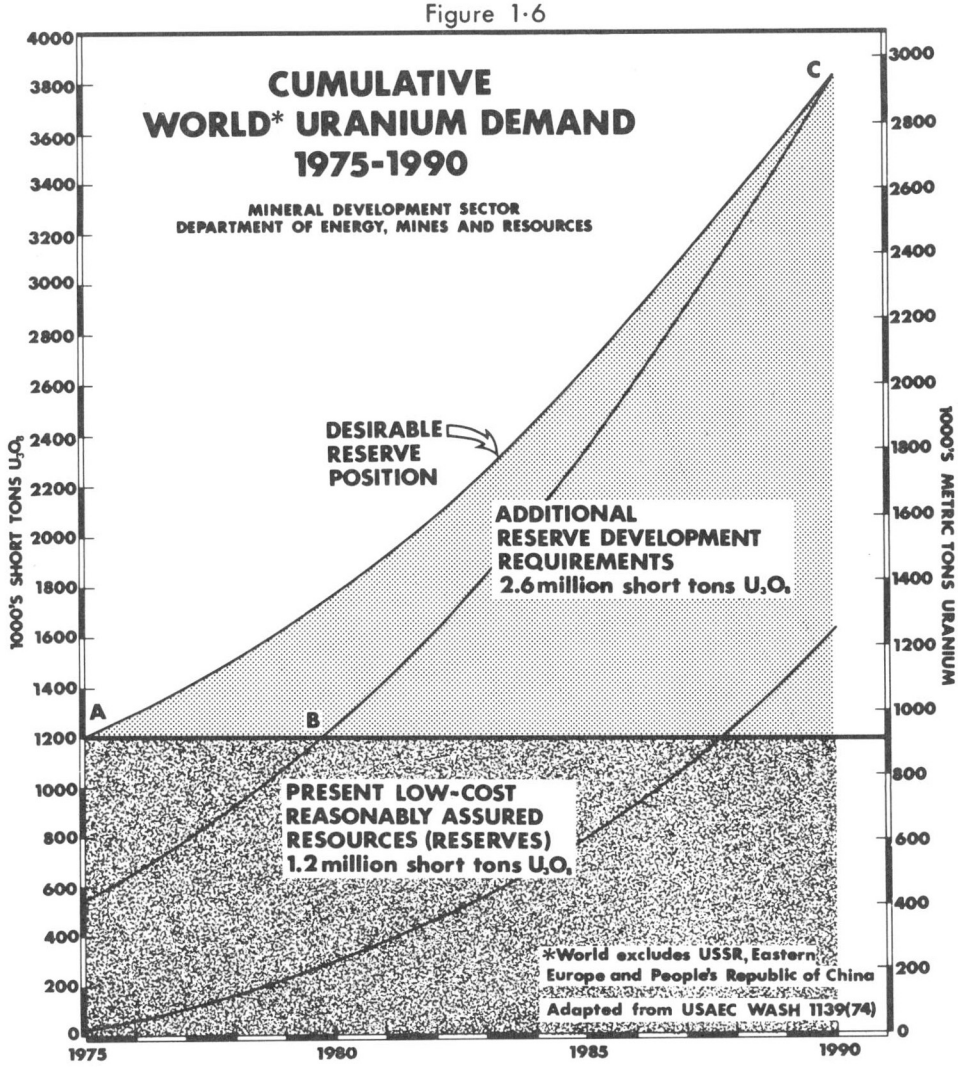


Table 1. 2

Relationship between metal production capacity
and required reserves (contained metal)
in three types of copper mines

Number and Size of Mines	Ore Reserves Per Mine: During Early-Life[1] (Tons x 10^6)	Ore Reserves Per Mine: "Life-Time"[2] (Tons x 10^6)	Ore Grade (% Cu)	Total Contained Metal In Reserves All Mines (Tons Cu)	Daily Mine Production Per Mine (Tons Ore)	Annual Total Metal Production[3] All Mines (Tons Cu)
3 Large	200	250	0. 5	3 750 000	30 000	135 000
6 Medium	40	60	1. 5	5 400 000	5 000	135 000
10 Small	5	10	3. 0	3 000 000	1 500	135 000

[1]Typical "Proven reserves" during early life of mine.

[2]Total reserves cumulated over the life of the mine.

[3]Assume 100 per cent recovery.

Figure 1-7

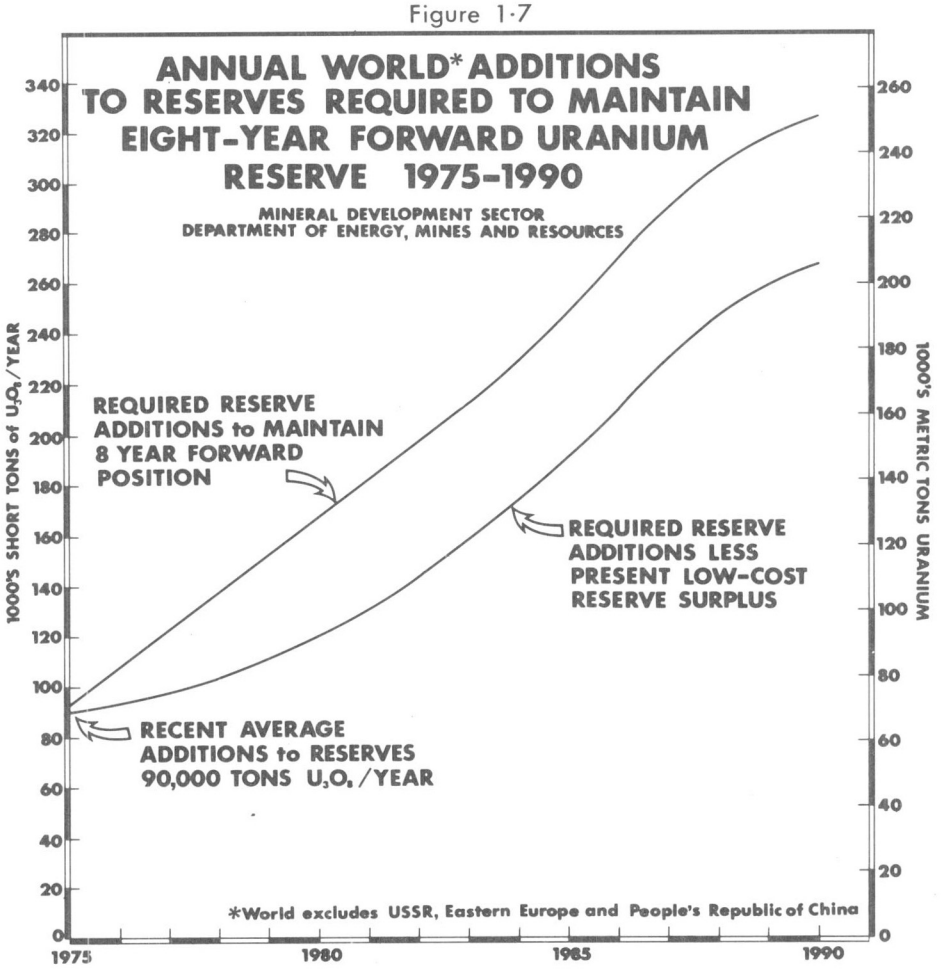


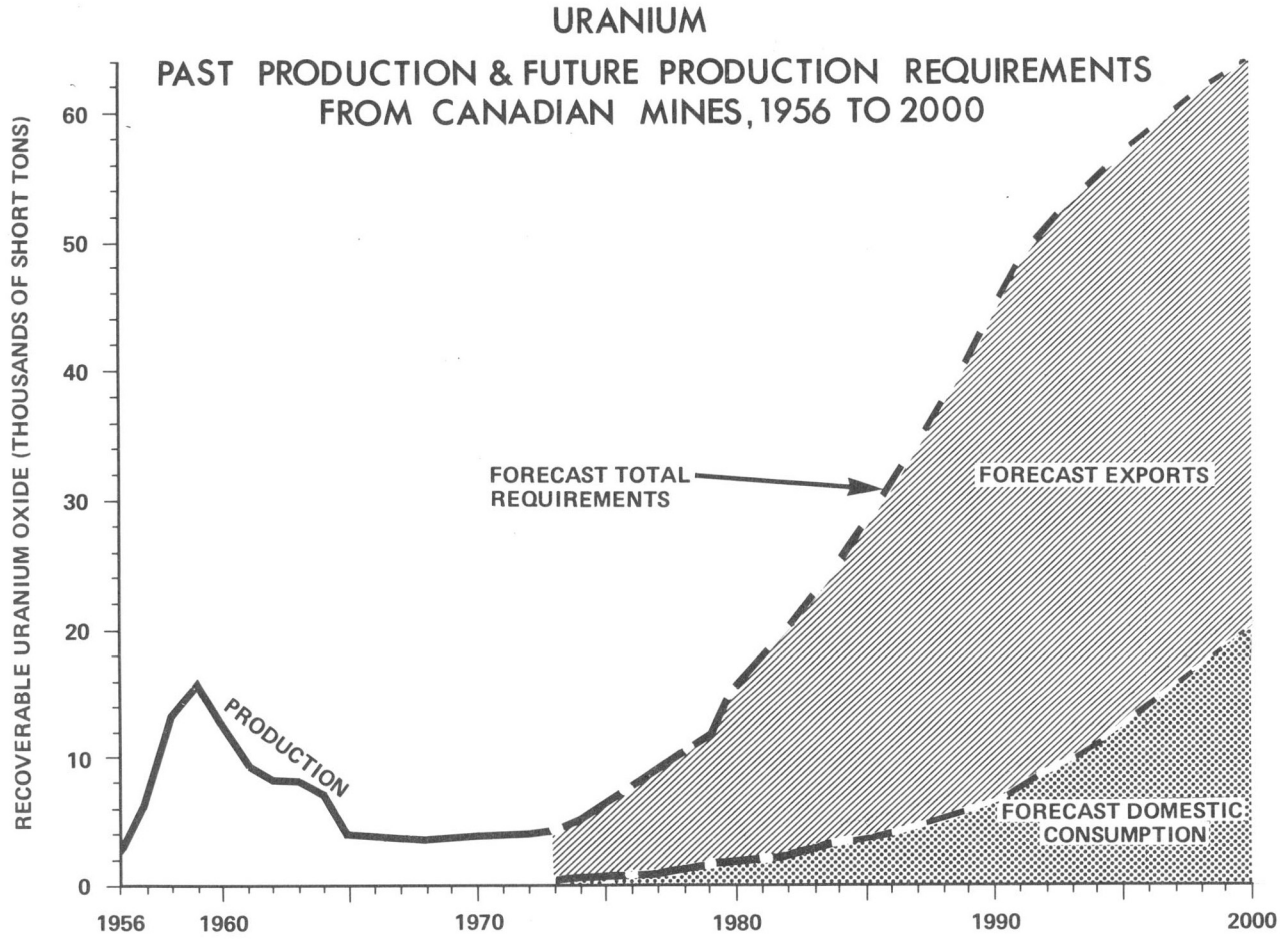
Table 1.3

Future discovery requirements for uranium in Canada, 1976 to 1995

	If all new source requirements are met from A or B or C					
	A		B		C	
	Small-Sized Mines of Medium Grade		Medium-Sized Mines of Medium Grade		Medium-Sized Mines of Low Grade	
Discovery Period	"Life-Time" Reserves Tons U_3O_8 X 1000	Number of Mines	"Life-Time" Reserves Tons U_3O_8 X 1000	Number of Mines	"Life-Time" Reserves Tons U_3O_8 X 1000	Number of Mines
1976-80	80	8	280	5	100	8
1981-85	180	19	660	12	230	18
1986-90	280	30	770	14	280	22
1991-95	280	30	390	7	240	19
1976-95	820	87	2 100	38	850	67

"Life-Time" reserves of a mine are meant to express the total tonnage of contained U_3O_8 likely to be produced during the life of that mine.

Figure 1·8



shows that, in terms of providing a certain amount of annual production, the largest quantity of total metal reserves is required if production comes from medium-sized mines. It follows that, if we were to discover and develop a large number of small-sized, medium- to high-grade deposits, on an appropriate time scale, we could meet our future requirements with a minimum of forward reserves.

The study by the Department of Energy, Mines and Resources assessed discovery requirements for several commodities for the period 1976 to 1995, allowing for development lead-time to meet the production required from new sources to the year 2000. The assumption was made that all new sources were yet to be discovered. In the case of uranium, three combinations of size and grade were considered; the results are summarized in Table 1. 3. Again, it is more important to observe the range and order of magnitude of these projections than the absolute values. As with all studies there were a number of assumptions that had to be made which can undoubtedly be debated. Certainly in the case of uranium, there is some risk in the use of the absolute values since the production history is short relative to other commodities and, consequently, the number of mines upon which the models were based is statistically small. The study does illustrate, however, that the total tons of U_3O_8 that need to be discovered and developed between now and the end of the century will vary widely depending on the order in which deposits of different sizes and grades will come on stream.

Future Exploration Strategy

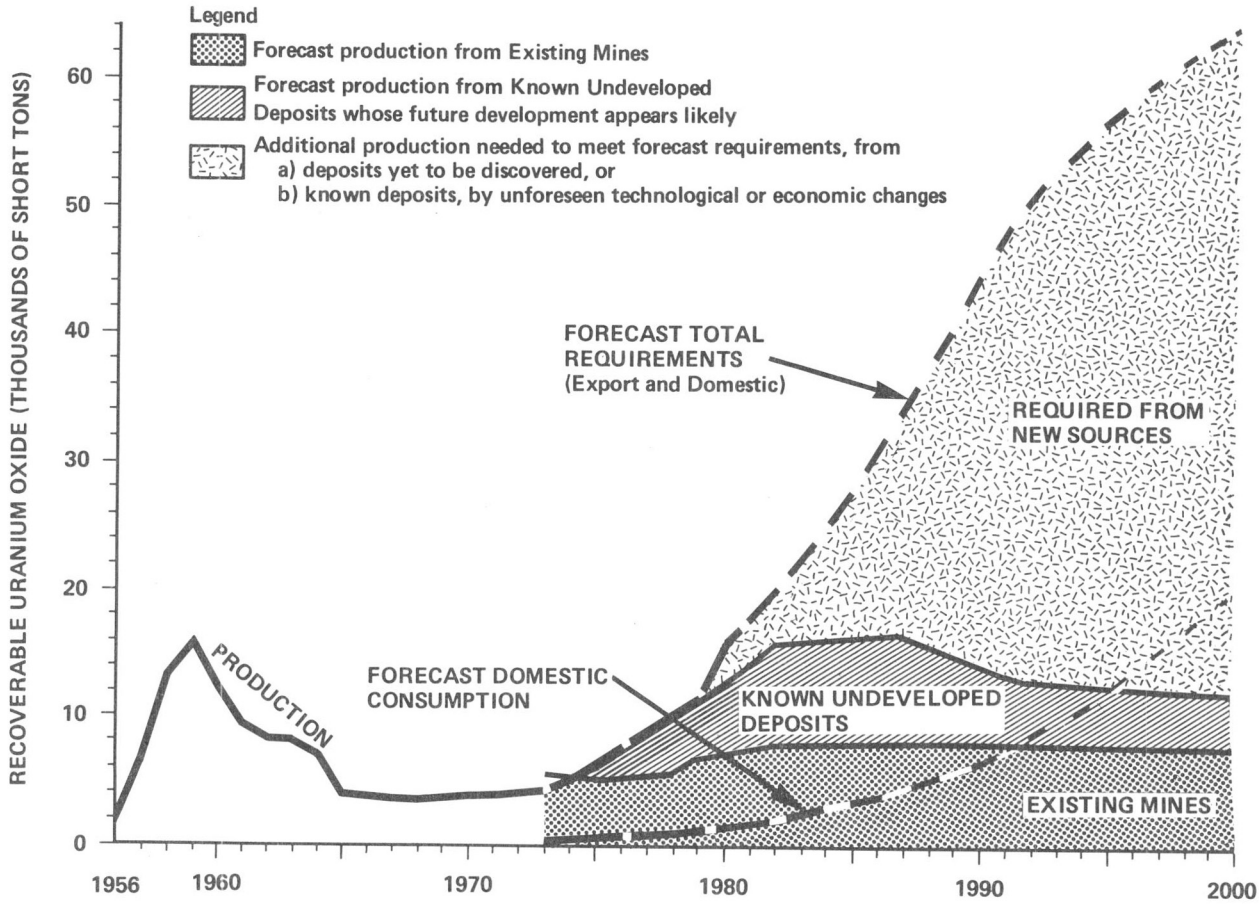
Having examined the projected demand for uranium from several points of view, it is clearly evident that the challenge is a great one, and that the time available to accomplish the task is all too short. If uranium is to be discovered and developed for production at a rate sufficient to meet demand, there must be a rapid and accelerating expansion of exploration effort. However, this alone will not be enough! Our exploration philosophy must be re-examined and perhaps modified to make more effective use of the exploration technology available to us. Even more important, new methods of financing these efforts must be developed to meet the needs of all participants, given the political realities of today. An examination of some of these factors may be useful.

In the past, exploration objectives have been biased to some extent by the types of deposits familiar to those conducting the programs and by the type of deposit that has proved to be the most lucrative prize. Geologists around the world have tended to specialize in the types of deposits that have provided production in their

Figure 1·9

URANIUM

FORECAST SOURCES OF CANADIAN PRODUCTION TO THE YEAR 2000 TO MEET FORECAST REQUIREMENTS



respective countries. United States geologists, for example, are acknowledged experts on sandstone-type deposits, Canadians generally know a lot about conglomeratic, vein-type and pegmatitic deposits, and French geologists have led the way with recent interpretations of the genesis of vein and replacement-type deposits. The bulk of exploration programs in these countries has, to date, been concentrated in areas favourable for the occurrence of the same types of deposits. In this respect, geologists in countries not blessed with large resources of uranium tend to be better prepared for the challenge of the 1980's, in that they have made it their business to familiarize themselves with the entire range of geological types of uranium deposits (Gableman, 1974b).

It is becoming more and more evident that we cannot expect to discover much larger deposits of the types now being exploited. Either new types of deposits must be found and developed or we must find much larger numbers of the same size deposits we are now exploiting, which may be a difficult task. There is a growing amount of evidence in the United States, for example, that the distribution of sandstone-type deposits may be limited and that this type of deposit may not be able to supply that country with its future needs (Nininger, 1974). Our philosophy should be to look for all types of deposits, including those which may be entirely new and which have yet to be identified.

Exploration to date has generally been directed toward deposits with average grades greater than 0.1 per cent U_3O_8. It is this quality of deposit from which the bulk of world production has come and with which we are most familiar in terms of economic geology and known reserves and resources. We also know quite a lot about resources of uranium available at very high costs, from such sources as the Chattanooga shales, from above average-grade granites such as the Conway granites, and from certain phosphate rock formations. Grades from these sources range from 0.01 to 0.001 per cent U_3O_8 and costs of recovery probably lie in the range of $50 a pound to more than $100 a pound U_3O_8. These sources have been investigated partly for

academic reasons and partly because they represent fall-back alternatives, should exploration for conventional sources be unsuccessful (Nininger, 1974; Bieniewski *et al.*, 1971). There is, however, a great gap in knowledge about sources of uranium between these two extremes, mainly because almost all exploration effort has been directed toward low-cost uranium.

There is every expectation to believe that once exploratory efforts are redirected toward sources of uranium with grades lower than 0.1 per cent U_3O_8 substantial resources will be identified. With increased prices of uranium and assured markets, some deposits containing as little as 0.03 per cent U_3O_8 will likely soon be economic; the Rossing deposit in South-West Africa (Namibia) is the first lower grade deposit to be developed (Armstrong, 1974). The potential for discovery of uranium deposits with grades in the range of 0.1 to 0.01 per cent U_3O_8 should be sufficient in order that dependence upon uranium from sources like granites and shales would not be necessary, at least not during this century.

As exploration expands in search of new types and lower grade deposits in areas away from traditional geological environments, it may be useful to re-examine our guiding geological concepts. The objective of many recent exploration programs has been to search for extensions of known geological districts, often using statistical or engineering approaches. Where interpretative geology has been used it is based on concepts modelled on known deposits. While this type of approach may be adequate for identifying new deposits in familiar environments, it may be totally inadequate for selecting new areas. It may be time to take a less conservative approach. Enough examples of different uranium occurrences have been found in the world so that complete ranges of genetic processes and controlling environments have been interpreted or conceived (Gableman, 1974a). It should no longer be acceptable to dismiss categorically particular environments as areas having little potential for uranium.

Exploration for uranium will become increasingly challenging, since the bulk of surface occurrences in readily accessible areas has likely already been discovered. Consequently, it will become more important to make the most effective use of all of the exploration technology available to us. There have been significant advances in recent years; for example, in gamma-ray spectrometry, radon emanometry and geochemical prospecting techniques. In addition, recent Canadian uranium exploration programs have successfully employed magnetic, resistivity, and gravimetric techniques. The search for concealed deposits will necessitate more 'wildcat' drilling which will contribute to the wider use in Canada of percussion drilling techniques, combined with radiometric logging. Even with all of these advanced techniques the search will be most difficult and there will be a continued need for improvements in exploration technology. Above all, programs will have to be more detailed and more systematic than in the past.

Financing Alternatives

One of the biggest challenges of the 1980's will be the financing of the required exploration and development effort. Two related factors which have contributed to the disinterest in uranium exploration during recent years have been low prices and oversupply. This situation has changed recently, however, with prices returning to more equitable levels and a sellers' market emerging over the past year. As to the future, a new mechanism is evolving based on world market prices at time of delivery, with a floor price to provide downside protection for the producer (Albino, 1974). In addition, recent contracts contain formulae for sharing the risk of currency fluctuations, and many have also provided for substantial down-payments to finance producers' expansions.

Another factor – the growing concern by various governments about the ownership of natural resources in general and of uranium resources in particular – has contributed to difficulties in financing exploration and development projects using foreign capital. In the face of these political realities however, there is growing evidence, although difficult to document, that new methods of foreign, non-equity financing are beginning to evolve. Various consumer entities in countries not blessed with domestic resources of uranium have been involved for sometime in uranium exploration and development ventures abroad. With the shift to a sellers' market during the past year, there also seems to be a shift in priority on the part of some consumer participants in these ventures, from equity participation, to any form of arrangement which will guarantee them a share of production for their nuclear power needs.

A similar kind of evolution is evident on a national scale in the United States, where a number of utilities have taken steps to obtain supplies of uranium by participating directly in uranium exploration programs. The principal example is the Tennessee Valley Authority (TVA) which has agreements with four United States uranium companies involving exploration rights and shares of production. In one case, the Tennessee Valley Authority must pay all exploration costs and, in addition, must pay all costs plus a royalty on future production equal to 50 per cent of the difference between costs and the market price for uranium at the time. A more recent example involves Texas Utilities Fuel Co. (TUFCO) which can participate for up to ten years in an exploration program with Ranchers Exploration and Development Corp., by providing over 85 per cent of the financing but gaining only 50 per cent of the equity.

The point to be made here is that a participant's share of production need not be directly related to his share of the equity. This type of consideration is not peculiar to uranium. An example in the case of oil, involves the agreement between the Saudi Arabian government and Arabian American Oil Co. (ARAMCO). ARAMCO's equity is limited to 40 per cent but its share of production is 76 per cent. In addition, ARAMCO is free to buy some of the remaining 24 per cent of production (Oil and Gas Journal, July 17, 1974). A

Canadian example in the case of coal is Kaiser Resources Ltd. In this case, Mitsubishi Corp. and its Japanese customers have an equity of some 30 per cent, but acquire essentially 100 per cent of the production. An example that may be more familiar to you is that of the Strathcona Sound lead-zinc project on Baffin Island, which is being developed by Mineral Resources International Limited. In this case, the foreign participants, Metallgesellschaft A. G. of West Germany and Billiton B. V. of Holland, have a combined equity position of 23 per cent but are guaranteed at least 80 per cent of the concentrates.

There are other ways of controlling equity limits, particularly at the development stage, including such things as production royalties and management agreements. The most obvious method, is the use of debt financing. It is pertinent to recall that the first large-scale application of debt financing in Canada's mining industry was for the development of the Elliot Lake deposits in the 1950's. Debt financing has become more common over the past decade. Recent Canadian examples include Gibraltar Mines Ltd. and Mattabi Mines Limited, which negotiated term loans with chartered Canadian banks in the amounts of $63.9 million and $45 million respectively, representing close to their total cost of development. Significant portions of debt capital can also be made available under the terms of sales contracts. This was the case, for example, with Lornex Mining Corporation Ltd. which borrowed $28.6 million from its Japanese customer-consortium and with Sherritt Gordon Mines, Limited, which borrowed $15 million (US) from the Mitsubishi group for the development of its Ruttan mine (Worth, 1974; Fielder, 1974). It is this latter type of debt capital which will likely become more commonplace for the development of future uranium projects.

Conclusion

It is worth noting that a major turning point in the history of Canada's uranium industry has been reached and that the outlook for uranium is enviable with respect to the future of other commodities. Demand is growing at an unprecedented rate, a sellers' market will likely prevail for an extended period of time, present prices are about $15.00 a pound U_3O_8 and an equitable future pricing mechanism is being developed. The history of uranium exploration in Canada has been relatively short, and the geological potential for future discoveries is considered excellent. Hopefully, there will be a continued evolution in methods of financing exploration and development efforts, in ways that will satisfy the growing aspirations of governments and, at the same time, provide the needed financial incentive to industry, as well as an assurance of supply to any participating consumers. Given these prerequisites, together with an exploration philosophy designed for the 1980's, there is every reason to expect that uranium may once again rank as Canada's principal mineral product.

These views may appear to be optimistic or even a little bit unrealistic but there can be no denying the fact that the challenges of the 1980's will be difficult and that there are many issues yet to be resolved; however, a pessimistic and conservative response to these challenges will not likely contribute to successful solutions.

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2. NEW SOURCES OF URANIUM? TYPES OF URANIUM DEPOSITS PRESENTLY UNKNOWN IN CANADA

V. Ruzicka

Abstract

Most of the main genetic types of uranium deposits occur in Canada. They contain a significant portion of the world's uranium resources. However, there are other economically important types of uranium deposits that to date have not been discovered in this country. As there is no fundamental reason why they could not be present, geologists working in Canada need to be aware of their characteristics so that they are not overlooked in future exploration programs.

The following examples indicate the variety of geological settings that may be important.

The Rössing uranium deposit near Swakopmund, South West Africa, is an example of a syngenetic deposit, formed by primary differentiation of granitic rocks, and later enriched in uranium secondary minerals by supergene processes.

Epigenetic uranium deposits in sandstones comprise the major portion of the United States uranium resources. Environments favourable for this type of mineralization can be found in some Canadian nonmarine sedimentary basins.

Cambrian alum shales in Sweden contain more than one million tons of U_3O_8 in low-grade ores. Uraniferous shales are known to occur in Canada.

Examples of other types of uranium deposits are the sedimentary-metamorphic deposits of the Ronneburg basin in East Germany, the metasomatic deposit near Krivoy Rog, U.S.S.R., the effusive-sedimentary deposits of the West Carpathians, the uraniferous coals and lignites of the United States and the uraniferous calcrete of Western Australia. There are presently subeconomic or unexplored Canadian occurrences of uranium mineralization, which may be classified as belonging to some of these particular types of uranium deposits.

Introduction

Canadian prospectors have a great advantage, in comparison with their colleagues from other countries, because Canada possesses a vast mineral endowment consisting of a broad spectrum of various commodities. For example Canada is one of the few countries of the world that has large uranium resources. Several main types of uranium deposits are know in Canada and some only in Canada. Many criteria for uranium exploration have been derived from studies of Canadian uranium deposits. Canadian geologists and prospectors have also participated significantly in the discovery or development of uranium deposits in the United States, Australia, South Africa and in many other countries.

However, increasing demand for energy will undoubtedly bring demand for further expansion of our uranium resources, demand for new exploration targets and for new prospecting hypotheses. In connection with these problems many questions can be asked.

Does Canada have enough sources of uranium for the future? Is it possible to find new sources of uranium? Can prospectors get some new aids today to find the Canadian uranium mines of the future?

The answer is certainly yes. And one way is to look for new types of uranium deposits presently unknown in Canada.

In the following section the basic types of uranium deposits are reviewed briefly and then selected types not yet found in Canada are discussed using examples from outside of Canada.

Geological Types of Economic Uranium Deposits

Figure 2. 1 shows a simplified scheme of metallogenic process leading to formation of basic types of uranium deposits. The primary distribution of uranium can be in various portions of the crust. This stage is shown in the diagram as "SOURCE".

According to relationship to rock-forming processes two groups of uranium ore-forming processes can be distinguished: The syngenetic, where both occur contemporaneously, and the epigenetic, where ore-forming processes acted later in already existing rocks. This stage is shown in the diagram in the second column: "RELATIONSHIP TO ROCK-FORMING PROCESS".

Various combinations of ore-forming processes are shown in the third and fourth columns as "ORE-FORMING PROCESS I" and "ORE-FORMING PROCESS II". These combinations give rise to fourteen types of uranium deposits.

The first three types result from igneous and/or metamorphic processes and include "PEGMATITES" (e. g. Faraday Mine in Bancroft area, Ontario), "CARBONATITES" (e. g. Palabora or Oka deposits), and "PERALKALINE SYENITES" (e. g. Ilimaussaq, Greenland). Differentiation is the essential action causing concentration of uranium-bearing minerals.

The fourth type, shown as "GRANITES", is a result of primary differentiation and further supergene enrichment of granitic rocks (e. g. Rössing uranium deposit near Swakopmund, South West Africa).

Sedimentary processes can lead to concentration of uranium-bearing minerals in "CONGLOMERATES" with prevailing syngenetic mineralization (e. g. in Elliot Lake deposits), or to fine dispersions in "SHALES, PHOSPHATIC ROCKS etc.". Here the uranium compounds can be further redistributed and in this way further concentrated as in the alum shales in the Ranstad area, Sweden. Uranium, primarily concentrated in sediments, can be remobilized and reconcentrated by metamorphism in "SEDIMENTARY-METAMORPHIC" uranium deposits.

A combination of volcanic and sedimentary processes can lead to formation of "EFFUSIVE-SEDIMENTARY" type of uranium mineralization, where uranium is confined to water-deposited tuffs, i. e. tuffites (e. g. Huta and Muran deposits, West Carpathians).

