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Assessment of uranium deposit types and resources — a worldwide perspective

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FOREWORD

While there is uncertainty about the long term utilization of nuclear power, it is expected that its use may continue for many years given its environmental advantages and ability to contribute to the reduction of greenhouse gases and other undesirable substances. A modest growth is expected notably in eastern Europe and Asia. In 1997 only about 60% of the annual uranium requirements to fuel the existing nuclear power reactors was met through uranium production. The rest was primarily met by inventory drawdown.

Continuing fluctuations of the uranium spot price, which has remained below the production price of most production centres, has not provided the incentive for expansion of the world uranium production. However, with excess inventories expected to be used up over the next few years, expansion of several existing, as well as opening of new production centres, is being planned.

The Technical Committee Meeting on Recent Development in Uranium Resources, Production and Demand was held in Vienna from 10 to 13 June 1997. The meeting, held in co-operation with the OECD Nuclear Energy Agency, was successful in bringing together 41 specialists representing 22 Member States and one non-governmental organization (Uranium Institute). A total of 23 papers were presented, describing a wide variety of activities related to the theme of the meeting. The last meeting on the same theme was organized by the IAEA in Vienna in May 1993. The current meeting was convened to review all new developments that might influence world uranium resources, supply and demand in the immediate future. As indicated by the contributed papers, the TCM was very successful in obtaining information on most of the major production facilities that are expected to meet uranium requirements over the next 10 years and beyond. The review of the economics of some of the known resources, particularly in the Russian Federation and Central Asia, is of special interest.

The IAEA is grateful to those participants who contributed papers and took part in the discussion. Thanks are also extended to the session chairmen: R.Whillans (Canada), J. Surán (Czech Republic), F. Barthel (Germany), and L. Ainslie (South Africa), as well as to: F. Dahlkamp (Germany), and D. McCarn (United States of America), who together with F. Barthel, conducted the Panel Discussion on the estimation of the world's undiscovered uranium resources. The IAEA staff member responsible for the organization and implementation of the meeting and for the present publication was D.H. Underhill of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

SUMMARY 1

The new UN international framework classification for reserves/resources
and its relation to uranium resource classification 9
F.H. Barthel, D. Kelter
An analytic uranium sources model...27
C.E. Singer
New development stage of China's uranium industry..39
Zhang Rong
The uranium industry in the history of the Czech Republi and recent developments 45
J.Surán, P. Veselý
The current uranium exploration activities of the Power Reactor And Nuclear Fuel
Development Corporation (PNC), Japan 53
H. Miyada
Characteristics of uranium districts of the Russian Federation..61
A.V. Boitsov, A.L. Nikolsky
Industrial types of uranium deposits in Kazakhstan 77
G.V. Fyodorov
South African uranium resources — 1997 assessment methodology and results.....................85
L.C. Ainslie
Uranium favourability and evaluation in Mongolia (Phase II),
recent events in uranium resources and production in Mongolia..93
T. Batbold
Current uranium activities in Pakistan...101
M.Y. Moghal
Production of uranium in Navoi Mining and Metallurgy Combinat, Uzbekistan...................117
N. Kuchersky, E.A. Tolstov, A.P. Mazurkevich, S.B. Inozemtsev
Status of uranium in Brazil 119
S.A. Majdalani, A.M. Tavares
Bhima Basin, Karnataka, India uranium mineralisation in the Neoproterozoic 129
K.K. Achar, S.A. Pandit, V. Natarajan, M.K. Kumar, K.K. Dwivedy
Investigation of the characteristics of sandstone type uranium deposits
in the Patagonia region: Recent advances 141
P.R. Navarra, G.C. Tomellini, N.M. Marveggio
McArthur River Project, Saskatchewan, Canada...149
G.D. Pollock
Recent developments in Australia's uranium mining industry..159
A.D. McKay
The Crownpoint and Churchrock uranium deposits, San Juan Basin, New Mexico:
An ISL mining perspective...171
D.W. McCarn
The McClean Lake uranium project 185
J.R. Blaise
Market outlook for Australian uranium producers 195
M. Lindsay
Uranium recovery from phosphate fertilizer in the form of a high purity compound............213
F. Bunus, T. Coroianu, G. Filip, D. Filip

Reliability and deviations of radiometric data 219
M. Matolín
Contribution to characteristics of uranium oxides 223
R. Fritsche, F.J. Dahlkamp
Regularities of mineral and commercial ore types: Location in
uranium deposits of Streltsovsky District (Russia) 239
A. Nikolsky, A. Schulgin

LIST OF PARTICIPANTS 251

SUMMARY

The world has experienced a depressed uranium market price for about two decades. Consequently, world uranium production has been in the decline for nearly as long. This is despite the fact that uranium production has been meeting only 50 to 60 per cent of world requirements to fuel the existing nuclear power reactors. A small percentage of growth in nuclear power generation is expected at least for the next fifteen years. Projections in the 1997 Red Book indicate uranium demand is expected to grow from 63 800 t U in 1997, to between 62 500 and 82 800 t U in 2020.

Increases in the uranium spot price after mid-1994 appeared to signal the beginning of a more stable market that would encourage producers to expand uranium output. The recent prices, however, have remained below the value considered sufficient to justify reactivation and development of many of the presently dormant uranium deposits.

The majority of the papers presented at this meeting report historical reviews and recent developments in the uranium related activities in their respective countries (Australia, Brazil, China, Czech Republic, Kazakhstan, Japan, Mongolia, Pakistan, the Russian Federation, South Africa, Uzbekistan). A number of papers described new developments or expansions of production centres in Australia (Olympic Dam, Ranger, Jabiluka, Kintyre, Honeymoon and Beverley), Canada (McArthur River and McLean) and the United States of America (Crownpoint and Churchrock). Several of these projects are expected to contribute to increased world uranium production over the next five or more years. Based on the plans described in this publication, a significant increase in uranium production can be expected, particularly in Australia. The reports indicate that much change is under way or expected regarding the production centres that will provide a major portion of the world uranium supply in the early part of the 21st century. It is also important to note that a few of the projects described here will be capable of providing uranium for several decades.

A comprehensive review of the respective country's resources is presented by Boitsov and Nikolsky for the Russian Federation, and in two separate papers by McKay and Lindsay for Australia. A similar review for Kazakhstan, with a reflection on the current economic situation, is also of interest. The papers from Argentina, India and Pakistan review recent exploration activities focusing on those areas considered to have the greatest potential. These, and papers noted earlier, provide supportive information for understanding the joint IAEA and OECD/NEA world report: "Uranium Resources, Production and Demand", or the "Red Book".

Other related publications are: IAEA-TECDOC-823, Recent Developments in Uranium Resources and Supply, IAEA-TECDOC-961, Changes and Events in Uranium Deposit Development, Exploration, Resources, Production and the World Supply–Demand Relationship; and IAEA-TECDOC-1033, Critical Review of Uranium Resources and Production Capability to 2020.

Based on presentations at this meeting it is expected that a significant change in uranium development and expansion will take place over the next five years or more. Based on past experience, and the uncertainty of the uranium market, some of these plans may not materialize, or may be significantly delayed.

To provide background and place the proceedings of this Technical Committee Meeting in perspective, an overview of world uranium activities is provided here. Additional information is available in the publication: Uranium Resources 1999 – Resources, Production and Demand, which is jointly prepared by the OECD/Nuclear Energy Agency and the IAEA and published by the OECD (Paris, 2000). The long term perspective is provided in IAEA Special Publication Analysis of Uranium Supply to 2050 (IAEA, Vienna, 2001).

Overview of uranium resources, production and demand

The world uranium market continues to experience dramatic changes due to important trends observed in nuclear power generation, and political and economic developments in uranium producing and consuming regions of the world. In particular, several events that have taken place over recent years may well foreshadow developments in the next decades.

The changes in uranium supply, which have been ongoing, were accelerated in 1997 and 1998, and are expected to continue over the next several years. The modifications involve the relatively rapid market introduction of new supplies from non-production sources, as well as major changes within the uranium production industry. The availability of information regarding the amount of uranium held in inventory by utilities, producers and governments has increased. As a result the market uncertainty regarding these inventories has decreased. Uncertainty still exists, however, regarding the magnitude of the inventory in the Russian Federation and the availability of secondary supplies from other sources.

Since the beginning of commercial exploitation of nuclear power in the early 1960s and up to the mid 1980s, the uranium market, in world regions excluding Eastern Europe and the former Soviet Union, was characterised by an over supply situation. Over supply was mainly the consequence of a lower than expected nuclear electricity generation growth rate. Although limited information is available, it also appears that production substantially exceeded reactor requirements in Eastern Europe and the former Soviet Union extending to 1994. The political and economic reorganisation of this region in the early nineties resulted in major steps toward development of an integrated world uranium market. A consequence of the decrease in political tensions between the East and West has been greater availability of uranium supplies from the former Soviet Union and the successor republics of Kazakhstan, the Russian Federation, Ukraine and Uzbekistan.

World over-production, lasting until 1990, and the availability of excess inventories resulted in uranium spot prices dropping in 1994 to their lowest level in 20 years. Between 1990 and 1994 there were severe reductions in many sectors of the world uranium industry including exploration, production and production capability, despite the continuous growth in world uranium requirements. This decreasing supply situation combined with growing demand for new uranium purchases resulted in a recovery in uranium prices from October 1994 through mid-1996. This trend, however, has reversed and uranium prices have fallen sharply through mid-1999.

World uranium mine production decreased from 1988 until 1994 despite the continuous growth in world uranium requirements. Production then increased in 1995, 1996 and 1997, before falling back in 1998. In 1996 production grew by about 9% over 1995 to 36 200 t U. Production in 1997 was about 36 700 t U, and then declined by about 5% to 35 000 t U in 1998. During 1997 and 1998 Canada remained the leading producer contributing just over 30% of the annual total. The decrease in production in 1998 was primarily caused by the oversupply of uranium offered at very low prices and the resulting decline in both the long-term and spot market prices. Starting in 1993 production from mines has met less than 60% of world reactor demand. Over much of the period to 1998 the balance was met by surplus uranium produced prior to 1990 to meet both expected civilian requirements and demand for military uses.

Following an increase in medium and long-term prices from 1994 to mid-1996, prices again sharply declined in 1997 and 1998. After medium and long-term prices on the US market increased by US\$ 2-3/lbU_3O_8 for domestic and foreign purchases between 1995 and 1996 there was again a downturn of US\$1.50-2/lb U_3O_8 through 1998 . Following an increase of nearly US\$3/lbU_3O_8 in 1997 the EURATOM multi-annual contract price also fell by less than US\$1/lbU_3O_8 in the same period. The spot-market price continued as a two-tiered system, with some countries allowing unlimited imports from the Newly Independent States (un-restricted) and others (mainly the USA and the European Union) imposing restrictions. Following a recovery of the unrestricted price from its lowest point of about US\$7/lbU_3O_8 in 1994 to about US\$15.50/lbU_3O_8 by mid-1996 the price plunged to US\$9.65 by the end of 1997 and continued down to US\$8.45 by year-end 1998. The corresponding restricted price increased to US\$16.50/lbU_3O_8 by mid-1996. From September 1996, however, spot market prices started to decrease, reaching about US\$ 12/lbU_3O_8 and US\$ 8.75/lbU_3O_8 respectively by year-end 1997 and 1998.

Production

Now that nearly all of the uranium producing countries provide official reports of annual production, it is possible to have a better understanding of worldwide uranium production. (China, India and Pakistan do not provide official reports.) After reaching its lowest level for several decades in 1994 (about 31 600 t U), mine production increased to about 36 700 t U in 1997. It then fell to 34 900 in 1998. In 1997 and 1998 over 90% of world production was from the 10 major producing, each of which produced over about 1000 t U, or more. (In 1997 Canadian production reached 12 030 t U before falling back to 10 922 t U in 1998. Australian production increased by 10% to 5488 t U in 1997 before falling back to about 4910 t U in 1998. Increases in production in Niger (1997 output: 3 487 t U), Namibia (2 905 t U) and Uzbekistan (1764 t U) in 1997 were offset by decreases in France, Gabon, Kazakhstan, South Africa and USA. In 1998 the increases in Gabon (1998 output: 725 t U), Kazakhstan (1 270 t U), Niger (3 714 t U) and Uzbekistan (1 926 t U) were more than offset by the decreases in all of the other major producing countries.

The Newly Independent States (NIS) Kazakhstan, Russian Federation, Ukraine and Uzbekistan have a long history of uranium production. They continue to be major suppliers. Following a continual decline in production from 1988 (15 000 t U) to 1996 (6274 t U), cumulative annual output from these countries stabilized over the 3 year period – to 1997 (6434 t U) and 1998 (6726 t U). This is equivalent to about 17% to 19% of world production. There are ongoing projects to develop new uranium mines in all of these countries using in situ leach (ISL) technology.

About 49% of the production in 1997 was from open-pit mining, versus 32% from underground. About 13% was produced using ISL technology. The balance was produced by other methods. The distribution by mine-type remained about the same in 1998. The increasing importance of open-pit mining as compared with 1996 was caused by closure of underground mines and increased output from existing large open-pit mines.

Several significant changes have occurred in production facilities in individual countries. The changes include the closure of smaller centers with higher production costs. These centers are being replaced by the expansion of facilities of some low cost producers, and the development of new high grade mines that are in the construction and licensing stage. As a result the world uranium production capability of existing and committed centers increased about 7% from 1997 to 1999. In Canada all production comes from three high-grade ore bodies located in northern Saskatchewan. For three additional new mining projects the process of regulatory and environmental approval made progress in 1998. In 1998 authorization was received to use the Key Lake processing facility to process ore from the new McArthur River mine. Construction and licensing activities continued on the new McClean mine-mill project. The start-up of these new production facilities is contingent on the receipt of licenses and on decisions made by the owners regarding market developments.

In Australia the milling capacity at Ranger was expanded to 4240 t U/year by mid-1997, while construction was underway to increase the milling capacity at Olympic Dam by more than 200% to 3900 t U/year. In early 1998 the operator of the Beverley in situ leach project commenced field testing for a new operation planned to produce 850 t U/year starting by 2000. In the USA, production decreased from 2432 t U in 1996 to 1810 t U in 1998. In 1998 the Uncle Sam phosphate by-product operation closed, while the new Smith Ranch ISL operation started production. No additional new projects are expected to come on-stream unless market conditions become more favorable.

In other countries in 1997 mines were closed in Brazil, France, Hungary and South Africa. In 1998 the small phosphate uranium by-product plant in Belgium was closed. No other new mines were brought into production in either 1997 or 1998. Increased production in Namibia and Niger was the result of improved capacity utilization in existing mines and mills. South Africa has seen a cut in production, because uranium is recovered primarily as a by-product of gold mining, and is thus dependent on the gold market price. Increased production costs at deep underground mines have forced un-profitable projects to close.

A summary of the changes that occurred or are expected to occur in uranium production facilities in the 1997–1999 period and following years include:

Facility closures

- 1997: Brazil (Poços de Caldas, 425 t U); France (Lodève 1 000 t U); Hungary (Pécs, 650 t U); South Africa (Western Areas, 200 to 200 t U);
- 1998: Belgium (PRT Phosphate, 45 t U); USA (Uncle Sam Phosphate, 290 t U);
- 1999: Canada (Eagle Point, 3 900 t U); Gabon (Mounana, 540 t U); USA (Kingsville Dome ISL, 500 t U); Rosita ISL Mine, 380 t U; Sunshine Bridge Phosphate, 160 t U);
- 2000: Canada (Cluff Lake, 1 900 t U); Spain (Fe Deposit, 800 t U).

New mine opening

- 1998: USA (Smith Ranch ISL, 769 t U).
- 1999: Australia (Beverley, 760 t U); Brazil (Lagoa Real, 300 t U); Canada (McClean Lake, 2 300 t U).

Expansion of exiting facilities

- 1999: Australia (Olympic Dam facility expansion by 2 290 t U to 3 900 t U and Ranger mill expansion of 1 270 t U to 4 240 t U); Canada (Key Lake mill).

New mines planned

- 2000: Australia (Honeymoon, 850 t U); Canada (McArthur River, 6 900 t U to be processed through expanded Key Lake mill); Russian Federation (Transural ISL project, capacity not published).
- 2002: Canada (Cigar Lake, 4 600 t U to be processed though McClean Lake and Rabbit Lake mills).

Resources and exploration

Much more complete information for uranium resources with low production costs of US$ 40/kgU (US$ 15.40/lb U_3O_8), or less, are available than at the time of the last Survey. The improved information is reported in the recent publication *Uranium 1999–Resources Production and Demand,* a joint report of the OECD Nuclear Energy Agency and the International Atomic Energy Agency. The so-called "Red Book" contains information on nearly forty countries that have reported uranium resources. The resources are classified by the level of confidence in the estimates, and by production cost categories. The known resources are classified into Reasonably Assured Resources (RAR) and Estimated Additional Resources I (EAR-I), and this is followed by a breakdown of undiscovered resources – EAR-II and Speculative.