Uranium, liberated from the source, can be transported in aqueous solutions and deposited in various environments due to redox changes, adsorption, precipitation or metasomatism, or due to a combination of some of those processes. The deposition can occur under various P-T (pressure and temperature) conditions.

Uranium-bearing fluids can carry unstable compounds in the oxidation zones of porous sediments and deposit their load along the oxidation/reduction front, as in the nonmarine sandstones in the western United States, forming epigenetic deposits in "SANDSTONES". Adsorption, along with redox changes, can form uranium deposits in "COALS and LIGNITES". Uranium can be precipitated from solutions in fractures or in structural and lithological traps and deposited as "VEINS" (e. g. Beaverlodge, Rabbit Lake, Cluff Lake deposits in Canada), in "CARBONATES" or "CALCRETES" (e. g. Tyuya Myuyun, Yeelirrie, etc.) or as "METASOMATIC" deposits (e. g. Krivoy Rog).

Attention will be paid to those deposits presently unknown as exploitable in Canada, but which might be considered as potential future sources of uranium in this country.

These types are shown with numbers 3, 4, 5, 7, 8, 9, 11, 12, 13, and 14 in Figure 2. 1.

Granites and Peralkaline Syenites

As examples are two deposits:

(a) The Rössing deposit near Swakopmund, South West Africa;
(b) Low-grade uranium mineralization in peralkaline syenites in the Ilimaussaq intrusion, South Greenland.

Rössing deposit. It has been known since before World War I, that uranium and copper mineralization is found in coarse grained leucocratic granite intruded into highly metamorphosed calcareous and non-calcareous sedimentary rocks, namely marble, schist, granulite and quartzite of the Damara System and Nosib Formation near Swakopmund, South West Africa (Becksteöm, 1970).

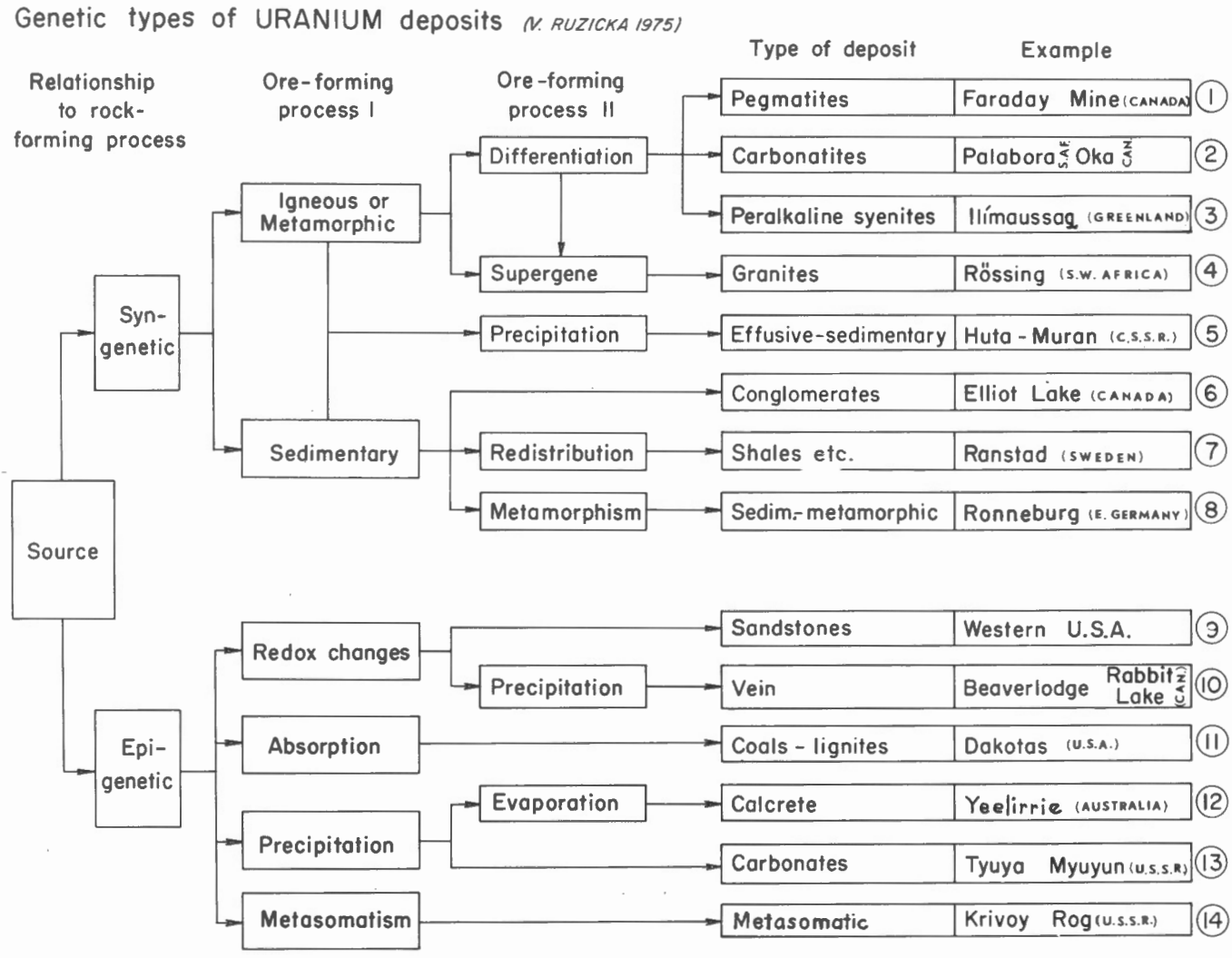


Figure 2. 1. Genetic types of uranium deposits.

The host rock is mainly pegmatitic alaskite containing xenoliths of metasediments. The absolute age of the host rock has been determined as 510 ± 40 m. y.

The mineralized zones, up to about 2100 feet in diameter, contain fine dispersions of microscopic grains of radioactive minerals: approximately 55% uraninite, less than 5% betafite, and 40% of secondary uranium minerals, such as metatorbernite, uranophane, thorogummite and gummite. The primary uranium mineralization is apparently syngenetic. The secondary mineralization occurs along joints and fractures in quartz, feldspar and biotite and is of supergene origin.

The Rössing deposit is among the world's largest uranium deposits. Although all data have not been published, it is believed, that the deposit contains about 150 000 short tons of U_3O_8 in ore grading 0.7 pound per ton.

Some geological features of the Rössing deposit are analogous with either Faraday or Gunnar deposits in Canada. However, a specific combination of metallogenic, tectonic and geochemical factors makes the Rössing deposit a unique genetic type.

The possibility that the Rössing type of mineralization occurs in Canada cannot be excluded. Areas of granitic rocks, with high uranium contents, are common in the Canadian Shield and in some parts of the Cordillera.

The place to look for the Rössing type of mineralization is where such areas are subjected to intensive weathering and where uranium-bearing leached products were preserved from dispersion. It is certain that in analogous environments in Canada, accumulation of secondary uranium minerals in granitic rocks could be important.

The Ilimaussaq intrusion. Some peralkaline rocks, such as those of Ilimaussaq, Greenland, exhibit high levels of radioactivity due to thorium, but in some places they contain up to 1500 ppm of U_3O_8. Uranium is, however, mainly concentrated in refractory minerals, which make recovery at the present time uneconomic, unless other associated elements, such as beryllium or niobium could be co-products.

In Canada radioactive syenites with high thorium contents are known from Port Coldwell Complex, Ontario, Seal Lake area, Labrador, and elsewhere.

Epigenetic deposits in sandstones

Uranium resources in sandstone deposits represent a substantial portion of world's uranium sources.

The most favourable environment for this type of mineralization is intramontane basins containing non-marine sediments. Such regions, when subjected to regional uplift and effects of igneous activity, usually contain abundant tectonic traps for deposition of uranium mineralization. Reducing agents can be derived from organic matter, bacterial activity or inorganic substances.

The host rocks favourable for uranium mineralization are, as a rule, permeable feldspathic, arkosic or tuffaceous sandstones. Tuffaceous sediments are commonly present in the stratigraphic succession of the host rocks. The concentration of uranium occurs at the oxidation-reduction front (Rubin, 1970; Grutt, 1972).

The ore-forming process can be demonstrated on the diagram (Fig. 2.2):

(1) The fresh sandstone, which occurs before the redox front, is as a rule, grey, green or tan, containing pyrite, fresh carbonaceous matter or humic compounds. Vegetal carbon is an excellent nutrient for desulfovibrio bacteria, which produce hydrogen-sulphide – another strong reducing agent. Hanging-wall and footwall are shaly beds.

(2) Beds dip at the time of formation less than 5 degrees. Gentle dips assure slow migration of groundwaters at a rate preventing flushing of reducing agents and allowing uraniferous groundwaters to circulate.

(3) The altered sandstone, which occurs behind the redox front, contains, as a rule, kaolinite (an alteration product of feldspar), hematite or limonite (products of oxidation of pyrite), and sporadic fragments of dull and flaky carbonaceous matter.

(4) Many metallic elements can be associated with uranium, but only vanadium, molybdenum, selenium and copper may be useful prospecting geochemical indicators of uranium mineralization in outcrops (in addition to radioactivity and typical secondary uranium minerals) because:
- vanadium is relatively stable in the oxidation zone and shows yellow stains;
- molybdenum forms blue crusts of hydrous oxide
- selenium is recognizable by red staining; its presence often coincides with the presence of the Astragalus indicator plant;
- copper produces green secondary minerals and is a component of "green uranium micas", i.e. torbernite.

(5) The orebodies contain either oxidized or unoxidized uranium ore. They can be:
(a) "C" shaped (so called "roll" deposits) in cross-section, a few to 50 feet thick and up to a few hundred feet wide. The rolls can contain several hundred thousand tons of ore grading 2-10 pounds U_3O_8 per ton (Figs. 2.3, 2.4, 2.5).

(b) "blanket" deposits, 3-15 feet thick extending in large areas and containing millions of tons of ore at 3-8 pounds U_3O_8 per ton each;

(c) "stack" deposits occurring along fault zones and containing more than one million tons of ore at 2-5 pounds U_3O_8 per ton.

Large uranium deposits of this type in sandstones occur in the Western United States (e.g. Jack Pile Mine, Lucky Mac Mine, etc.), in East Germany (Koenigstein), in Czechoslovakia (Hamr), in Hungary (Mecsek), in U.S.S.R. (Uchkuduk, Sa-byr-Say) and elsewhere.

Although the epigenetic uranium deposits in sandstones represent more than 90 per cent of the United States uranium reserves, no economic deposit of this type is known in Canada yet. Environments favourable for the uraniferous sandstones occur in the Canadian Cordillera, in the Interior Plains, in the Canadian

Appalachians, in the Arctic region (Roscoe, 1966) and in sedimentary basins containing nonmarine sandstones adjacent to or derived from acidic igneous rocks.

Uraniferous shales, phosphatic rocks, etc.

The best examples of uranium-bearing shales are the Cambrian alum shales near Ranstad in Sweden, where uranium forms an organouranium complex associated with pyrite, quartz, feldspar, illite and kaolinite. Reserves exceed one million short tons of U_3O_8 at ore grade of 300 parts per million (i.e. 0.6 lb U_3O_8 per ton) (Peterson, 1967).

Extensive low-grade uranium mineralization occurs in the Chattanooga shales in the United States. These Upper Devonian and Lower Mississippian sediments in central Tennessee and adjacent Kentucky and Alabama contain a 12-18 feet thick radioactive zone extending over an area of about 4000 square miles and averaging approximately 70 parts per million (0.14 lb /ton) U_3O_8. Moreover, the Chatanooga and its correlatives underlie about 800 000 square miles extending from eastern Tennessee to Texas and Montana; its uranium-bearing strata average about 40 feet in thickness and about 35 parts per million U_3O_8 in grade (Finch *et al.*, 1973).

In Canada uraniferous shales have been only little tested. Occurrences grading far below those in Sweden have been reported from outcrops of the Exshaw and Banff formations in western Canada with contents of 47 and 70 parts per million U_3O_8 respectively (Chamberlain, 1960). Recently uranium contents of 20-80 ppm U_3O_8 have been reported from MacNeil Formation in the Marion Bridge area of Cape Breton, Nova Scotia (Anon. 1975). Mesozoic shales containing up to 40-65 ppm U_3O_8 have been found in Ellesmere Island, Canadian Arctic (Ruzicka, 1971). These shales could be of economic interest if they had higher uranium contents.

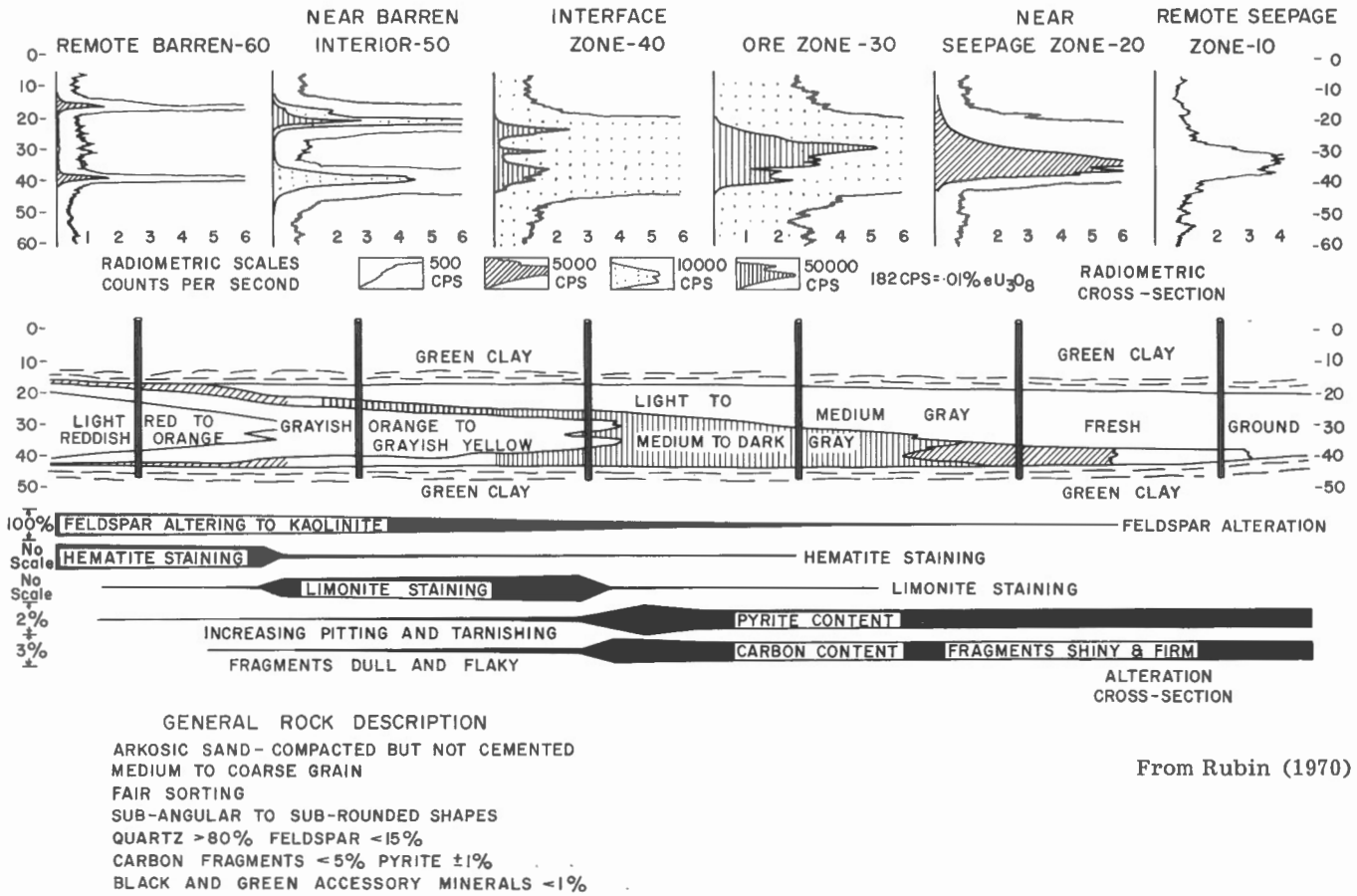
Syngenetic uranium mineralization occurs in phosphatic rocks, such as those of the Phosphoria Formation of Permian age in Idaho, Utah, Montana and Wyoming and those of the Bone Valley Formation of Pliocene age in Florida (Finch *et al.*, 1973).

Thicknesses of these beds range from 5 to 10 feet and grades range from 70 to 700 ppm U_3O_8 with averages between 100-200 ppm.

Sedimentary-metamorphic deposits

Uranium, syngenetically deposited in shales, can be remobilized and redeposited under conditions of thermal and dynamic metamorphisms.

Large uranium deposits in the Ronneburg area, East Germany, occur in Lower Paleozoic metamorphic



From Rubin (1970)

Figure 2.2 Sandstone type of uranium deposit, Powder River Basin, Wyoming.

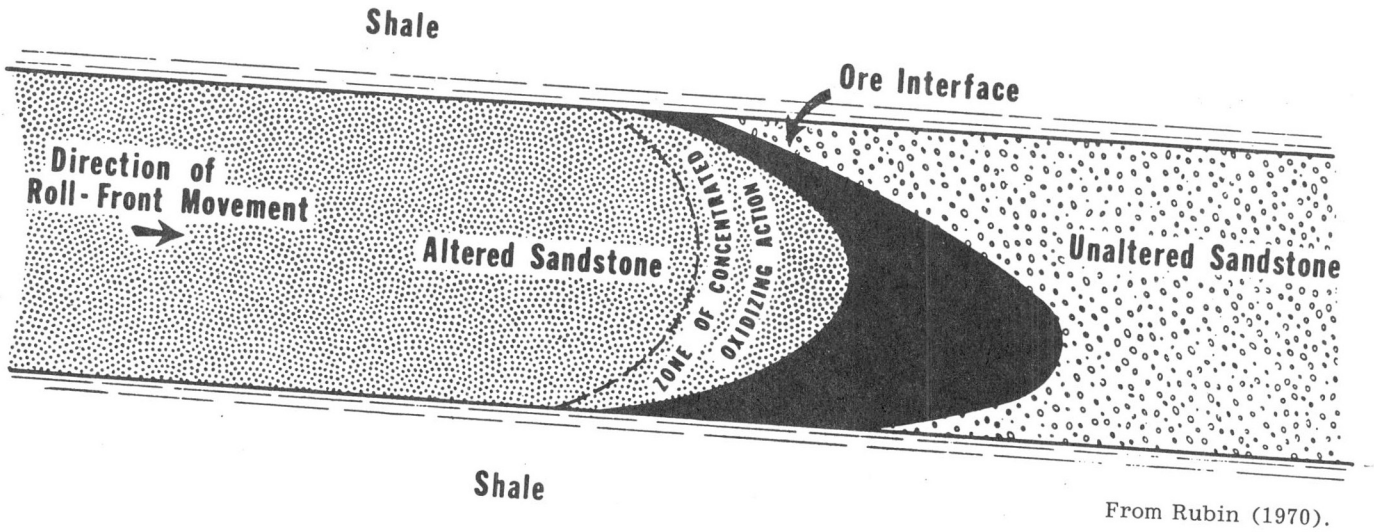


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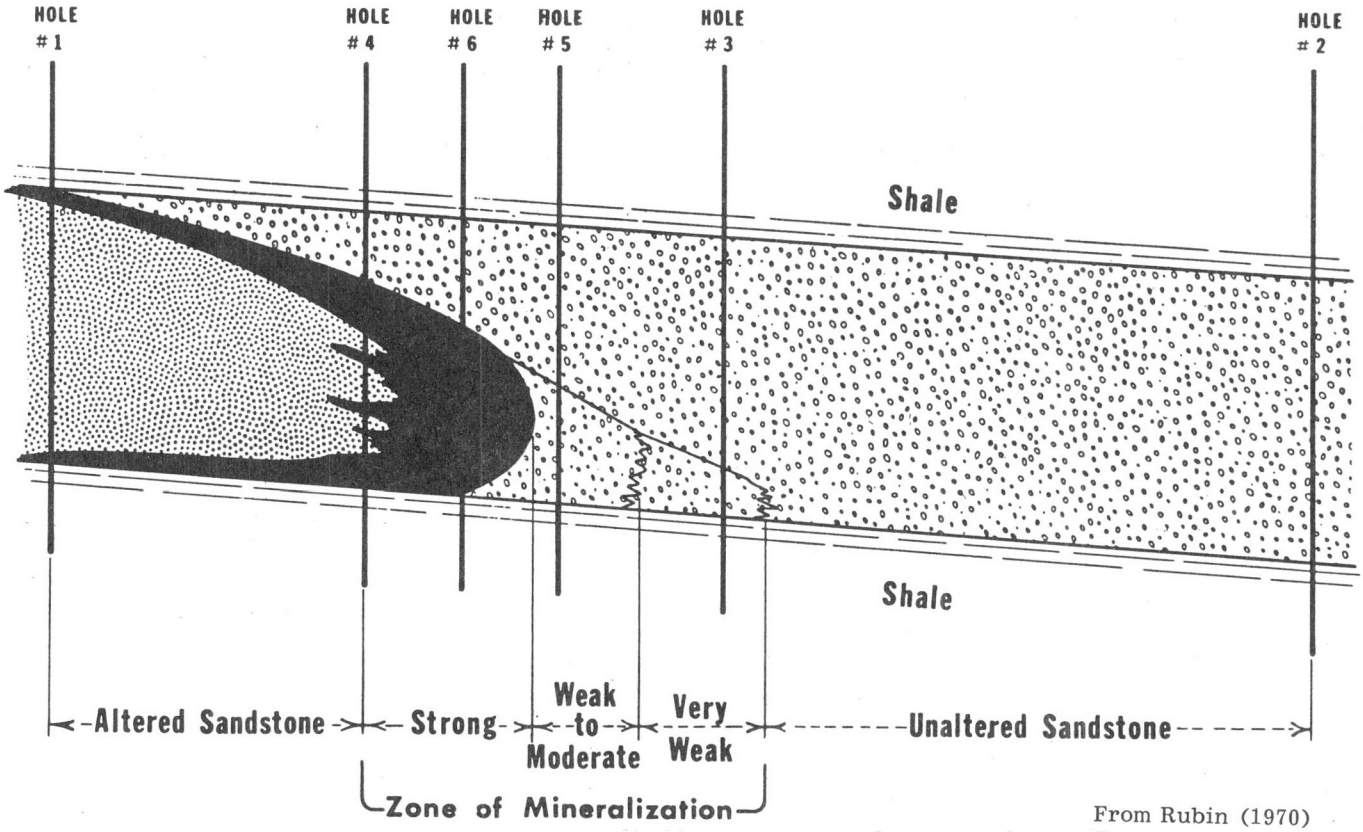
Figure 2. 3. Cross-section illustrating the "classic-type" uranium "roll-front".



From Rubin (1970)

Figure 2. 4. Cross-section illustrating a typical South Powder River basin type "roll-front" and holes drilled using the "splitting the distance" technique.

complexes. Metamorphic processes caused destruction of the adsorption bond of organic material with uranium, carbonatization and polymerization of the organic matter, migration of uranium-bearing solutions, redeposition of pitchblende near reducing agents and formation of secretionary veins. An interesting feature is the association of uranium mineralization with the highly pyritized graptolitic member of the sequence (Gatseva, 1958). The ore forms irregular bodies with average grades between 2 and 4 pounds U_3O_8 per ton.

In Canada this type could be found in any syngenetically uranium-bearing rock sequences (sediments, volcanics) that have been affected by thermal or dynamometamorphism or both.

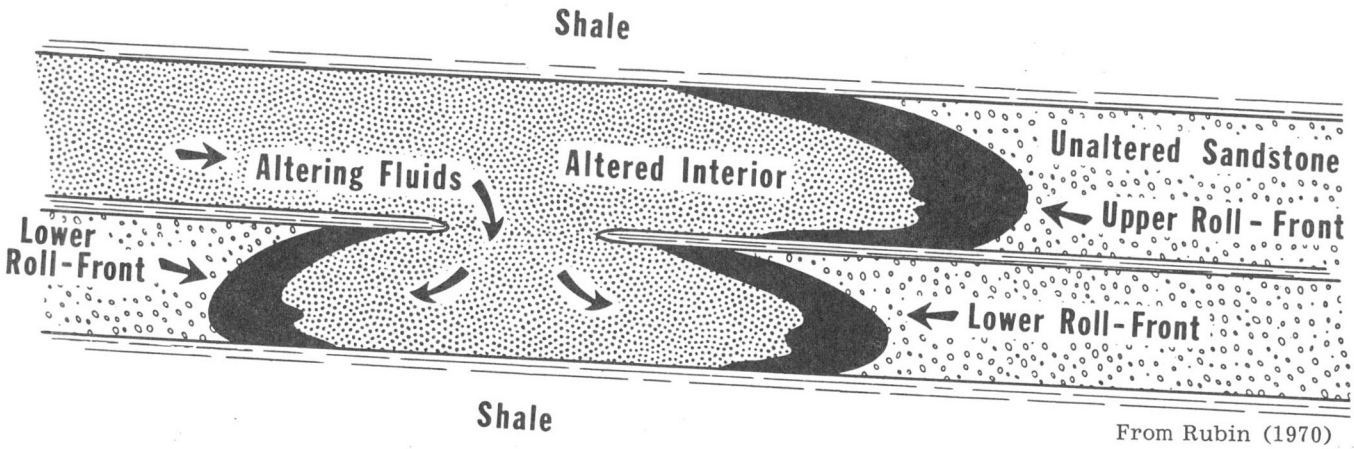


Figure 2. 5. Cross-section illustrating vertical movement of "roll-fronts".

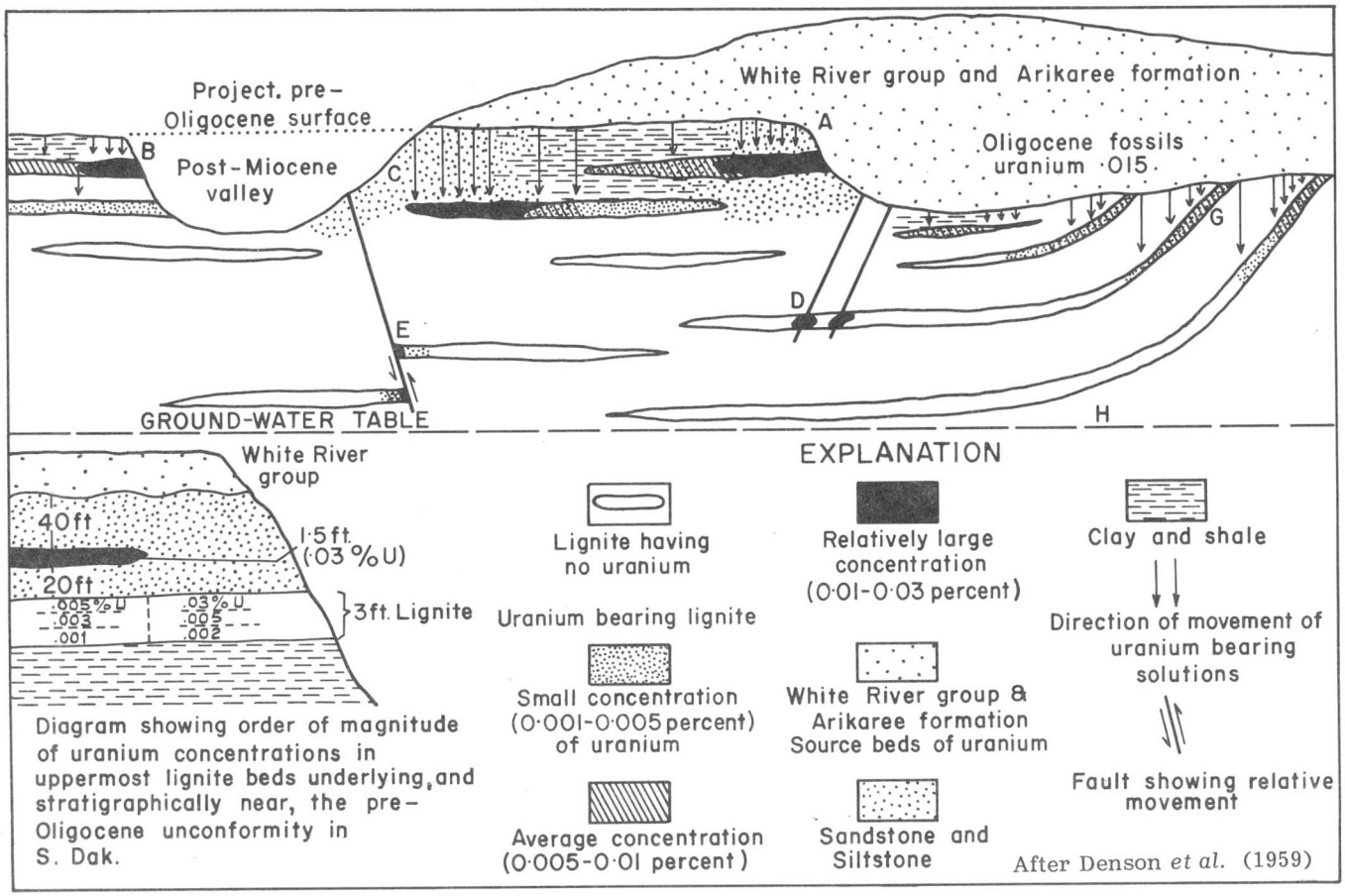


Figure 2. 6. Magnitude of uranium concentrations in lignite beds.

Uraniferous coals and lignites

Most of the uranium in coals and lignites is of epigenetic origin and was derived from rocks containing abnormal contents of uranium, such as acidic tuffs, granites and others.

The genesis of uranium lignite deposits is shown in Figure 2. 6 (Denson *et al.*, 1959). The source is tuffaceous rocks. Uranium in solutions circulated through porous sandstone and was absorbed on lignites. Lignites under shaly horizon are commonly barren.

Uranium-bearing coals have been mined solely for their uranium content in Europe, United States and elsewhere.

In Canada large areas of uranium-bearing lignites are known near the United States border. As a result

of renewed interest in fossil fuels, the known Canadian uraniferous lignites and coal deposits will be restudied.

Uranium in calcrete

Uranium mineralization in Yeelirrie area, Western Australia, was found in calcrete. The deposit occurs in a semi-arid climatic zone. During the Tertiary, large river channels were eroded and later filled with a mixture of clay and sand, cemented by carbonate. Uranium was deposited mainly as carnotite (potassium uranium vanadate) in the porous calcrete. The grade of ore is on the average 3 pounds U_3O_8 per ton. In the richest main zone, which is some 6 km long, mineralization is approximately 8 m thick. Reserves of U_3O_8 are estimated at 46 000 metric tons (Anon. 1974).

In Canada similar geological conditions may occur in old evaporites in areas with anomalous uranium contents.

Carbonates

Occurrences of uranium-bearing carbonates are known in the United States. Thus the Todilto Limestone of New Mexico contains irregularly distributed uranium mineralization. Tyuya-Myuyan uranium deposit in the Asian part of the U. S. S. R. occurs in cavernous dolomitic limestone.

In Canada a molybdenum-low-grade uranium occurrence in Grenville dolomite was discovered recently near East Aldfield, north of Ottawa (Martel, 1974). Also uranium occurrences in Ordovician sandy dolomite or dolomitic sandstone were found near South March, west of Ottawa. Uranium mineralization in this type of environment could occur elsewhere in Canada, most likely in sedimentary basins near major unconformities.

Effusive-sedimentary deposits

The hosts for uranium mineralization of this type of deposit are mainly tuffites, which are mixtures of pyroclastic and sedimentary detritus. However, uranium mineralization can occur in the tuffs only or in the sediments alone.

Deposits of this type occur in the Alpine-Carpathian system. Novoveska, Huta and Muran deposits are examples (Ruzicka, 1971).

Uranium minerals, mainly massive and sooty pitchblende, are finely disseminated in irregular orebodies and accompanied by molybdenite, chalcopyrite and other base metal minerals.

Uranium-molybdenum association in tuffs of the Aillik Group in Labrador resembles, to a certain degree the deposits in West Carpathians. Presence of the effusive-sedimentary deposits can be expected in Canadian Cordillera in the volcano-sedimentary areas and in similar environment in other uranium provinces.

Metasomatic deposits

A relatively large deposit, classified by some authors as uranium-iron-formation, occurs at the edge of the Knivoy Rog magnetite-hematite iron deposit in Ukraine (Ruzicka, 1971).

Apparently a combination of two factors controlled deposition of uranium:

(1) Migmatization of ferruginous quartzites; and

(2) Alkali metasomatism represented by aegiritization, albitization and carbonatization.

Uranium occurs only within the zone of alkali metasomatism.

This type of uranium deposit is presently unknown in Canada. Some uranium occurrences in the vicinity of iron-formations, but associated with graphitic and pyritic shales of Animikie Series, were reported from the western Great Lakes region of the U. S. A. (Vickers, 1956).

Conclusion

In this report a brief review of types of uranium deposits presently unknown in Canada has been presented. It is probable that some of them will be a substantial source of uranium in Canada's future and thus they warrant serious consideration by those engaged in uranium exploration in Canada.

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3. GEOPHYSICS IN URANIUM EXPLORATION

A. G. Darnley

Abstract

There are no revolutionary new methods of uranium exploration on the horizon. Continuing improvements in existing methods and types of instrumentation are to be expected, but the main scope of improvement will hinge upon using the best of the available methods more meticulously and systematically, and paying more attention to the analysis of data.

Geophysical methods that are specific for uranium depend upon the fact that uranium is radioactive, and both it and its decay products disperse relatively easily. Occurrences of uranium mineralization seldom occur in isolation and they are normally found in association with both regional and local zones of enrichment which are amenable to detection. Exploration for uranium also entails the use of complementary non-specific geophysical methods in order to detect and trace features associated with particular types of uranium mineralization. These associated features may be structural or compositional, and may entail tracing an unconformity, a joint system, a lithology, or associated sulphides.

Wherever there is a large surface concentration of uranium very simple instrumentation will suffice to locate it, but it is unlikely that undiscovered occurences of this type still exist to be found in Canada except in very remote areas. The new exploration effort must recognize that the whole natural environment is radioactive, and that it has now become necessary to search for significant signals which are of the same order of magnitude as the background radiation. It is now essential to be able to identify low concentrations of uranium in unfavourable circumstances. This can only be done by using sensitive equipment in a precise quantitative manner, and by using every other available tool or source of information as a filter in the analysis of the data.

In airborne gamma-ray spectrometry it is essential that all systems employed are capable of providing a statistically significant measure of the uranium to thorium ratio since this is the most versatile indicator of uranium mineralization. For all types of radiometric instrumentation, gamma-ray spectrometers, scintillation counters or Geiger counters, and for all types of application, airborne, ground, borehole or subaqueous, it is necessary that all users become aware of the advantages of adopting standardized systems of measurements, in order to be able to interrelate measurements, and to establish and periodically confirm the sensitivity of equipment in use.

Introduction

The first thing to be stated about geophysical methods in uranium exploration is that there are no indications of any revolutionary new methods awaiting development. The problems which face producers in the immediate future with respect to finding new uranium deposits must be solved by maximizing the sensitivity of existing methods, increasing the thoroughness and care with which they are applied, and by analyzing the results in conjunction with every other sort of available geoscience information. The possibility that there are large, obvious but undiscovered radiometric anomalies relating to uranium mineralization in any of the more accessible areas of the country is now very unlikely. Most of the geologically obvious target areas have been searched several times during the past 20 years, but generally not with the meticulous attention to detail that now becomes necessary. It is useful to recall that the Kidd Creek deposits of Texas Gulf Sulphur remained undiscovered for many years because the EM anomaly which related to it was not considered significant. It is prudent to assume that most of the large uranium deposits which remain to be found will likewise not be marked by prominent anomalies.

Most people when they begin to think of searching for uranium think of measuring radioactivity. This is the obvious thing to do and much of this paper is devoted to this particular topic. However, it is important to remember that in addition to geochemical methods, other non-radiometric geophysical methods may be of great value in order better to define the target area and to trace zones of mineralization beyond their surface exposure. Figure 3.1 summarizes in a schematic way some of the situations in which concentrations of uranium may be found. Uranium may be concentrated in granitic rock especially those intruded late in an orogenic cycle. It may be concentrated in high temperature pegmatites, or in lower temperature vein deposits. All of these provide a potential source of uranium for later erosion, transportation and reconcentration into peripheral younger deposits. The more stable high temperature uranium minerals may survive mechanical transport and be found concentrated in quartz pebble conglomerates such as at Elliot Lake. The prime time for this process to have occurred seems to have been soon after the end of the Archean, but it is unwise to be too dogmatic about age because unaltered detrital uraninite can be found at the present day in Pakistan, for example, in silts associated with river flood plain gravels (Zeschke, 1959; Darnley, 1962).

Discoveries during the past few years in both Australia and Canada emphasize the tendency for uranium transported in solution to reprecipitate on or close to major unconformities both in Proterozoic and later times. Uranium can be transported considerable distances along aquifers if conditions are suitable and be precipitated wherever it encounters an interface with reducing conditions, giving rise to the now well-known roll front orebodies. Each of these mineralization scenarios is shown in Figure 3.1. Consider the problems of locating such concentrations. Any which are at surface even in very small amounts can be detected radiometrically. It is for uranium mineralization which is not at or close

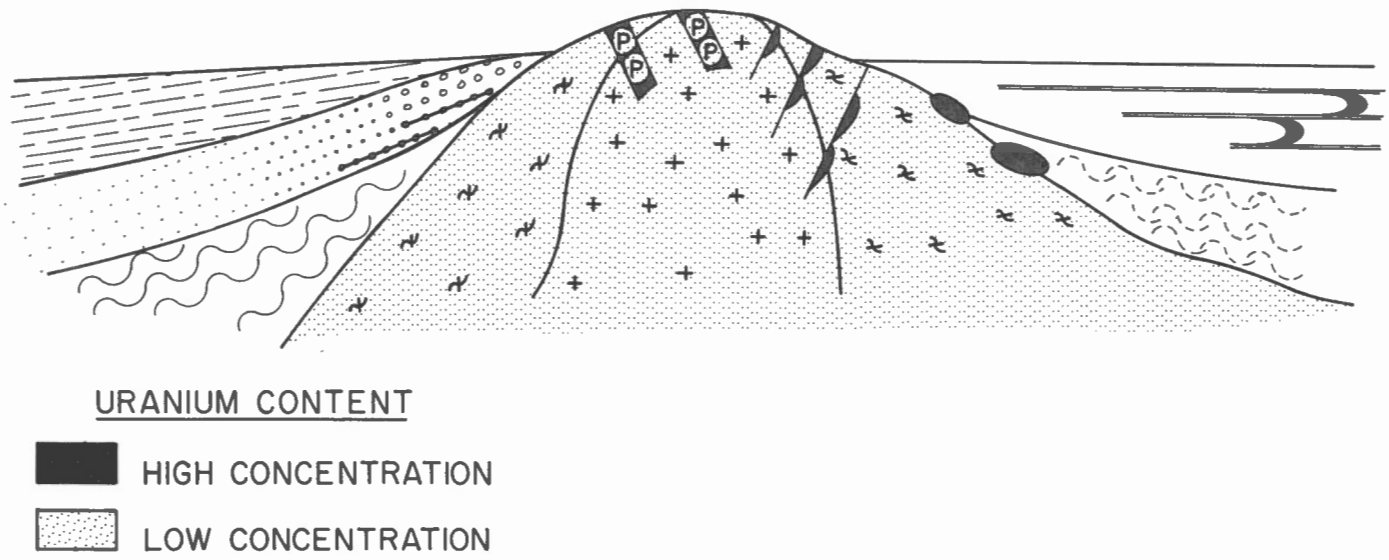

Figure 3.1. Schematic diagram: uranium source and depositional areas.

to the surface where non-radiometric geophysical methods may play a vital role in discovery. In Canada, for example, knowledge of the depth and configuration of the unconformities underlying the Athabasca and Dubawnt sandstones may be very significant with respect to locating the most favourable zones for uranium mineralization; the dips and hollows in the unconformity underlying the Paleozoic sediments along the western and southern edge of the Shield may be very significant. The pre-Carboniferous surface in the Maritimes may be a key feature in controlling later mineralization processes. The depth to an unconformity, and the alignment of features along it may be defined by magnetic, seismic, or in favourable circumstances, gravity surveys. Geophysical surveys of this type may offer considerable economy in outlining possible areas for uranium mineralization in circumstances where extensive drilling will be required to search and test possible target horizons.

Uranium occurs commonly but not always with other metallic minerals. Thus, uranium may be associated with disseminated sulphides, as at Elliot Lake, in which case IP methods could be useful in tracing its continuity. Uranium may be associated in veins with other sulphides which are amenable to detection by electromagnetic methods as at Port Radium; uranium mineralization may be associated with fracture or shear zones which can be traced by electrical, EM or magnetic methods. The magnetic signature of the host rock containing uranium mineralization, or of an adjoining formation, may be characteristic and thus a magnetometer survey may enable a mineralized zone to be traced a greater distance or to greater depths than would be possible by radiometric or geochemical methods.

Radioactivity surveys

Radioactivity from the three naturally occurring radioactive elements, potassium, uranium and thorium, is rapidly absorbed by matter. Gamma radiation, which is the most penetrating, is almost totally absorbed by one foot of rock or 18 inches of dry soil. Thus the measurement of radioactivity can only provide a superficial search. This being so, it is perhaps surprising that radioactivity surveys have achieved the success that they have in exploration. This is undoubtedly because of the ready dispersion of both uranium and its decay products in primary and secondary geochemical processes. Paper 4 deals with the relative mobilities of uranium, radium, radon and helium, and reference should be made to it for a summary of the radioactive decay process, and methods based on measurement of radon. Radioactive decay involves the emmission of alpha, beta and gamma radiation, but only gamma radiation is considered in this paper.

Figure 3.2 shows the spectrum of gamma radiation from a typical rock containing potassium, uranium and thorium. It shows a spectrum as seen by a typical

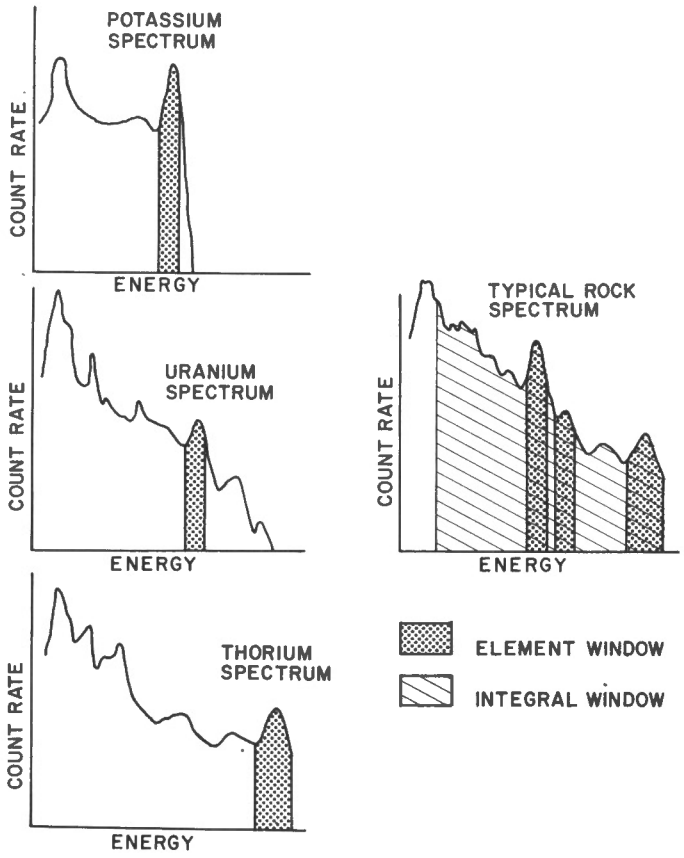

Figure 3. 2. The natural gamma spectrum.

sodium iodide detector. Sodium iodide detectors remain the most satisfactory means of measuring radiation in the field, but their resolution and counting efficiency are far from ideal. The instrument used for obtaining information about a gamma-ray spectrum is, of course, a gamma-ray spectrometer. In geophysical practice the identification and measurement of uranium and thorium by gamma-ray spectrometry is an indirect rather than a direct method. This is because the strongest most convenient gamma peak for estimating uranium is that of its decay product, bismuth-214, and the most suitable gamma emission for thorium is that of its decay product, thallium-208. As long as no loss of material takes place, these decay products are present in a fixed proportion relative to the parent elements. In this situation the radioactive decay series is said to be in equilibrium, and for most practical exploration purposes involving work over bedrock or shallow overburden, the amount of disequilibrium is not usually significant as far as radiometric measurements are concerned. However, radiometric anomalies which appear to coincide with swampy areas or springs should be assessed bearing in mind the possibility of disequilibrium processes being operative in the vicinity, involving the transportation and precipitation of radium some distance from its uranium sources. For grade evaluation purposes strict tests for disequilibrium should always be applied. A direct spectral readout from a spectrum such as shown in Figure 3. 2 is not capable of providing a direct measure of potassium and uranium content even under theoretically ideal conditions unless a correction is made for Compton scattering. In simple terms, the low energy end of the spectrum is boosted in count rate by the scattering of degraded higher energy radiation. In geophysical use the biggest single variable in the magnitude of the Compton correction relates to the dimensions of the detector crystal being used for the measurement.

The factors which influence the field measurement of radioactivity in the geophysical environment are low count rates, source geometry, extraneous radiation, and moisture. In most exploration situations the small magnitude of the radiation field provides the principal problem. This is because radioactive decay is a random process and unless a large number of events are observed, considerable fluctuation in rate may take place over the short term. For this reason either large detectors have to be used or observations have to be extended over a considerable period of time in order to minimize the uncertainty of the counting statistics.

The geometry of the source relative to the detecting crystal is an important consideration in both airborne and ground work. For a given limiting source-detector distance, the upper diagram in Figure 3. 3 shows how at constant ground clearance the solid angle through which radiation is reaching the helicopter is larger when it is in the valley than when it is over the ridge. Conversely, for an aircraft flying at constant terrain clearance, the aircraft over the ridge is receiving radiation over a wider solid angle than the aircraft over the valley. The count rate over the ridge is further enhanced by the fact that the aircraft is much closer to the source of radiation than when it is over the valley. It is possible to make a satisfactory correction for variations in terrain clearance, but it is not usually practical to compensate for changes in solid angle. The solid angle effect is most critical in measurements on the ground particularly, for example, in the case of comparing a measurement made on a flat rock surface with a measurement made in the bottom of a trench. The count rate observed in the trench may be twice as high as on the plane surface even if the composition is the

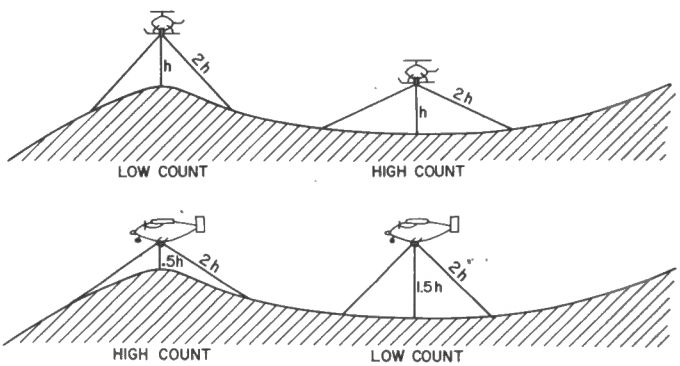

Figure 3. 3. The effect of source geometry upon count rate.

same. Obviously either corrections must be applied or standard geometry adhered to if measurements are being made for comparative purposes.

Extraneous background radiation must be minimized or corrections applied. In airborne surveys, a correction must be applied for variations in atmospheric radioactivity which can vary by an amount equal to 2 ppm equivalent uranium at ground level. Since average ground contains no more than 2 ppm uranium, this is significant. Radioactive dials, watches, instruments, emergency signs, should all be removed from the vicinity of any radioactivity measurements.

As measurements of radioactivity seek to become more precise and quantitative, increasing attention must be given in airborne work to making measurements under conditions of fairly constant and preferably low soil moisture content. Ground which is saturated with moisture because of spring thaw conditions, or after a prolonged period of heavy rain, will exhibit a substantially lower level of radioactivity compared with the same ground during the driest period of the year. In situations where small anomalies are being sought, this may make the difference between finding and not finding them. Conversely, some heavy summer thunderstorms may be accompanied by a short-lived increase in bismuth-214, the decay product which is the marker for uranium. None of these points are particularly novel; they have all been documented in the literature in different places at different times, but it is most important that newcomers to uranium exploration should be aware of these limitations and should anticipate or avoid potential difficulties.

As indicated at the beginning of this paper, there are no major new developments in instrumentation for measuring radioactivity, although continuing improvements in design detail and reliability and stability are to be expected. There is a proprietary development of a polycrystalline detector which may make for greater economy and efficiency, and there is the possible future use of photodiodies to replace photomultipliers and thereby result in reduced detector dimensions.

The rapidly diminishing dimensions of electronic components as demonstrated by the dramatic improvement in the capabilities of small pocket calculators should in time be applied to geophysical instrumentation in general. In the case of radiometric instrumentation it will permit the incorporation of built-in correction factors, and the ability to obtain a direct read-out in terms of significant parameters.

The use of radioactive methods in exploration

The search for uranium has to be conducted in a radioactive environment. All common rocks are radioactive in varying degree, and all common surface materials which have been derived from them are radioactive. The radioactivity from swamps and waterlogged soils may be very low; this is because the water that is present is a strong absorber of radiation, not because they do not contain radioactive material. In the present and future exploration context any radioactivity measuring system which is not sufficiently sensitive to show the small differences between different rock types is unlikely to possess sufficient sensitivity to find the small occurrences of mineralization which may be all there is to see of an almost totally concealed uranium deposit.

It is important to be aware of the present units for measuring natural radioactivity in mineral exploration. No uniformly applied units exist, few of the units employed are scientifically defined, or they cannot be readily equated with any geologically meaningful quantity, and some of the units employed are used in more than one way. There is a distinct need for standardization in the methods of measurement and reporting, and for much stricter calibration procedures in order to achieve and maintain these standards. There has been a substantial duplication of effort in the past with radiometric surveys, as with geophysical and geochemical surveys in general, because data collected at different times, or data collected from different areas, or data collected by different companies, can only be compared in a qualitative manner. In most instances it is not possible to make meaningful compilations of data from different sources, or to compare the sensitivities of the methods which have been used because of the lack of any agreed common standards. It is as if every manufacturer defined his own yardstick for his own products. In surveys involving the measurement of total radioactivity for example, reporting units have included millivolts, equivalent uranium, microroentgens per hour, and counts per unit time. Counts per unit time are entirely dependent upon the characteristics of the particular instrument being used, and may not be the same for two instruments with identical detector sizes. This is not the occasion to go into the arguments for and the details by which a standardized system of measurement can be achieved beyond mentioning the fact that the International Atomic Energy Agency has a working group which is currently preparing recommendations to this end, and it is the intention of the Geological Survey of Canada to encourage their implementation to the fullest extent possible in Canada. The Geological Survey already possesses some standardization and calibration facilities in Ottawa which are being used by both Canadian and United States companies, and we wish to expand this use. In brief, it is recommended that all gamma spectrometry measurements should be reported in terms of element abundance (% K, ppm eU, ppm eTh), and there is a proposal that all measurements of total radioactivity should be made in terms of a new unit of radioelement concentration, which is defined in terms of equivalent uranium.

Airborne methods enable the greatest area to be searched in the shortest time, and where surface access is difficult and the topography is relatively flat, airborne methods are a prime choice. Measurements of total radioactivity can serve a useful purpose by eliminating ground from further examination by more expensive gamma spectrometric methods. Alternatively, over small areas where uranium is known to be the only radioactive element concentrated in significant amounts, total count surveys may be all that is required. However, for the general case of uranium exploration, gamma-ray

spectrometry is the most effective tool. The following facts account for the importance of gamma-ray spectrometry in airborne work. Potassium, uranium and thorium occur together in most common rock types, their relative proportions varying only within quite narrow limits throughout a wide range of lithologies. Thus, in granite with a high potassium content, there is a relatively high uranium and thorium content. In the case of diabase where potassium content is low, then uranium and thorium are also proportionately low. The occurrence of uranium mineralization changes the proportionality and the ratio of uranium to potassium and uranium to thorium immediately becomes anomalous.

Mention has been made of factors which influence the measurement of radioactivity, such as source geometry. Source geometry clearly affects the absolute count rate but it does not affect relative count rates. This removes one very important variable, amount of interpretation. However, it cannot be stressed too strongly that satisfactory ratio measurements depend upon both a high count rate and a stable spectrometer. The key phrase to remember in planning an airborne survey is the need for high count rate per unit distance flown. This can be achieved with quite a small detector volume if the aircraft is flown low enough and slow enough. For the purpose of comparing different systems flown under different conditions, it is possible to compute a figure of merit which gives guidance in selecting the best of the available systems and operating parameters. This information has been published (Darnley, 1973).

The Geological Survey of Canada has established a computer drawn format for displaying airborne gamma-ray spectrometer profiles of which Figure 3.4 is an example. This is fully corrected data. Eight stacked profiles are shown, all relating to the same flight line and the successive sampling steps on each profile relate to a sampling length of approximately 500 feet. This particular sample of a flight line is six miles in length across the St. Andrews East Carbonatite, 35 miles west of Montreal. The lowest profile on the figure indicates integral (or total) radioactivity, and shows a prominent anomaly. Reference to the other profiles shows that it is entirely caused by an increase in thorium.

Figure 3.5 is an example of a flight line showing a total radioactivity anomaly of similar dimensions to that in Figure 3.4, in this case entirely caused by uranium. This particular example was taken across the South March uranium occurrence, 15 miles west of Ottawa. Figure 3.6 is a second flight line from the South March area, illustrating a total count anomaly which is solely due to potassium in an unusual unidentified crystalline rock.

Figures 3.4, 3.5 and 3.6 collectively illustrate the additional information that is provided by using gamma-ray spectrometry rather than total radioactivity alone. They also show how the ratio measurements respond to the changes in the individual element concentrations. Whereas the ratio measurements are superfluous in these instances, there are other situations where they are very advantageous. The following two examples are taken from areas which are particularly difficult from an exploration viewpoint.

Figure 3.7 is from a flight line across the Athabasca Sandstone and it can be seen that there is very little noteworthy information in the total count portion of the profile. Every point along this 150-mile line where the count rates decrease to zero is caused by the presence of lakes or swamps. In the case of the uranium profile the count rate sometimes shows a negative value in these situations because of counting statistics. Note that one spike at the west end of this profile which looks

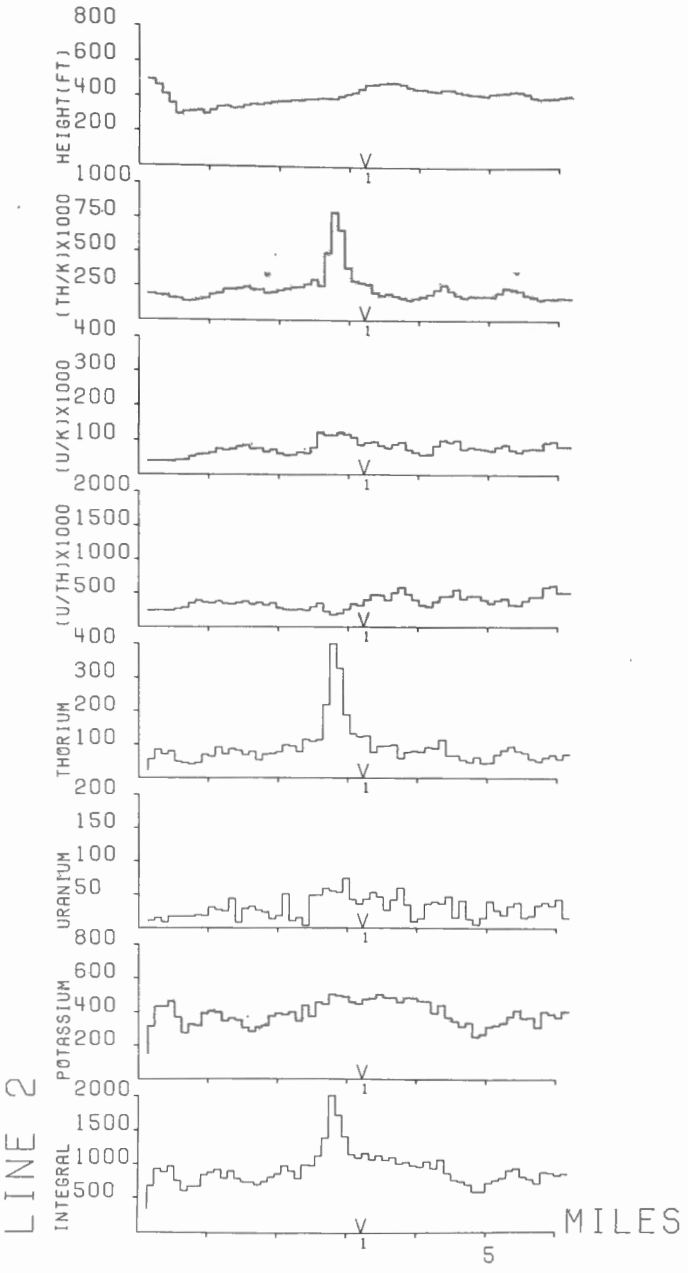

Figure 3.4. Flight line profile over St. Andrews East Carbonatite, Quebec.

as though it might be significant from a mineralization viewpoint is caused by potassium. The profile which contains most information in this area is the uranium to thorium ratio, and there are several anomalies which could be worth following up. It must be emphasized that these results were obtained with the Geological Survey's high sensitivity system, but even so it is working close to the limit of detection. Figure 3. 8 is the second example of an airborne profile over a difficult area of nearly uniform radioactivity, in this case, Prince Edward Island. Again the system is close to the limit of detection; there are two small anomalies which could be significant but only ground follow-up will tell. If these two turn out to be significant, then of course attention should be turned to some of the other features of this profile which appear to be very close to the noise level.

For rapid ground reconnaissance on foot, a scintillation counter which measures only the total gamma radiation has much to recommend it because it is light to carry and can be used whilst traversing. Maximum count rate combined with the least possible inconvenience

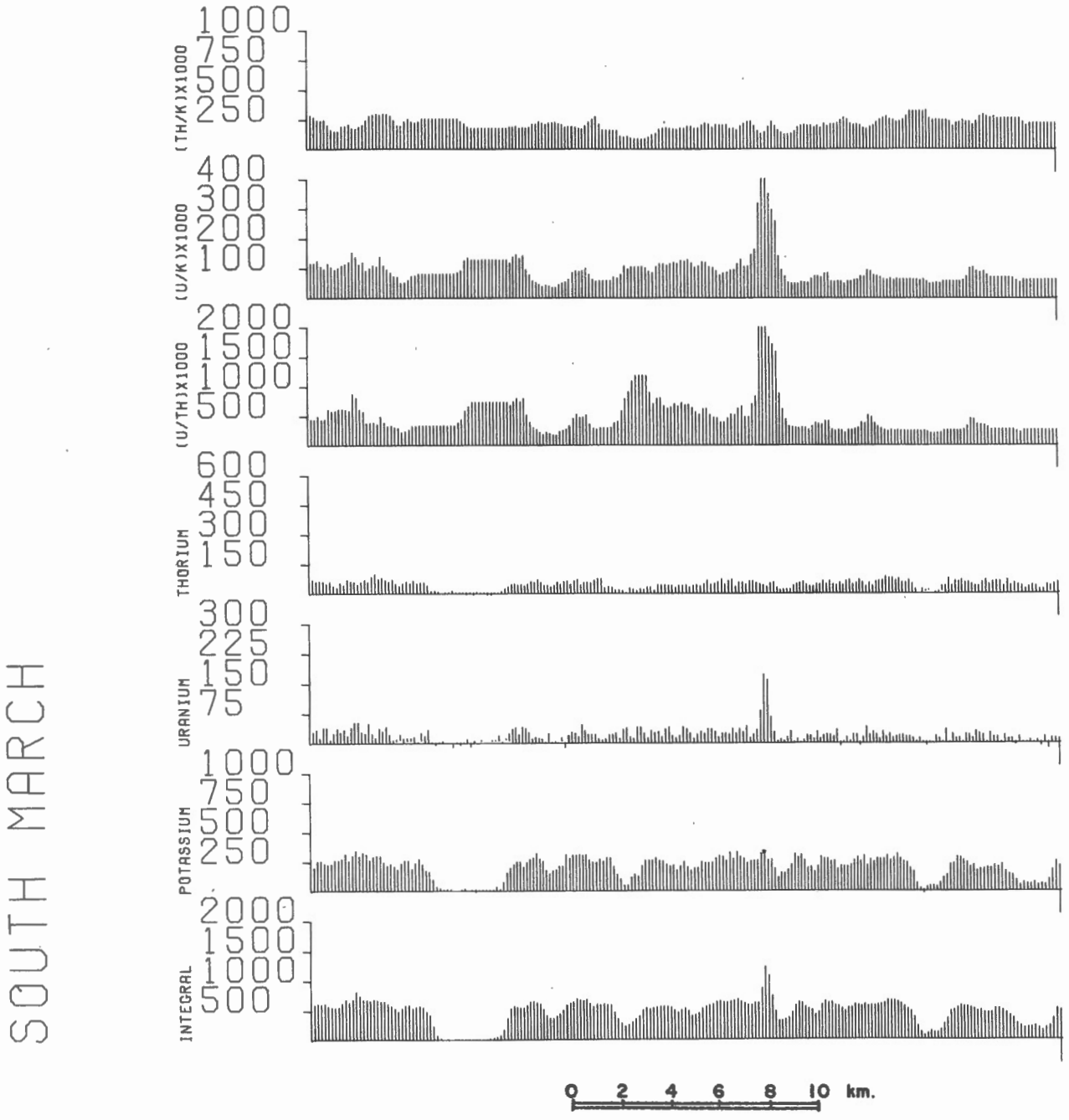

Figure 3. 5. Flight line profile over South March uranium occurrence Ottawa, Ontario.

is perhaps the main criteria for selecting this type of instrumentation. It must be sensitive, reliable and stable, but there must be a strong emphasis on convenience. This is necessary in order to encourage field personnel to carry an instrument and use it even when they are in a location where there is no expectation of finding uranium. The unexpected has a habit of happening from time to time. Geiger counters are not to be recommended for general field reconnaissance because of their lack of sensitivity.