World RAR recoverable at a cost of US$ 130/kgU (equivalent to US$ 50/lbU_3O_8) or less, amount to 2.96 million t U, while those recoverable at US$ 80/kgU (US$ 30/lbU_3O_8) or less, are 2.27 million t U. Furthermore RAR recoverable at US$ 40/kgU (US$ 15/lbU_3O_8) or less, for thirteen reporting countries, are more than 1.25 million t U. For the first time Canada, which holds 31% of these resources, reported in this category.

In addition, EAR-I recoverable: at US$ 130/kgU or less, have been estimated as 990 000 t U; at US$ 80/kgU or less, as 728 000 t U; and at US$ 40/kgU or less, at more than 338 000 t U. (These totals exclude EAR for the USA, as the USA does not provide separate estimates for EAR-I and EAR-II).

By comparison with the world totals in tables 6.1 and 6.2, the tonnages of RAR and EAR-I reported above have been adjusted by the NEA-IAEA to take into account estimated mining and milling losses not accounted for in some of the national estimates.

Because complete estimates for individual resource categories were not reported in previous editions of the Red Book, it is difficult to account for all of the changes. However, the estimates available indicate that world known uranium resources recoverable at US$ 130/kgU or less, decreased by about 8% between 1 January 1997 and 1 January 1999. In comparison, a decrease of only about 2.5% for RAR recoverable at US$ 80/kgU or less, occurred. The more complete information for resources in the US$ 40/kgU or less, category is very significant. This indicates that several countries possess uranium resources that can be mined at low cost.

These resources provide the potential for supplying uranium to the nuclear industry at a lower cost than would be the case if these resources were not available.

Annual expenditures on uranium exploration for 24 reporting countries increased by 37% to US$ 153 million in 1997. The increase of expenditures from 1996 to 1997 resulted from activities associated with advanced projects in Australia, Canada, the USA, the Russian Federation and India. Twenty-one countries reported exploration expenditure in both 1997 and 1998. The total exploration expenditures for these countries decreased from US$ 148 million to US$ 132 million, with decreases outnumbering increases by more than two to one.

Outlook

To understand the outlook for uranium it is necessary to consider recent history. Uranium is an unusual commodity because a major portion of market demand is met from sources other than new mine production. From 1991 through 1998 about 187 000 t U or nearly 40% of the total world requirements was met from non-mine supplies. During the early part of this period a major supply came from drawdown of the commercial inventory held by nuclear utilities. However with the passing of each year additional new sources have developed. For example, during the period 1992 to 1998 a total of 87 300 t U was delivered to the European Union from the Newly Independent States (Kazakhstan, Russian Federation, Ukraine and Uzbekistan), with the bulk of this material coming from the Russian Federation. During this period the Russian Federation was also using around 5700 t U annually for the production of nuclear fuel for reactors of Russian design. A total of about 17 800 t of Russian origin uranium was purchased by US utilities from 1993 to 1998. Analysis indicates that about 100 000 t or more, of Russian Federation origin stockpile uranium was used or sold over the period 1991 through 1998.

Another major source of uranium supply developed starting in 1995. This is based on a government-to-government agreement signed in February 1993 between the United States and the Russian Federation concerning the disposition and purchase of 500 t highly enriched uranium (HEU) from dismantled nuclear weapons. From 1995 to 1998 about 15 850 t U natural equivalent was delivered to the United States. About 1800 t U of this material was purchased and transferred to the United States Enrichment Corporation (USEC) for sale. The balance was held in stockpiles in the USA. In addition to the material from the Russian Federation it was anticipated that the 50 t HEU transferred from USDOE to USEC was expected to begin in 1999.

Other supplies that are being used in place of new mine production include re-enrichment of tails from the enrichment of uranium, use of mixed oxide (MOX) fuel and re-processed uranium.

It is anticipated that most of these supplies will continue to be available over the next 10 years or so. The greatest uncertainty is the size of the stockpile of natural and low enriched uranium in the Russian Federation, and how long this stockpile will continue to supply world markets. the Russian Federation has for nearly a decade been one of the largest uranium market suppliers. If this supply should end, or decrease significantly, it will be necessary to increase other supplies to make up the shortfall. Furthermore because of the ongoing closure of production facilities over the last decade or more, there is relatively little excess capacity or flexibility to increase mine production over the short term.

The total world uranium resources indicate that there are ample quantities to cover the demand of existing and planned nuclear power stations over the next decade. However, because of the amount of anticipated supply from non-production sources it is expected that mine production will continue to meet only a portion of the annual requirement over the next five to ten years.

The annual world uranium requirements are projected to fall within a range increasing from about 61 600 t U in 1999 to about 79 800 t U/year by 2015, or decreasing to about 54 500 t U/year by 2015. The annual production capability in 1999 was 45 800 t U, or about 75% of requirements. Projections based on available capability developments and the phase-out of existing mines show that the capabilities for 2015 may range between 42 000 and 62 000 t U/year.

Provided that non-production supplies continue to be available as projected the combination of mine and non-production supply could meet most of the requirements. However, if there is an unexpected interruption in supply a shortfall could develop. This could lead to unstable market conditions until the equilibrium between supply and demand is re-established.

Projections of production capabilities of planned and prospective centers supported by known resources indicate that major producer countries could increase their production from the current level by up to 30% by 2005. Viewed optimistically, this would help assure that the supply remains in balance with requirements. However, market uncertainties may postpone decisions regarding new facilities. Despite the uncertainties about converting military stockpiles to civilian use and the amount of weapons-grade material reaching the commercial market, the need for newly produced uranium will continue as long as nuclear electric generation continues.

THE NEW UN INTERNATIONAL FRAMEWORK CLASSIFICATION FOR RESERVES/RESOURCES AND ITS RELATION TO URANIUM RESOURCE CLASSIFICATION

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Abstract

Resources traditionally are classified according to the degree of geological confidence and economic attractiveness. Various names are in use to describe nationally the different resource categories. Commonly, proven, probable or A+B are terms for the category RESERVES, meaning the recoverable portion of a resource under prevailing economic conditions. Since 1965 uranium resources are classified by the Nuclear Energy Agency of OECD and International Atomic Energy Agency using the terms Reasonably Assured Resources (RAR) and Estimated Additional Resources (EAR) in combination with cost categories. The definitions for RAR and EAR have been refined over the time and cost categories have been adapted according to market developments. For practical purposes a comparison of RAR and EAR with major national classification systems is provided in each of the NEA-IAEA publication on "Uranium Resources Production and Demand" (Red Book). RAR of uranium are defined as quantities recoverable at given production costs with proven mining and processing technology, commonly RAR of the lowest cost category are referred to as Reserves. In 1992 the Committee on Energy — Working Party on Coal of the UN Economic Commission for Europe (UN/ECE) started to develop a new scheme for resource classification under the coordination of one of the authors (Kelter). The main purpose was to create an instrument permitting the classification of reserves and resources on an internationally consistent and uniform basis using market economic criteria. In April 1997 the UN/ECE approved the new "United Nations International Framework Classification for Reserves/Resources-Solid Fuels and Mineral Commodities" at its 50th Anniversary Session. The new classification will enable the incorporation of national systems into an unified framework in order to make them compatible and comparable. Assistance will be given to economies in transition in reassessing their deposits according to market economy criteria and to facilitate investments. The UN Framework Classification provides information about:

- the stage of geological assessment, subdivided into: Reconnaissance, Prospecting, General Exploration and Detailed Exploration,
- the stage of feasibility assessment, subdivided into: Geological Study, Prefeasibility Study and Feasibility Study/Mining Report,
- the degree of economic viability, subdivided into: Economic, Potentially Economic and Intrinsically Economic.

The Mineral Reserve is defined as the economically extractable part of the Total Mineral Resource, demonstrated by feasibility assessment. A numerical codification of the eight resource classes available was introduced to facilitate the application. Due to many similarities to the classification of uranium resources used by the NEA and IAEA the new UN Framework Classification can be used to classify uranium resources. In general Reasonably Assured Resources of the lowest cost category (presently economically extractable amounts) are consistent with the UN term Proved Reserve. It is therefore hoped that the UN Framework, which now will be tested internationally for three years, will be accepted by all countries and for all mineral commodities including uranium.

1. INTRODUCTION

In 1979 at the IAEA "International Symposium on Uranium Evaluation and Mining Techniques" (Buenos Aires, 1–4 Oct. 1979 J. Schanz [1] presented a paper on "The United Nations Endeavor to Standardize Mineral Resource Classification". Schanz was the leading rapporteur of an Expert Group of the UN which over years had prepared an international classification system using both criteria for geological assurance of resources and their economic recoverability. The Expert Group [2] recommended international application but closed its report with a cautionary statement saying: "If the classification system is placed into common use for international reporting of resource information, it will be only the first step towards general harmonization. The collection, aggregation and dissemination of resource estimations on a world-wide scale are at present only carried out regularly by the IAEA for uranium and the World Energy Conference for other energy resources". It is well known that individual countries and single mining companies are using standardized classification systems, but comparison of individual terms on an international scale remains to be difficult due to different terminology.

The OECD Nuclear Energy Agency and International Atomic Energy Agency are involved in collecting and evaluating uranium resource information since 1965 through an expert group which is now called the Uranium Group. General accepted terms are "Reasonably Assured Resources and Estimated Additional Resources — Category I" for Known Resources and "Estimated Additional Resources — Category II and Speculative Resources", for "Undiscovered Resources". The terminology presently in use has been revised and refined over the time. To accomplish economic characteristics the individual resource categories are further divided into cost categories.

The work for the new United Nations International Framework Classification for Reserves/Resources started in 1994 by the UN Economic Commission for Europe (ECE) Working Party on Coal. It has its roots in a proposal by the German Government in 1992 [3] based originally on a classification developed by one of the authors (Kelter) of the Federal Institute for Geosciences and Natural Resources in 1991 [4]. The predecessor of the present UN Classification, the so called Three Dimensional Reserve/Resource Classification System and its possible application for uranium was presented by both authors at the Technical Committee Meeting of the IAEA "Recent Developments in Uranium Resources and Supply" in May 1993 [5].

The UN International Framework Classification for Reserves/Resources: Solid Fuels and Mineral Commodities.

Working since many years with international organizations and in projects in different countries throughout the world on various mineral commodities including coal and uranium the Federal Institute for Geosciences and Natural Resources has realized the need for the harmonization of various existing classification systems for resources.

A proposal by Kelter in 1991 was considered by the working Party on Coal of the ECE which than started to create a Working Group. After preparatory consultations and collections of proposals from various nations, two workshops with international participation were conducted in 1994 and 1995, plus one ad hoc meeting 1995 and two Task Force meetings in 1995 and 1996. More than 60 countries were involved, providing information through questionnaire replies. Input was also received from the Council for Mining and Metallurgical Institutions (CMMI) and the United Kingdom Institution of Mining and Metallurgy (IMM). The final version was approved in Geneva 24 April 1997 by the ECE at its 50th Anniversary Session quoting:

"The classification framework will enable the incorporation of national and regional classification systems into a consistent, unified framework in order to make them compatible and comparable; help to enhance communication on a national and international level; provide for a better understanding and firmer knowledge of available reserves/resources; assist economies in transition in reassessing their solid fuels and mineral deposits according to market economy criteria; and facilitate investments, notably in transition and developing countries.

The classification framework has been endorsed by the Working Party on Coal and the Committee on Energy. In addition, the elaboration of the classification was supported by major coal and minerals producing non-ECE countries, among which were Argentina, Australia, Brazil, China, Columbia, Ethiopia, India, Indonesia, Iran, Malaysia, Philippines, South Africa and Thailand. More than sixty ECE and non-ECE countries participated in the elaboration of the Classification.

The new system is available as full text in the Final Version "United Nations International Framework Classification for Reserves/Resources — Solid Fuels and Mineral Commodities" [6] through UN Economic Commission for Europe in Geneva. The same is also available as Executive Summary [7].

Taking the objectives of the new classification into account the system provides information about the three stages of resource assessment (Figure 1).

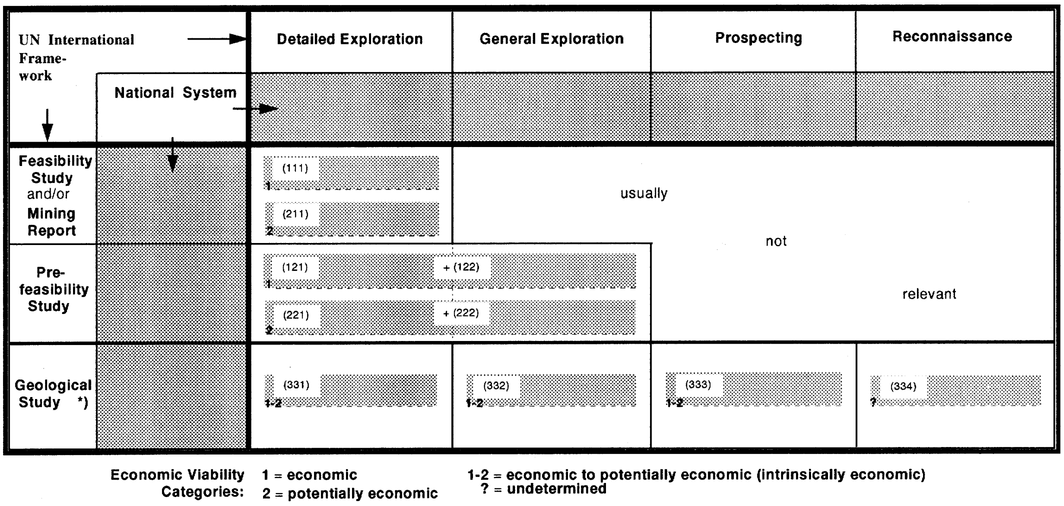


FIG. 1. Matrix: United Nations International Framework Classification for Reserves/Resources — Solid Fuels and Mineral Commodities.

- Geological Assessment: Reconnaissance, Prospecting, General Exploration and Detailed Exploration. These conveniently provide four categories of resources with increasing degree of geological assurance.

- Feasibility Assessment: Geological Study, Prefeasibiltity Study, Feasibility Study/Mining Report. These three categories are reflecting the degree of economic viability in increasing order of assurance.

- Economic Viability as obtained from the Feasibility Assessment and quoting whether a resource can be recovered under prevailing economic conditions i.e. *proved mineral reserve* or has to be considered as *potentially economic*.

The above given terms and definitions are explained in detail in the annex of the Final Version (see appendix).

As described in detail in the Final Version the new classification system provides:

"The categorization of reserves/resources according to stage of assessment, which reflect the successive stages of investigation generally undertaken in standard professional practice in all mining countries, makes the UN Framework Classification applicable to all solid fuels and mineral commodities. The terms used for these stages are considered to be familiar to all users, not only to geologists and mining engineers but also to investors, bankers, shareholders, and planners engaged with solid fuels and mineral commodities. The terms and definitions currently used in the existing classification systems can easily be related to and assigned to the corresponding stages of assessment of the UN Framework Classification, allowing the national terms to be maintained and making them comparable at the same time. In this way, the UN Framework Classification truly provides a framework integrating the diverse national classifications, enhancing national and international communication and reducing the risk of misinterpretation of reserve/resource figures derived from different classification systems."

Figure 2 represents the UN Framework Classification in the form of a table, which can be conveniently used for reporting and summing several individual deposits.

Deposit / Mine	Feasibility Study and/or Mining Report		Prefeasibility Study		Geological Study			
	Economic	Potentially economic	Economic	Potentially economic	Detailed Exploration	General Exploration	Prospecting	Reconnais-sance
	(111)	(211)	(121) (122)	(221) (222)	(331)	(332)	(333)	(334)
Total								

= National System

FIG. 2. Table: United Nations International Framework Classification for Reserves/Resources — Solid Fuels and Mineral Commodities.

If necessary, the main categories of the UN Framework Classification can be subdivided on a national level to allow for specific needs, thus giving the classification system the necessary flexibility.

For the level of global surveys such as those of the International Atomic Energy Agency, Nuclear Energy Agency, International Energy Agency and World Energy Council, the UN Framework Classification can be condensed as shown in Figure 3, which distinguishes four main classes.

During the preparation of the UN Framework Classification it became obvious to clearly distinguish between the terms *Reserve* and *Resource* which have a variety of meanings in national classifications, most of them with a long history. It therefore was agreed to incorporate the CMMI definition as a basis for further discussion about their use in national languages. The reason for giving preference to the CMMI definitions is that the terms are used by its members and are well understood by investors, shareholders and bankers in English speaking mining countries. The definition of the terms are given as:

- Total Mineral Resource: naturally occurring concentration of mineral raw material of economic interest and with specific geological certainty.

- Mineral Reserve: Economically mineable part of Total Mineral Resource as demonstrated by feasibiltiy assessment.
- Remaining Mineral Resource: the balance of the Total Mineral Resource that has not been identified as a Mineral Reserve.

According to the different stages of assessment Mineral Reserves and Remaining Mineral Resources can be subdivided in to eight classes as shown in figure 4.