In situations where airborne work has shown that there is a possibility of confusing thorium-rich and uranium-rich mineralization, it may be advantageous to commence a ground search using a portable field

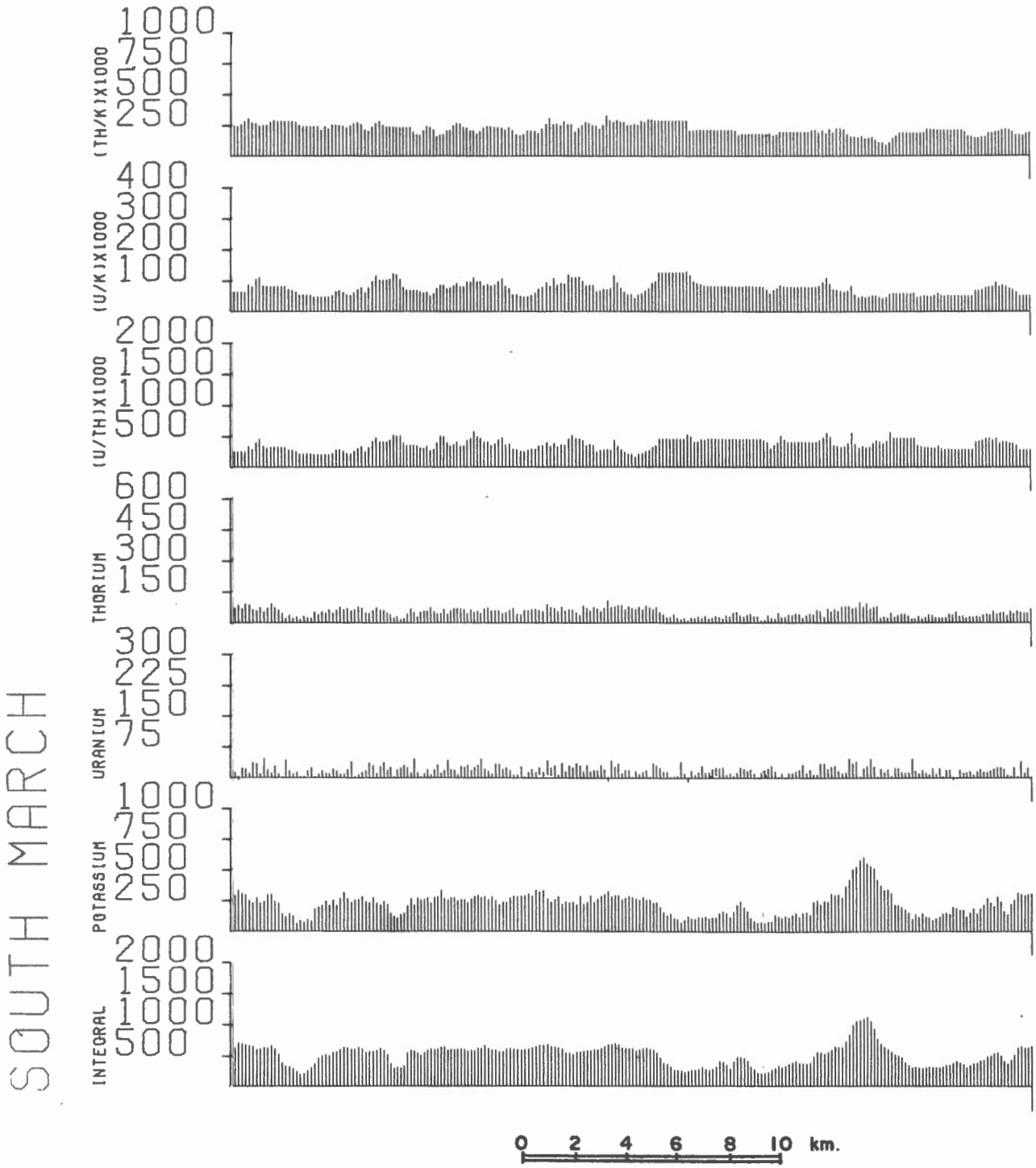

Figure 3. 6. Flight line profile over potassic rocks.

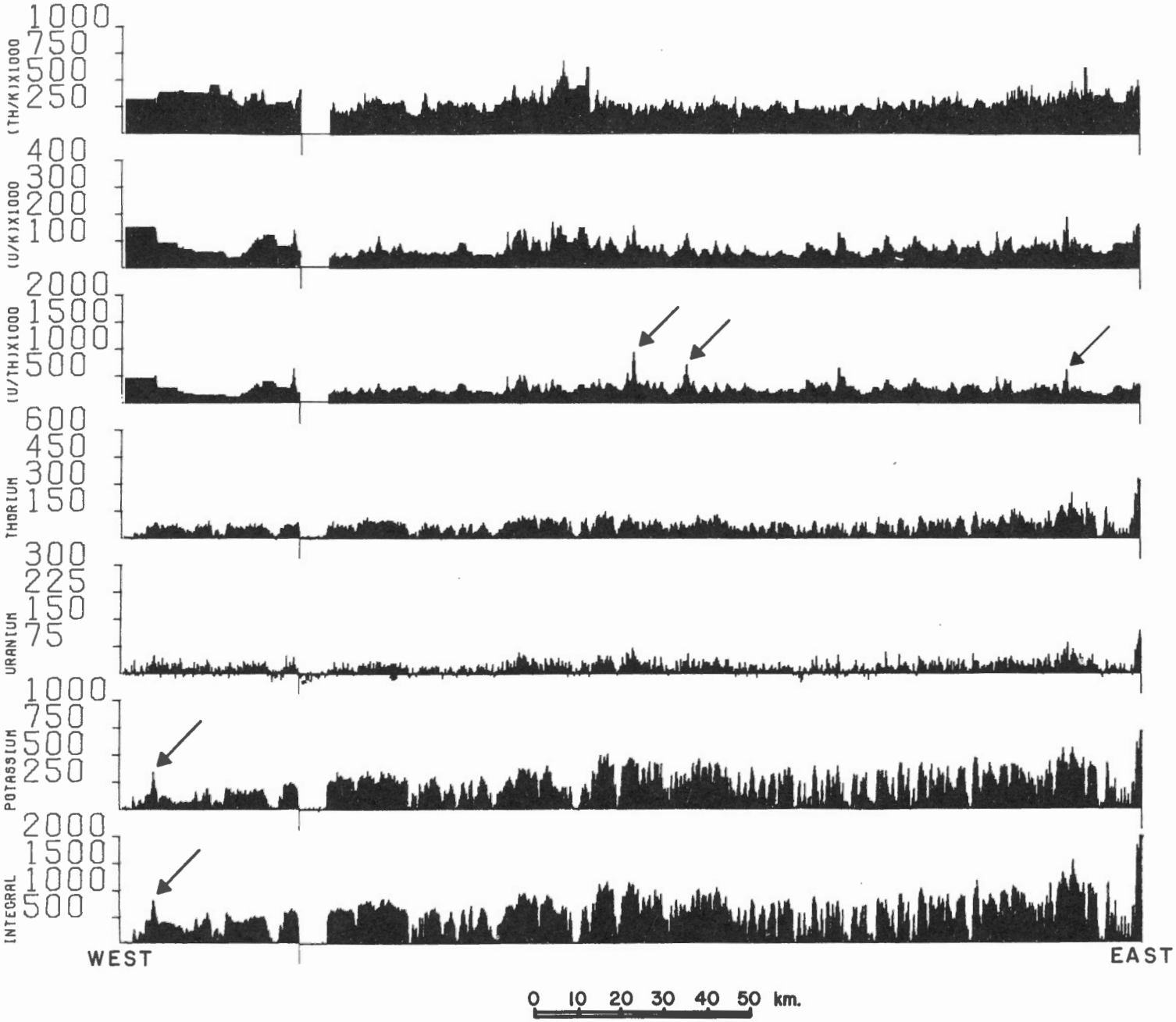

Figure 3.7. Flight line profile across part of Athabasca Sandstone.

PRINCE EDWARD ISLAND 1974

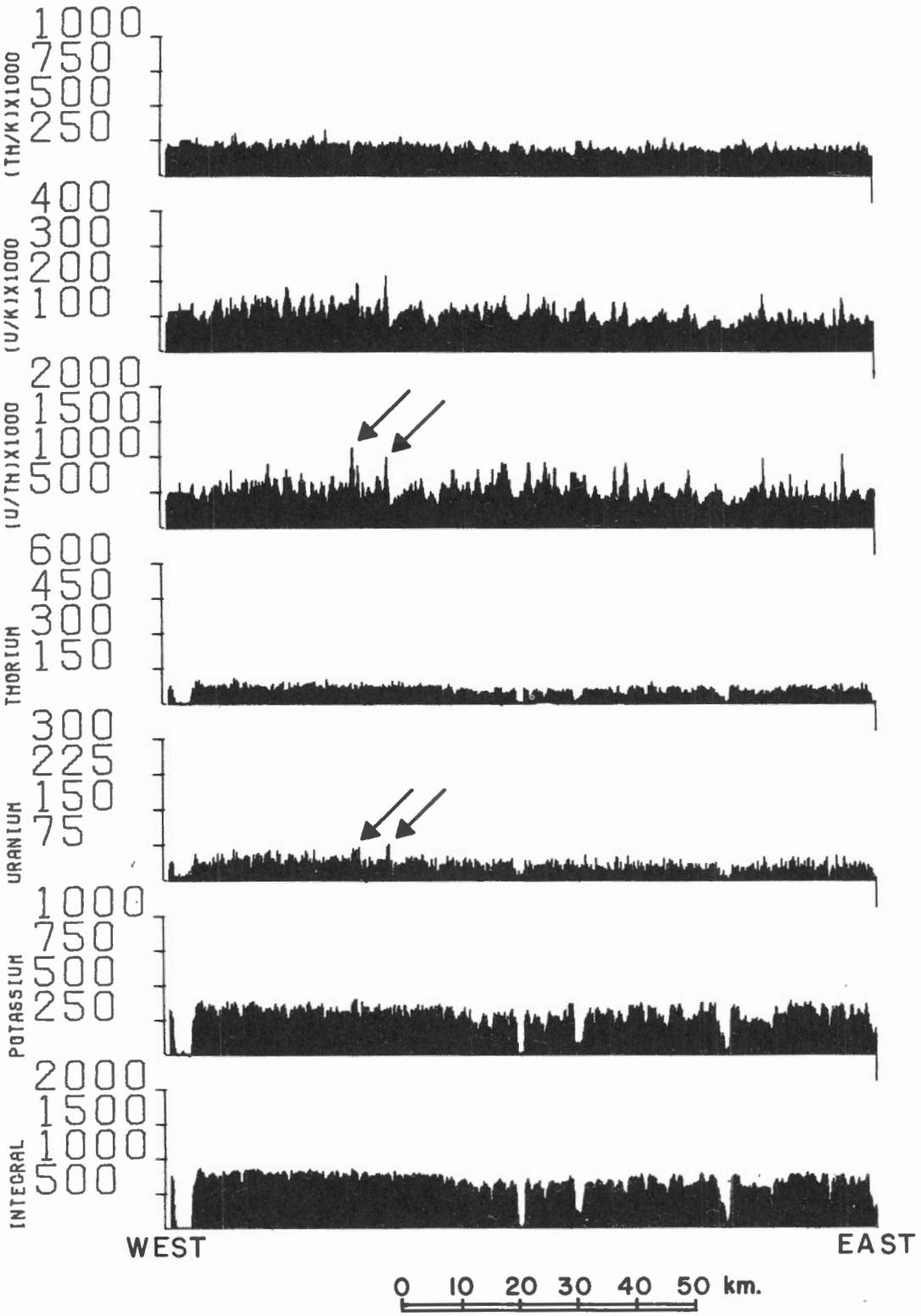

Figure 3. 8. Flight line profile across part of Prince Edward Island.

gamma spectrometer. Instruments now available are much lighter and more reliable than those which were available only a few years ago, although prices still remain high. Five or six scintillation counters can be bought for the price of one good spectrometer. Once the composition of an occurrence of radioactivity has been established, there is not usually any need to use a spectrometer for more detailed work unless it is a situation where thorium is present in appreciable quantities alongside uranium.

Relatively simple radioactivity meters, either Geiger counters or scintillation counters, may be of considerable use in monitoring grades of mineralization, both during assessment and in mining operations. Probes are often custom made according to the particular requirements of the operation. In this type of measuring situation, the question of radioactive equilibrium referred to earlier may be of critical importance in order to convert count rates to concentration of uranium. In situations where disequilibrium is a serious problem, as in many of the uranium deposits in Wyoming, a portable X-ray fluorescence analyzer provides a reliable alternative to the conventional Geiger or scintillation counter. Such an instrument, which employs a radioisotope source, is the same size as a field gamma spectrometer. Whichever type of instrumentation is being used as a direct measure of uranium content, suitable calibration procedures must be established. This entails preparing standard samples of material typical of the locality where the measurements are being made.

Borehole logging

Radiometric logging of boreholes is standard practice in the petroleum industry, primarily to obtain lithological correlations. Radioactive logging has been much less used in metalliferous exploration even in known uranium areas. A practical problem in the past has been the limited availability of small diameter probes to fit inside the narrow holes commonly used in hard-rock exploration. The desirability of using radiometric probes in connection with uranium exploration is obvious, especially in any situation where there is the possibility of incomplete core recovery. The U. S. Atomic Energy Commission in Grand Junction, Colorado, now part of ERDA, performed a commendable duty during the 1960's in establishing facilities and procedures for the standardization and calibration of radiometric borehole probes used by industry in all United States uranium mining areas. Their work in this direction should be studied by anyone who wishes to use radiometric logging on a systematic basis. The Geological Survey is seeking to arrange the construction of similar facilities in Canada, designed to match the requirements of the various types of mineralization found here.

Underwater measurements of radioactivity

The large number of lakes in Canada and the natural tendency for lakes to develop along fracture zones makes it possible that more vein type uranium mineralization is concealed under water than elsewhere. Where such geological situations are suspected, subaqueous measurements may be a desirable preliminary to wintertime drilling. Although gamma radiation is rapidly attenuated in water, a radiation detector which rests directly on the surface to be examined is shielded by the water above from any extraneous radiation. Therefore, although the signal is small, the signal-to-noise ratio is favourable. If only a small area is to be surveyed, then suitable waterproof detectors can be lowered to the bottom, but if a larger area is to be searched, a different approach must be adopted. Probes need to be mounted so that they are suitably protected to withstand dragging along the bottom and can ride over obstacles without becoming snagged. This entails the use of much heavier equipment and a larger and more powerful vessel with adequate deck space. Such preparations would only be warranted and practicable in large lakes such as Huron, Wollaston, Athabasca, Great Slave or Great Bear for example. A technique has been developed in the United Kingdom whereby a borehole probe is mounted inside an armoured hose and this assemblage has been towed for thousands of kilometres along the North Sea and the Irish Sea floors, primarily for mapping purposes (Miller, 1973).

Conclusion

Beyond the various techniques of exploration geophysics which have been touched upon in this review, there are other geophysical methods which some might regard as more academic and more indirect. These include greater attention to age determination studies of known mineralization, and the search for similar environments of similar age; also the study of the isotopic composition of common lead in rocks and minerals as an indicator of abnormally radiogenic environments.

It is certain that in order to satisfy the forecasted world uranium requirements, every possible method that holds any promise of success will have to be brought into play, the quality of application will have to be pushed to the limits; and if the maximum value is to be obtained from these expensive operations great care must be taken to ensure all data are properly integrated and assessed.

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4. GEOCHEMISTRY APPLIED TO URANIUM EXPLORATION

Willy Dyck

Abstract

The elements of the ^{238}U decay series of interest in geochemical exploration are uranium radium, radon, and helium. Each element has specific radiochemical and/or geochemical properties which make it a useful tracer for uranium ore deposits.

Uranium is easily oxidized to the hexavalent state in the presence of oxygen in natural waters. Its mobility in surface waters is enhanced by the complexing action of carbonates in neutral and basic waters, of sulphates in acid waters, and of silicates in neutral waters. Organic matter adsorbs uranium strongly and is responsible for decreasing migration of the UO_2^{2+} ion in natural waters. The effect of complexing and adsorption of uranium in natural environments explains some of the results of field surveys carried out by the Geological Survey of Canada in Bancroft, Ontario and Beaverlodge, Saskatchewan areas.

The hydrogeochemical techniques employing radium and/or radon are best suited to detailed or semidetailed investigations of radioactive occurrences. Their ease of detection and short range make them excellent tracers for pinpointing uranium occurrences or outlining radioactivity too weak for the gamma-ray spectrometer or the fluorimeter.

Helium and radon in well waters in the National Capital region correlate well with the geology. Radon highs correlate with the Precambrian igneous and metamorphic rocks and except for one instance also with the March member of the March-Oxford Formations of Lower Paleozoic age in which surface radioactivity near South March and Marchhurst has been found. Helium highs coincide with the outcropping sandstones of the Rockcliffe Formation.

Introduction

Uranium is once more the "in" metal and can be expected to remain "in" for longer than it has at any time in the past. The energy crisis will see to that, unless, of course, vast new oil pools are discovered quickly.

There is probably more written about uranium than any other element. No doubt its potential for war and peace is responsible for this concerted effort. As an energy source, independently of oil, it can maintain and even improve our standard of living in spite of the prophets of doom who see only the dark side in man's efforts to use the earth. Although nuclear and thermal pollution are problems – they are soluble.

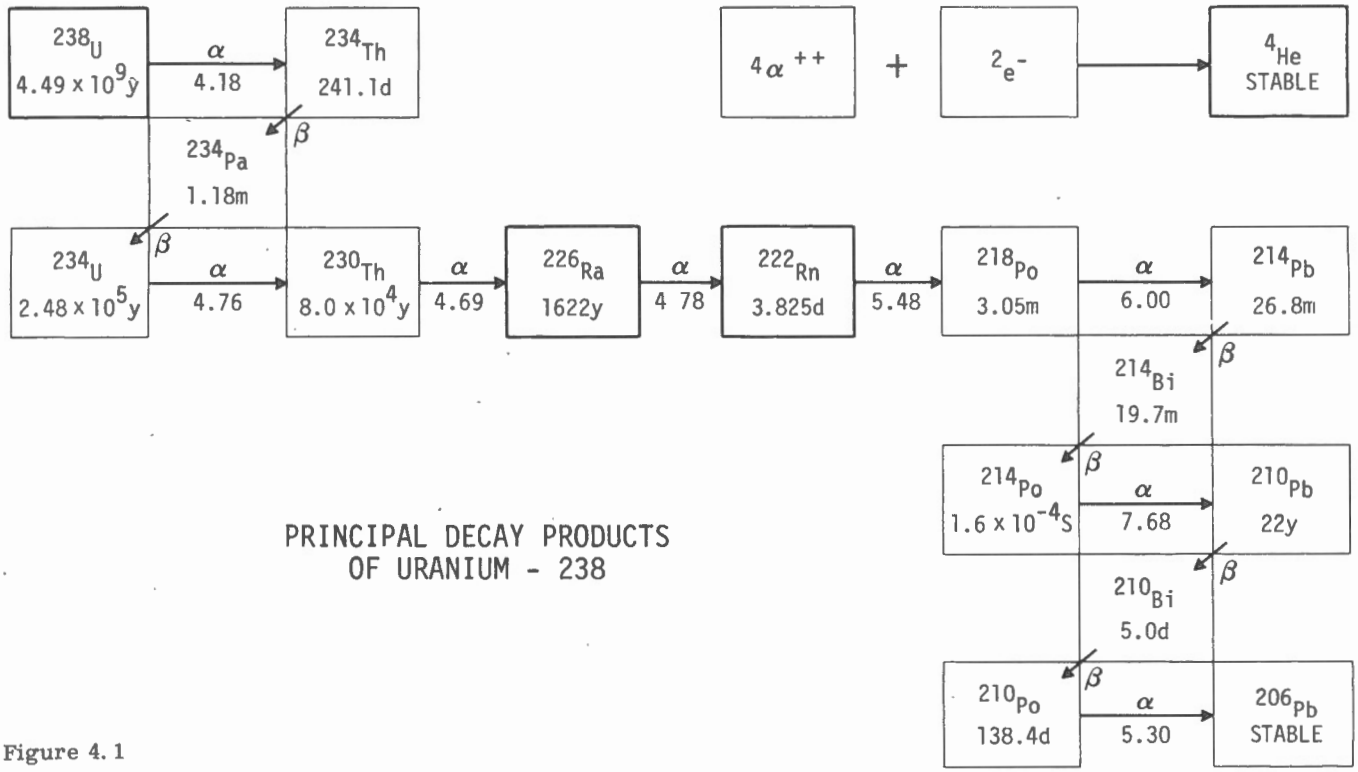
It is the business of the prospector to find this precious metal – uranium. Geochemistry is one way. This paper reviews the main radiochemical and geochemical principles which make possible the detection of uranium in the natural environment and illustrates with field tests where possible.

Radiochemical and Geochemical Principles of Uranium and its Decay Products

Pure uranium consists of two isotopes; ^{238}U (99.3 per cent) and ^{235}U (0.7 per cent). It is actually that little bit of ^{235}U that turns our Canadian heavy water nuclear reactors on. Both uranium isotopes have nearly identical physico-chemical properties and hence are never found separate in the natural state. Furthermore, their per cent abundance is quite constant. Recently, however, for the first time an ore deposit in Africa reportedly has only 0.4 per cent ^{235}U and there is evidence that this orebody was a natural reactor at one time. Each isotope decays to lead through a number of discrete transformations and characteristic half-lives by the emission of several radioactive alpha and beta particles and gamma rays. For the exploration geochemist ^{235}U is of no importance. Unless specifically mentioned the subsequent discussion will refer to ^{238}U only.

The principal decay products of ^{238}U are shown in Figure 4.1. The elements of interest to the exploration geochemist are accentuated by heavier boxes. The Ra-Rn couple is easily detected and quite specific for uranium. The third naturally occurring radioactive series, ^{232}Th, also is of interest. The other elements in the series are difficult to detect, have too short a half-life, or are not specific for uranium to be of use in geochemical exploration. The various characteristic gamma rays emitted by the various decay products and the branching decay modes of several of the products are not shown in Figure 4.1. These characteristic radiochemical properties of the decay products of ^{238}U make it relatively easy to detect the element with high precision at low concentrations provided the whole chain remains intact. Thus, the principal gamma ray of 1.76 Mev emitted by ^{214}Bi is used in gamma-ray spectrometry to identify uranium.

Weathering usually causes some disproportionation particularly in the surface environment. The main reactions of ^{238}U and ^{226}Ra in the surficial environment are listed in Figure 4.2. The first reaction occurs everywhere in the solid phase and is partly responsible for the occurrence of pitchblende, the mineral with a varying composition of UO_2 and UO_3 depending on the age and preservation of the mineral. In addition to making it easy to detect uranium the radioactivity also disrupts the crystal structure in which the uranium is bound and hence permits water and oxygen to enter and oxidize UO_2 to UO_2^{2+}. This species, in neutral or basic waters, complexes easily with carbonate ions and forms soluble silicates, and in acid media, complexes with sulphate ions. In areas of intensive vegetation, humic acids either in solution or in the sediments of lakes and streams strongly complex with uranium. Most of the uranium is found in the sediments because



PRINCIPAL DECAY PRODUCTS
OF URANIUM - 238

Figure 4. 1

of the larger amounts of organic matter in the sediments relative to that dissolved in water. As a result of the ease of oxidation and complexing of uranium its mobility or range in the surficial environment is relatively large compared to almost any other trace element. Radium, on the other hand, forms insoluble compounds with the ever present carbonates and sulphates and it is only in the presence of chlorides that it becomes more mobile. Radium, however, will move long distances by successive adsorption and desorption on the walls of water channels even at very low concentrations and with time an appreciable radium concentration will build up. This build-up becomes particularly noticeable at the mouth of springs where iron and manganese precipitate upon oxidation coprecipitating radium.

Radium and helium are chemically inert. They belong to the noble gas family. Radon because of its relatively short half-life of 3. 8 days is closely tied to radium, its immediate parent. Its range, as a rule, is not much greater than that of radium. Tests indicate that radon can move up to 6 m in soils and less than that in still waters, but in moving waters, such as streams or lake surfaces, its range can be 100 to 200 m beyond that of radium. Helium is very light and therefore diffuses rapidly, and, as a result, near surface soil gases have atmospheric helium concentrations even over weakly radioactive zones which are easily picked up by the radon method.

Idealized profiles of these four elements of the uranium series over a deposit are shown in Figure 4. 3. The relative intensity scale is rather subjective and may apply only under certain conditions. The offset from the vertical is meant to illustrate the downslope movement of soil and water over the deposit. One can present a number of arguments for deviations from this norm. Thick overburden, particularly clays, can effectively seal off the deposit and leave no surface expression over the deposit. In such instances drilling to bedrock is necessary. But even minute movement of groundwater between overburden and bedrock can result in an anomaly some distance downslope if the water comes to the surface or enters wells. As indicated in Figure 4. 2, uranium is quite mobile in an oxidizing environment and hence will produce extensive weak haloes when the water regime is active. Radium being much less mobile will focus sharply and more intensely over the deposit. Radon will extend the radium range but seldom by more than 100 m. Radon is rather closely tied to radium because of its short half-life. The relative sharpness of the anomaly for radium and radon is due to the low mobility of radium and the high sensitivity of the method of detection, namely individual alpha particle counting. Ideally, helium should have the largest range but because of its great mobility it dilutes rather quickly near the surface to a concentration level which is indistinguishable from atmospheric air. In groundwater systems sealed from the atmosphere, however, a rather long path for helium could be expected. The fact that considerable quantities of helium are found in natural gas pockets confirms this postulate.

THE GEOCHEMISTRY OF URANIUM AND RADIUM

1. Self oxidation of uraninite

$$2\ UO_2 \rightarrow PbO + UO_3 + 8\ He$$

2. Oxidation and complexing of U in water

$$UO_2 + H_2O + O \rightleftharpoons UO_2^{2+} + 2\ (OH)^-$$

$$UO_2^{2+} + H_2O \rightleftharpoons UO_2OH^+ + H^+$$

$$UO_2^{2+} + HA \rightleftharpoons UO_2A + 2H^+$$

$$UO_2^{2+} + 2CO_3^{2-} \rightleftharpoons UO_2(CO_3)_2^{2-}$$

$$UO_2^{2+} + 2SO_4^{2-} \rightleftharpoons UO_2(SO_4)_2^{2-}$$

$$UO_2^{2+} + SiO_3 \overset{H_2O}{\rightleftharpoons} UO_2(OH)HSiO_3$$

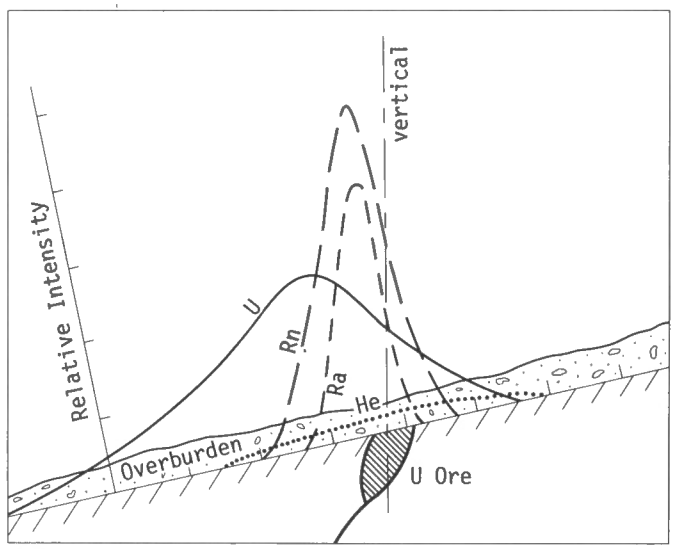
3. Precipitation of Ra from solution

$$Ra^{2+} + CO_3^{2-} \rightarrow RaCO_3 \downarrow$$

$$Ra^{2+} + SO_4^{2-} \rightarrow RaSO_4 \downarrow$$

4. Rn and He are innert chemically

Figure 4. 2.



Idealized profiles over a uranium deposit

Figure 4. 3

Hydrogeochemical Methods of Prospecting for Uranium

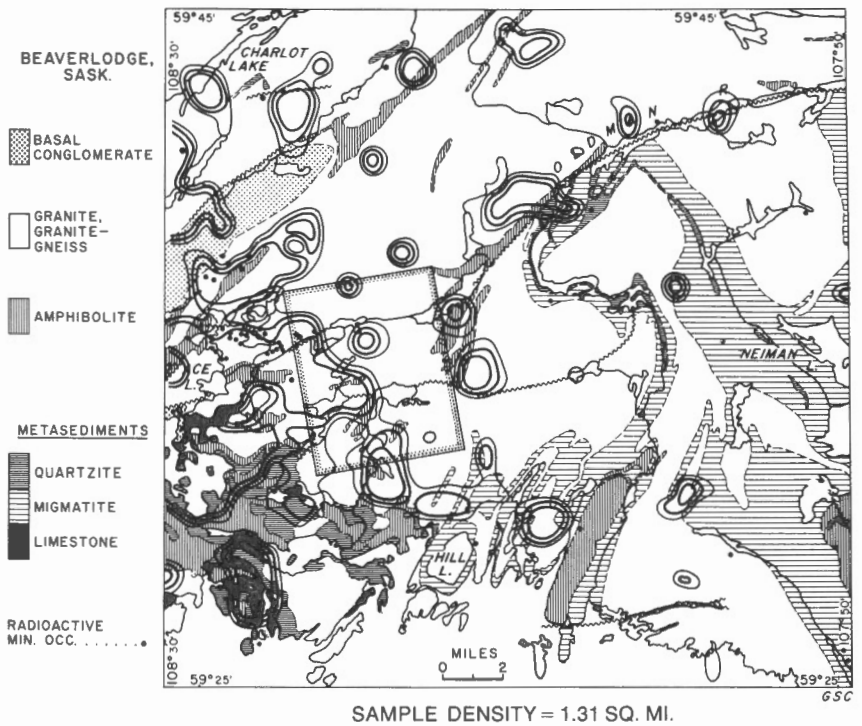
Regional and semidetailed surveys

To illustrate the geochemical principles summarized in the previous section, the results of a number of field tests carried out by scientists of the Geological Survey of Canada are presented below. Most of the work is published hence only brief reference to the highlights will be made here. Hydrological techniques, particularly those employing surface lake and stream waters, are well suited to large parts of the Canadian Shield; this becomes evident at once by glancing at the map. The distribution and range of uranium and radon in surface lake waters in the Beaverlodge area are shown in Figures 4. 4 and 4. 5, respectively (Dyck *et al.*, 1970). The uranium still zeros in on the Beaverlodge Camp even at the low sample density of 1 sample per 12 square miles, whereas radon already loses coherency at a sample density of between 1 sample per square mile and 1 sample per 5 square miles. The effect of organic matter and limestone on the uranium content in stream sediments and waters is shown in Figure 4. 6. While the anomaly pattern is affected little by applying a correction to the uranium content depending on the amount of organic matter present in the sample, the size of the anomalies are reduced. Humic acids in organic matter strongly complex uranium and when these sink to the bottom they carry with them the uranium which would otherwise be in solution. In areas of intense vegetation the range of uranium in the surface water systems is reduced noticeably. Sampling densities, therefore, have to be adjusted to allow for this factor. A good example of the effect of carbonate ions complexing uranium is evident in the southwest corner of the map-area shown in Figure 4. 6. This is the only area containing carbonate rocks with the result of a much enhanced uranium content in the stream waters and a correspondingly suppressed uranium content in the sediments.

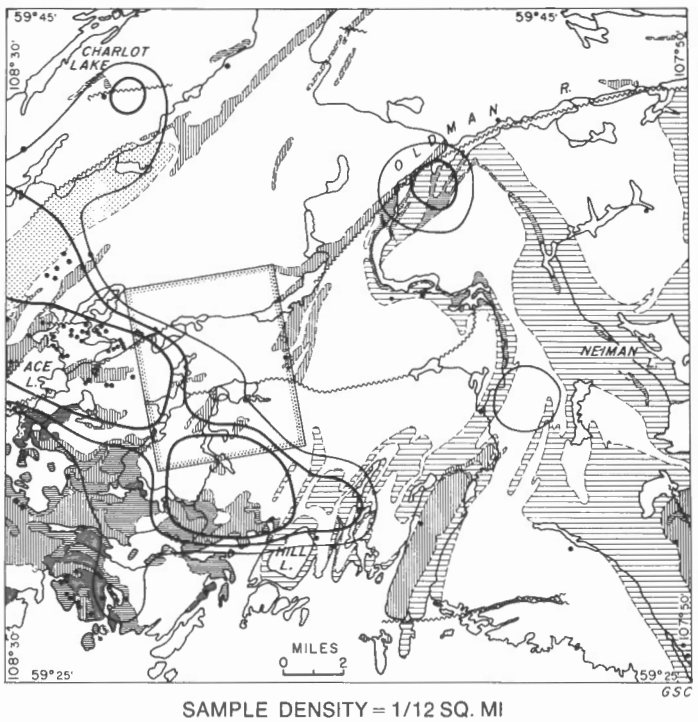
The uranium and radon maps of stream waters of the Bancroft area produced by A. Y. Smith in 1968 (Boyle *et al.*, 1971) show the relative ranges of the two elements fairly well. A large uranium anomaly downstream from the actual occurrences indicates its greater mobility in water. No doubt the carbonates in the area enhance this mobility. Radon on the other hand is confined to the radioactive zones, and hence points out its potential for more detailed work. Since radon is so closely linked to radium it is not suprising that Morse (1969) got equally good results by analyzing stream sediments for radium.

During the summer of 1974, Dyck and Cameron (1975) carried out a semidetailed radon-uranium survey of the uranium anomaly mapped out by Allan and Cameron (1973) during the geochemical reconnaissance of parts of the Bear-Slave province. This anomaly had shown up clearly at a lake sediment sampling density of 1 sample per 10 square miles. The lake water uranium and radon survey was carried out at a density of 1 sample per square mile. The results are shown in Figure 4. 7. Both elements outline new highs within the original anomaly. No mineralization was discovered in a one day ground follow-up in this area but the results illustrate the usefulness of the hydrogeochemical technique in reducing areas of search in successive steps involving smaller areas with increased sampling densities.

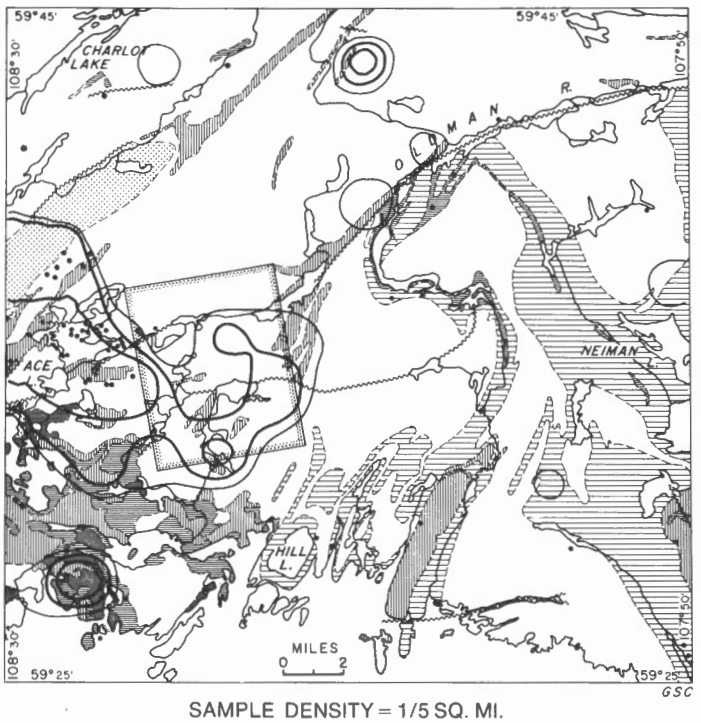
Figure 4. 4. Uranium in surface lake waters, Beaverlodge, Saskatchewan, 1969.



SAMPLE DENSITY = 1.31 SQ. MI.

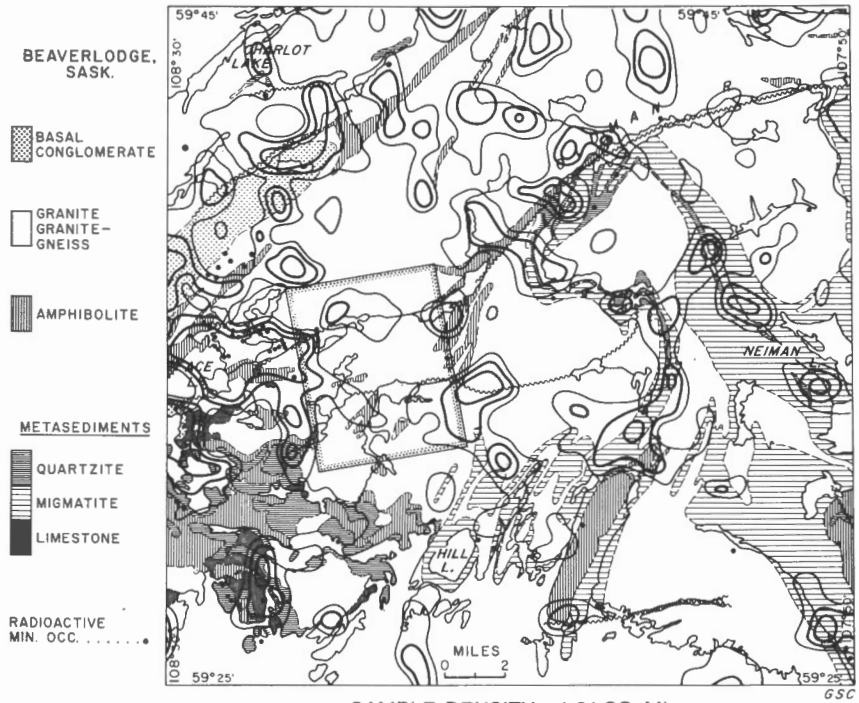


SAMPLE DENSITY = 1/12 SQ. MI

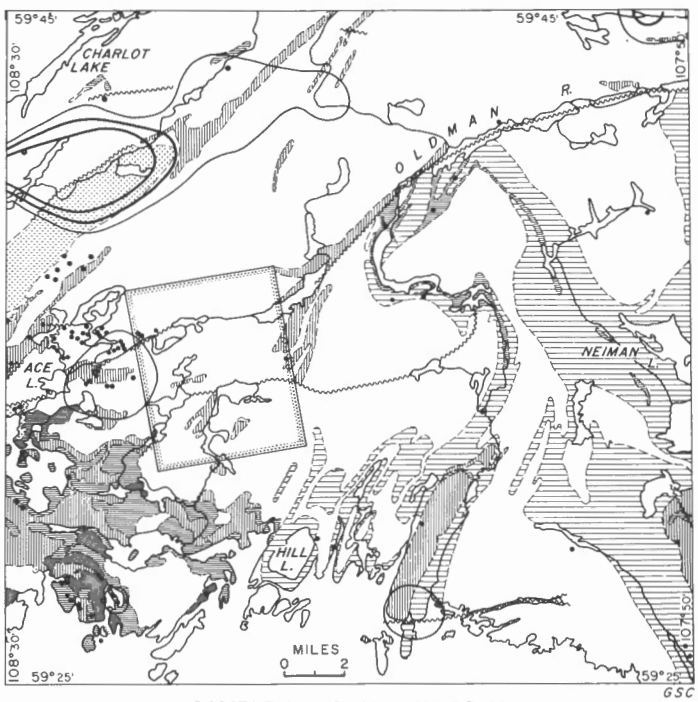


SAMPLE DENSITY = 1/5 SQ. MI.

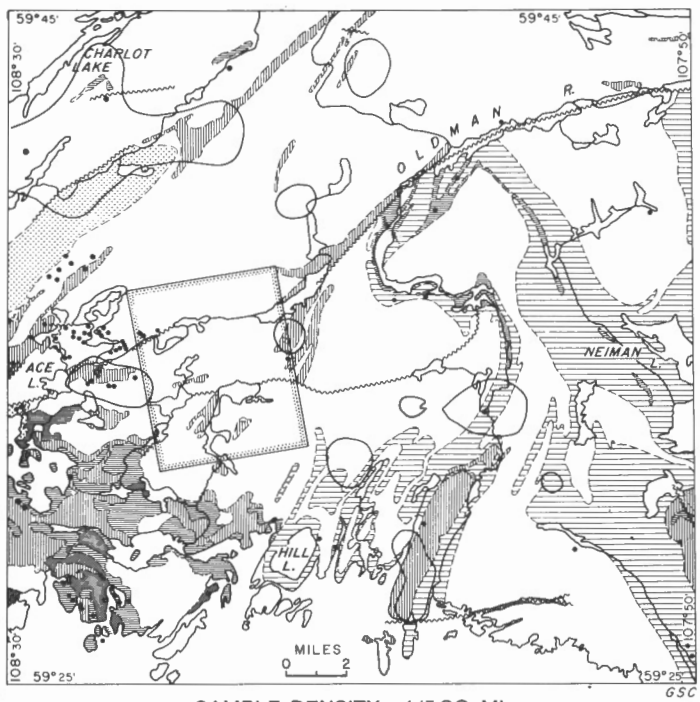
Figure 4.5. Radon in surface lake waters, Beaverlodge, Saskatchewan, 1969.



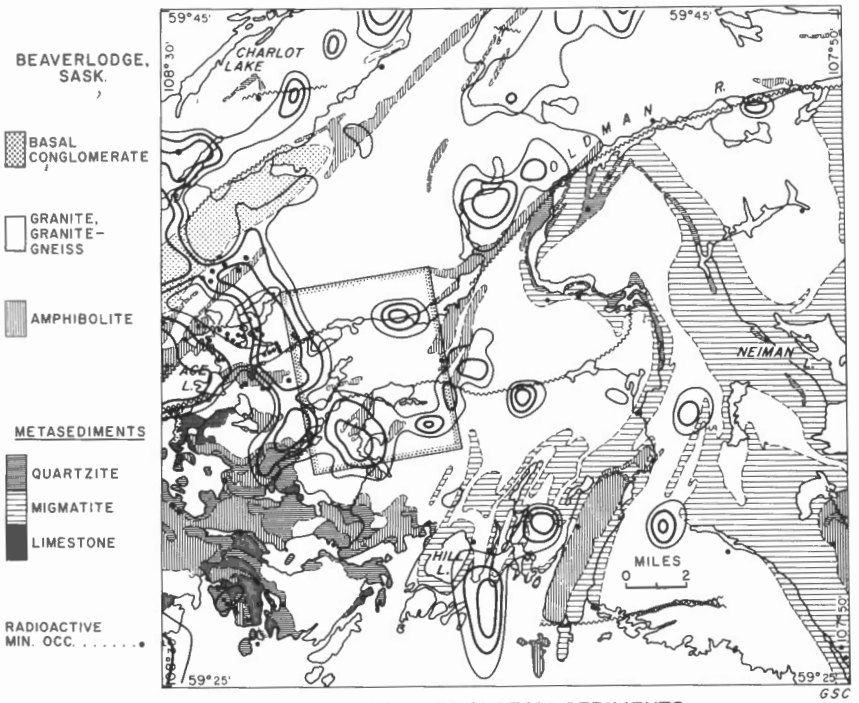
SAMPLE DENSITY = 1.31 SQ. MI.



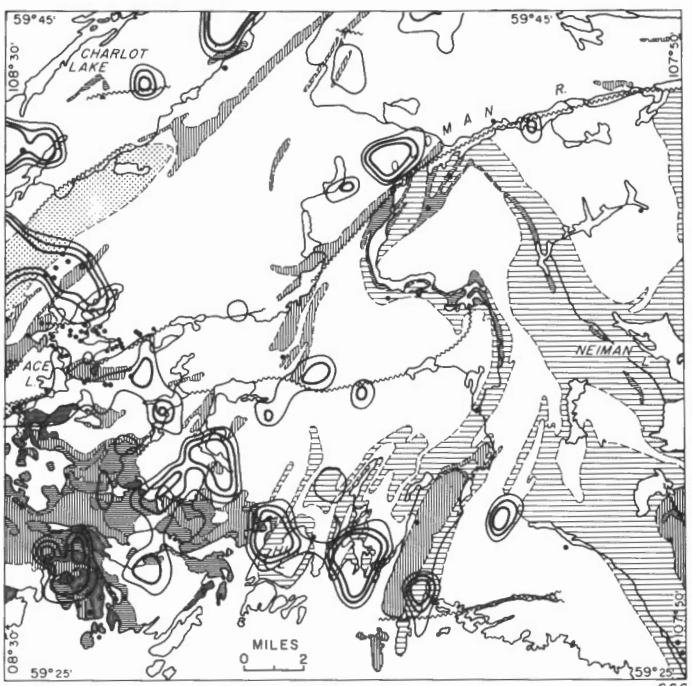
SAMPLE DENSITY = 1/12 SQ. MI.



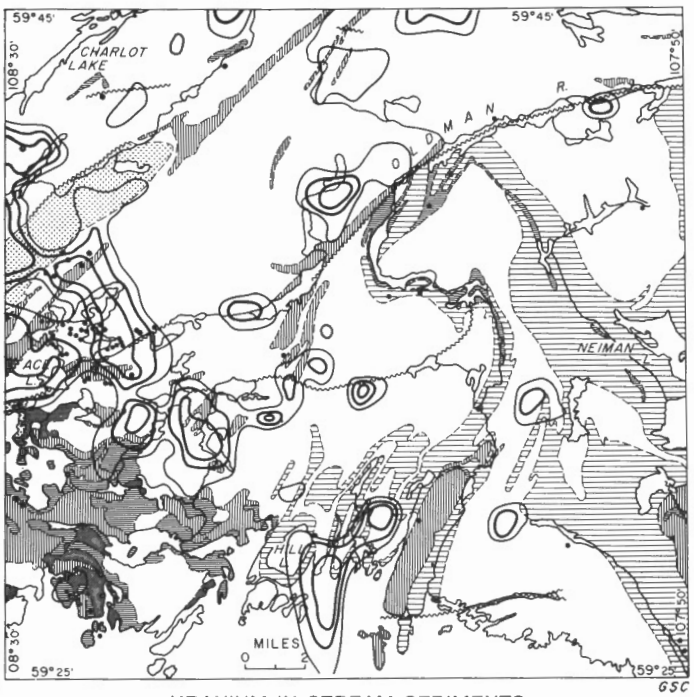
SAMPLE DENSITY = 1/5 SQ. MI.



URANIUM IN STREAM SEDIMENTS



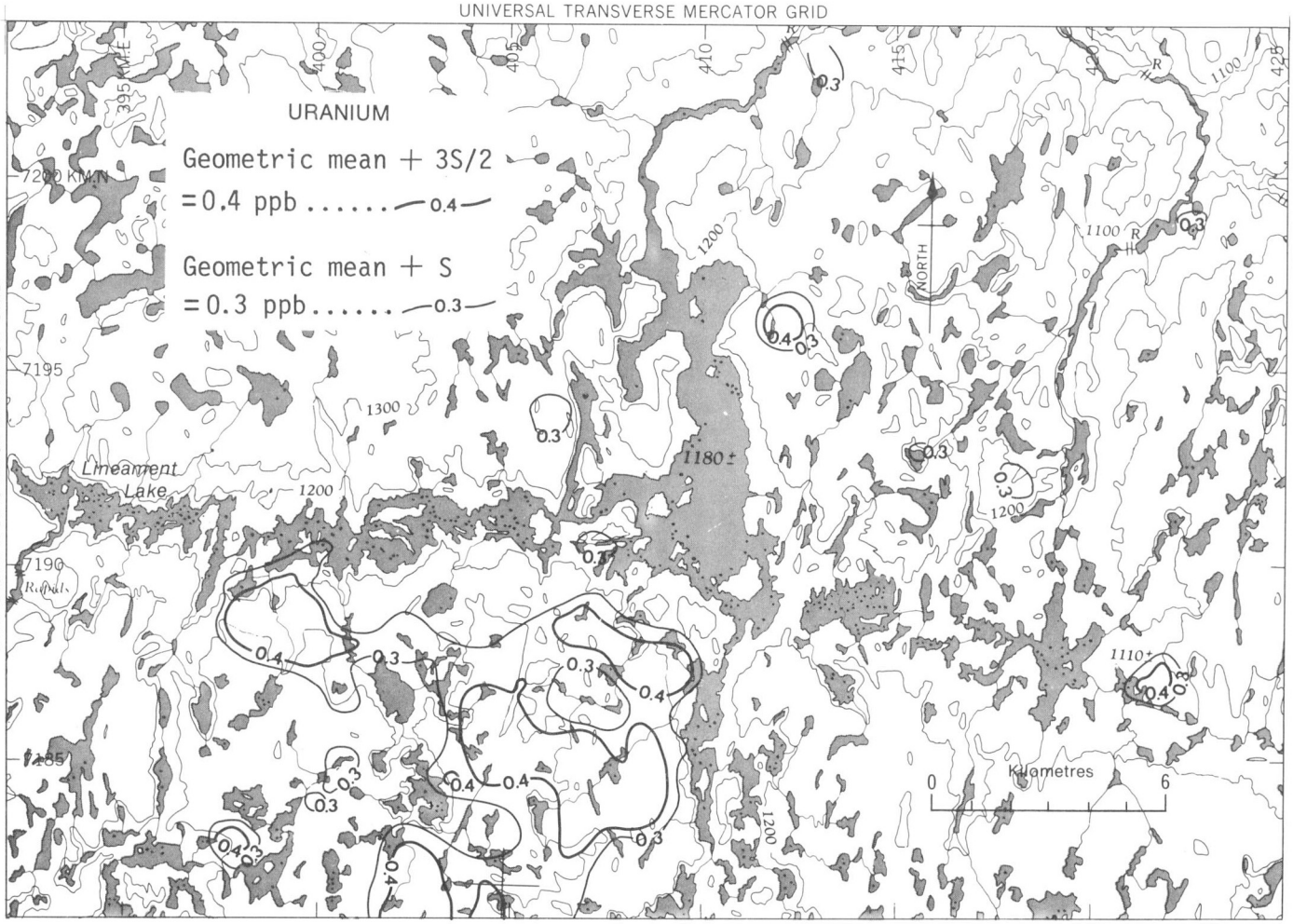
URANIUM IN STREAM WATERS



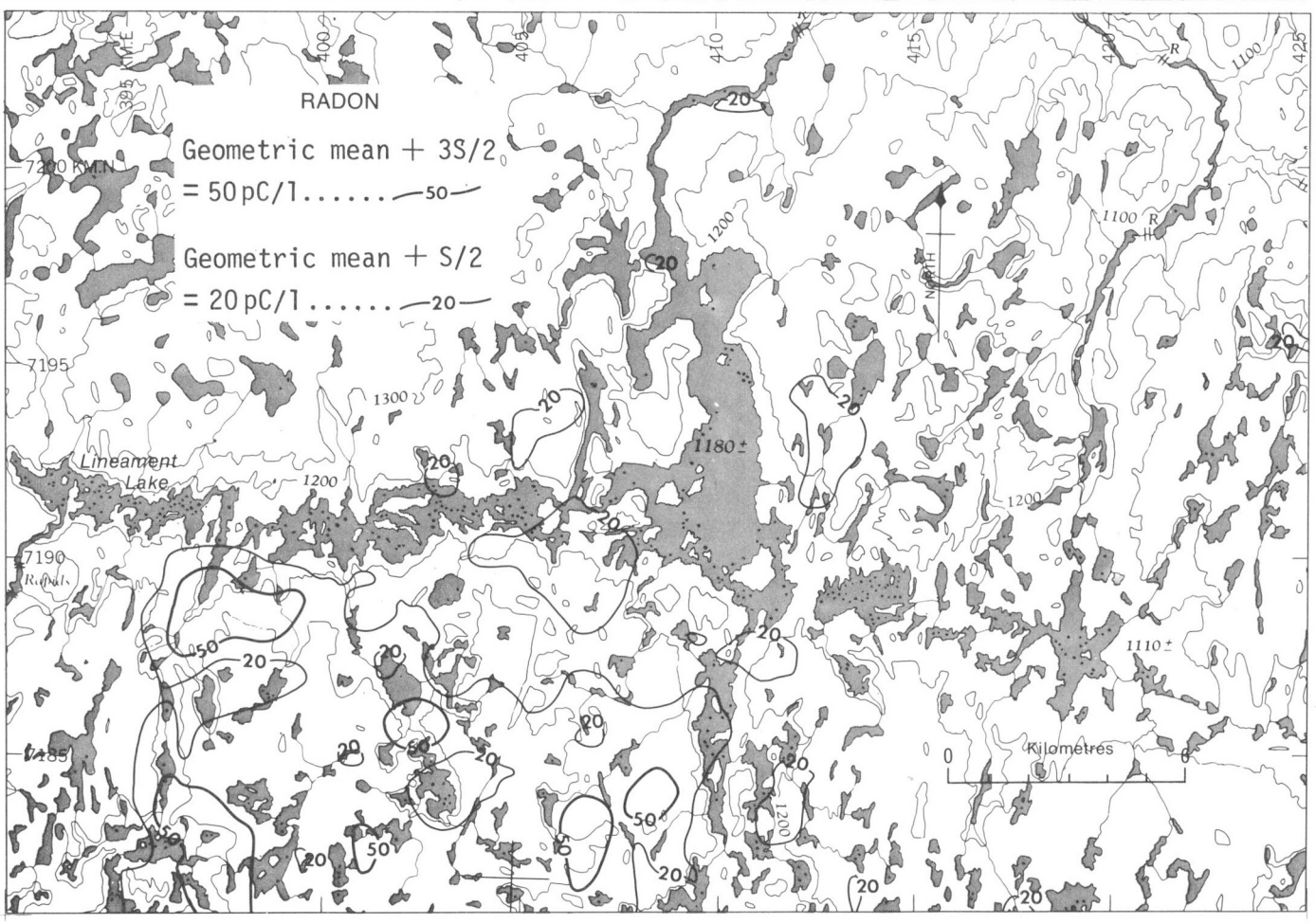
URANIUM IN STREAM SEDIMENTS
(ORGANIC CORRELATION REMOVED)

Figure 4.6. Effect of organic matter and limestone on the uranium content of streams in the Beaverlodge area, Saskatchewan, 1969.

Figure 4.7. (opposite) Radon and uranium in surface lake waters, Lineament Lake geochemical survey, 1974.



UNIVERSAL TRANSVERSE MERCATOR GRID



It should be pointed out that while radon and uranium in water surveys are perfectly adequate for outlining uraniferous areas and pinpointing mineralized zones they have a drawback relative to sediments; namely, radon decays and uranium may disappear into the wall of bottles upon long storage. A sediment, on the other hand, can be analyzed for a number of elements besides uranium at some future date. Since sample collection is a major part of the total cost of a geochemical survey it makes good sense to collect sediments. Collecting water samples, however, is a great deal faster than collecting sediment samples; a good crew can take 25 to 30 water samples per hour compared with 12 to 15 sediment samples per hour using a turbine helicopter.

The method of using radon and helium concentrations in well water surveys is still in the experimental stage. Figure 4. 8 shows the results of a survey in the National Capital region, with samples collected as recently as January 1975. No attempt has been made to correct for variations in well depth or type of pumping system. A clue as to the effect these variables

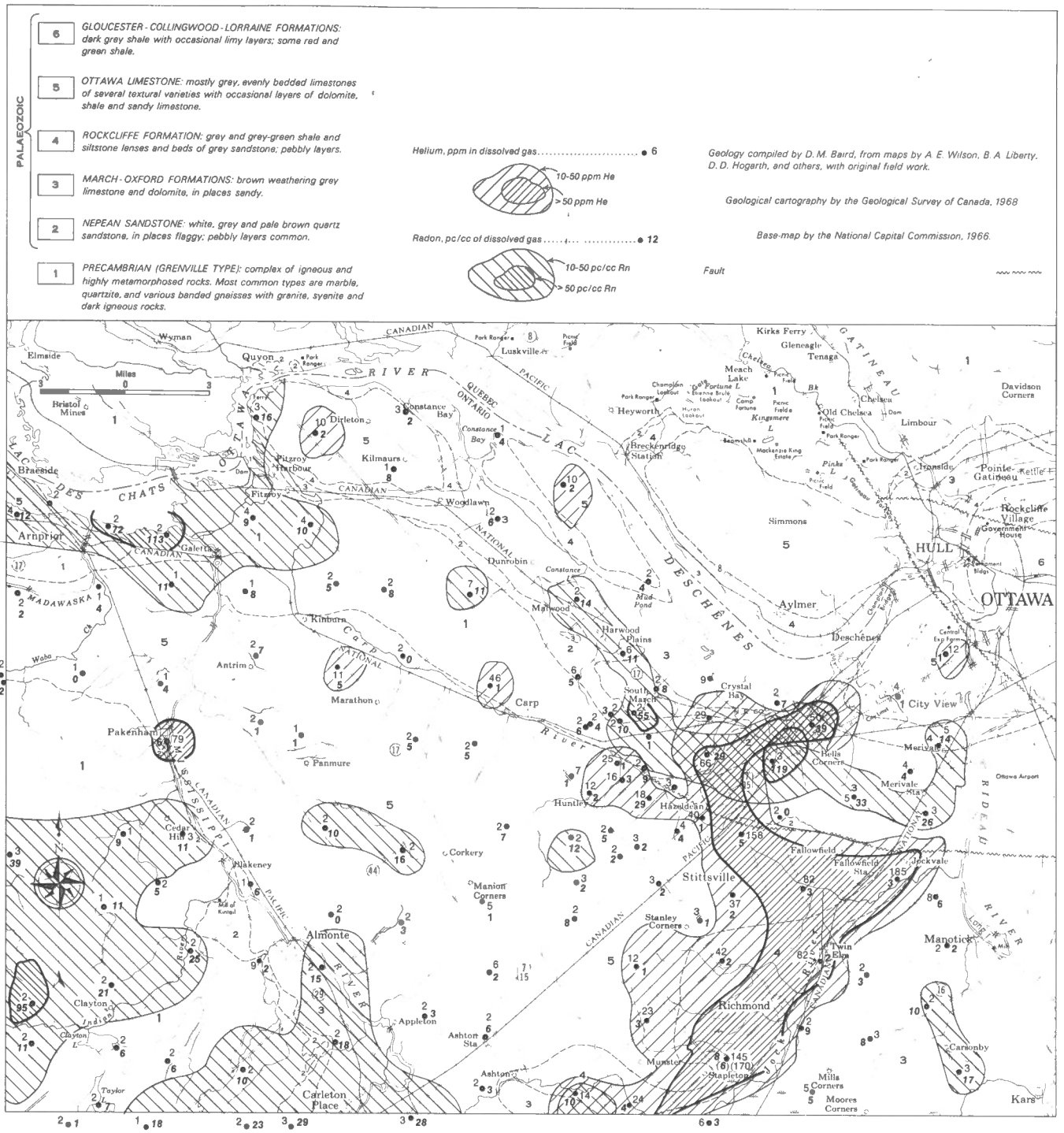


Figure 4. 8. Helium and radon in wells of the National Capital region.

have on the concentration of helium and radon is found in the oxygen content of the water. It is a measure of the combined effects of automatic volume control which bleeds atmospheric air into the pressure systems, nearness to surface waters, and intensity of oxygen consumption in the groundwater. All that can be said at this point is that of the 130 samples tested so far none with a high oxygen content have had above background helium levels. Samples with no oxygen or low oxygen contained background or anomalous helium levels. Broadly speaking the radon highs coincide with the igneous rocks and/or the limestones of the March Formation clustering around the southeasterly-trending tongue of Ottawa limestone. An unmistakable helium high appears roughly coincident with the grey-green shales and sandstones of the Rockcliffe Formation and tapers out in the limestones and dolomites of the March-Oxford Formations. The northerly trending helium anomaly suggests an aquifer which drains into the Ottawa River at Graham Bay. The author does not wish to imply that these helium values are indicative of uranium ore but believes that roll-type uranium ore deposits, for example, should produce helium haloes which could move considerable distances in groundwater channels under the right conditions and hence be detectable by sampling well waters on a regional scale. There are several weakly radioactive surface showings at the contact of the March and Nepean Formations in the South March area which have been described in several reports: Grasty *et al.*, 1973, Steacy *et al.*, 1973, and Jonasson and Dyck, 1974. Both radon and helium in the wells increase in content between Bells Corners and South March. At this time one can only postulate mechanisms for the increased helium content. It is known that anomalous radon is closely related to uranium mineralization but the source of helium is not so easily established. It can and does move large distances through porous formations and can come from great depths along fractures. Natural gas and oil pools attest to this. While atmospheric air contains 5 ppm and gases in surface waters in equilibrium with air 2 ppm, some natural gas wells contain as much as 8 per cent helium (Lipper and Wilcox, 1960). Gases in spring waters from the Canadian Rockies contain 1.4 per cent helium and in Tanzania a spring gas contained as much as 17.9 per cent helium (James, 1967). By comparison the helium content of gases from waters in or near uranium deposits in Elliot Lake can reach 5.7 per cent (Dyck, unpublished). Russian scientists report up to 2.7 per cent helium in such gases (Shukolyukov and Tolstikhin, 1965).