Countries	**Prefeasibility Study, Feasibility Study** and / or **Mining Report**		**Geological Study**	
	Economic	**Potentially Economic**	**Detailed & General Exploration**	**Prospecting & Reconnaissance**
	(111) (121) (122)	(211) (221) (222)	(331) (332)	(333) (334)
Total World				

= International System Date :......................

Code: (123)

FIG. 3. Table for Worldwide Survey: United Nations International Framework Classification for Reserves/Resources — Solid Fuels and Mineral Commodities.

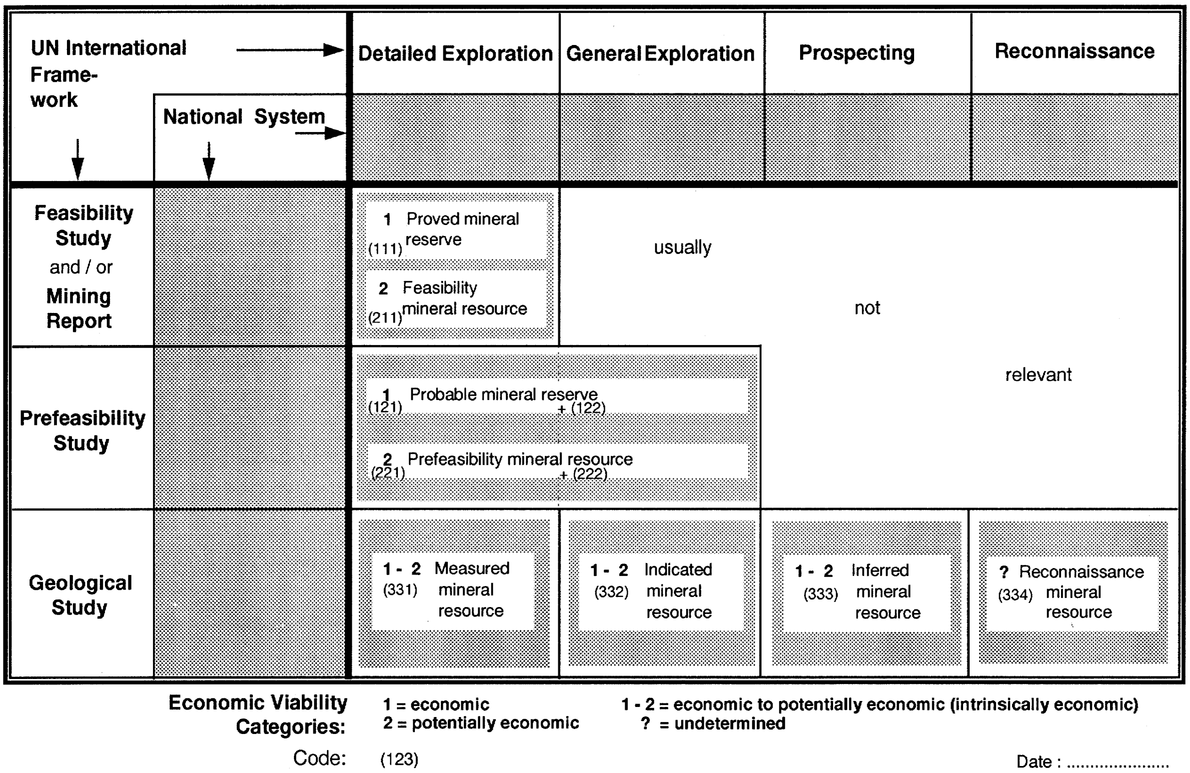


FIG. 4. Proposed UN Mineral Reserve/Resource Terminology: United Nations International Framework Classification for Reserves/Resources — Solid Fuels and Mineral Commodities.

In order to incorporate existing classification system into the UN Framework Classification and to simplify their comparison a codification was introduced as shown in figure 5.

The class coded 111 means a resource of prime interest. The first digit 1 refers to Economically Mineable Quantities, the second digit 1 means proved by a Feasibility Study and the third digit 1 means quantities are based on Detailed Exploration.

Each codified class has a specific set of assessment stages and economic viability degree which are arranged in a table (Fig. 5). According to this table it is possible to codify any kind of reserve and resource and to transfer any class from one system to another.

Resource classification for uranium

Since 1965 uranium resources are assessed by an expert group of the Nuclear Energy Agency of OECD and the International Atomic Energy Agency. This exercise is carried out in a two-years interval. Beside information on uranium resources data on exploration, annual uranium production and uranium demand are collected from requests sent do individual countries via questionnaire. The results are published biennially as "Uranium Resources Production and Demand" also known as the "Red Book". Until now 16 Red Books have been published, the next edition with data for 1997 in preparation.

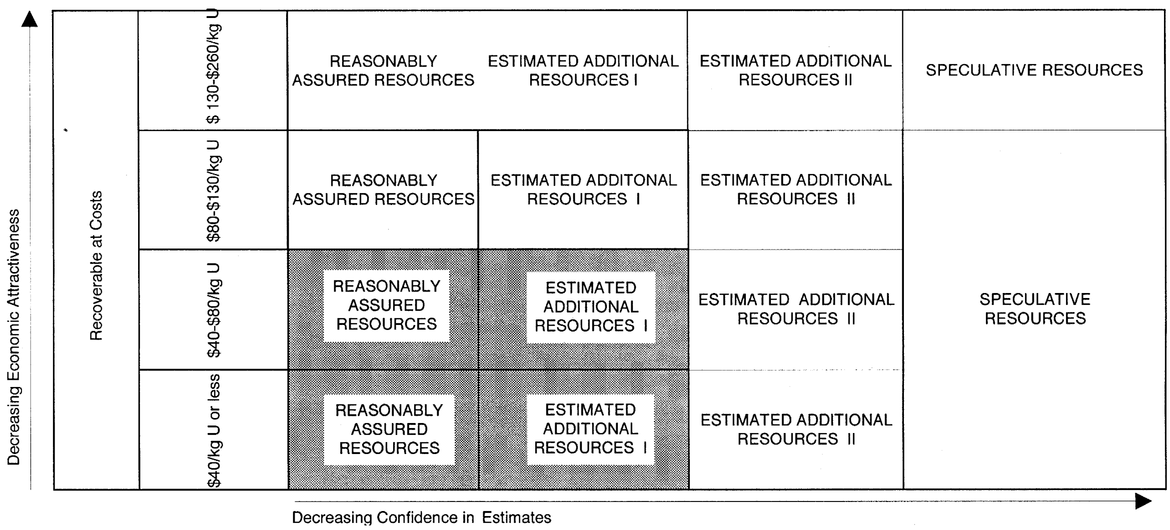
In order to achieve a common base, resources have been classified according to the degree of confidence of existence and the degree of economic attractiveness (Figure 6). Other than for other mineral commodities cost classes are applied describing to which costs estimated resources can be recovered.

The terminology and definitions have been refined over the time and cost categories have been adapted according to market developments. Similar to the approach in the UN Framework Classification a correlation of the terms with major national resource classification systems is provided to allow comparison (Figure 7).

Economic Axis	Feasibility Axis	Geological Axis	Code
Economic	Feasib.st.&Min. Rep.	Detailed Exploration	111
Economic	Prefeasibility Study	Detailed Exploration	121
Economic	Prefeasibility Study	General Exploration	122
Potentially Economic	Feasib.St.&Min. Rep.	Detailed Exploration	211
Potentially Economic	Prefeasibility Study	Detailed Exploration	221
Potentially Economic	Prefeasibility Study	General Exploration	222
Intrinsically Economic[1]	Geological Study	Detailed Exploration	331
Intrinsically Economic[1]	Geological Study	General Exploration	332
Intrinsically Economic[1]	Geological Study	Prospecting	333
Undetermined Economic	Geological Study	Reconnaissance	334

[1] Economic to potentially economic

FIG. 5. Codification of Classes



Source: Uranium Resources Production and Demand 1995
OECD-NEA and IAEA, Paris 1996

FIG. 6. NEA/IAEA Classification scheme for uranium resources.

The currently used terminology for uranium resource assessment is given below (from: Uranium Resources Production and Demand 1995) [8].

"Resource estimates are divided into separate categories reflecting different levels of confidence in the quantities reported. The resources are further separated into categories based on the cost of production. *All resource estimates are expressed in terms of metric tons (t) of recoverable uranium (U) rather than uranium oxide (U_3O_8).*

Resource estimates are expressed in terms of recoverable tonnes of uranium, i.e. quantities of uranium *recoverable from* mineable ore, as opposed to quantities *contained* in mineable ore, or quantities in situ. Therefore both expected mining and ore processing losses are to be deducted. *In situ* resources are recoverable resources in the ground not taking into account mining and milling losses.

Definitions of resource categories

Reasonably Assured Resources (RAR) refers to uranium that occurs in known mineral deposits of delineated size, grade and configuration such that the quantities which could be recovered within the given production cost ranges with currently proven mining and processing technology, can be specified. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of deposit characteristics. Reasonably Assured Resources have a high assurance of existence.

Estimated Additional Resources — Category I (EAR-I) refers to uranium in addition to RAR that is inferred to occur, mostly on the basis of direct geological evidence, in extensions of well-explored deposits, or in deposits in which geological continuity has been established but where specific data, including measurements of the deposits, and knowledge of the deposits characteristics are considered to be inadequate to classify the resource as RAR. Estimates of tonnage, grade and cost of further delineation and recovery are based on such sampling as is available and on knowledge of the deposit characteristics as determined in the best known parts of the deposit or in similar deposits. Less reliance can be placed on the estimates in this category than on those for RAR.

	← Known Resources →			← Undiscovered Resources →		
NEA/IAEA	Reasonably Assured		Estimated Additional I	Estimated Additional II	Speculative	
Australia	Reasonably Assured		Estimated Additional I	Undiscovered		
Energy, Mines and Resources Canada	Measured	Indicated	Inferred	Prognosticated	Speculative	
France	Reserves I	Reserves II	Perspective I	Perspective II		
Germany	Proven	Probable	Possible	Prognosticated	Speculative	
South Africa	Reasonably Assured		Estimated Additional I	Estimated Additional II	Speculative	
United States DOE	Reasonably Assured		Estimated Additional		Speculative	
NIS	A + B	C 1	C 2	P1	P2	P3
Czech Republic, Hungary, Romania	Reasonably Assured		Estimated Additional I	Estimated Addistionall II	Speculative	

The terms illustrated are not strictly comparable as the criteria used in the systems are not identical. „Grey zones“ in correlation are therefore unavoidable, particularly as the resources become less assured. Nonetheless, the chart presents a reasonable approximation of the comparability of terms.

Source: Uranium Resources Production and Demand, 1995
OECD-NEA and IAEA, Paris 1996

FIG. 7. Approximate correlations of terms used in major resources classifications systems for uranium resources.

Estimated Additional Resources — Category II (EAR-II) refers to uranium in addition to EAR-I that is expected to occur in deposits for which the evidence is mainly indirect and which are believed to exist in well-defined geological trends or areas of mineralisation with known deposits. Estimates of tonnage, grade and cost of discovery, delineation and recovery are based primarily on knowledge of deposit characteristics in known deposits within the respective trends or areas and on such sampling, geological, geophysical or geochemical evidence as may be available. Less reliance can be placed on the estimates in this category than on those for EAR-I.

Speculative Resources (SR) refers to uranium, in addition to Estimated Additional Resources — Category II, that is thought to exist, mostly on the basis of indirect evidence and geological extrapolation, in deposits discoverable with existing exploration techniques. The location of deposits envisaged in this category could generally be specified only as being somewhere within a given region or geological trend. As the term implies, the existence and size of such resources are speculative."

Cost categories

When estimating uranium resources in the above described categories an estimate of the costs of recovery of uranium by mining and ore processing should be given. For estimating uranium availability (short and median term) mostly cost categories for RAR and EAR I resources (known resources) are relevant.

Currently, the cost classes are

<$ 40/kgU = $ 15/lbU_3O_8

<$ 80/kgU = $ 30/lbU_3O_8

<$ 130/kgU = $ 50/lbU_3O_8

(conversion factor 1 kgU = 2.6 U_3O_8)

When estimating the cost of production for assigning resources within these cost categories, account has been taken of the following costs:

- the direct costs of mining, transporting and processing the uranium ore,
- the costs of associated environmental and waste management,
- the costs of maintaining non-operating production units where applicable,
- in the case of ongoing projects, those capital costs which remain unamortized,
- the capital cost of providing new production units where applicable, including the cost of financing,
- indirect costs such as office overheads, taxes and royalties where applicable,
- future exploration and development costs wherever required for further ore delineation to the stage where it is ready to be mined.

Sunk costs are not normally taken into consideration.

It is commonly understood that Reasonably Assured Resource of the lowest cost category (i.e. $ 40/kgU, $ 80/kgU) by definition are regarded as the recoverable portion of resources under prevailing economic conditions — equal to *proved mineral reserve* of the UN Framework Classification.

Uranium resource classification and the UN International Framework Classification for Reserves/Resources

As by given definition mineral resources should be divided into the economically mineable part of the total mineral resource i.e. the mineral reserve. In the uranium classification this would refer to *reasonably assured resources* (RAR) in the lowest cost category (= presently economically extractable amount).

Until 1993 the lowest cost category for RAR was <$ 80/kgU. Reflecting prices changes for uranium on the world market, since 1993 the cost category of < $ 40/kgU was introduced, however, few countries provided resource estimates in this cost category for reasons such as non-availability of estimates or confidentiality. Therefore, for the time being RAR of

$ 40/kgU and $ 80/kgU should be considered as *mineral reserves* knowing that only a portion of RAR < $ 80/kgU can be considered as presently reserves.

In an expert group meeting of the IAEA on the harmonization of resource classification for uranium in 1996 in Kiev the application of the UN Framework Classification was reviewed. The group reached agreement on judging the NEA-IAEA resource classification to be consistent with the UN International Framework Classification for Reserves/Resources. Examples from various countries have shown that resources estimates in national systems can be harmonized and reported according to the NEA-IAEA and UN International Framework Classification.

Subject to further discussion with experts from countries, e.g. representatives in the NEA-IAEA Uranium Group the proposed correlation of both classification systems is presented in the following figures 8 to 11.

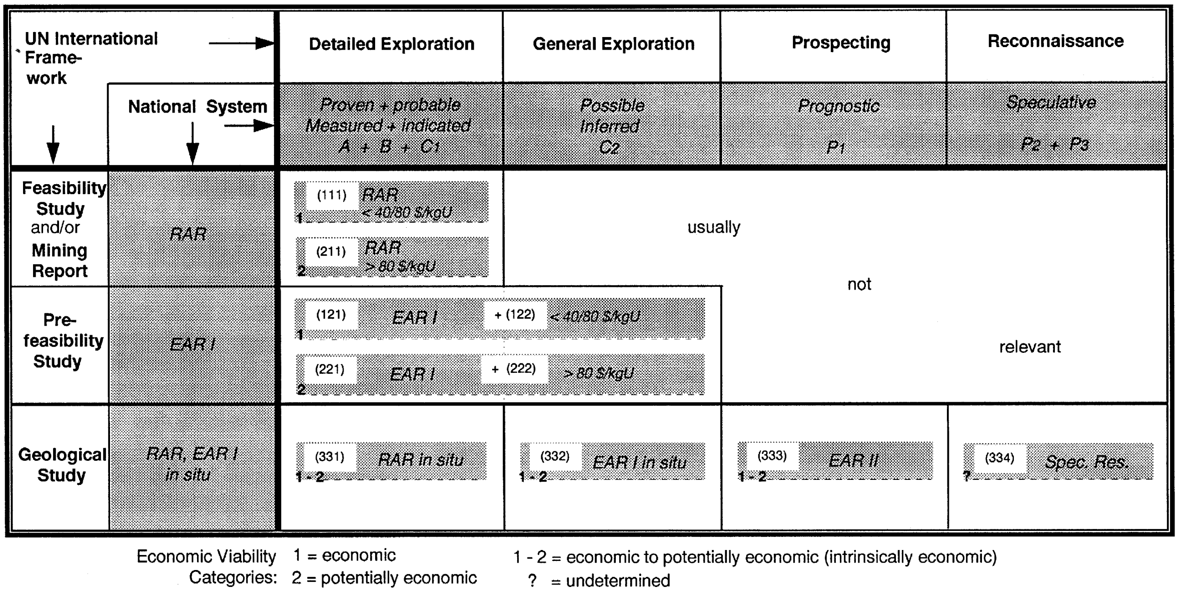


FIG. 8. Matrix: Preliminary attempt to classify uranium resources — United Nations International framework classification for reserves/resources — solid fuels and mineral commodities.

Deposit / Mine	Feasibility Study and/or Mining Report		Prefeasibility Study		Geological Study			
	Economic	Potentially economic	Economic	Potentially economic	Detailed Exploration	General Exploration	Prospecting	Reconnais-sance
	(111) RAR < 40/80$/kgU	(211) RAR > 80$/kgU	(121) (122) EAR I < 40/80$/kgU	(221) (222) EAR I > 80$/kgU	(331) RAR in situ	(332) RAR in situ	(333) EAR II	(334) Spec. Res.
Total								

[shaded box] = National System or Uranium Resource Categories

FIG. 9. Table: Preliminary attempt to classify uranium resources: United Nations International framework classification for reserves/resources — solid fuels and mineral commodities.

Countries	Prefeasibility Study, Feasibility Study and / or Mining Report		Geological Study	
	Economic	Potentially Economic	Detailed & General Exploration	Prospecting & Reconnaissance
	(111) RAR < 40/80 $/kgU (121) EAR I } < 40/80 $/kgU (122) EAR i	(211) RAR > 80 $/kgU (221) EAR I } > 80 $/kgU (222) EAR i	(331) RAR in situ (332) EAR I in situ	(333) EAR II (334) Spec. Res.
Total World				

= International System, Uranium Resource Categories

FIG. 10. Table for worldwide survey: Preliminary attempt to classify uranium resources: United Nations International framework classification for reserves/resources — Solid fuels and mineral commodities.

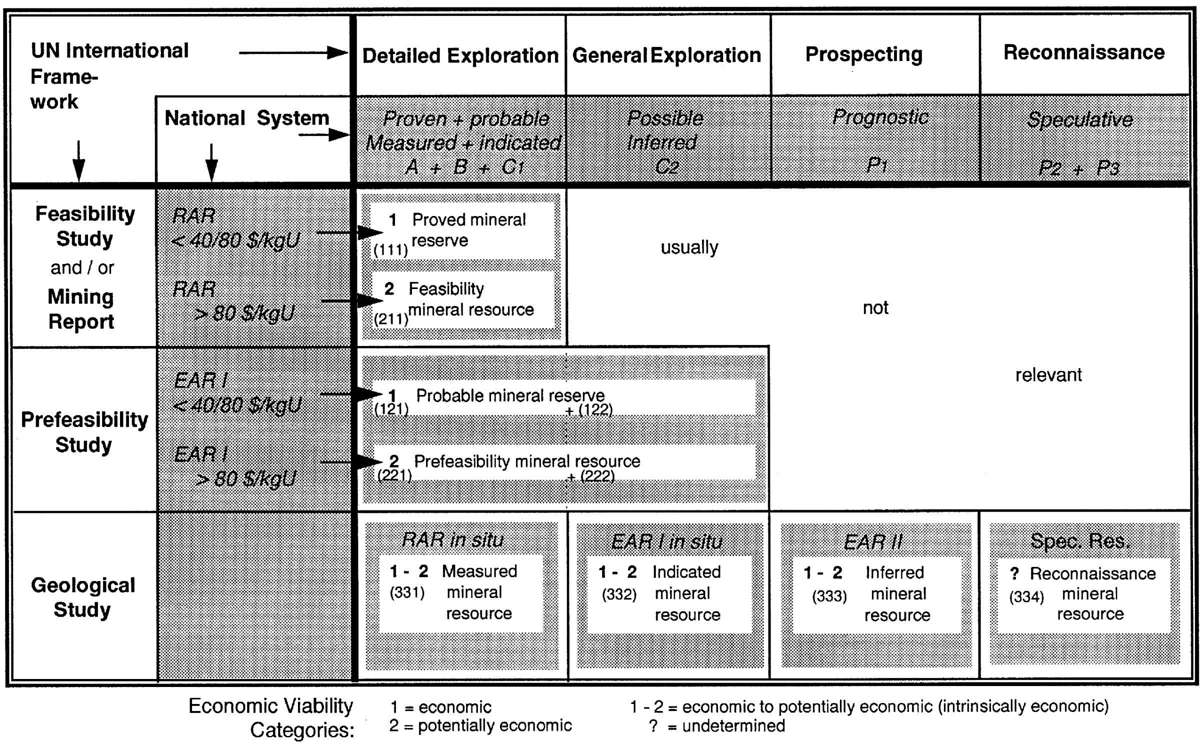


FIG. 11. Proposed UN reserve/resource terminology: preliminary attempt to classify uranium resources — United Nations International Framework classification for reserves/resources — Solid fuels and mineral commodities.

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Appendix I and II from: UN Economic Concen. for Europe: UN International Framework Classification Reserves/Resources (ENERGY/W.1R.70) 1997

Appendix I

Definitions of Terms to be used in the English Language Version of the United Nations International Framework Classification for Reserves/Resources — Solid Fuels and Mineral Commodities -

Definitions of Stages of Feasibility Assessment

Mining Report

A **Mining Report** is understood as the current documentation of the state of development and exploitation of a deposit during its economic life including current mining plans. It is generally made by the operator of the mine. The study takes into consideration the quantity and quality of the minerals extracted during the reporting time, changes in Economic Viability categories due to changes in prices and costs, development of relevant technology, newly imposed environmental or other regulations, and data on exploration conducted concurrently with mining.

It presents the current status of the deposit, providing a detailed and accurate, up-to-date statement on the reserves and the remaining resources.

Feasibility Study

A **Feasibility Study** assesses in detail the technical soundness and Economic Viability of a mining project, and serves as the basis for the investment decision and as a bankable document for project financing. The study constitutes an audit of all geological, engineering, environmental, legal and economic information accumulated on the project. Generally, a separate environmental impact study is required.

Cost data must be reasonably accurate (usually within ±10%), and no further investigations should be necessary to make the investment decision. The information basis associated with this level of accuracy comprises the reserve figures based on the results of Detailed Exploration, technological pilot tests and capital and operating cost calculations such as quotations of equipment suppliers.

Prefeasibility Study

A **Prefeasibility Study** provides a preliminary assessment of the Economic Viability of a deposit and forms the basis for justifying further investigations (Detailed Exploration and Feasibility Study). It usually follows a successful exploration campaign, and summarizes all geological, engineering, environmental, legal and economic information accumulated to date on the project.

In projects that have reached a relatively advanced stage, the Prefeasibility Study should have error limits of ± 25%. In less advanced projects higher errors are to be expected. Various terms are in use internationally for Prefeasibility Studies reflecting the actual accuracy level. The data required to achieve this level of accuracy are reserves/resources figures based on Detailed and General Exploration, technological tests at laboratory scale and cost estimates e.g. from catalogues or based on comparable mining operations.

The Prefeasibility Study addresses the items listed under the Feasibility Study, although not in as much detail.

Geological Study — A **Geological Study** is an initial evaluation of Economic Viability. This is obtained by applying meaningful cut-off values for grade, thickness, depth, and costs estimated from comparable mining operations.

Economic Viability categories, however, cannot in general be defined from the Geological Study because of the lack of detail necessary for an Economic Viability evaluation. The resource quantities estimated may indicate that the deposit is of intrinsic economic interest, i.e. in the range of economic to potentially economic.

A Geological Study is generally carried out in the following four main stages: Reconnaissance, Prospecting, General Exploration and Detailed Exploration (for definition of each stage see below). The purpose of the Geological Study is to identify mineralization, to establish continuity, quantity, and quality of a mineral deposit, and thereby define an investment opportunity.

Definitions of Stages of Geological Study

Reconnaissance — A **Reconnaissance** study identifies areas of enhanced mineral potential on a regional scale based primarily on results of regional geological studies, regional geological mapping, airborne and indirect methods, preliminary field inspection, as well as geological inference and extrapolation. The objective is to identify mineralized areas worthy of further investigation towards deposit identification. Estimates of quantities should only be made if sufficient data are available and when an analogy with known deposits of similar geological character is possible, and then only within an order of magnitude.

Prospecting — **Prospecting** is the systematic process of searching for a mineral deposit by narrowing down areas of promising enhanced mineral potential. The methods utilized are outcrop identification, geological mapping, and indirect methods such as geophysical and geochemical studies. Limited trenching, drilling, and sampling may be carried out. The objective is to identify a deposit which will be the target for further exploration. Estimates of quantities are inferred, based on interpretation of geological, geophysical and geochemical results.

General Exploration — **General Exploration** involves the initial delineation of an identified deposit. Methods used include surface mapping, widely spaced sampling, trenching and drilling for preliminary evaluation of mineral quantity and quality (including mineralogical tests on laboratory scale if required), and limited interpolation based on indirect methods of investigation. The objective is to establish the main geological features of a deposit, giving a reasonable indication of continuity and providing an initial estimate of size, shape, structure and grade. The degree of accuracy should be sufficient for deciding whether a Prefeasibility Study and Detailed Exploration are warranted.

Detailed Exploration — **Detailed Exploration** involves the detailed three-dimensional delineation of a known deposit achieved through sampling, such as from outcrops, trenches, boreholes, shafts and tunnels. Sampling grids are closely spaced such that size, shape, structure, grade, and other relevant characteristics of the deposit are established with a high degree of accuracy. Processing tests involving bulk sampling may be required. A decision whether to conduct a Feasibility Study can be made from the information provided by Detailed Exploration.

Definitions of Economic Viability Categories

Economic Quantities, reported in tonnes/volume with grade/quality, demonstrated by means of a Prefeasibility Study, Feasibility Study or Mining Report, in order of increasing accuracy, that justify extraction under the technological, economic, environmental and other relevant conditions, realistically assumed at the time of the determination.

The term economic comprises both normal economic and exceptional economic as defined below. These two subcategories are for optional use on a national level.

Normal Economic Normal economic reserves are reserves that justify extraction under competitive market conditions. Thus, the average value of the commodity mined per year must be such as to satisfy the required return on investment.

Exceptional Economic
(conditional economic) Exceptional (conditional) economic reserves are reserves which at present are not economic under competitive market conditions. Their exploitation is made possible through government subsidies and/or other supportive measures.

Potentially Economic Quantities, reported in tonnes/volume with grade/quality, demonstrated by means of a Prefeasibility Study, Feasibility Study or Mining Report, in order of increasing accuracy, not justifying extraction under the technological, economic, environmental and other relevant conditions, realistically assumed at the time of the determination, but possibly so in the future.

The term potentially economic comprises both marginal and submarginal as defined below. These two subcategories are for optional use on a national level.

Marginal Economic Marginal economic resources are resources which at the time of determination are not economic, but border on being so. They may become economic in the near future as a result of changes in technological, economic, environmental and/or other relevant conditions.

Submarginal Economic Submarginal economic resources are resources that would require a substantially higher commodity price or a major cost-reducing advance in technology to render them economic.

Economic to Potentially Economic (intrinsically economic)

Quantities, reported in tonnes/volume with grade/quality, estimated by means of a Geological Study to be of intrinsic economic interest. Since the Geological Study includes only a preliminary evaluation of Economic Viability, no distinction can be made between economic and potentially economic[1]. These Resources are therefore said to lie in the range of economic to potentially economic.

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1 Except in the case of low investment mineral commodities like sand, gravel and common clay, where a distinction between economic and potentially economic can be made.

Appendix II
Definitions of Mineral Reserve/Resource Terms in the UN Framework Classification and proposed by CMMI

Terms and Code	UN Framework Classification	CMMI Proposal
Proved Mineral Reserve (111)	Demonstrated to be economically mineable by a Feasibility Study or actual mining activity usually undertaken in areas of Detailed Exploration.	A Proved Mineral Reserve, stated in terms of exploitable tonnes/volume and grade/quality is that part of a Measured Mineral Resource on which detailed technical and economic studies have been carried out to demonstrate, at the time of reporting, that it can justify exploitation under specific technical and economic conditions.
Probable Mineral Reserve (121+122)	Demonstrated to be economically mineable by a Prefeasibility Study usually carried out in areas of Detailed Exploration and General Exploration.	A Probable Mineral Reserve, stated in terms of exploitable tonnes/volume and grade/quality is that part of a Measured or Indicated Resource on which sufficient technical and economic studies have been carried out to demonstrate, at the time of reporting, that it can justify exploitation under appropriate technical and economic conditions.
Feasibility Mineral Resource (211)	Demonstrated to be potentially economic by a Feasibility Study or prior mining activity usually carried out in areas of Detailed Exploration.	See definition of Measured Mineral Resource.
Prefeasibility Mineral Resource (221 + 222)	Demonstrated to be potentially economic by a Prefeasibility Study usually carried out in areas of Detailed Exploration and General Exploration.	See definition of Indicated Mineral Resource.
Measured Mineral Resource (331)	Estimated to be of intrinsic economic interest based on Detailed Exploration establishing all relevant characteristics of a deposit with a high degree of accuracy.	A Measured Mineral Resource is that part of a Mineral Resource which has been explored, sampled and tested through appropriate exploration techniques at locations such as outcrops, trenches, pits, workings and drill holes which are spaced closely enough to confirm geological continuity and from which collection of detailed reliable data allows tonnage/ volume, densities, size, shape, physical characteristics, quality and mineral

		content to be estimated with a high level of certainty. This category requires a high level of confidence in and understanding of geology and controls of the occurrence.
Indicated Mineral Resource (332)	Estimated to be of intrinsic economic interest based on General Exploration establishing the main geological features of a deposit providing an initial estimate of size, shape, structure and grade.	An Indicated Mineral Resource is that part of a Mineral Resource which has been explored, sampled and tested through appropriate exploration techniques at locations such as outcrops, trenches, pits, workings and drill holes which are too widely spaced or inappropriately spaced to confirm geological continuity but which are spaced closely enough to assume geological continuity and from which collection of reliable data allows tonnage/volume, densities, size, shape, physical characteristics, quantity and mineral content to be estimated with a reasonable level of confidence, but not a high degree of certainty. An Indicated Mineral Resource is estimated with less certainty and lower level of confidence than for a Measured Mineral Resource, but will be more reliable than for an Inferred Mineral Resource. Confidence in the estimate is such as to allow the application of technical, economic and financial parameters and to enable an evaluation of economic viability.
Inferred Mineral Resource (333)	Estimated to be of intrinsic economic interest based on Prospecting having the objective to identify a deposit. Estimates of quantities are inferred, based on outcrop identification, geological mapping, indirect methods and limited sampling.	An Inferred Mineral Resource is that part of a Mineral Resource inferred from geological evidence and assumed but not verified continuity, where information gathered through appropriate exploration techniques from locations such as outcrops, trenches, pits, workings and drill holes is limited or of uncertain quality and reliability but on the basis of which tonnage/volume, quality and mineral content can be estimated with a low degree of certainty and low level of confidence. The level of confidence associated with an Inferred Mineral Resource is lower than that for an Indicated Mineral Resource.

		This category is intended to cover situations where a mineral occurrence has been identified and limited measurement and sampling completed but where the data are insufficient to allow the geological framework and/or continuity of mineralisation to be confidently interpreted. It should not necessarily be assumed that all/or part of an Inferred Mineral Resource will be upgraded to an Indicated or Measured Resource by continued exploration. Caution should be exercised if this category is considered in preliminary technical and economic studies. Because of the low level of confidence and reliability of this category, Inferred Mineral Resources should not be combined with Measured Mineral Resources and Indicated Mineral Resources.
Reconnaissance Mineral Resource (334)	Based on Reconnaissance, having the objective to identify areas of enhanced mineral potential. Estimates of quantities should only be made if sufficient data are available and when an analogy with known deposits of similar geological character is possible and then only within an order of magnitude.	The term Exploration Information is broadly equivalent to the IMM term Mineral Potential, which is defined as follows: Mineral Potential describes a body of rock or mineralisation or other material or an area for which evidence exists to suggest that it is worthy of investigation but to which neither volume, tonnage nor grade shall be assigned.

Definition of Occurrences

	The term Occurrence is used with two different meanings as defined below:
Uneconomic Occurrence	**Uneconomic Occurrence** — Materials of estimated quantity, that are too low in grade or for other reasons are not considered potentially economic. Thus, **Uneconomic Occurrence** is not part of a Mineral Resource. If quantity and quality are considered worthy of reporting, it should be recognized that an **Uneconomic Occurrence** cannot be exploited without major technological and/or economic changes, which are not currently predictable.
Mineral Occurrence	A **Mineral Occurrence** is an indication of mineralization, that is worthy of further investigation. The term **Mineral Occurrence** does not imply any measure of volume/tonnage or grade/quality and is thus not part of a Mineral Resource.

AN ANALYTIC URANIUM SOURCES MODEL

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Abstract

This document presents a method for estimating uranium resources as a continuous function of extraction costs and describing the uncertainty in the resulting fit. The estimated functions provide convenient extrapolations of currently available data on uranium extraction cost and can be used to predict the effect of resource depletion on future uranium supply costs. As such, they are a useful input for economic models of the nuclear energy sector. The method described here pays careful attention to minimizing built-in biases in the fitting procedure and defines ways to describe the uncertainty in the resulting fits in order to render the procedure and its results useful to the widest possible variety of potential users.