Detailed investigations

The hydrogeochemical method of prospecting for uranium deposits mainly employs the elements uranium, radium, and radon in natural waters and is well suited for detailed investigations. Helium, because it is expensive, too difficult to measure, and even more difficult to interpret, has not been used often in uranium exploration. In Canada, surface waters have been used almost exclusively, but in Russia groundwater have been used quite extensively and profitably. Under favourable conditions this method can detect uranium deposits at considerable depth. In mountainous terrain this method can detect deposits buried 300 to 400 m and in foothill regions 50 to 70 m (Novikov and Kapkov, 1965). The interpretation of results of hydrogeochemistry are rather difficult because the results depend on so many environmental factors including climate, chemistry of the elements, geology, mineralogy, hydrodynamics, etc. of the region. Of utmost importance is the background concentration of the elements in an area. In northern climates and mountainous regions a uranium concentration of 10^{-6} g per litre may be anomalous, whereas in arid regions evaporation of water will give backgrounds of the order of 10^{-4} g per litre. In zones of intensive oxidation (high eH) uranium is leached from rocks; in zones of reduction (low eH) uranium is precipitated from solution. Waters from acidic rocks enriched in uranium are more radioactive than waters circulating in rocks of basic composition. Waters with intensive circulation and intensive outflow are weakly radioactive. Flow waters with a limited circulation tend to become mineralized and may become strongly radioactive. In mountainous areas with rugged relief, waters near the peaks are weakly radioactive but at the foot of mountains one can encounter highly radioactive springs even in the absence of uranium deposits. Hotsprings may be particularly misleading. Coming from a deep and reducing environment where uranium is immobile and radium mobile, the waters become loaded with radon from the radium which has deposited on the water channel walls and mouths of the springs at or near the surface. It is conceivable that the source of this radium may be ordinary rock situated miles from the hotspring

The uranium content in water is also influenced by the total solids content or the main ion content of water such as HCO_3^- and SO_4^{--}. Carbonated waters will be enriched in uranium, especially in rocks with disseminated uranium. Sulphate ions will carry uranium in solution only in acidic waters. Evaporation in arid regions will lead to the concentration of salts and hence uranium and radium in water. Therefore a rise in the uranium content is of greater interest if it is based on total solids in water. A quick and useful approximation of total solids can be obtained by measuring the specific conductance of the water.

The extent of radioactive equilibrium between the three main elements of interest in uranium exploration is a useful guide in recognizing ore potential. In general the radon/radium ratio in waters is either one or greater than one. Because radon is a gas it is more mobile than radium. Radon, therefore, will enter the water phase while its parent remains trapped in the solid phase either as part of the mineral or as adsorbed ions on the walls of the water channels. In surface waters the radon/radium ratio is much greater than one; most of the radon in surface waters comes from the radium adsorbed on the sediments at the bottom of streams and lakes. The radium/uranium ratio in groundwaters is less than one under oxidizing conditions and greater than one under reducing conditions.

These ratios simply reflect the redox conditions in existence in any one environment. In surface waters where oxidizing conditions prevail the radium/uranium ratio is invariably much less than one.

In summary several criteria are given below which will help in deciding on the significance of radioactive anomalies in groundwater:

(1) A threefold or greater increase in the content compared to the background of a region.

(2) Occurrence of anomalous amounts of all four elements (Rn, Ra, U, and He).

(3) Increased content of tracers such as molybdenum, lead, copper, zinc, arsenic, phosphorous, and vanadium.

(4) A sharp rise in concentration of mobile radioactive elements after a rain or thaw period of up to ten times in the presence of uranium deposits; not more than four times in the absence of a uranium deposit.

Once a radioactive zone has been outlined by the techniques described above, detailed tests are required to detect the source of the radioactivity. Naturally the gamma-ray scintillometer plays a large part in these investigations. However, uranium and radon in waters and soils can be applied profitably, particularly in regions of persistent overburden. The zinc sulphide (silver activated) radon counter is more sensitive than the scintillometer; under favourable conditions mineralization at depths of 20 feet have been observed. The soil radon traverse obtained in Elliot Lake (Dyck, 1969) illustrates the use of the radon counter in soil tests. Other soil tests over radioactive pegmatites in the Gatineau Hills and in Bancroft have shown that the radon counter can be used advantageously to outline buried uranium mineralization. Tests over ore in the Bancroft area carried out by Liard and Phelan (pers. comm.) again show a clear soil radon signal over buried uranium mineralization which is stronger than the gamma-ray scintillometer signal. These tests are of special interest because they were carried out in the winter with snow and with frost in the ground. Soil radon tests, however, are not applicable nor are they successful everywhere.

For example, in Beaverlodge a soil radon traverse over the St. Louis Fault not far from the uranium mine at the edge of the town of Eldorado was essentially negative because the area as a whole has very little overburden and hence radon soil tests become difficult.

Recently a new radon detection method called the Track-Etch Technique has detected uranium ore at depths of several hundred feet (Gingerich, 1974). As radon cannot diffuse such distances migration of radon to the surface or underground pressure pulses forcing radon up at irregular intervals must be postulated to explain this depth penetration. Track-Etch has the advantage of integrating the radon signal over a longer period of time. It works on the principle of alpha particle track formation in photographic emulsions which are buried in the ground for a specified length of time. Its disadvantages compared to the zinc sulphide (silver activated) radon counter are: its results are not available immediately, and the emulsions cannot differentiate between ^{222}Rn and ^{220}Rn, the Rn isotope of the ^{232}Th series.

In parts of Labrador and elsewhere, groundwater is very near the surface so that soil air is virtually nonexistent (Dyck, 1972; N.R. Newson, pers. comm.). In such instances detailed work is best carried out by measuring radon in the water.

Winters in Canada are rather severe and long. The question as to what happens to radon in or under ice frequently comes up. As a result of such enquiries a test was carried out in the winter of 1970 in the Gatineau Park. A hole was drilled through lake ice where a small radioactive pegmatite dyke juts into the lake. An unexpected complication arose when water was discovered between two layers of ice. The radon content of this water was appreciable, but much lower than in the main body of the lake suggesting diffusion through the ice or movement of water through cracks in the ice. About 20 water samples from the main body of the lake were taken in sixteen ounce plastic bottles, some were frozen immediately and kept frozen for a day; others were kept in the liquid state for a day; still others were analyzed immediately. The results showed clearly that samples in the liquid state lost appreciable amounts of radon in a day whereas the frozen samples retained essentially all the radon. The radon retentivity of ice makes possible radon surveys of lakes and streams in sub-zero temperatures using plastic bottles.

The diffusion of radon in soils has been studied by a number of authors. It is generally accepted that radon cannot move beyond about 20 feet in soils by true diffusion. In water the diffusion path seems to be even shorter. This is evident from the results shown in Figure 4.9. Both radon and uranium drop to zero within the top 10 to 20 feet and experience a rise within the bottom 10 to 20 feet. The behaviour of radon is easily explained by diffusion and decay – that of uranium is not.

The 1968 radon pattern is similar to that of 1971 although not quite the same spot was sampled (note the difference in depth). The source of radon and uranium are pegmatite dykes on the north shore of the lake. Natural flow and wind action moves the constituents across the lake and down to a certain depth. The radon concentration gradually goes to zero due to dilution and decay. Near the bottom radon diffuses from the sediments into the water until it is again depleted by decay and dilution. But uranium has a very long half-life and therefore cannot disappear by decay. And yet the uranium profile is similar to that of radon. The rise in uranium near the bottom can be due partly to carbonate complexing and partly to finely suspended organic matter which slowly settles out. But the increase near the top is difficult to explain unless one postulates a recent injection of uranium into the lake as a result of a flushout of uranium from the pegmatite dykes.

Helium could also become a useful tracer for uranium ore deposits during or after the drilling phase

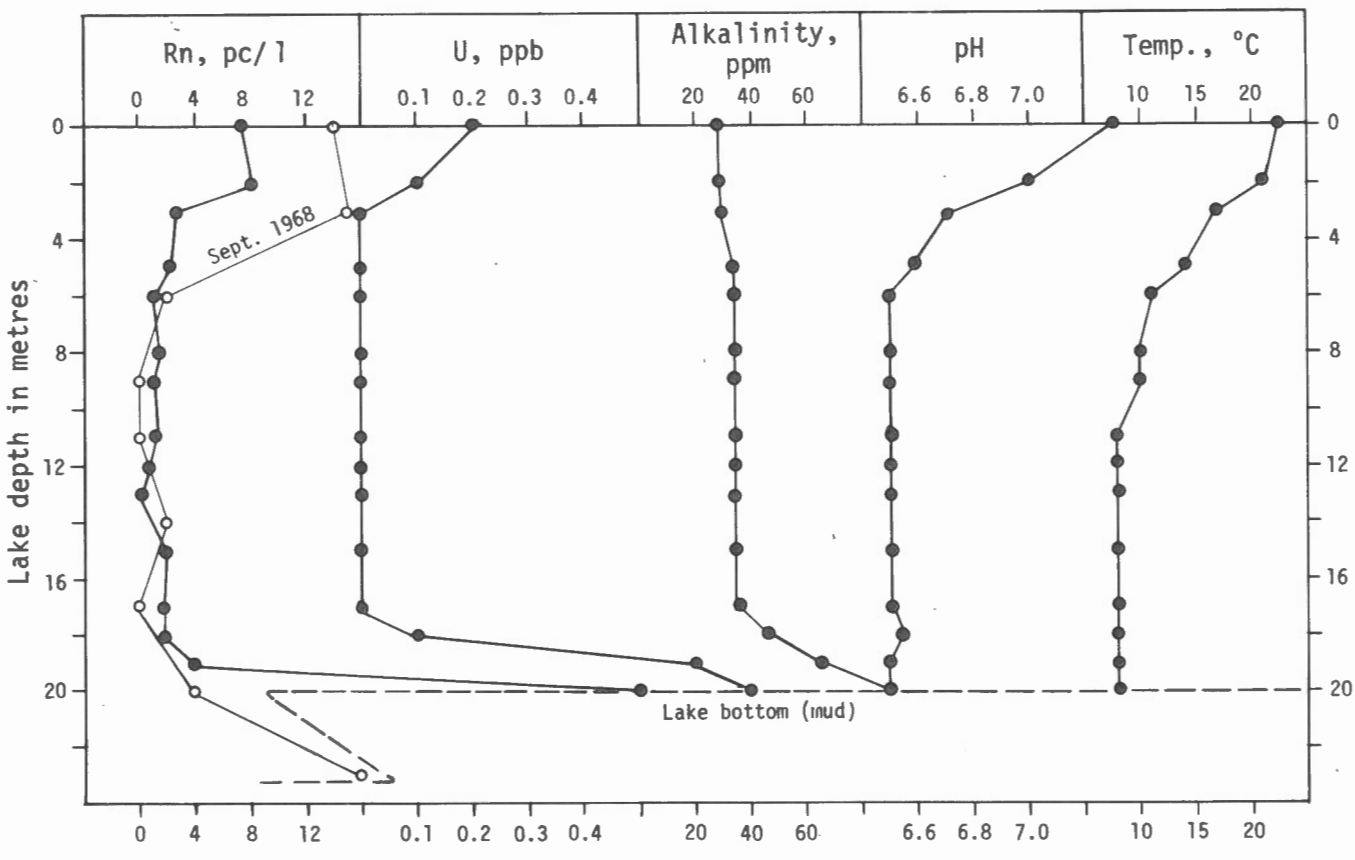


Figure 4.9. Vertical distribution of radon, uranium, alkalinity, pH and temperature in Fortune Lake, Gatineau Park, Quebec in July 1971.

of exploration. Its great mobility even in rocks suggests that drillholes in the vicinity of a uranium deposit would act as conductors of helium from the deposit and hence reveal the presence of ore even though the drill encountered only weak mineralization. Analysis of water samples from drillholes in radioactive zones show that helium does increase with an increase in uranium content but the relationship is not linear. There is no doubt that rock porosity and rate of groundwater turnover play an important role in the rate of loss of helium from the ore. Background information to evaluate the usefulness of helium in detailed uranium exploration has been collected by the author over the past two years.

At the end of May 1973, 46 water samples from 2 radon anomalies in the vicinity of Moncton, New Brunswick comprising 2 stream, 10 spring, 11 well, and 23 drillhole water samples were collected and analyzed. The anomalies occur in Pennsylvanian and Mississippian red sandstones, conglomerates, and minor shales. Radon concentrations of from 0 to 18 nanocuries per litre of water were encountered. Drillhole profiles from these anomalies suggest that one stems from a weak shallow radioactive zone as indicated by decreasing radon with depth and showing only background levels of uranium and helium. The second anomaly gives increasing concentrations of radon, uranium and helium with depth, indicating greater uranium potential than the first. Both locations have a rapid turnover of water as indicated by the relatively high oxygen content. The presence of oxygen may also explain the lack of radium and hydrogen sulphide in the water samples; radium becomes extremely immobile and hydrogen sulphide is oxidized in an oxidizing environment. Only four samples contained less than 2 per cent oxygen; these were also the only samples with measurable contents of hydrogen, ranging from 0.1 to 1 per cent.

A drillhole in radioactive pegmatitic rock in the Gooderham, Ontario area was sampled twice in order to confirm the exceptionally high radon content in the water. The radon level was the highest encountered to date by the author, including drillholes on the old Bicroft Mine property near Bancroft, Ontario, and waste water and drillhole water in the Elliot Lake uranium mines. Yet the uranium concentration of bulk samples from this drill core did not exceed 350 ppm. In pc per litre of water the values range around

500 000. To maintain this radon concentration requires as many picograms of radium or 1500 ppm uranium in solution in equilibrium with its decay products. In actual fact the water samples contained not more than 160 ppb uranium and 170 pc per litre radium. So practically all the radon in the water originated from the radium in the rocks. To explain the high radon content in the water one can postulate (1) the existence of rich uranium ore within range of the drillhole and porous rock permitting the radon to diffuse onto the water; or (2) the accumulation of radium on the walls of the hole or in cracks nearby through which radon can move onto the drillhole with the groundwater. The relatively low helium content of the water samples seems to preclude the existence of large amounts of high grade ore unless one further postulates rapid loss of helium by diffusion. If that were the case in this drillhole, however, a helium gradient should be evident. Even though the helium content in the dissolved gas is relatively low (12 to 42 ppm) it is 6 to 21 times larger than that in surface waters.

A weaker radioactive zone nearby drilled many years ago gave much lower radon and helium values in the drillhole waters reaching a maximum of 420 pc per cc and 20 ppm helium in the dissolved gas.

On a third radioactive showing in the same general area as the above two, 8 drillholes were sampled. Drill core analyses for uranium give a maximum of 0.18 per cent U_3O_8. The relatively high helium and radon and radon contents (up to 384 ppm and 6000 pc per cc in the dissolved gas or 12 ppm helium and 160 000 pc per litre radon in the water) also suggest near ore grade material comparing these values with values found in drillholes of known uranium mines. It should be pointed out though that the highest values of helium and radon came from the same drillhole but the higher U_3O_8 content from another. More detailed correlative investigations are required to evaluate the usefulness of helium in detailed uranium exploration.

Conclusions

Geochemical surveys and field tests over the past six years have shown that uranium, radium, and radon are useful pathfinders for uranium ore deposits. The techniques employed are based on sound radiochemical and geochemical principles.

Uranium, because of its high mobility in the oxidized state, moves relatively large distances in the surficial environment along drainage sheds, making possible regional surveys of large tracks of land. Major geochemical provinces or larger near surface uranium deposits may be outlined with lake water or sediment sample densities as low as one per 10 square miles. In regions of dense vegetation sample densities of one per 3 to 5 square miles may be required because of the strong adsorption of uranium by the organic rich sediments.

Radium and radon, because of their much shorter ranges than uranium in the surficial environment, are more suitable for detailed or semidetailed exploratory work. In swampy, wet terrain radon in streams or groundwaters may be used; in dry porous soils radon is suitable.

Recent tests with helium and radon in well and drillhole waters indicate that they will become useful regional tracers for uranium ore deposits in flat-lying sedimentary strata. Cost of analysis and difficulty of interpretation of helium results are the main deterrents to its wider use in uranium exploration at the present time. The potential of helium as a tracer for underground structure seems good.

Although any one of the four elements uranium, radium, radon, and helium can, under favourable conditions, reveal the existence of an ore deposit, it is usually a matter of probabilities. This probability increases every time another indicator over a prospect is positive.

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5. THE FEDERAL-PROVINCIAL URANIUM RECONNAISSANCE PROGRAM

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Abstract

The overall objectives of the Federal-Provincial Uranium Reconnaissance Program are to provide industry with high quality reconnaissance exploration data to indicate those areas of the country where there is the greatest probability of finding new uranium deposits, and to provide government with nationally systematic data to serve as a base for uranium resource appraisal.

The program will involve high sensitivity airborne gamma-ray spectrometry over areas of low relief and some outcrop, required geochemistry in mountainous terrain and in areas with extensive overburden, and special emphasis on hydrogeochemistry in flat-lying sedimentary basins.

The administrative arrangements for the program are being modelled as closely as possible upon the Federal-Provincial Aeromagnetic Program which commenced in 1961. The Federal Government, through the Geological Survey of Canada and in consultation with the relevant provincial agencies, will be responsible for designing and administering contracts for the execution of this work which will be undertaken by Canadian contractors. The Geological Survey of Canada will be responsible for conducting limited airborne and ground pilot studies ahead of the contracted operation in order to verify the suitability of particular areas for the available methods, and in order to provide control data.

Results from the program will be published as rapidly as they can be compiled. They will be released simultaneously by the Federal and Provincial authorities as has been the practice in the Aeromagnetic Program.

Introduction

In December 1974, there was a meeting of the Federal and Provincial Ministers of Mines in Ottawa to discuss various aspects of Canadian mineral policy. At the conclusion of that meeting a communique was issued which announced that "The Ministers agreed in principle with the establishment of a Uranium Reconnaissance Program as proposed by the Federal Government, provided agreements are negotiated with each province on an individual basis and without prejudicing financing of any other project". The communique concluded with the statement that "The requirement of searching for other minerals as a complementary activity to the Uranium Program should be considered within the framework of the program if such is a provincial priority". This was reported in the Northern Miner for December 26, 1974. As a matter of record, preliminary discussions between Federal and Provincial officials commenced about twelve months ago, culminating in a presentation to Technical Committee Number 1 at the annual conference of the Provincial Ministers of Mines in Moncton last October, but the research and development program which permitted this to be launched goes back at least ten years (see bibliographies).

In summary, the overall objectives of the Uranium Reconnaissance Program are to provide industry with high quality reconnaissance exploration data to indicate those areas of the country where there is the greatest probability of finding new uranium deposits, and to provide governments with nationally consistent systematic data to serve as a basis for uranium resource appraisal. The Federal-Provincial Uranium Reconnaissance Program will be administered and executed in a manner similar to the Federal-Provincial Aeromagnetic Program which commenced some fourteen years ago. The operation, however, is considerably more complex involving both geophysics and geochemistry. The program will involve the following technical activities:

(1) Airborne gamma-ray spectrometry will be undertaken over all areas of relatively flat topography where there is some outcrop and generally thin overburden. High sensitivity equipment will be employed with a specification similar to that developed by the Geological Survey and proved in use over the last six years. Line spacing for reconnaissance purposes will normally be 5 km. In areas which are rather remote and may not be reached by the main program for a number of years, some advance reconnaissance work will be done at very wide spacing, for example 25 km, in order to assign priorities for later work. Airborne gamma-ray spectrometry will be used principally over the Shield although coverage may be extended over some adjoining areas, and over other parts of the country where the topography is not so rugged as to prevent effective coverage by fixed wing survey aircraft.

(2) Regional geochemistry will be used primarily in mountainous areas, in areas with extensive overburden, in selected areas which are considered particularly favourable for uranium occurrence, and in some areas where the potential for other metals is equal to or greater than the potential for uranium. Regional geochemistry will be based upon stream sediment, lake sediment, or bedrock analysis. Sample spacing will normally be in the range of one per 12.5 km^2 to one per 25 km^2.

(3) Hydrogeochemistry will be carried out wherever possible as part of the regional sampling program. In addition, this technique has a unique application for the analysis of subsurface waters from aquifers to detect possible uraniferous horizons in flat-lying sediments, or below thick overburden.

Results from this program will be published as rapidly as they can be compiled. They will be made available simultaneously by the Federal and Provincial authorities, following the established practice of pre-announced time releases.

The Basis for the Program

The design of the Uranium Reconnaissance Program owes much to the now long-established aeromagnetic program. However, it differs in one important respect and for this reason the philosophy underlying the Uranium Reconnaissance Program needs to be closely examined. The feature by which the Uranium Reconnaissance Program will differ from the aeromagnetic surveys is in density of coverage. The standard specification for the aeromagnetic program with half-mile line spacing and a flight elevation of 1000 feet above terrain has resulted in what is effectively saturation coverage for near surface magnetic bodies with dimensions of the order of 1000 feet. In other words all bodies of that size will be found. Unfortunately there is neither time nor funds to make it possible to obtain such coverage with the Uranium Reconnaissance Program. The planned line spacings and sample densities only permit the equivalent of 5 to 10 per cent coverage of any particular area. It is for this reason the logic underlying the program is important.

The program rests upon the concept that most uranium deposits occur within or marginal to regions of the crust containing higher than average amounts of uranium. Reference should be made again to Figure 3. 1 of this publication. As mentioned in paper 3 uranium may be found to be weakly concentrated in granitic rocks especially those late in an orogenic cycle. It may be found concentrated in high temperature pegmatites or in lower temperature vein deposits. These are all components of a primary source area which through erosion and redistribution can provide the material to form secondary deposits in any suitable adjacent geochemical trap. The reconnaissance program is designed primarily to identify all zones of primary enrichment within the country, and secondly to indicate, if possible, the limits of areas where secondary processes have operated. The primary source areas are undoubtedly the easier targets to find, but it is important and logical that we should begin at the beginning and find these before going on to find the more difficult secondary targets, since our present knowledge of even the gross distribution of uranium in the country is far from complete. It is important not to dismiss anomalous areas as simply being low-grade igneous rocks of no economic importance. Such areas may have considerable potential as source areas, and geological knowledge must be brought into play to determine where the eroded material from these source areas has been deposited. It is the

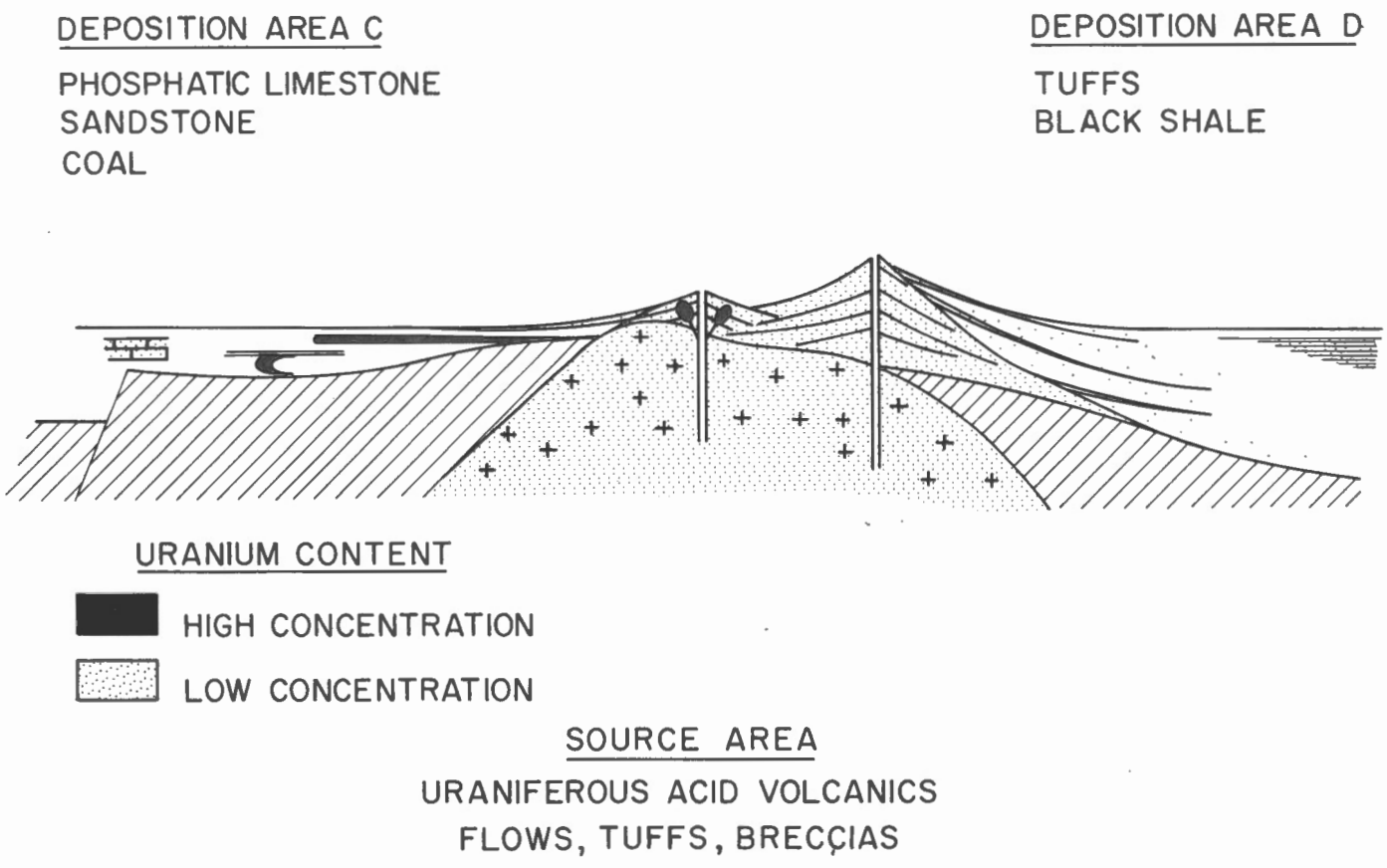

Figure 5. 1. Schematic diagram: uranium source and depositional areas.