1. INTRODUCTION

The process of extracting uranium accounts for a substantial portion of nuclear power generating costs, and the share may increase rapidly when uranium resources become more depleted in the future. The magnitude of uranium extraction costs may come to play a decisive role in choices between different fuels for electricity generation as well as for choices between different fuel cycle options within the nuclear industry. Higher uranium prices make nuclear power less attractive and favour reprocessing of nuclear materials over other disposal and storage options. With concomitant globalization of uranium marketing, estimates of available uranium resources as a function of extraction costs may become increasingly useful for long-term energy planning. The work reported here is part of a larger project investigating whether near term investments in plutonium reprocessing and/or breeding technology are economically favourable under various assumptions about the access to global markets for natural gas, oil, coal, and uranium. There are three possible answers to such questions at a given confidence level: “yes”, “no”, and “we don't know”, each with different policy implications. Allowing for the third of these possibilities draws attention to the importance of quantifying the uncertainties any such analysis is inevitably fraught with. To this end, we develop a probabilistic approach to uranium resource estimates and conclude the paper with comments on how the reported resource estimates may be supplemented with confidence level calculations. Since 1965, the Nuclear Energy Agency of the OECD has reported information on uranium resources in their bi-annual publication *Uranium Resources, Production, and Demand,* the so-called Red Books[1]. Resources are reported for different price categories, e.g. resources extractable at a cost of up to $40, $80, or $130 per kg of uranium metal. Resource estimates are also differentiated according to the certainty of the estimate, i.e. Reasonably Assured Resources (RAR), Estimated Additional Resources (EAR I, EAR II), and Speculative Resources (SR). Since 1991, the Red Books have achieved adequate coverage to estimate global as well as regional uranium resources, and the work described here is based solely on the information reported there. This restriction causes us to omit some other available information, but it has the advantage that our analysis is based on a widely available and well-defined database. The substance of the present preliminary discussion is divided into two parts. First, we examine how total uranium estimates for different regions have evolved over time in order to get a good sense of how complete these estimates really are. To make the

[1] Please see NEA/IAEA (1996). Previous editions are referenced on p.353 [1].

analysis and examination of the available data readily tractable, countries are grouped into nine areas according to their geographical location and their reporting methodology. For most of the regions the estimates remain fairly stable over time. However, our analysis suggests that the reporting of two regions may still be incomplete, with the consequence that future upward revisions can be expected. The two regions include the large group of countries that had centrally planned economies prior to 1989 and a Pacific region that is dominated by Australia's substantial resources. Another two regions, whose resources are dominated respectively by France and by francophone Africa, do not report the category of Speculative Resources. In order to estimate those resources we use regression analysis to establish how the share of total resources a country reports as speculative depends on its exploration expenditure. The analysis suggests that for the two regions Speculative Resources may constitute respectively a negligible and a modest portion of total resources. Second, we use data for nine individual countries which reported fairly complete information in the 1993 and 1995 Red Books in order to examine how a country's available uranium resources vary with extraction costs. The model underlying the analysis accounts for both the progressive exploitation of lower grade ores and for increasing costs of extracting progressively less accessible ores of the same grade. We estimate uranium resources as a function of extraction costs and obtain a result which is nearly linear over the \$40/kg to \$130/kg range. However, the function extrapolates nonlinearly for both lower and higher cost levels. The latter result may justify the additional complication of the more physically based model. Otherwise, “blind” extrapolation of a mathematically more convenient linear model could cause us to significantly overestimate the accuracy of the resulting fits outside the range where data is available.

2. COMPLETENESS OF RESOURCE ESTIMATES

In order to analyze how complete current uranium estimates are, we have looked at the time series of past resource reports. Figures 1 to 3 show such time series of uranium resource estimates per unit land area for the regions Pacific Rim, Asia+, and EuroSpec. All countries for which estimates have ever been reported in Red Books are subdivided into the nine regions. The “Canadian Region” includes only the large resources reported for Canada. The countries in other regions are listed in Table I.

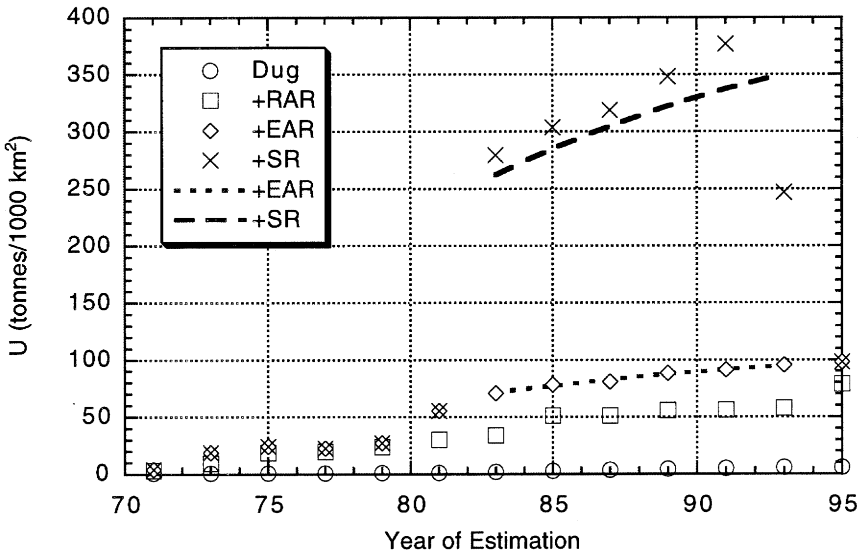

FIG. 1. Estimates of uranium resources in the Pacific Rim region.

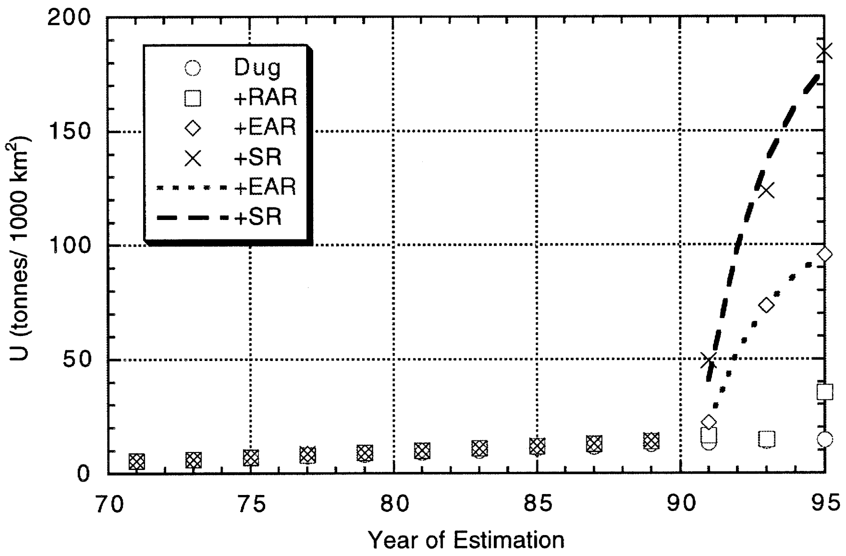

FIG. 2. Estimates of uranium resources in the Asia+ region.

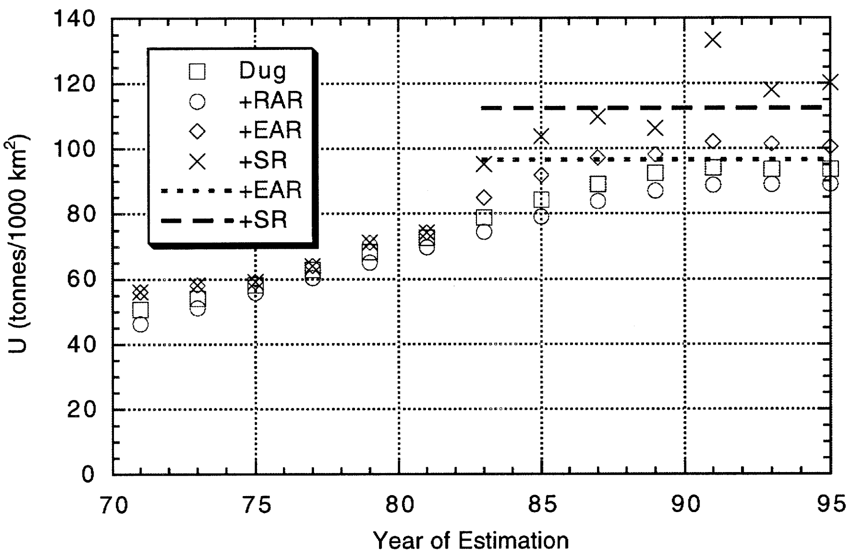

FIG. 3. Estimates of uranium resources in the EuroSpec region.

TABLE I. REGIONS WITH MORE THAN ONE COUNTRY

N. America	S. America	Pacific Rim	Asia+	EuroSpec	EuroOther	AfricaSpec	AfricaOther
Greenland	Argentina	Australia	Bulgaria	Egypt	Algeria	S. Africa	Angola
Mexico	Bolivia	Indonesia	China	Germany	Austria	Zambia	Botswana
U.S.	Brazil	Japan	CFSR	Greece	Finland	Zimbabwe	Cameroon
	Chile	Korea, S.	Hungary	Italy	France		CAR
	Colombia	Philippines	India	Portugal	Somalia		Gabon
	Peru		Kazakstan	U.K.	Spain		Madagascar
	Venezuela		Mongolia		Sweden		Namibia
			Romania		Turkey		Niger
			Russia		Yugoslavia		Zaire
			Thailand				
			Ukraine				
			Uzbekistan				
			Vietnam				

"N. America Other" includes the USA, Mexico, and Denmark's reporting for Greenland. "Pacific Rim" includes Australia, Indonesia, Japan, the Republic of Korea, and the Philippines. "Asia+" includes formerly centrally planned economies in Europe except for East Germany and the remaining reporting countries in Asia. S. America includes Argentina, Bolivia, Brazil, Chile, Colombia, Peru, and Venezuela. "EuroSpec" includes European and North African countries which have reported Speculative Resources Other European and North African countries are included in "EuroOther". "AfricaSpec" includes African countries which have reported Speculative Resources, and "AfricaOther" includes other African Countries. Resource data for years prior to 1995 have been linearly interpolated to \$130/kg at 1995 prices[2]. Missing data for particular years are linearly interpolated and extrapolated as constant. Missing resource extraction data is extrapolated as proportional to reported production capacity, and as constant at the first reported amount back to the first reported post-World-War-II production where that information is also missing. We are most interested in the amount of total uranium resources which is calculated as the sum of already extracted uranium ("Dug") and all resources reported in the various categories at extraction costs of up to \$130/kg, including RAR (Reasonably Assured Reserves), EAR (Estimated Additional Resources, including both categories I and II where these are reported separately), and SR (Speculative Resources). If Speculative Resources were only reported at \$260/kg or without a cost category half of the reported amount was assumed to be extractable at \$130/kg. To investigate whether reporting of cumulative resources approaches a steady state, we fitted least-squares models for exponential saturation as a function of time beginning in 1983 when reporting of "Speculative Resources" began. Only for the "Pacific Rim" and "Asia+" regions were positive time constants less that 100 years obtained. The resulting fits for these are shown in Figures 1 and 2. We extrapolate them to a steady state to get the resource estimates listed below. For the other regions we use the average amount of resources reported since 1983. For the EuroSpec region, this procedure is indicated by the horizontal lines in Figure 3. The regions "EuroOther" and "AfricaOther" do not report Speculative Resources. To obtain a reasonable figure, we use a least squares regression to estimate the share of Speculative Resources as a decreasing function of cumulative exploration expenditures per unit land area, E. We assume that the fraction of total resources that are reported as non-speculative follows the function $1 - \exp(-\omega E)$, where ω is the coefficient to be estimated. The fitted function and the resulting estimates are shown in Figure 4. It should be noted that the above inflation adjustment, linear interpolation, and constant extrapolation procedures were also used for missing exploration expenditure data. For the few countries that did not report exploration expenditures we assumed their expenditure per unit land area to be equal to the average for the region they are included in. With the above procedure we estimate total uranium resources remaining in the ground in 1981 to be (all data in Mill. tonnes): North America 3.5, South America 0.6, Pacific Rim 4.5, Asia+ 7.4, Europe and North Africa 0.7, and for the rest of Africa 2.3. By comparison the International Uranium Resource Evaluation (IUREP) estimates[3] are: North America 1.6, South America 0.8, Australia 1.5, Centrally Planned Economies 3.5, Western Europe 0.5, and Africa 1.6 [2]. The global total of 18.8 Mill. tonnes we obtained is approximately twice as high as the 9.5 Mill. tonnes for the IUREP estimate. The ratio of total resources to speculative resources reported in the 1983 Red Book is 1.6, whereas the ratio of total resources from the present estimate to the inflation adjusted "IUREP" estimate is 2.0. The midpoint of these ratios is 1.8, with an approximately ±10%

[2] This price data is adjusted for inflation with the US Consumer Price Index so that all prices are in 1995 US dollars.

[3] See IAEA (1984). The data were similarly adjusted for inflation and linearly interpolated to \$130/kg at 1995 prices. They are reproduced in the 1983 Red Book.

spread, as reported for a nominal 50% confidence interval as the "most likely range" of total Speculative Resources for the IUREP estimate. This comparison does not, of course, account for the possibility of a systematic bias common to both estimates, an analysis of which is outside the scope of the present calculations and would require additional expert opinion.

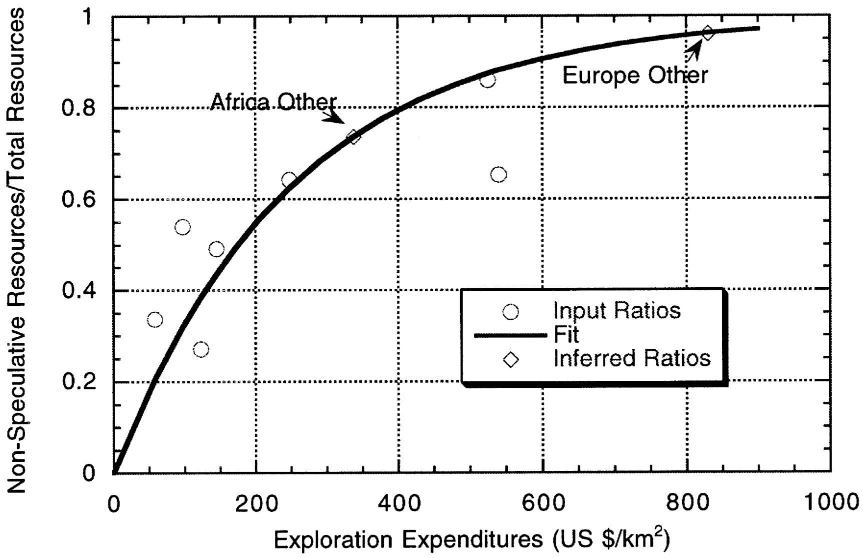

FIG. 4. Fraction of non-speculative resources vs. exploration expenditures.

3. RESOURCES AS A FUNCTION OF EXTRACTION COSTS

Having examined estimates of uranium resources extractable at a reference price, we now turn to the question of how extractable resources vary with extraction costs. We choose here a model that is sufficiently flexible to capture some of the complexity of the topic. On the other hand, it the number of free parameters is small enough to be conveniently examined with the limited database. We assume that the distribution of uranium by ore grade y (measured in weight-%) follows the function $\eta_i f$ where

$$f = e^{-\zeta \ln^{\upsilon}(y/\rho)}$$

and η_i is a country-specific proportionality constant determining the total endowment of country i. For the purposes of this paper we will restrict ourselves to the common assumption of a log-normal distribution (i.e. $\mu = 2$) and ($\zeta \sim 7$, a value that can be estimated from the ratio of average crustal abundance to that of typically mined ores. Both assumptions may be relaxed in future versions of this paper. We also assume that extraction costs per unit uranium ore consist of a fixed cost γ and a depth-dependent cost which increases as a power of the difficulty ξ of accessing it. Costs per kilogram uranium metal p are then inversely proportional to the ore grade.

$$p = (\beta\xi^b + \gamma)/y$$

In the simple case of an inclined seam of uniform grade and thickness, ξ is proportional to the cost of excavating to the depth of the seam, so as a convenient notational shorthand here we shall refer to the parameter ξ as "depth[4]". This model is more general than the simplest mathematical fits of resource vs. extraction cost but simpler than more complex models of individual ore bodies, which may also account for deposit size and grade non-uniformity [3]. The latter are avoided here due to their greater complexity and the lack of data bases that report the characteristics of deposits in entire countries or regions. Solving equation 2 for ξ yields

$$\xi(y,p) = \left(\frac{py-\gamma}{\beta}\right)^{b}$$

When the market bears extraction costs of p, material of concentration y can be profitably extracted up to depth $\xi(y,p)$, while material at greater depth is not yet worth extracting. For country i, the uranium in the range y to $y + dy$ which can be profitably extracted in the limit of small dy is $\xi f_i\,(y)\,dy$. Integrating over all relevant ore grades and dividing by integrated resources at a reference cost, here called p_3, gives the share of total resources u which is extractable at cost up to p.

$$u = \int_{\gamma/p}^{y_{\max}} \xi f dy \Big/ \int_{\gamma/p3}^{y_{\max}} \xi f dy$$

Here p is extraction cost divided by a reference cost taken here to be \$130/kg, and in these units the reference cost used here is $p_3 = 1$. We shall restrict ourselves here to the physically-sensible cases where the available resources drop sufficiently fast with increasing ore concentration so that the results are essentially independent of the maximum possible ore grade, y_{max}. For log-normal ore grade distributions, it is convenient to transform to the new variable

$$\phi = \ln\,(y/\rho)$$

and define

$$c \equiv \ln\,(\gamma/\rho)$$

Then the lower limit of integration for a given extraction cost p_j is $\phi_j = c - \ln p_j$. For given ζ the amount u_j initially extractable at a given cost p_j for sufficiently large $\phi_{\max} = y_{\max}/\rho$ is then proportional to a function of only the two parameters b and c:

$$u_j = p_j^{(1/b)} \frac{\int_{\phi_j}^{\phi_{\max}} (\exp\phi - \exp\phi_j)^{1/b} \exp(\phi - \zeta\phi^2)\,d\phi}{\int_{c}^{\phi_{\max}} (\exp\phi - \exp\phi_j)^{1/b} \exp(\phi - \zeta\phi^2)\,d\phi}$$

The integrals can be computed in terms of standard functions for the cases $b=1$ and $b=½$ but in general must be computed using a common numerical integration routine. We restrict the present analysis to those countries recently reporting data complete enough that it includes both speculative and other resources available up to \$130/kg as well as at least one lower cost category. Including Australia's 1993 Red Book estimate of Speculative Resources with other

[4] In more complex situations this parameter also accounts for increasing difficulty of accessing successively extracted ores of a given concentration due to problems with terrain, underground conditions, etc.