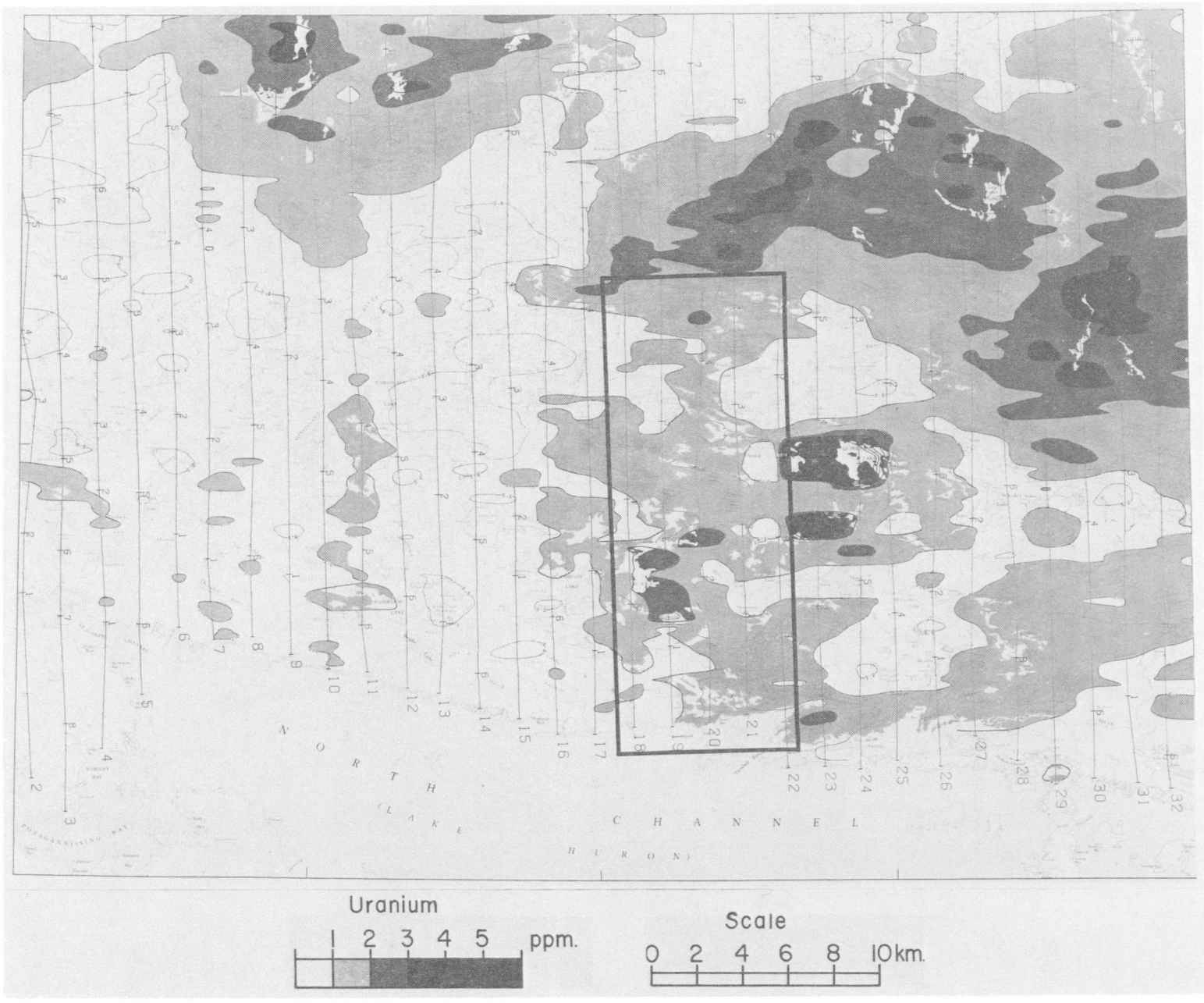

Figure 5. 2. Uranium distribution, Blind River sheet, Ontario.

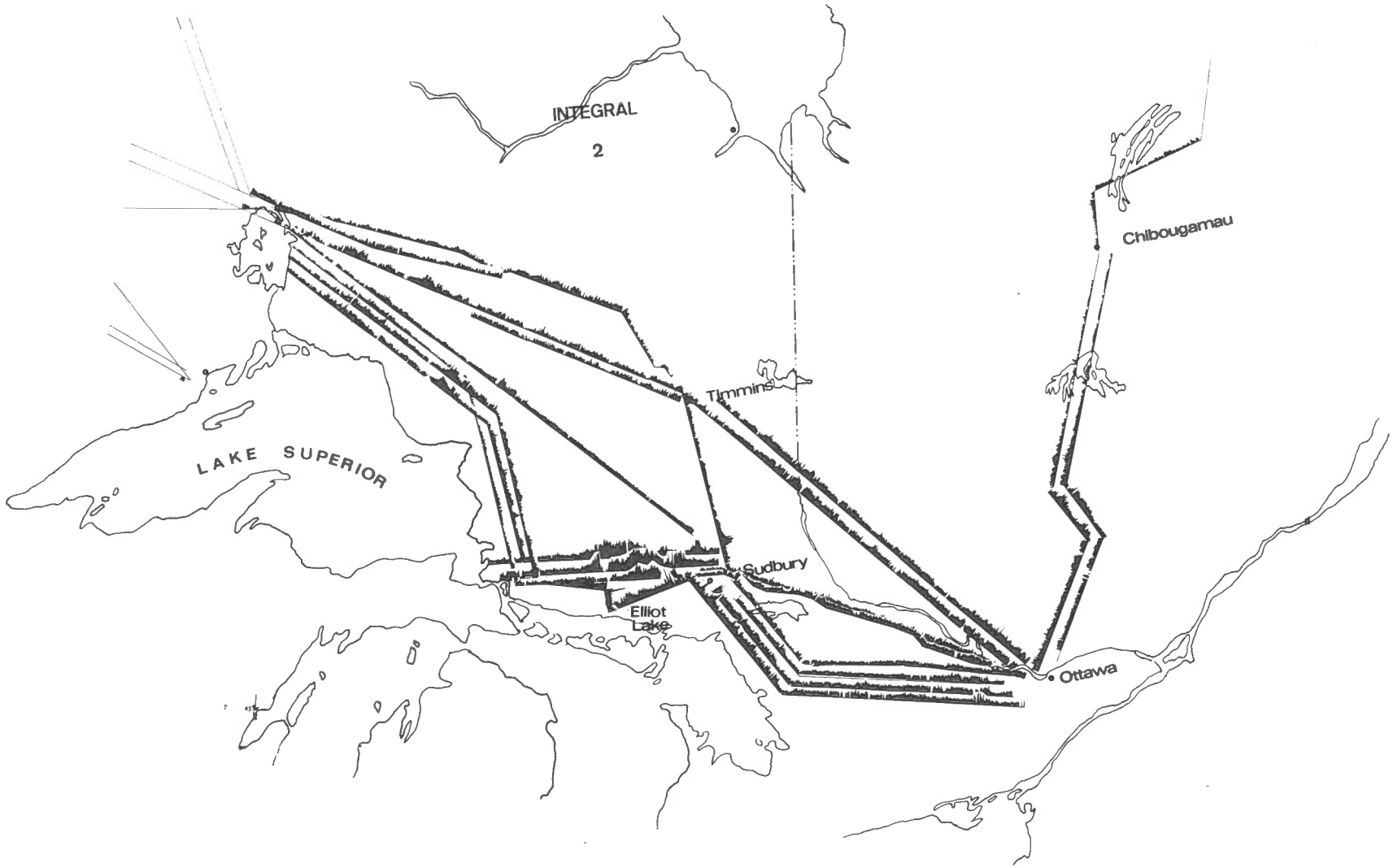

Figure 5.3. Regional variation in total radioactivity shown by profiles along flight lines crossing N.E. Ontario and W. Quebec.

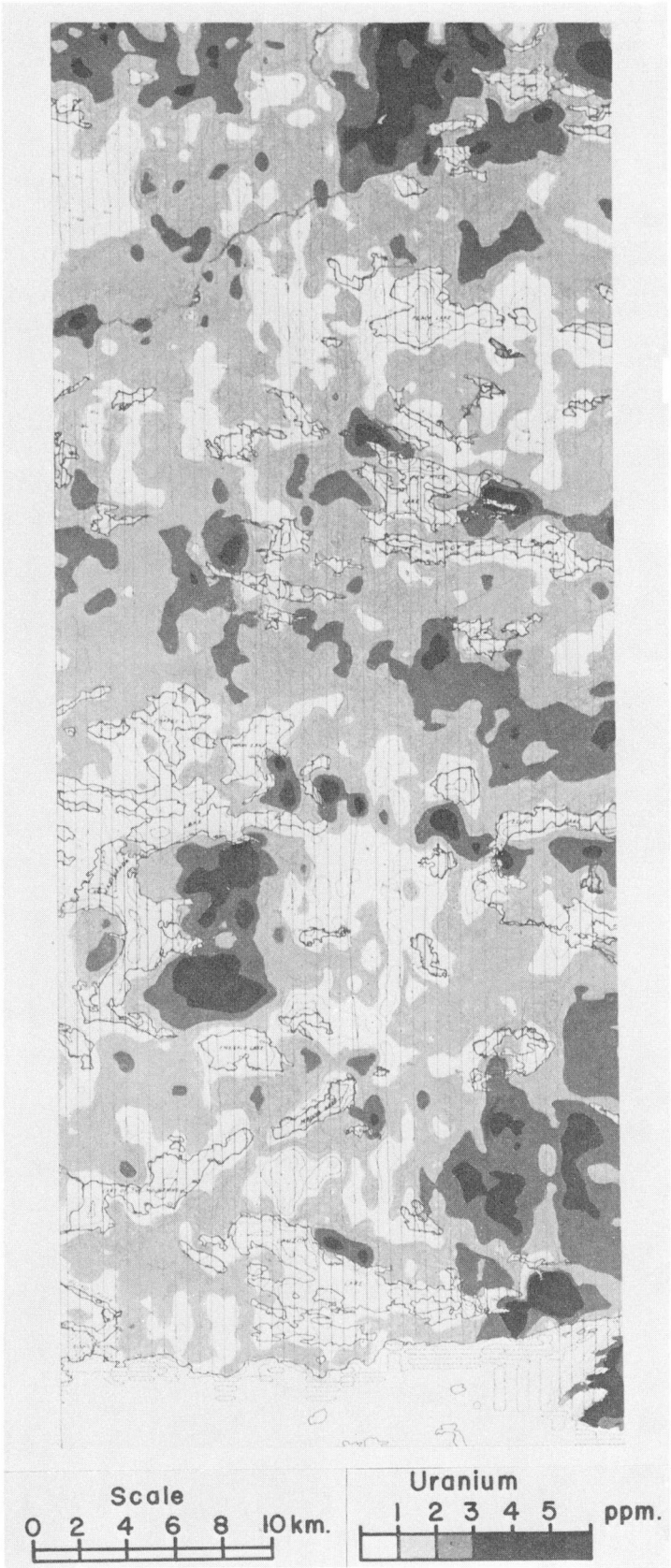

Figure 5. 4. Uranium distribution, area immediately west of Elliot Lake outlined in Fig. 2, from 0. 5 km flight line spacing.

first objective of the Uranium Reconnaissance Program to delineate as rapidly as possible the major areas of uranium enrichment in Canada. There is reason to believe that there are more of these than are generally known at the present time.

Figure 3. 1 illustrates one idealized composition type of source area which might be found in the Canadian Shield environment. Figure 5. 1 illustrates another combination of source area and depositional environments which is perhaps more akin to situations known in the United States. This represents a source area of acid volcanics with weakly uraniferous flows, tuffs and breccias, between two sedimentary basins. Typically these are restricted and nonmarine. On one side there is a uraniferous coal, uranium in sandstone and uraniferous phosphatic limestone, on the other, tuffs and uraniferous black shale. Wherever potential source areas or potential widespread source materials such as uraniferous tuffs are found, efforts should be concentrated to search for possible mineralization. The South March uranium occurrence outside Ottawa referred to elsewhere appears to provide a text-book example of the conjunction of a potential source area (the Gatineau Park vicinity) on the margin of the Shield and a depositional area in nearby overlapping dolomitic sandstone of Paleozoic age. The uranium content of the Gatineau Park area is weakly but distinctly anomalous on a regional basis. Dyck (this publication, paper 4) has shown some of the various types of anomaly associated with this area.

Results from Recent Airborne Radioactivity Surveys

A series of figures now follows to illustrate and substantiate two points: first, the concept of regional uranium enrichment and source areas; and second, that airborne surveys with a 5 km flight line spacing are adequate to locate and delineate the various types of area that show uranium enrichment.

It must be stressed that the contoured maps which follow indicate the mean surface equivalent uranium concentration (eU) expressed in parts per million. This value is normally less than the bedrock uranium concentration. Local highs and lows caused for example by variations in the amount of outcrop and swamp are smoothed out in the compilation process. For detailed examination reference should always be made to the flight line profiles.

The first example is the Elliot Lake area. Figure 5. 2 shows the uranium distribution over the Blind River map-sheet (1: 250 000). The contours are in parts per million equivalent uranium and this is compiled from a survey at 5 km line spacing, flown by the Geological Survey Skyvan aircraft in the summer of 1974. Disregard the area of high concentration immediately north and east of Elliot Lake, caused by the combination of rock dumps, tailings and natural exposure. These can be separated only by very detailed work. Note that there is an extensive area of above average uranium content covering hundreds of square miles lying to the north and northwest of Elliot Lake and extending beyond

the limits of this map sheet. On the basis of extensive cross-country reconnaissance flights flown by the Geological Survey across Ontario in recent years, this can be shown to be a regionally anomalous feature (Fig. 5. 3). This conjunction does not prove, but makes it plausible to believe, that the source of the Elliot Lake uranium mineralization was in the extensive area of pre-Huronian basement to the north. This has been proposed previously by Roscoe and Steacy (1958) with evidence based on the analysis of individual rock samples, but questioned by Bottrill (1971). It is now possible to confirm the existence and show the magnitude of this source area.

The rectangular block west of Elliot Lake outlined within Figure 5. 2 was flown by the Geological Survey in 1970 with a line spacing of 0. 5 km. Both surveys were flown with north-south flight lines. Results compiled from the detailed survey are shown in Figure 5. 4. The two maps show considerable similarity with the highest concentrations occurring southeast of Matinenda Lake on both maps. The detailed map shows more extensive areas of low concentration and higher peak concentrations, features that are modified by the smoothing of data necessary to produce contour maps from the reconnaissance survey.

Figure 5. 5 shows uranium distribution over the Havre St. Pierre map-sheet (1: 250 000) in Quebec,

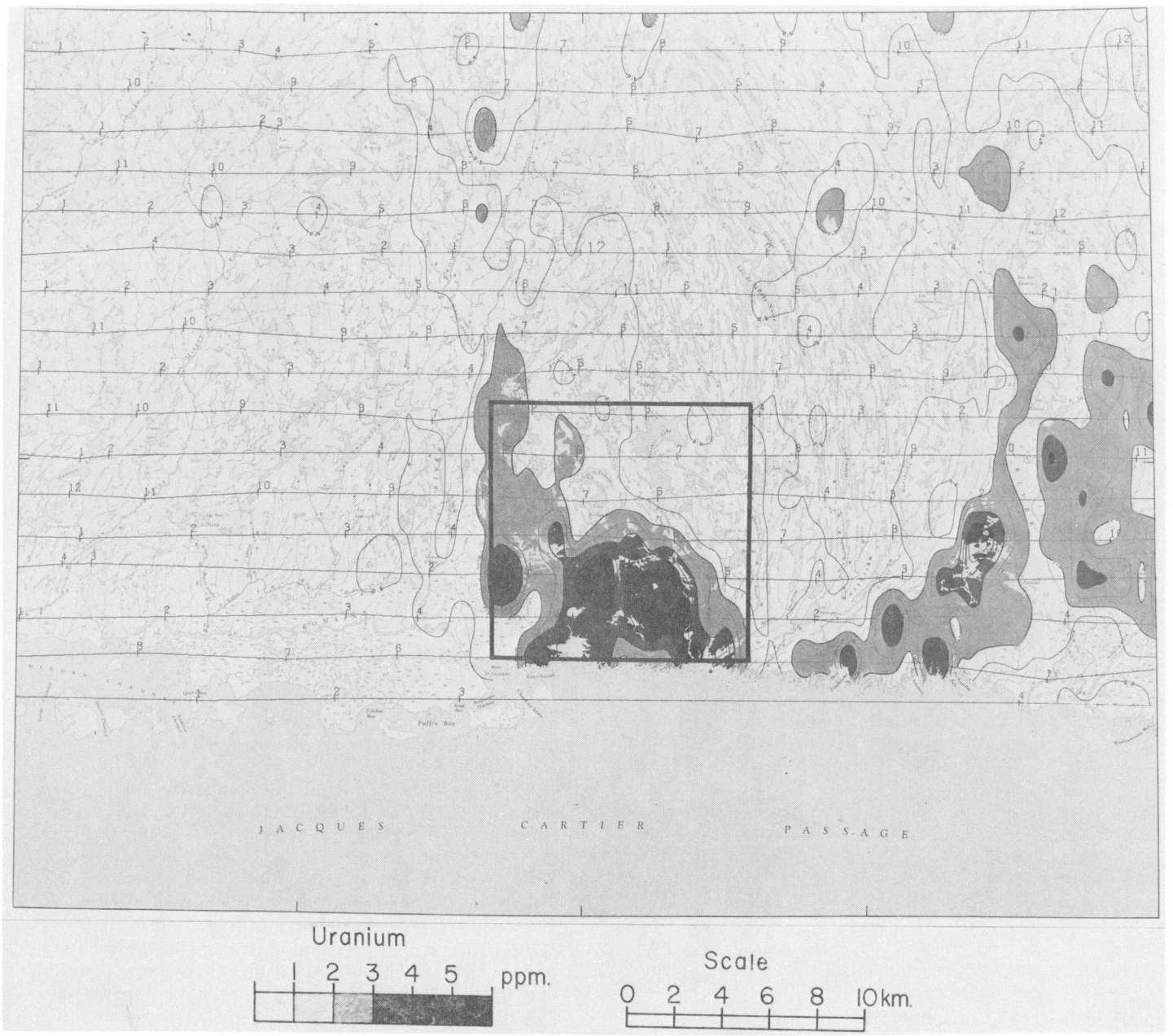

Figure 5. 5. Uranium distribution, Havre St. Pierre sheet, Quebec, from 5 km flight line spacing.

again for a survey flown with 5 km line spacing. Figure 5.6 shows that part of the area around Johan Beetz flown with 1 km line spacing. Unusually uraniferous pegmatitic granite is known to occur there. Flight lines were east-west in both cases. The reconnaissance survey is clearly adequate to outline this anomalous region.

Figure 5.7 shows the Tazin Lake map-sheet (1: 250 000) in Saskatchewan. This was flown at 5 km spacing with east-west flight lines. Figure 5.8 shows a portion of this area around Beaver-lodge with north-south flight lines at 2 km spacing. There is no way in which the anomalous nature of the Uranium City area could be missed, even if there were no mine dumps scattered around the surface. It can be seen that the wide flight line spacing results in some distortion of the shape of the enriched region, but all anomalous areas such as this, supposing they were virgin, should

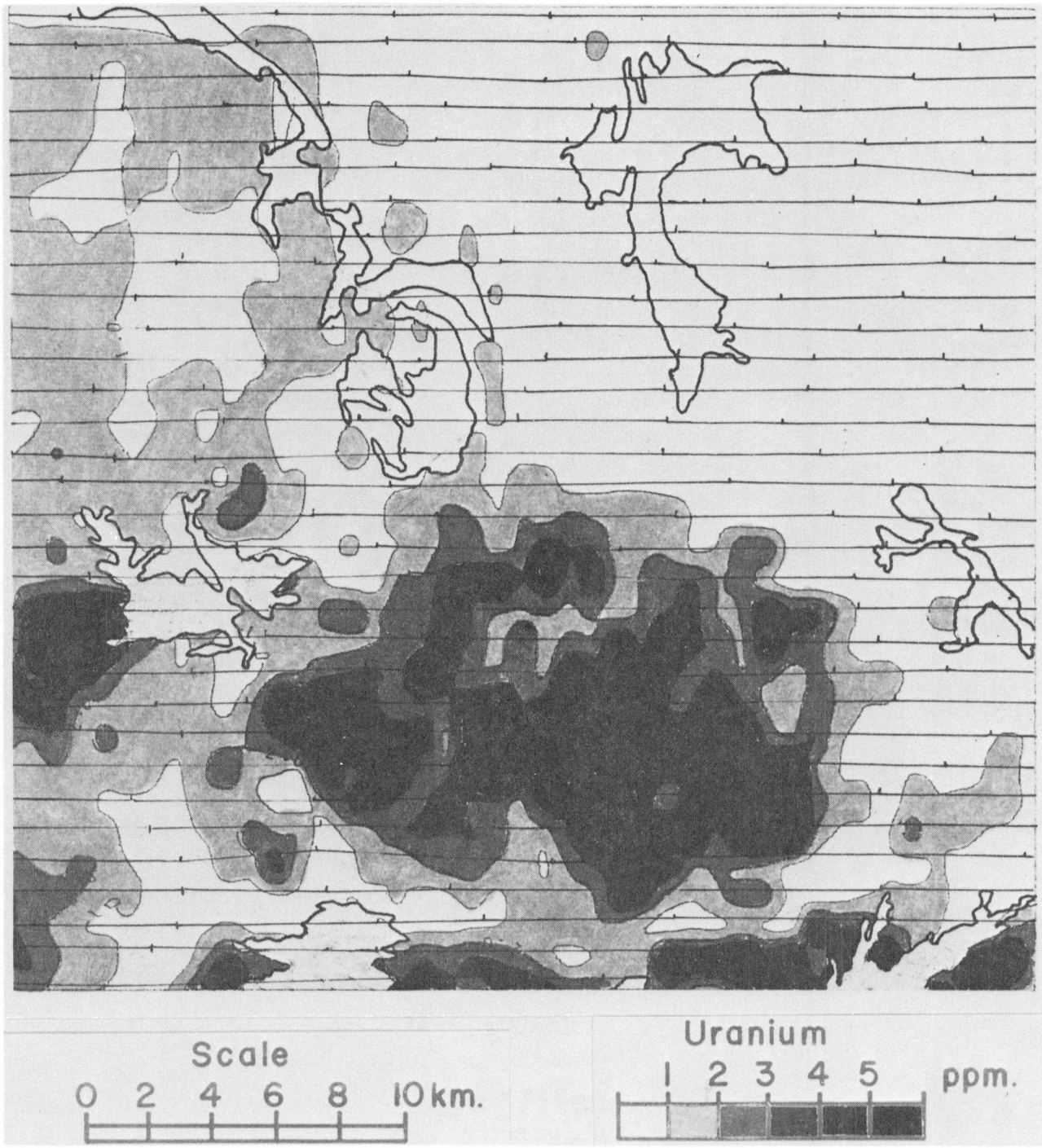

Figure 5.6. Uranium distribution in Johan Beetz area, outlined in Fig. 5, from 1 km flight line spacing.

be followed up with closer line spacing in order to obtain better definition of their features, and identify target zones.

To emphasize the fact that Canada's known major uranium districts are associated with large areas of uranium enrichment, further examples can be provided.

Figure 5. 9 is a map of the Bancroft area in Ontario showing a 3 to 4 mile wide zone of above-average uranium content stretching from the southwest side to the northeast corner.

Figure 5. 10 from the Mont Laurier map-area in Quebec, once again shows a broad zone of high uranium content extending across the map-area, which in this case is of the order of thirty miles across.

Figure 5. 11 is an east-west profile, about 75 miles long, running through Wollaston Lake in Saskatchewan. The Gulf Minerals Rabbit Lake orebody is about 1. 5 miles north of the flight line on the west side of the lake. It can be seen that this is on the edge of a large belt of high uranium content which occupies the ground between Wollaston and Reindeer lakes. This particular zone or belt appears to be more or less continuous over a distance of several hundred miles trending north-easterly and extending into the Territories.

The magnitude of some of these regional zones of uranium enrichment can be gauged from Figure 5. 12 which is another map of uranium distribution compiled at a scale of 1: 1 million from Geological Survey airborne radiometric surveys extending over 600 miles from

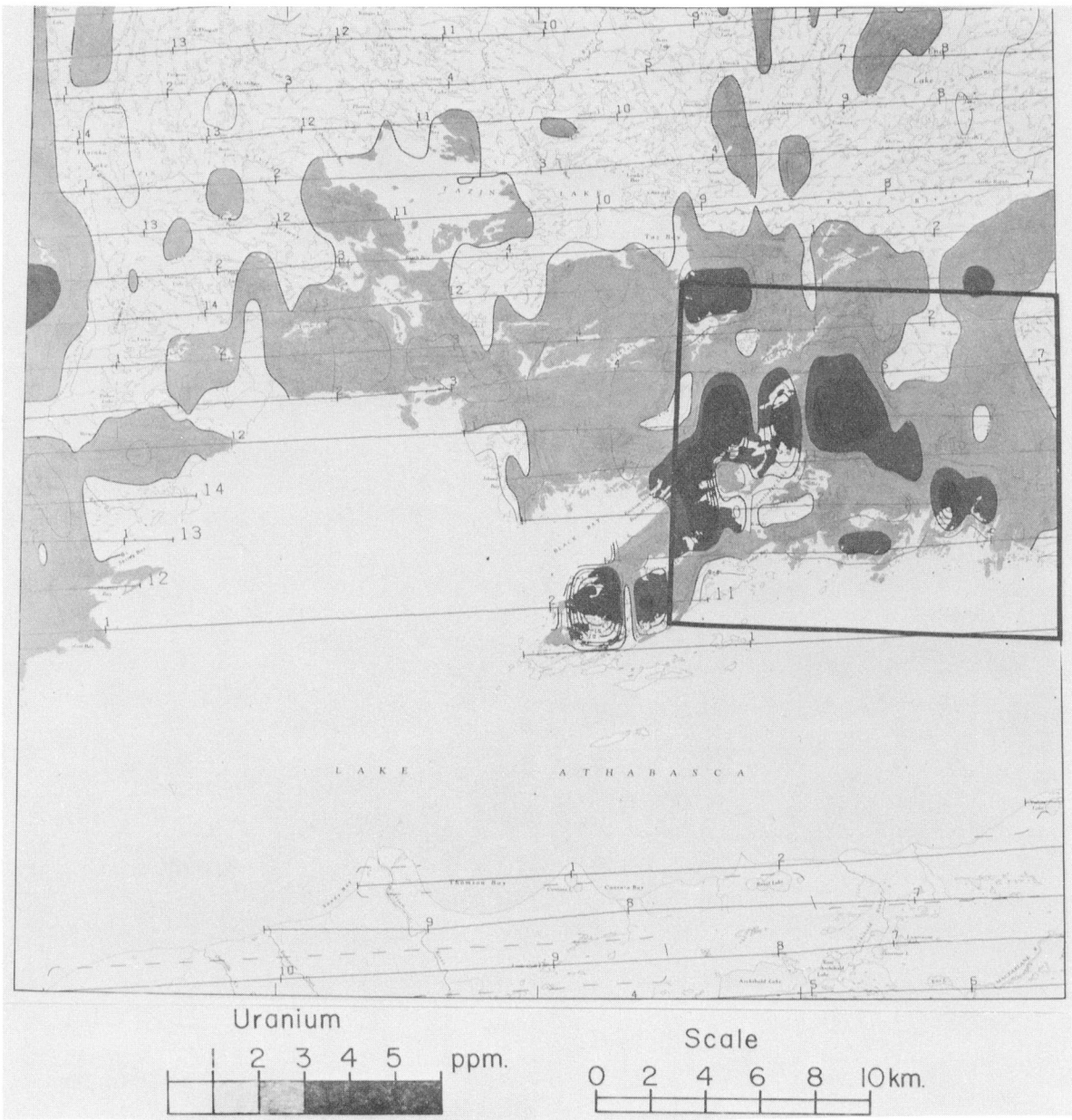

Figure 5. 7. Uranium distribution, Fazin Lake sheet, Saskatchewan, from 5 km flight line spacing.

Great Bear Lake in the northwest to south of Fort Smith at the southern margin. The apparent continuity of this feature from the Bear structural province of the Shield, through the Slave and into the Churchill is of particular scientific interest. Groundwork at selected sites along this feature has demonstrated that the zone is definitely characterized by above-average uranium content, and that it is not a spurious effect caused solely by the extensive outcrop and relatively thin overburden along this edge of the Shield. There are large areas of granitic rocks in the Yellowknife vicinity which are well exposed but which do not approach the levels of high uranium content found in the region farther to the northeast of Yellowknife. Erosion of this well endowed portion of the Shield must have removed a very large amount of uranium, and any ideas as to where it might have been deposited would seem to be well worth pursuing.

Regional Geochemical Surveys

The results presented in the previous section were gathered from the air but a similar general pattern of uranium distribution can be demonstrated by geochemical sampling carried out at ground level.

Figure 5. 13 shows how the country can be divided according to physiographic characteristics into areas of suitability for different geochemical reconnaissance methods. In the Cordillera, the Appalachians, and other regions with moderate to high relief, the greatest reliance will be placed on stream sediment sampling. This method has been proved in Canada and other

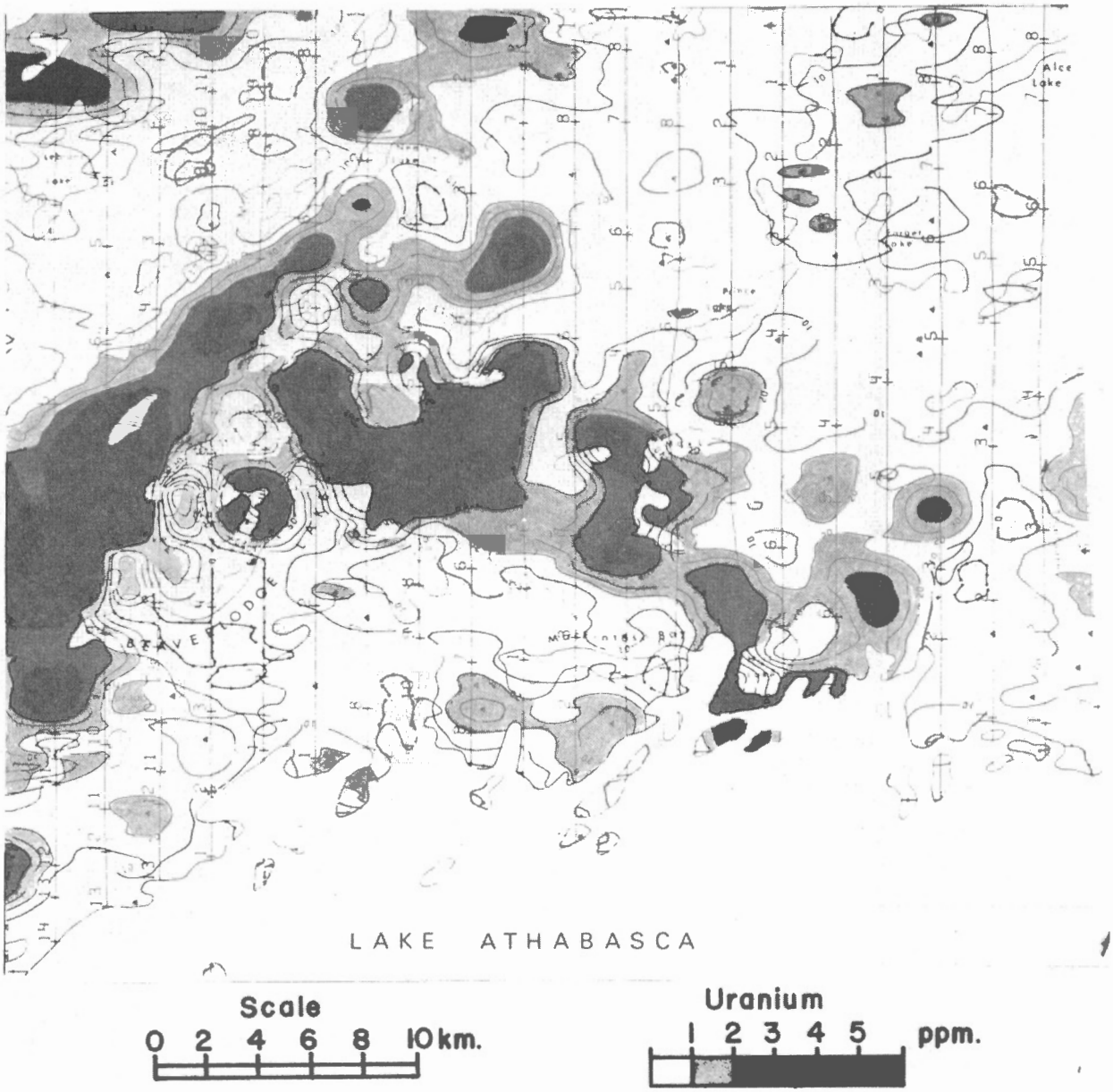

Figure 5. 8. Uranium distribution, in Beaverlodge area, outlined in Fig. 7, from 2 km flight line spacing.