TABLE II. AREA AND URANIUM RESOURCES FOR SELECTED COUNTRIES
(in K tonnes/Mill km^2)

	Area	Non-Speculative Resources			Speculative
	(Mill. Km^2)	< \$40/kg	< \$80/kg	< \$130/kg	Resources
Bulgaria	.111	75.8	292.7	335.2	144.3
Kazakhstan	2.717	240.1	365.7	463.0	184.1
Romania	.238	4.6	74.6	135.9	8.4
Canada	9.971	0.0	58.5	90.8	70.2
Peru	1.285	0.0	8.0	18.4	15.6
U.S.	9.809	0.0	129.5	211.5	87.5
Vietnam	.330	0.0	18.8	322.2	394.5

data from the 1995 Red Book, this gives seven countries, three of which report at \$40/kg as well as at \$80/kg and \$130/kg. We expect that the largest uncertainties will result from Speculative Resources and their (unreported) distribution of extraction costs, so we lump extracted resources ("Dug"), Reasonable Assured Resources, and Estimated Additional Resources together and list Speculative Resource estimates separately, as shown in Table II. The purpose of the above physically-based model is to estimate total resources as a function of extraction costs. However, Speculative Resources, which account for an important portion of total resources, are not broken down into the \$40/kg, \$80/kg, \$130/kg categories. It is therefore necessary to estimate how Speculative Resources are distributed among these price categories within the model calibration procedure. We allow here for the plausible possibility that Speculative Resources are listed as such in part because they are less economically attractive than those listed in other categories. In particular, we assume that the expected value of the fraction g_{ij} of resources listed in the non-speculative category in country i at price p_j decreases exponentially on a scale τ_j, with that scale itself an exponential function of extraction cost. The resulting function is

$$g_{ij} = e^{\frac{-qj}{\tau j}}$$

where

$$\tau_j = 1 - e^{-pjd}$$

The reference rate constant q_i describes how a country's fraction of speculative resources depends on its exploration expenditures and possibly other factors. The a-priori uncertain dependence of the rate on the cost category of the reported resources is assumed here for simplicity to depend on a single universal constant, d. Here we will use the reasonably good first approximation that the fraction g_{i3} of speculative resources extractable up to reference cost p_3 are known in terms of the reported values s_{i3} and r_{i3} for speculative and other resources respectively, so that

$$g_{i3} = \frac{s_{i3}}{(r_{i3} + s_{i3})}$$

Using this approximation, the a-priori uncertain ratios of speculative to total resources for other cost categories depends only on the known values g_{i3} and the single a-priori uncertain parameter d via the relation

$$g_{ij} = g_{i3}^{\frac{\tau 3}{\tau j}} = g_{i3}^{\frac{1-e^{-p3d}}{1-e^{-pjd}}}$$

We further assume that the differences between the predictions of the model and the reported data are a random sample from normal distributions with common variance σ^2. These "residuals" are referred to here for Speculative Resources as

$$\delta_i = a_i u_3 g_{i3} - s_{i3}$$

where a_i is a constant proportional to the resource endowment for each country, and for other resources as

$$\varepsilon_{ij} = [a_i u_j g_{ij} - r_{ij}] h_{ij}$$

The h_{ij}'s are mere bookkeeping factors that take the value zero if the corresponding r_{ij}'s are not reported and unity otherwise).

A reference "point model" for this case can be obtained by maximizing the probability of obtaining the given data through adjusting the parameters a_i, d, σ^2, b, and c without any prior assumptions about the likely values of these parameters. Such a procedure would, however, neglect potentially useful a-priori knowledge, for example that a physically sensible interpretation of the resulting model requires that the parameters b and c be non-negative[5]. Extreme values of the parameter d are also common-sensically precluded, as the limits $d \to -\infty$ and $d \to \infty$ correspond to all Speculative Resources being extractable respectively only at zero cost with none dearer, or at the reference cost with none cheaper. We represent this assumed prior knowledge here for the positive-definite quantities b and c with unit log-normal prior probability functions and for d with a unit normal prior probability function. A reference value of $b \approx 1.5$ represents a point midway between a linear and quadratic increase of the non-constant portion of extraction costs with "depth". A reference value of $c \approx 7$ is obtained from an order of magnitude estimate that 10^{-6} of the total crustal abundance extracted to an overburden of 100 tonnes/m^2 can be obtained at the reference price down to a concentration of c.10^3 times the mean crustal abundance. The use of prior probability distributions described here is conceptually convenient to avoid non-physical results. It is also mathematically convenient since it allows us to initialize the optimization search and prevents it from "wandering off" into non-physical parameter space regions which might otherwise provide local optima and/or be connected to the physically desired solution by a relatively "flat" region in parameter space. Nevertheless, the prior probability distributions used here still allow for a wide variety of possible solutions (e.g. forcing only a 67% prior probability that the parameter b will lie between the physically remarkable values of $b = 1.5/e \approx 0.6$ and $b = 1.5xe \approx 4$). With these assumptions, the desired estimation procedure amounts to maximizing

$(2\pi)^{-(N+3)/2} \exp(-l)$ where

$$l = (1/2)\left[d^2 + \ln^2(b/1.5) + \ln^2(c/7)\right] + (1/2)\sum_{i=1}^{I}\left[\ln\sigma^2 + \delta_i^2/\sigma^2 + \sum_{j=1}^{3}(h_{ij}\ln\sigma^2 + \varepsilon_{ij}/\sigma^2)\right]$$

For the example shown here, the number of countries considered is $I = 7$ and the total number of non-zero data entries is $N = 24$. The factors of 2π and N factors of $1/\sigma = \exp[-(l/2) \ln \sigma^2]$ have been collected for notational convenience, since the required maximization

[5] A negative value for b would correspond to extraction becoming cheaper with decreasing accessibility, and a negative value for c would correspond to extracting reference cost ores with concentration of less that the mean crustal abundance.

procedure is equivalent to minimizing a constant plus the so-called negative log likelihood, $-l$. This minimization can be done analytically for the country-specific parameters a_i and the variance σ^2 when b, c, and d are given. Therefore, we have a readily tractable numerical maximization problem for finding the maximum likelihood values of the latter parameters. The resulting overall maximum likelihood result includes the estimates $b = 1.6$, $c = 5.4$, and $d = 1.1$, all well within or near the unit variance range of their prior probability distributions. The resulting function of uranium resources vs. extraction costs is shown in Figure 5, along with two other curves which illustrate how the result would change for different values of the parameters b and c. The predominant influence of increasing b is to make the exploitation of less accessible resources more difficult, as illustrated by the presence of the leading factor $p_j^{1/b}$ in the above expression for u_j. This causes resource estimates for large values of b to be reduced below a linear extrapolation to higher extraction costs.

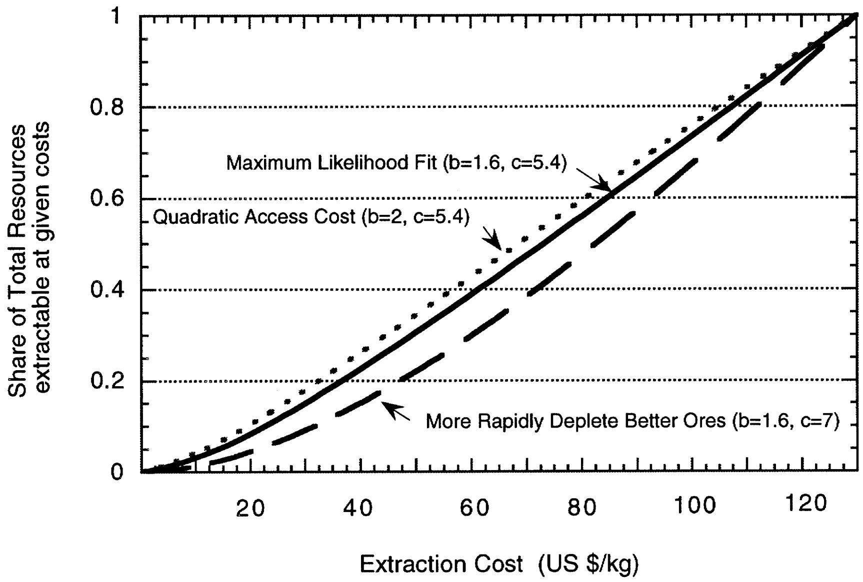

FIG. 5. Uranium resources vs. extraction cost.

The predominant influence of increasing the parameter c is to push the ores being exploited at lower costs farther out into the "tail" of the ore concentration distribution, where amounts of available ore fall off most rapidly with increasing ore grade. This means there is relatively less high grade ore to be exploited at low extraction cost. As a result, resource estimates at low prices are again smaller than they would be for a linear resource vs. extraction cost function. A combination of high b and c produces an S-shaped curve while a combination of low b and c produces a nearly linear curve. However, both combinations produce very similar results over the parameter range covered by the data base. Since results which are similar over the range that is covered by the reported data can produce very different but physically reasonable extrapolations to low and high costs[6] it may be important to provide estimates of how accurate parameters such as b and c are determined by the model. A convenient multivariate normal approximation to probability distributions for the parameters of the model can be defined by the inverse of the matrix of second derivatives of the negative log-likelihood with respect to the a-priori uncertain parameters, evaluated at the

[6] Uranium resources at high costs, i.e. higher than \$130/kg, are relevant because studies have suggested that at such prices plutonium reprocessing and breeding can become competitive with the use of natural uranium in nuclear power stations.

maximum likelihood point (where the first derivatives all vanish). Integrating this approximation over the complete parameter space for which the sum of the a_i is less than any given value a also gives a convenient approximation to the probability of a given amount of uranium being extractable from all of the treated countries together being as much as a at any given extraction cost, p. Alternatively, more exact results can readily be obtained from this type of model by using Monte Carlo methods.

4. DISCUSSION

The first part of the above analysis suggests that there are only modest uncertainties about the global uranium resources that can be extracted at costs up to a given reference price, here \$130/kg at 1995 prices. The second part provides estimates of available uranium resources as a function of extraction cost, while noting that there is additional uncertainty concerning the extrapolation to both higher and lower extraction cost values. In the concluding discussion, we first list a number of issues where expert opinion might be helpful to improve upon the accuracy of the model and the corresponding error estimates. Then we discuss a number of additional procedures which might be helpful in producing useful estimates of regional and global uranium resources and the uncertainties involved. A first pair of questions where expert opinion might be useful concerns two of the explicitly defined prior probability distributions described above.

(a) What degree of certainty can one ascribe to the concept that resources reported as speculative tend to have higher extraction costs than resources reported in other categories (e.g. 50% as assumed here, ≥67%, ≥95%, or some other number)?

(b) What degree of certainty can one ascribe to the concept that the cost of accessing resources of a given average grade increase at least as fast as linearly with the amount extracted, averaged over a large variety of deposit types (e.g. ≥50%, ≥67%, ≥95%, or some other number)?

Another set of questions concerns how fast the availability of high grade ores initially present in the ground falls off with increasing ore grade (or alternatively, how much extractable lower grade ore is there likely to be at lower prices). The general question here concerns what type of assumption is appropriate for large-scale regional and global analysis as opposed to analysis of individual deposits or deposit types. A more specific formulation of this question would ask for mean values and 67% confidence regions for the parameters c, ζ, and μ in the type of model described above. A third set of questions deals with prior estimates of the likely variance in data reported in the Red Books. Do we have any useful prior information about likely random variations from true mean values of reported resource estimates amongst various countries.

(a) For non-speculative resources, for example, is the total amount reported likely to be within 50% of the true value for ≥67%, ≥95%, or some other fraction of the reporting countries?

(b) How much more uncertain are reports of Speculative Resources compared with non-speculative resources for the same extraction cost. (For example, do we expect a-priori that a factor of at least 2 for this ratio is expected at a ≥50%, ≥67%, ≥95%, or some other confidence level).

(c) Another question concerns Speculative Resources that are reported without an extraction cost category. Such information is formally useless for resource vs. extraction costs estimates without some assumption about the associated extraction costs. If we consider the reports to be an estimate of resources extractable up to some a-priori uncertain extraction cost, what is the most probable amount (e.g. \$130/kg, \$180/kg, \$260/kg, or some other number) and what level of confidence can we ascribe to this assignment a-priori (e.g. 67% confidence that this assumption is accurate to within a factor of 1.2, 1.4, 1.6, or some other number)?

(d) A final and most critical set of questions concerns the possibility of systematic deviations of reported estimates and actual resources. Have "conservative" biases towards underestimation which are referenced in some of the older literature been removed by recent changes in reporting procedures and coverage, or have they perhaps been overcompensated for?

(e) Are speculative and non-speculative resource on average likely to be underestimated due to unreporting (or perhaps overestimated)? If so, what is the most likely factors by which the actual amounts deviate from the estimates (e.g. 0.7, 0.8, 0.9, 1.1, 1.2, 1.4, or some other number), and with what degree of confidence do the estimates deviate from unity by this amount (≥67%, ≥95%, or some other number)?

With or without additional answers to these questions, there are a number of other types of data analysis that might be useful to obtain further insight into the relationship between resources and extraction costs. First, the use of \$130/kg data only for estimating the fraction of resources reported as speculative at various prices in all countries could be replaced by a full maximum likelihood estimator of this fraction that takes account of all the available data. This is expected to produce little difference in the estimates but would be more methodologically sound. Second, the ratio of variance for speculative and other resource categories could be taken to be a free parameter, subject to a probability estimate as appropriate. Third, the parameters ζ and/or μ could be freed up in order to allow a more general functional form for the ore grade distribution and/or consider other (e.g. "flatter") distributions than log-normal. It could also be useful to marry the two types of analysis described in this paper to produce complete quantity vs. extraction cost estimates based on the entire available Red Book data base. Estimates of how speculative resources are distributed amongst cost categories would have to be based on exploration costs in a systematic manner analogous to that illustrated in Figure 4. It might be useful to include estimates of changes in productivity over time as well as an inflation adjustment. Of particular importance in such an analysis could be the exploration cost of converting Speculative and Estimated Additional Resources to categories which are sufficiently well defined that they can actually be mined. Finally, we comment on a number of issues for which data outside the scope of the Red Books is needed. The first of these concerns uranium produced as a by-product of phosphate mining and other activities. The supply of uranium from such sources cannot be expected to be constant. Rather, it is likely to follow the evolution of global demand for fertilizer. An analysis of this source thus requires a global economic model of broader scope than the discussions of evolution of demand for nuclear power typically found in the Red Books[7]. The second issue concerns the possible recovery of uranium-235 from old enrichment tails as lower-cost resources are depleted. This requires an analysis of how the cost of enrichment technology will most likely evolve. Again, this is information that is not usually meant to be reported in sufficient detail in the Red Books. The third issue concerns to what extent mined uranium ore will be replaced by the approximately 0.1 to 0.2 Mill. tonnes of stockpiled natural uranium equivalent from military programs or a comparable amount of primarily civilian-source plutonium from nuclear reactors. The fourth issue concerns countries which have not reported resources in Red Books at all, although some have reported exploration expenditures and others are known to have, or suspected of having, some resources. As long as the above questions remain unanswered, it is quite clear that the analysis presented here is only a modest step towards estimating uranium resources as a function of extraction costs. Additional expert opinion as well as systematic analysis is certainly needed.

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[7] It should also be noted that some of the resources included in the data base may be dependent on the simultaneous extraction of other metals.