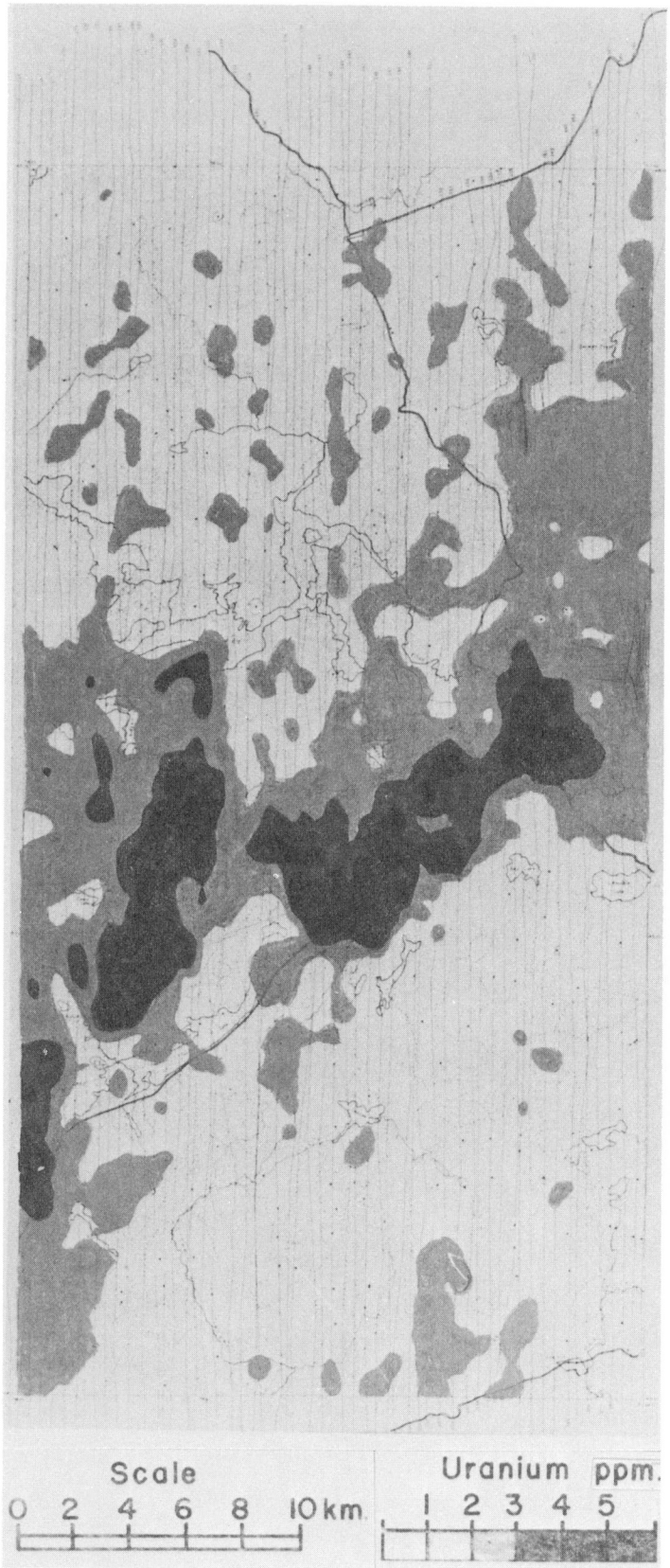

Figure 5. 9. Uranium distribution, in Bancroft area, Ontario, from ¼ mile flight line spacing.

parts of the world as a most effective reconnaissance exploration technique. Since large parts of the regions in question have already been sampled for stream sediments, consideration is being given to the use of existing sample material. Preliminary enquiries, however, suggest that the availabiltiy of reliable sample material collected over large blocks of the country is limited.

The Geological Survey has in recent years concentrated much effort on the development of geochemical methods for the Canadian Shield, based on lake sediment analyses. This is because prior to the development of such methods there was no effective technique for geochemical reconnaissance within this large area of the country. The methods developed, and still being developed, appear to provide a highly efficient method of reconnaissance for many areas of the Shield. Lake sediment reconnaissance has been shown capable of delineating areas containing a variety of mineralization including uranium and massive sulphides. Using fast turbine-powered helicopters, it has been possible to achieve sampling rates of 12 to 15 per hour at reconnaissance spacing. This allows the total cost of geochemical surveys including analysis to be kept below $10 per square mile of sampling at densities of 1 per 5 square miles in areas of the Shield with moderately good accessibility. In this way large areas can be covered very rapidly. For instance, a recent contract survey required little more than a month to sample a 20 000 square mile area of Saskatchewan using one helicopter at the above sample density.

The first full scale test of lake sediment reconnaissance was carried out in 1972 when a 36 000 square mile area of the Bear and Slave provinces was sampled in six weeks. A number of significant anomalies were located for uranium and other metals. In the Bear Province anomalous uranium appeared to be structurally controlled (Figure 5. 14). This is the type of regional correlation that becomes possible if data are collected over a large region. Follow-up studies on this survey have largely concentrated on multi-element anomalies derived from massive sulphide mineralization. This work has demonstrated a fact not previously widely known or appreciated that sulphide mineralization is being actively oxidized even in the permafrost environment. Mobile metals such as zinc and uranium are widely dispersed in solution before being precipitated in lake sediments. The dispersion pattern for zinc demonstrated in Figure 5. 15 indicates why a wide sampling interval can be used for reconnaissance sampling. Figure 5. 15 shows how the zinc concentration in water falls off over a distance of 7 km from its source and how it becomes fixed in centre lake sediments, and to a lesser extent in nearshore sediments.

Areas that may contain roll-type uranium deposits present particular problems. This is because these deposits by their nature occur at depth often with little surface trace of mineralization. For these areas emphasis will be placed on geochemical methods that Dyck (*see* this publication, paper 4), describes involving sub-surface water and spring sampling.

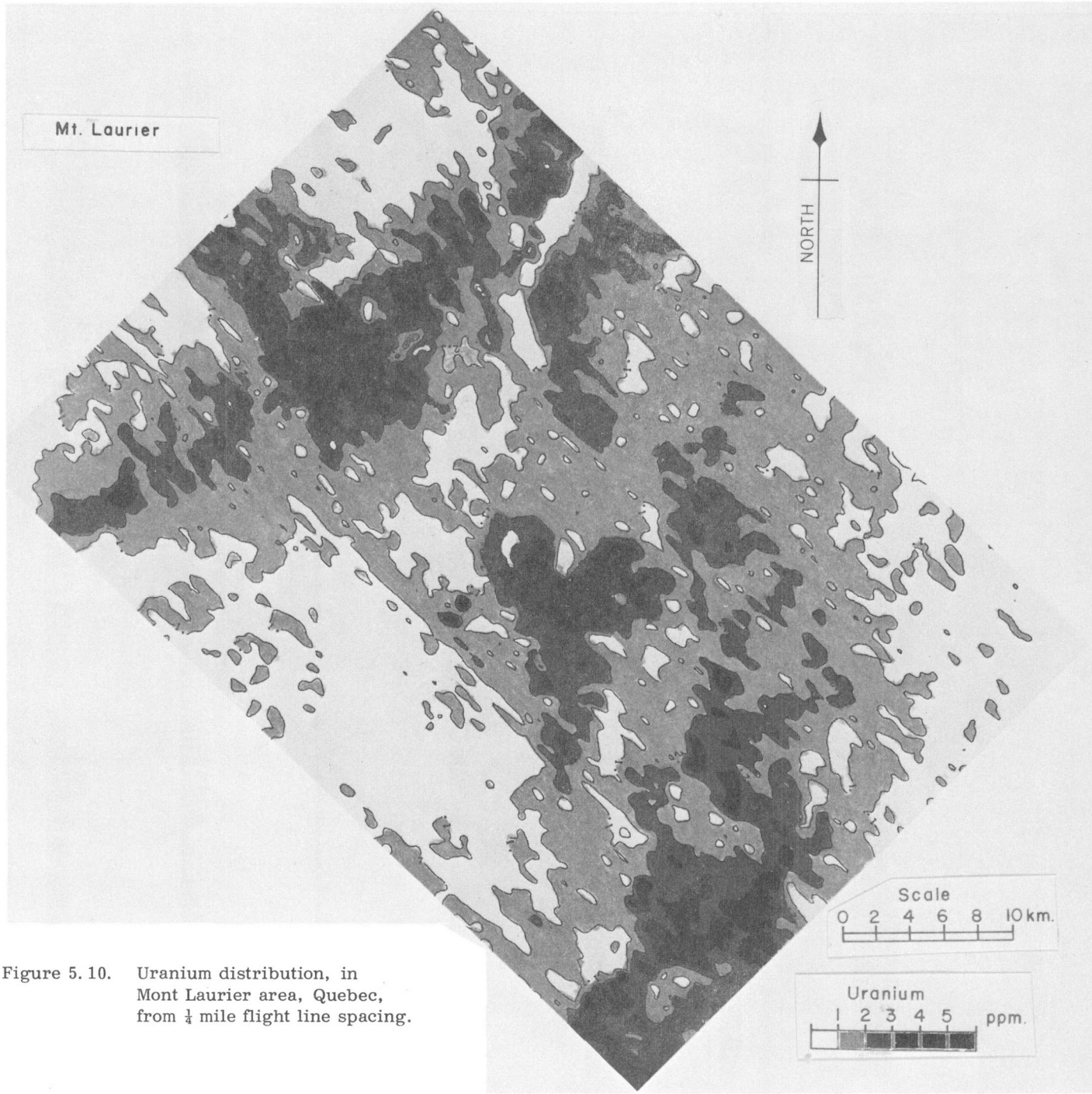

Figure 5. 10. Uranium distribution, in Mont Laurier area, Quebec, from ¼ mile flight line spacing.

The major costs of geochemical reconnaissance in Canada are sampling costs. It, therefore, would be missing a major opportunity to analyze samples for uranium alone, besides the fact that other metals may be associated with uranium and may in some circumstances be dispersed more widely. The samples which are collected under the program will be analyzed for a variety of constituents including zinc, copper, silver, cobalt, nickel, lead, mercury, molybdenum and arsenic. Thus the geochemical component of the program will provide data to assist in the search for and evaluation of a number of mineral commodities.

Implementation

Figure 5. 16 shows the steps involved in the organization of the geochemical component of the program. The principal part of the work will be carried out by Canadian contractors. Sampling and analytical work will be separate contracts. This is done in order that the Geological Survey may introduce blind duplicate samples and control standards for analytical quality control. This approach also reduces the number of persons with access to economically sensitive information on the location of anomalous samples. Orientation

NORTHERN SASKATCHEWAN 1973

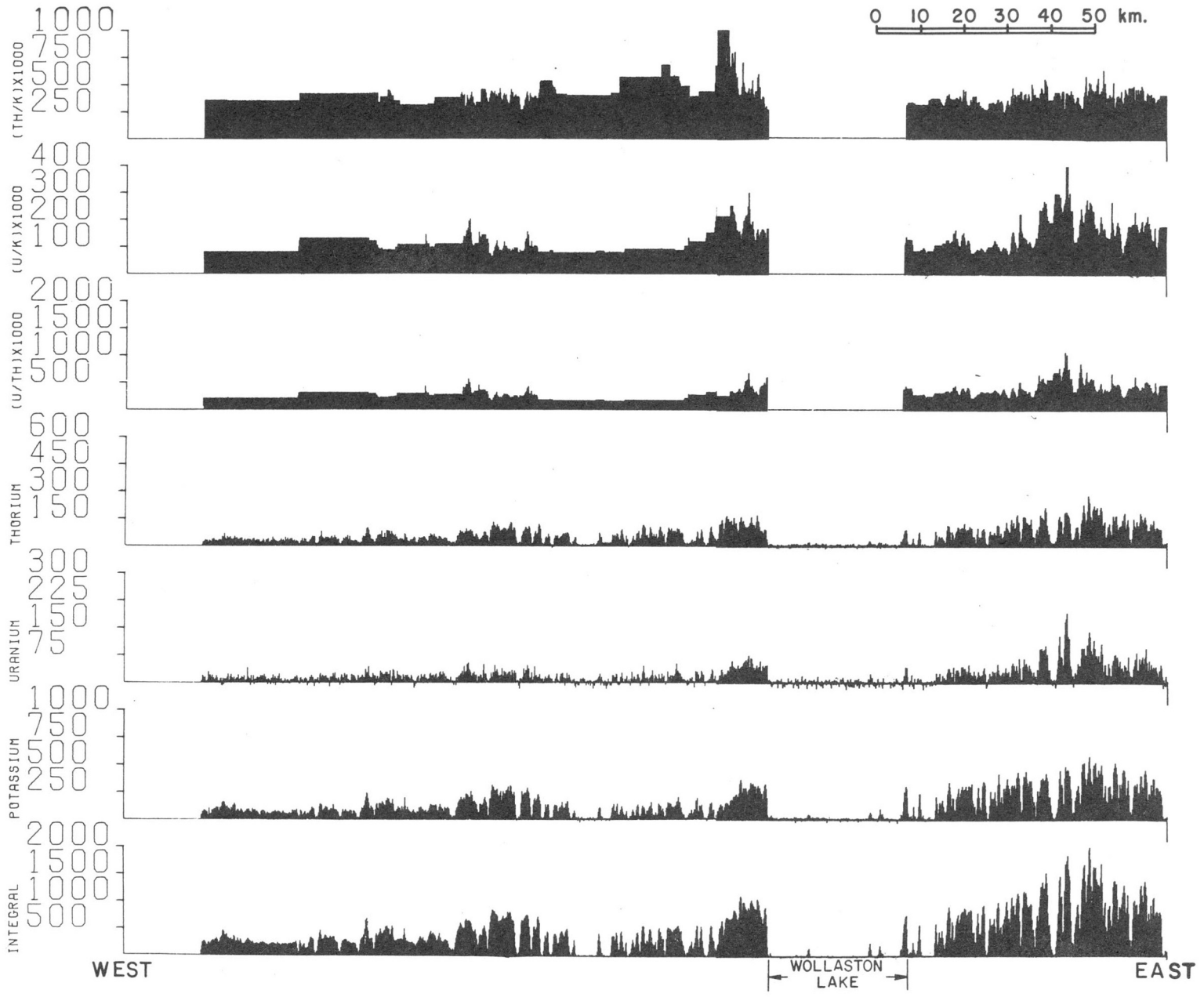

Figure 5.11. Profile across part of N. Saskatchewan, at about 58°10'N.

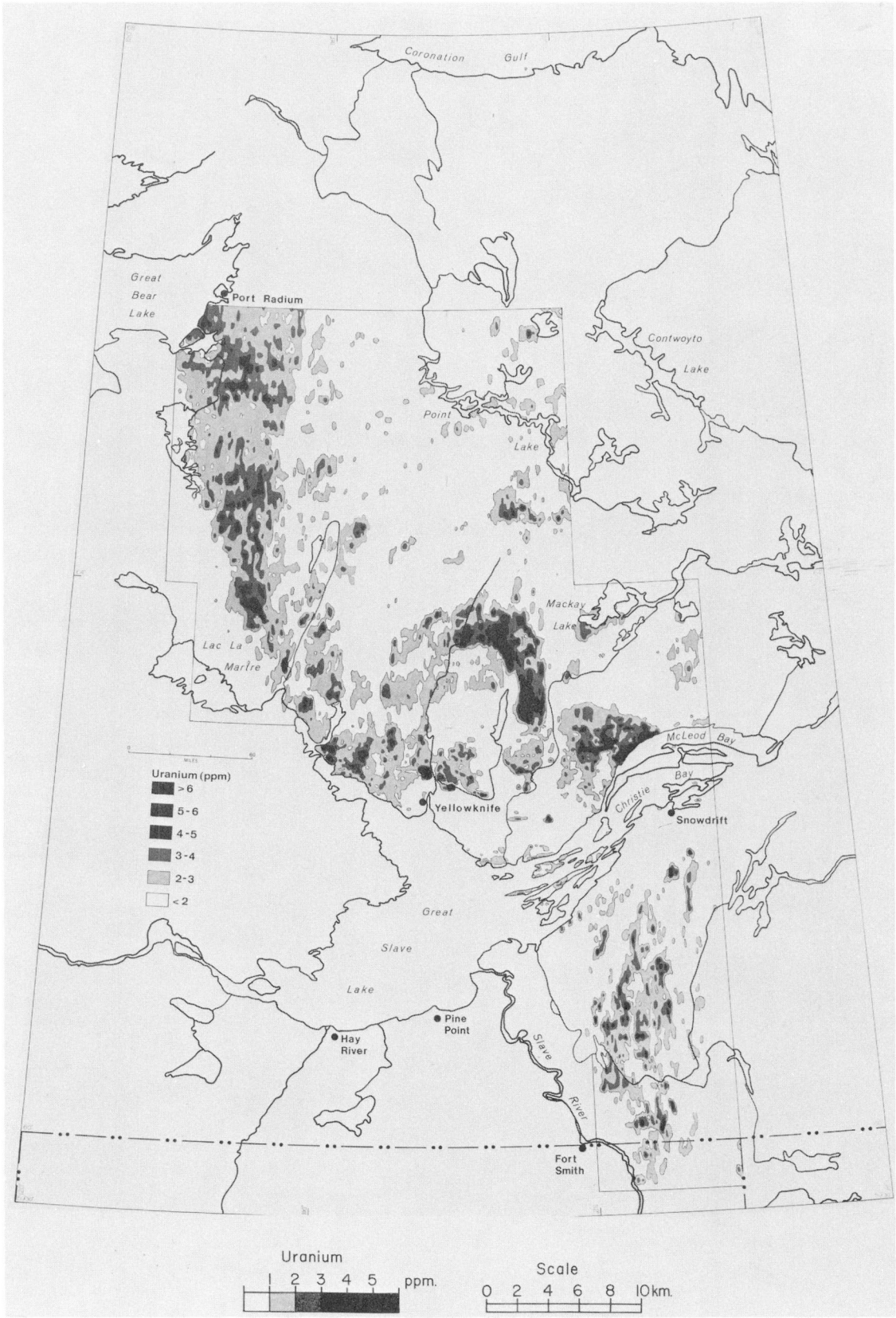

Figure 5.12. Uranium distribution, northwest margin of Canadian Shield.

Figure 5. 13. Suitability of various geochemical reconnaissance methods to different regions of Canada.

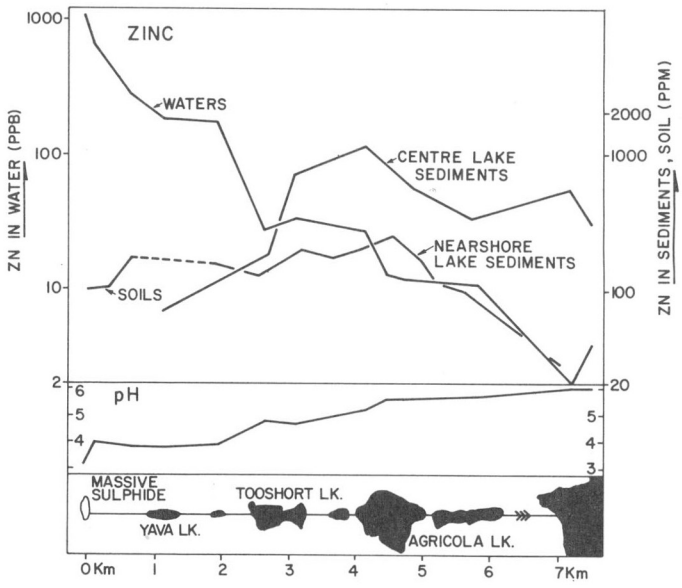

Figure 5. 15. Dispersion of mobile metal (zinc) from an orebody in a region of permafrost.

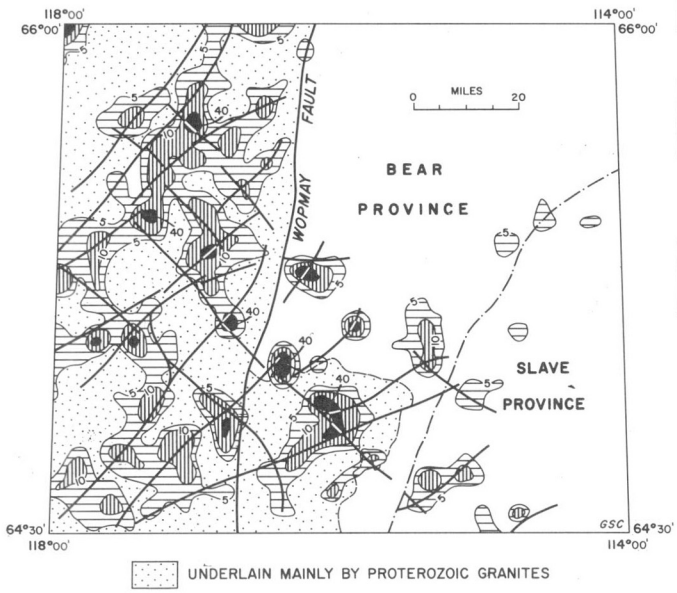

Figure 5. 14. Uranium distribution in Bear Province, from lake sediment geochemistry survey.

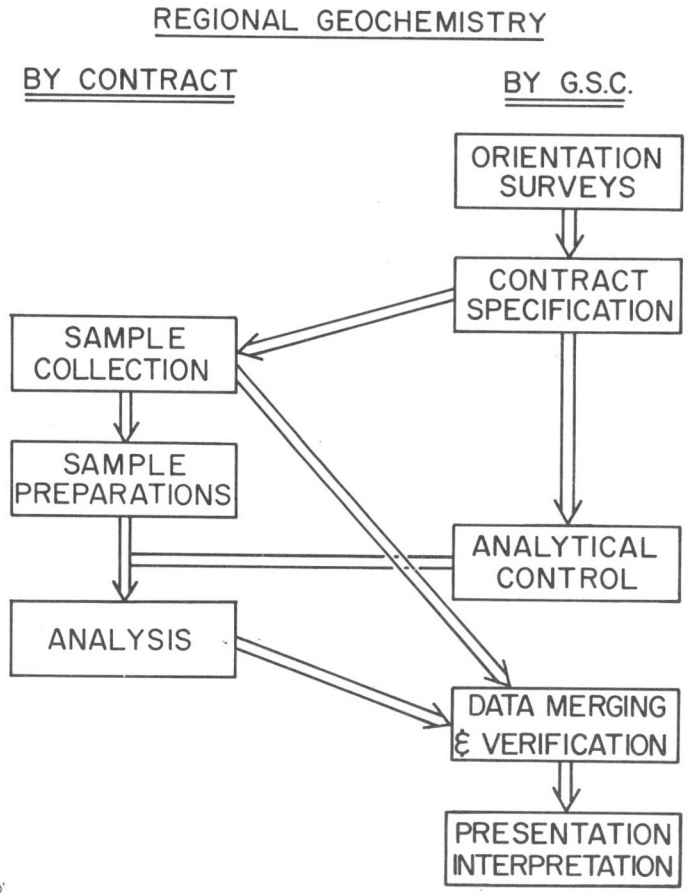

Figure 5. 16. Organization of regional geochemical surveys undertaken by the Geological Survey of Canada for the Uranium Reconnaissance Program.

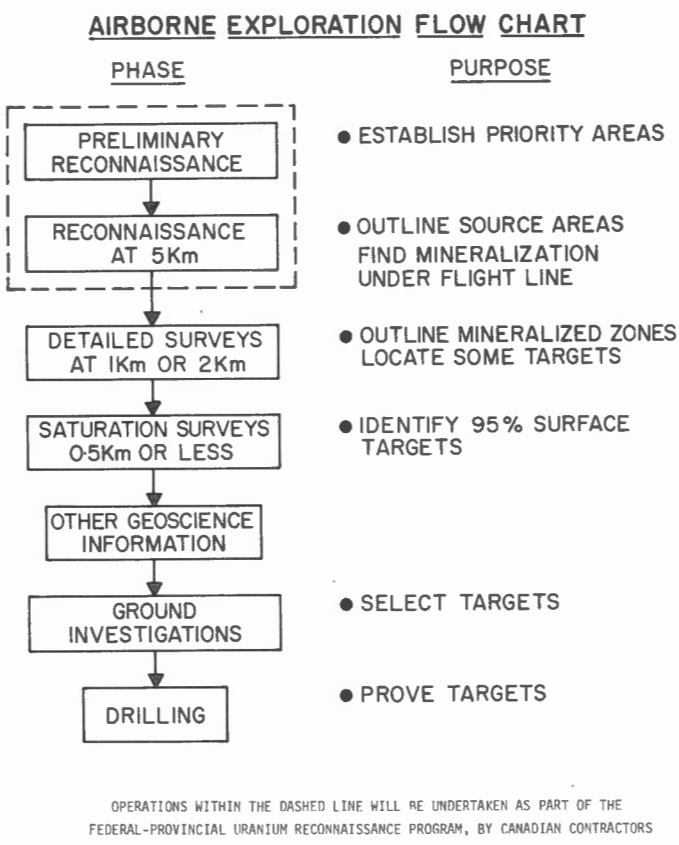

Figure 5.17. The relationship of airborne radioactivity surveys sponsored under the Uranium Reconnaissance Program, to the exploration sequence.

surveys carried out by Survey personnel are an essential part of setting up contract specifications. Although not shown on this sequence chart, it is hoped that Federal and Provincial staff will carry out a limited number of follow-up studies in order to verify the effectiveness of the methods, and to advise on methods of interpretation.

A similar schematic diagram can be shown for the airborne component of the program (Figure 5.17). This shows how the program is intended to fit into a total exploration sequence. The program will provide the first two phases contained within the dashed line. This work will be undertaken by Canadian contractors, as has been the case with the aeromagnetic program. Except for a few limited studies to be carried out by the Geological Survey as part of its on-going scientific investigations of type areas of mineralization, the initiative and responsibility for the remaining phases of the total exploration program must rest with industry. The Geological Survey of Canada is endeavouring to continue its traditional role of providing the best possible basic scientific information as guidelines for industrial initiative.

Present planning calls for the program to cover approximately two thirds of the land area of Canada at the reconnaissance level over the next ten years. The activities will be integrated to the greatest extent possible with related work being undertaken in connection with various Federal-Provincial Mineral Development Agreements sponsored by the Department of Regional and Economic Expansion. Contracted operations will commence in the summer of 1975 but these will not be fully established until 1976. Surveys in 1975 will include geochemical surveys in one province, and two separate areas in the Territories, plus airborne surveys in at least three provinces and the Territories. Geochemical orientation surveys, preparatory to future more extensive surveys will be undertaken by Survey personnel in both the Maritimes and Baffin Island, and probably also in other areas. The stakes are high in the search for uranium, and time, is short.

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APPENDIX 5.1

LIST OF AIRBORNE RADIOACTIVITY SURVEYS FLOWN BY THE GEOLOGICAL SURVEY OF CANADA

OPEN FILE NUMBER	AREA	FLIGHT LINE SPACING
22	1969 Cross-country	double profile across Shield (not shown on index map)
45	Bancroft, Ontario	¼ mile
63	Uranium City, Saskatchewan	2 km
75	Elliot Lake, Ontario	½ km
101	Fort Smith, N.W.T.	5 km
110	Mont Laurier, Quebec	¼ mile
124	Yellowknife, N.W.T.	2.5 km
140	Bear-Slave, N.W.T.	5 km
169	Northern Saskatchewan 53°N-60°N	50 km
188	Marian River, N.W.T.	5 km
242	Wollaston Lake, Saskatchewan	1 mile
254	Tazin Lake, Saskatchewan; Blind River, Ontario; Havre St. Pierre, Quebec; Prince Edward Island; Burin Peninsula, Newfoundland (uranium contour maps only)	5 km
257	Tazin Lake, Fond du Lac, Stony Rapids, Phelps Lake, Saskatchewan	5 km
258	Hatchet Lake, Saskatchewan	½ mile
259	Black Lake, Saskatchewan	½ mile
262	Blind River, Ontario	5 km
264	Ottawa-Arnprior Area, Ontario	½ km
269*	Prince Edward Island	5 km
270*	Burin Peninsula, Newfoundland St. George's Basin, Newfoundland	5 km 2 km
271*	Havre St. Pierre, Quebec Johan Beetz, Quebec	5 km 1 km

All the above Open File releases, except 22 and 169, comprise both flight line profiles and contour maps showing integral, potassium, uranium, thorium corrected count rates, and U/Th, U/K, Th/K ratios. The contour maps are intended to provide an overall view of radioelement distribution, whilst profiles provide detailed information along the flight lines. Open Files 22 and 169 comprise profiles only.

Open Files 101, 124, 140 and 188 provide continuous coverage of the western edge of the Shield from approximately 59°45'N to 66°N.

All are available for reference in the Geological Survey of Canada Library, 601 Booth Street, Ottawa. Copies may be purchased from K.G. Campbell Corporation Ltd., 880 Wellington Street, Ottawa, K1R 6K7.

*To be released in June 1975.

APPENDIX 5.2

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APPENDIX 5.3

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