NEW DEVELOPMENT STAGE OF CHINA'S URANIUM INDUSTRY

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Abstract

From the early 1980s China adjusted its uranium industry to better meet the market economy requirements. Until 1997, the adjustment has been completed. The technical and managerial improvements result in a more efficient uranium production. In 1996 a series of events related to the nuclear power development of China manifests very favorable situation for the uranium industry. The first two nuclear power plants with a total installed capacity of 2100 MW in the mainland of China have been operating safely and steadily for several years. The additional nuclear power projects to be constructed for the rest of this century are implemented in an all-round way. Four plants with eight reactors of a total of 6900 MW have entered their construction period in succession. In 1996 a commercial ISL mine in Xinjiang with annual capacity 100 tU was completed, and the larger scale of ISL mine is expected to be constructed by 2000. The Benxi uranium mine in northeast China was put into production. It applies some new mining and processing technologies and improved management, which might serve as a new model of uranium mines in China.

1. INTRODUCTION

China's uranium industry was founded in the 1950s. Through over 20 year effort it became a comprehensive industrial system with about 50 enterprises and institutions, including uranium mines and mills, machinery factories, construction and installation companies, research and design institutes, technical schools etc. The uranium output increased year after year. It was a rapid development period of China's uranium industry.

In the early 1980s, following the national strategic decision, the China's nuclear industry placed emphasis on developing nuclear power and promoting a diversified economy. The uranium production, as a part of nuclear industry, faced many organizational, technical and economic problems originated by the former economic system. It had to carry out a series of adjustment activities and form a new uranium community to meet the nuclear power requirement in the condition of market economy.

Over the last decade many progresses have been made in the uranium industry as well as the nuclear power development in China. As a historical review, China's uranium industry will have a new development stage to meet the coming new century.

2. COMPLETION OF URANIUM INDUSTRY ADJUSTMENT

In the period of adjustment and reform the uranium industry should shift its military production to civilian production with emphasis on the peaceful applications for nuclear power.

Most China's uranium deposits in the early days were small in size, low in grade and distributed extensively in many provinces. As a whole, the capital and operating costs were rather high. It was very important to take account of the economic effect of uranium production, that is to lower the costs of uranium products and overcome many difficulties in former uranium industry.

The basic targets and tasks of adjustment and reform of uranium industry might be summarized as follows:

– The main target of uranium production must be based on meeting domestic needs within the framework of the country's nuclear power programme, following the policy of "self-sufficiency of uranium" to fuel the nuclear power plants.

  During the period of adjustment there was only a little demand for uranium and China reduced uranium production and closed uranium mines and mills with comparatively high production costs. From 1980, China also started exporting uranium.

  However, to meet uranium demand around the turn of the century, in the recent years three uranium mines, Yining, Lantian and Benxi, were put into production. In 1996 Yining ISL mine reached annual output 100 tU. The other two mines have the same capacity. Their production is limited in capability, but the improved experiences of uranium production technology and management are very important for the further development of industry.

– Special effort has been put on improving technology with the objective of reducing production costs.

  The renovations using more advanced techniques in Hengyang and Renhua uranium plants are nearly completed.

  The former uranium purification facility in Hengyang plant went into production in the early 1960s. It must be updated to produce nuclear grade UO_2 for domestic nuclear power reactors. Now the technical assistance from IAEA on this project is of vital importance. The feed materials are ADU and SDU pulps with lower uranium content and higher impurity contents from other uranium mills. A new pretreatment process was established for the high concentration uranium extraction. The uranium oxide from pretreatment is dissolved using HNO_3. The uranium extraction is conducted in pulse sieve-plate column under the condition of 95% saturation of uranium in organic phase and two-stage scrubbing of loaded organic phase. The UO_2 product is obtained through ADU precipitation by ammonium hydroxide and reduction calcining of ADU. The technology improvement of uranium ore processing was carried out in Renhua mine. The new flowsheet abolished resin-in-pulp process and employed belt filter for liquid-solid separation. The whole process has been simplified.

  In 1997, the construction of new Uranium Extraction Laboratory and In-Situ Leaching Laboratory will be completed and put into work, respectively, in Beijing Research Institute of Chemical Engineering and Metallurgy and Hengyang Research Institute of Uranium Mining. They will develop more advanced techniques for uranium mines and mills.

  In the last decade in-situ leaching, surface heap leaching, underground in-place leaching after blasting and acid-curing followed by ferric-trickle heap leaching have been used successfully in uranium production. In 1996, the in-situ and heap leaching technology produced about 2/3 of total uranium.

– The important point of adjustment and reform of uranium production management is to appraise and reduce the direct employment in uranium industry. Ten years ago the total staff for uranium production amounted to 45,000 persons. This figure was reduced to 8,500 in 1996. The margin of employment reduction is much larger than the production decrease. A total of 26,000 employees formerly involved in uranium production have been transferred to diversified products. Another 10,000 employees have gone to other industries.

3. FAVORABLE SITUATION OF NUCLEAR POWER DEVELOPMENT

The first two nuclear power plants Qinshan and Daya Bay Nuclear power plants, with a total installed capacity of 2,100 MW in the mainland of China have been operating safely and steadily for several years. It is widely acknowledged that construction of nuclear power plants is an important solution to the problem of energy shortages and the nuclear power is a safe, economical and clean energy source. The successes of these 2 plants would lay a solid foundation for China to further develop its nuclear power industry.

Two years ago, when we prepared the last issue of "Red Book", the China's nuclear power programme seemed less certain than it does today. In 1996 a series of events occurred. Four nuclear power plants with eight reactors of total capacity 6,900 MW have entered their construction period in succession.

– The second Qinshan NPP project with two 680 MW started construction of unit 1 in June 2,1996. It is planned to reach full power in 2002. The first concrete for the reactor building of unit 2 was poured on March 23, 1997. This project is designed and built mainly by China National Nuclear Corporation.

– The third phase of Qinshan NPP is the largest economic co-operative project undertaken by China and Canada. The main contract was signed by China National Nuclear Corporation and Atomic Energy of Canada Ltd (AECL) on Nov. 26, 1996. AECL will construct two 728 MW heavy water reactors. The project construction will start in 1998.

– The Lianyungang NPP in Jiangsu province is the project which was planned to be built in Liaoning province. The removal of the plant site was decided by the State Council of China in September 1996. This NPP with two 1,060 MW will be supplied by Russia.

  The agreement between Sino-Russian counterparts was signed in Dec. 1996. The construction is expected to start in 1998.

– The Ling'ao NPP with two 984 MW in Guangdong province is located about 1 km from Daya Bay NPP. The French government has approved of providing the favorable credit for the plant equipment which will be supplied by FRAMATOME. The construction started on May 15, 1997.

China has entered a rapid development period of its economy, that presents a new challenge to the existing energy industry which can hardly meet the needs. China has an uneven distribution of traditional hydro and coal energy resources. About 93% of the exploitable hydro power potential is concentrated in the southwest, northwest and central areas, while about 80% of the coal reserves are in the north and northwest areas. However, the major load centres are in the eastern and coastal areas. Introduction of nuclear power into a certain number of power grids is a must, especially in the coastal provinces. The development of nuclear power is the only way to optimize the national energy structure and ensure the power supply. The nuclear power capacity in China is expected to have a larger programme in the first decade of next century. Experts estimate the increase in the nuclear power generating capacity to reach 20 GW by 2010 and 25 GW by 2015. The reactor-related uranium requirements should amount to 3,000 tU in 2010 and 3,700 tU in 2015.

4. EXPERIENCE OF A NEW URANIUM MINE

The technologies and facilities of the existing uranium mines and mills in China built over 20-30 years ago have become outdated and inefficient. The employment in the uranium enterprises usually was expanded into a large number and the productivity was very low.

One factor must be emphasized that all of the mines and mills are located in remote or rural areas and typically have much shorter lifetimes than mines of other raw materials. But they all have their own towns or called residential villages, including apartments for employees' families, schools, hospitals, shops etc. The production infrastructure is always self-sufficient. As a result, the capital and operating costs would increase by a large amount. When closing the mines or mills, a lot of troublesome problems will occur.

In the last decade in addition to closing uranium mines and mills with comparatively high production costs, some new uranium mines, such as Yining ISL mine, Lantian heap leaching mine and Benxi mine were put into production one after another. Among them the Benxi mine has its own distinguishing features in respect of the improvement of production technology and management. It has taken many measures to solve above-mentioned problems.

Benxi uranium mine started production in May 1996. It can produce 100 tU in the form of yellow cake.

Benxi uranium mine is located 50 km south of Benxi city, Liaoning province. The reserve in this mine is small in scale with grade of 0.34% U. The deposit is irregular in shape and the ore bodies are of complex configuration. Both host and surrounding rock are fractured and sudden roof collapse happens often in active workings. The deposit is developed by incline shaft and the upward cut-and fill method is used for mining.

In most cases of this kind of uranium mines in China the main equipment for mining should be the hand-held pneumatic rock drills and electric scrapers. In Benxi mine, however, single boom hydraulic drill jumbo H-104 and LHD-loader ST-1.5 are adopted. A satisfactory result has been obtained in the first year operation of mining and drifting. The productivity per man-shift has reached 5.8 tonne of ore, which is higher by 2-3 times than other mines with the similar conditions. These two mining machines can be operated efficiently in very small stopes, e.g. 70-300 m^2 area, and offer a safer and more comfort working condition for miners. The new self-designed mine truck with 5 tonne capacity and service vehicle will be put into use in August 1997. Then the further completion of the trackless mining system will produce more efficiency.

Benxi mine has used a new uranium extraction technology named acid-curing followed by ferric-trickle leaching (AFL) process.

The whole technology contains ore crushing, mixing with strong acid, curing the mixture in piles, trickle leaching with ferric solution, extracting uranium from pregnant solution with tertiary amine and precipitating product. Most of the process effluent runs in a closed circuit.

In comparison with the traditional agitation leaching the AFL process eliminates the ore grinding, solid-liquid separation and simplifies the solvent extraction and disposal of residue. Therefore, the energy and water consumption is reduced a lot. The environment impact can be improved. Usually there is a little process water discharged. The tailings can be disposed of in a pile or returned to the mine for filling, eliminating the need for a tailing pond.

In respect of the development strategy, Benxi Mine has made many changes, compared to other uranium mines. The most notable change is that there is no self-constructed residential village for staff's families near the mine area. The employees work 20 days a month and have 10 day vacation to go to city Xingcheng. On the mine site hostel and canteen were built. The production infrastructure in mine is simplified and supported by local conditions.

The average productivity of closed mines is 0.15 t ore/man shift, however, Benxi mine reaches 0.75 t ore/man shift.

The projected concept for Benxi mine has become now reality and many advantages and cost savings have been recorded. Its experience can serve as a new model for other uranium mines to be constructed in China.

THE URANIUM INDUSTRY IN THE HISTORY OF THE CZECH REPUBLIC AND RECENT DEVELOPMENTS

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Abstract

Uranium industry in Czech Republic was established on January 1, 1946 at the old Jáchymov silver and uranium deposit under the name Jáchymov Mines. Following its start in 1946, exploration and mining grew rapidly and developed into a significant branch of industry. During 50 years of uranium industry activities 194 uranium deposits and occurrences have been explored and 74 of them have been extracted. Due to the geochemical properties of uranium, U accumulations occur in the whole crystalline basement of the Bohemian Massif and in all stages of its platform cover. The Variscan tectogenesis was significant for the formation of the U ore deposits. The uranium resources of the Czech republic can be assigned to the following 2 ore types: vein deposits and sandstone deposits. The peak production of about 3000 t U was reached in about 1960 in the Czech Republic and production remained between 2500 and 3000 t U/year from 1960 until 1989, when it began to decline. During the period 1946–1996 a cumulative production of 104 748 tU was produced in the Czech Republic. 86 per cent of the total was produced by conventional mining methods while the remainder was recovered using in situ leaching (ISL). Eighty-one per cent of the known uranium resources (RAR + EAR-I) are tributary to existing production centres in Rozná, Hamr and Stráz, remainder occurs in Brzkov and Osecná-Kotel deposits. EAR-II are associated with the Rozná, Brzkov and Hvzzdov deposits.

1. INTRODUCTION

Uranium industry in the Czech Republic was established on January 1, 1946 at the old Jáchymov silver and uranium deposit under the name Jáchymov Mines. Uranium industry has been engaged in the exploration, mining and processing of uranium on the whole territory of Czechoslovakia. State enterprise DIAMO, the successor organization of the Czechoslovak Uranium Industry is the exclusive producer of uranium in the Czech Republic at present.

Following its start in 1946, exploration and mining grew rapidly and developed into a significant branch of industry. During 50 years of uranium industry activities 194 uranium deposits and occurrences were explored and 74 of them were extracted. Uranium industry carried out 550 shafts, 324 adits and 16 open pits in the Czech Republic and 8 mills operated intermittently.

These activities left behind numerous sites — mines, open pits, waste dumps, tailings impoundments and mill sites — requiring rehabilitation in order to transfer the areas into land for public use.

The restructuring of the Czech Republic uranium industry carried out since 1989 includes a substantial reduction in production capability. Currently, only two mines remain in operation: the Rozná underground mine in Western Moravia and the Stráz ISL facility. Employment in the Czech uranium industry has declined from 12 200 in 1990 to some 3600 as of the end of 1996.

2. GEOLOGY OF URANIUM DEPOSITS IN THE CZECH REPUBLIC

The Bohemian Massif is a heterogenous, polycyclic metallogenic province [1]. Due to the geochemical properties of uranium, U accumulations occur in the whole crystalline basement of the Bohemian Massif and in all stages of its platform cover (Fig. 1), [2].

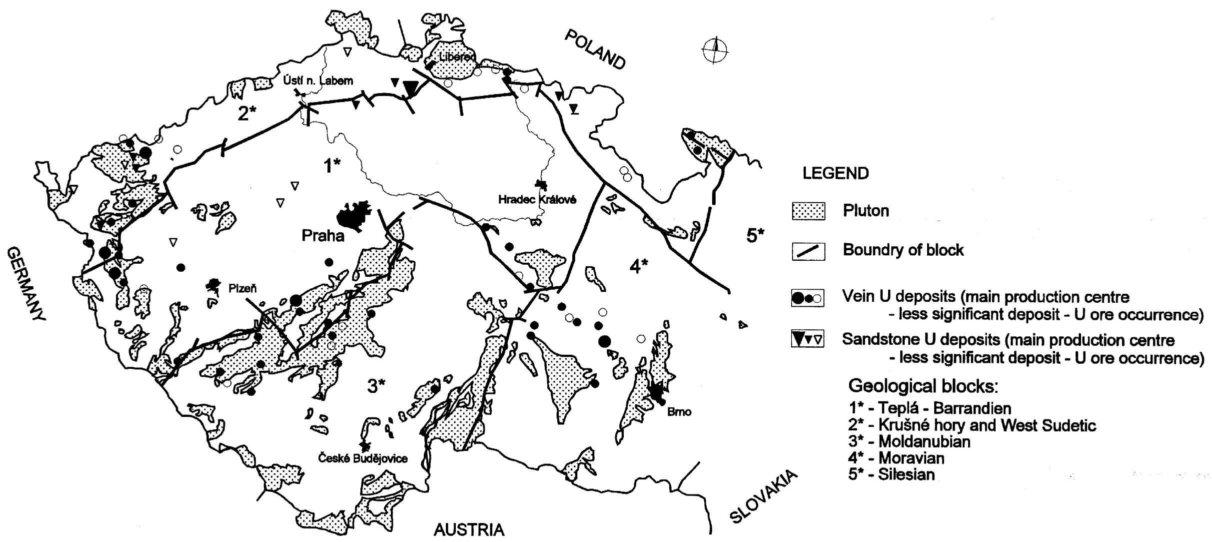


FIG. 1. Uranium mineralization in the Czech Republic.

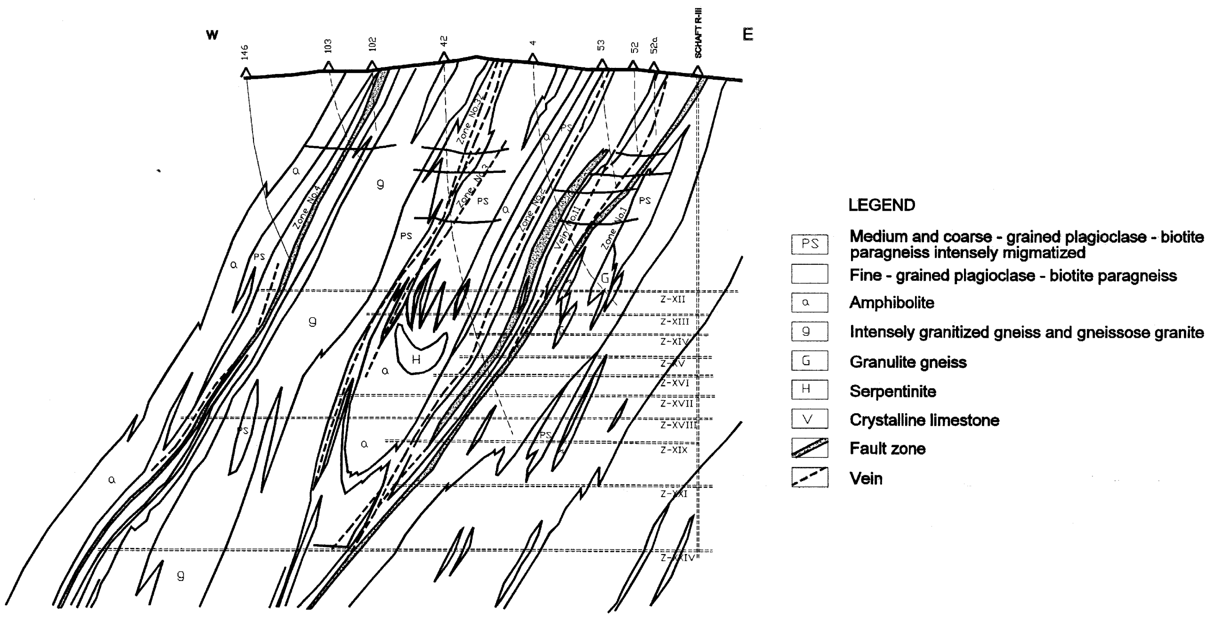


FIG. 2. Rozná uranium deposit, cross section and development system.

The uranium resources of the Czech Republic can be assigned on the basis of their geological setting to the following 2 ore types:

- vein deposits
- sandstone deposits

Vein deposits occur mostly in metamorphic complexes of Precambrian and early Paleozoic age, the smaller part occurs in Variscan granitoids (Vítkov and Nahošín-Mecichov deposits). Uranium ores are accumulated in typical veins (Príbram, Jáchymov, Slavkov, Predborice, Slavkovice etc.) or form thick zones (Rozná, Zadní Chodov, Dylec, Okrouhlá Radoun etc. — Fig. 2). The isotopic age of vein deposits mineralization was determined as late Variscan (265

± 5 Ma) and Kimerian (185 ± 15 Ma and 150 ± 20 Ma). The mineralization is characterized mostly by carbonate — uraninite and albite — chlorite — coffinite — hydromica associations, smaller amount of sulphides Fe, Pb, Zn and Cu and selenides, occurring in some veins. The Jáchymov deposit is typical for its vein Ag-Bi-Co-Ni-As-U mineralization, in some deposits the mineralization is also formed of uranium-organic complex [3, 4].

The most significant deposits of the sandstone type occur in Upper Cretaceous sedimentary rocks of the Bohemian Cretaceous Basin in Northern Bohemia (Figs 3, 4). The major uranium deposits in this area are Hamr, Stráz, Brevnište, Osecná-Kotel and Hvzzdov. Mineralized beds are developed in the freshwater Cenomanian and predominantly in the lower parts of the marine Cenomanian. Characteristic features of U mineralization are its link with the sedimentary complexes with organic substance and pyrite and its occurrence in the vicinity of the boundaries of different lithological rock types. The mineralization is characterized by U-Zr-Ti-P element assemblage [5].

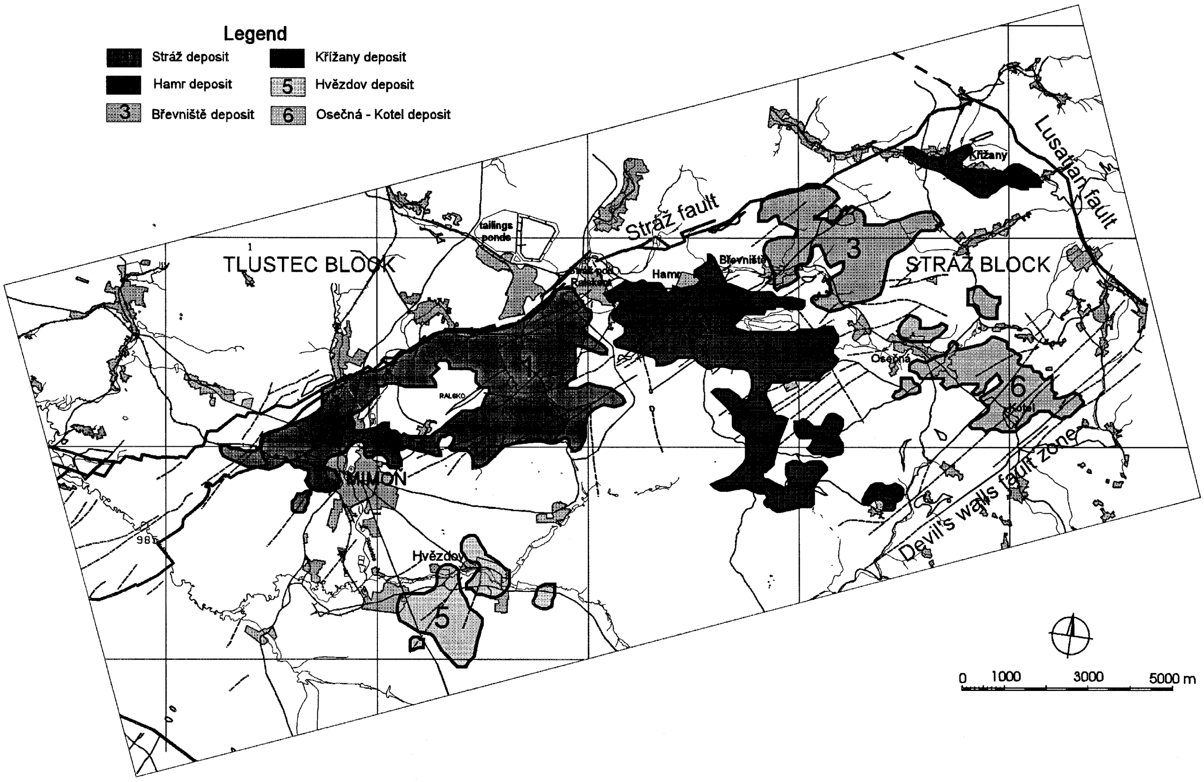


FIG. 3. Uranium deposits in Stráz block.

Uranium mineralization in the Permian-Carboniferous basins is mostly developed in coal beds and coal clays and their environment. The assemblage U-Pb-Zn-Cu-Mo is typical. The uranium mineralization occurs at Rybnícek, Radvanice and Svatonovice in Northern Bohemia.

Uranium accumulations in the Tertiary sedimentary rocks of the Sokolov basin, NW Bohemia, are concentrated in areas where the basement and environment of the sedimentary rocks is formed of Variscan granites. The uranium accumulation occurs in sandstones, coal clays, tuffs and tuffites. There are several small deposits there: Odec, Ruprechtov, Hroznztín, Hájek, Mecirolí and Kocourek (Fig. 5).

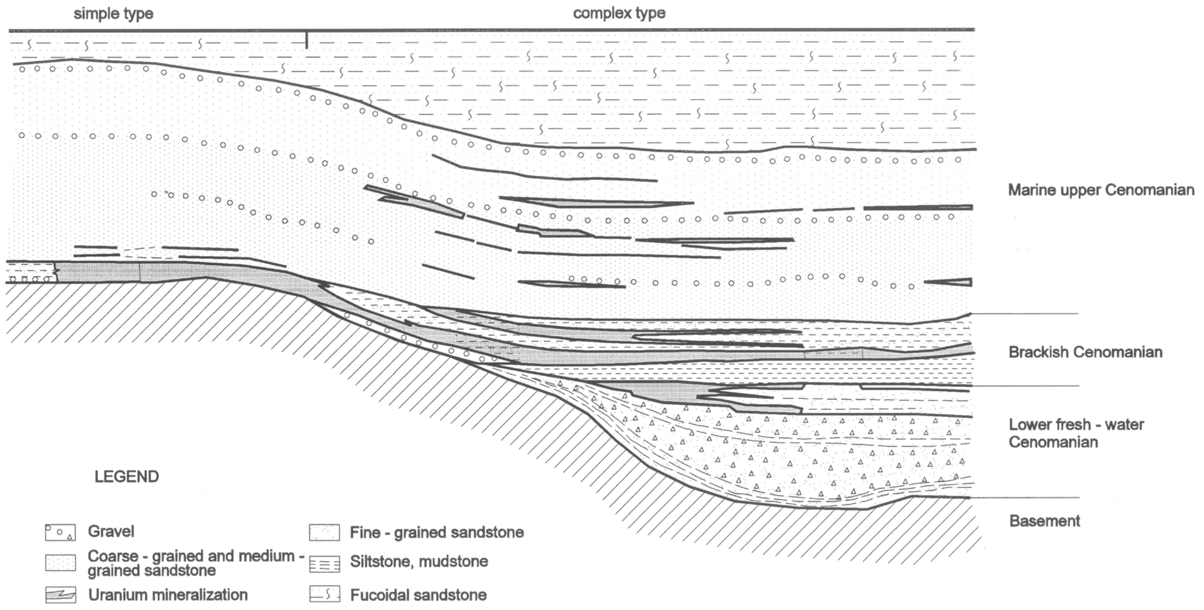


FIG. 4. Uranium mineralization in Cenomanian sediments of Stráz block — schematic cross section.

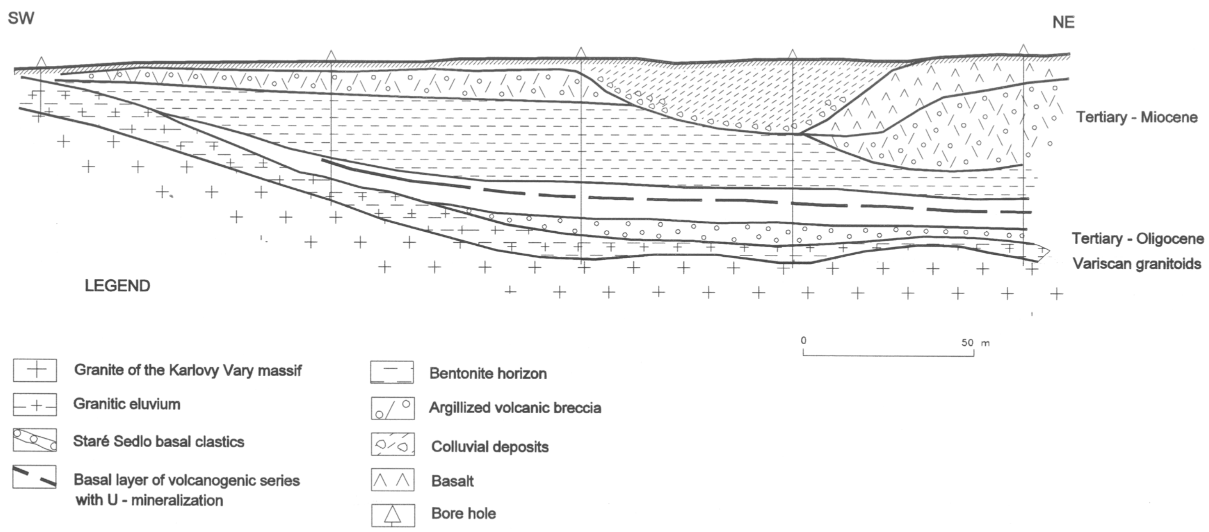


FIG. 5. Hájek Uranium Deposit — cross section through the southern part.

3. EXPLORATION AND PRODUCTION

3.1. Exploration

Systematic exploration programme including geological, geophysical and geochemical surveyes and related research, was carried out to assess the uranium potential of the entire Czech Republic. Areas with identified potential were explored in detail using drilling as well as underground workings.

The exploration activity initiated in 1946 in the Jáchymov ore district extended in a short time to other prospective areas defined predominantly in crystalline rocks of the Bohemian Massif. Regional geological and geophysical survey and its results showed the significance of the Variscan tectogenesis for the origin of uranium deposits.

Exploration continued in a systematic manner through 1989 with annual exploration expenditures in the range of $ 10–20 million and an annual drilling effort in the range of 70 – 120 km.

3.2. Production

Along with the exploitation of the Jáchymov deposit, the mining was started at the deposits Horní Slavkov (1948), Príbram (1950), Zadní Chodov (1952), Rozná-Olší (1957), Vítkov II (1962), Dylec (1965), Okrouhlá Radoun (1972) and other vein deposits occurring in crystalline rocks, and at the deposits Stráz (1967) Hamr (1967) and Brevnište (1983) with U accumulations in sedimentary rocks.

The peak production of about 3000 t U was reached in about 1960 and production remained between 2500 and 3000 t U/year from 1960 until 1989, when it began to decline (Fig. 6). During the period 1946–1996, a cumulative production of 104 748 t U was produced in the Czech Republic. Eighty-six per cent of the total was produced by conventional mining methods while the remainder was recovered using in situ leaching (Fig. 7).

Between 1946 and the dissolution of the Soviet Union all uranium produced in Czechoslovakia was exported to the Soviet Union. At present the uranium production of the Czech Republic covers the whole domestic reactor — related uranium requirements, no production is exported.

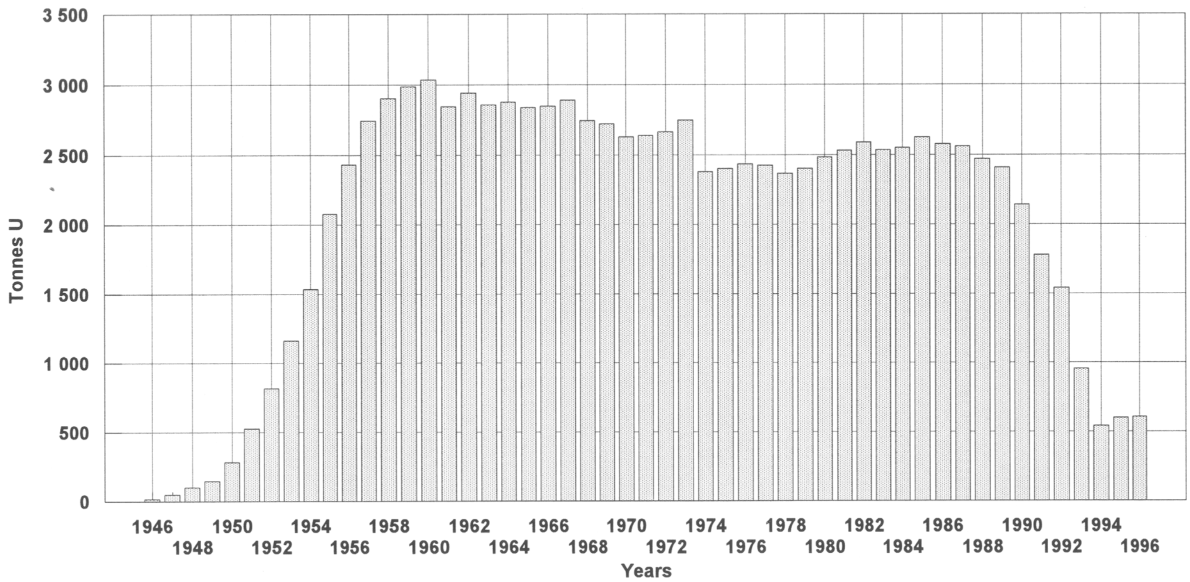
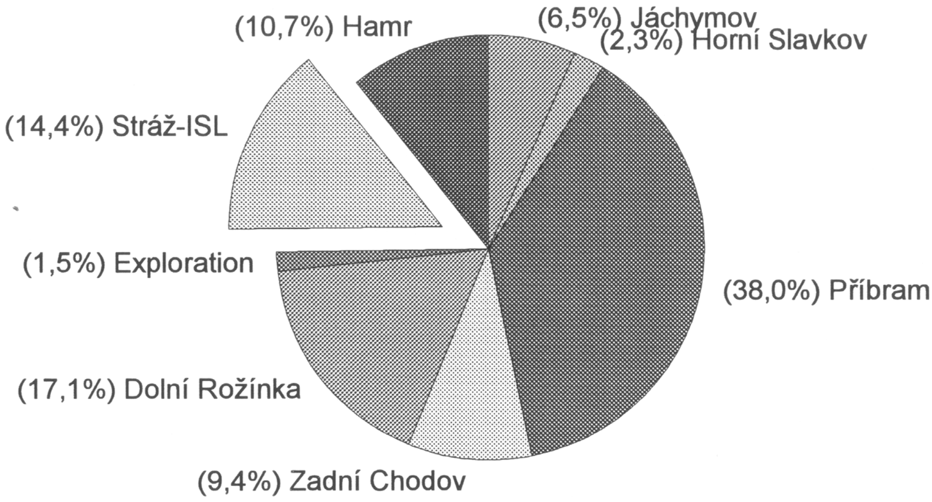


FIG. 6. Trends in uranium production of the Czech Republic, total in 1946–1996.



Notes :

1. **Z.Chodov includes production from Zadní Chodov, Vítkov II, Dyleň, Okrouhlá Radouň, Hájek, Odeř and Ruprechtov**
2. **Hamr includes production from Hamr and Břevniště**
3. **D.Rožínka includes production from Rožná, Olší, Javorník-Zálesí, Chotěboř, Slavkovice-Petrovice, Rybníček and Radvanice**

FIG. 7. Uranium production by districts: 1946–1996.

4. URANIUM RESOURCES, PRODUCTION CAPABILITY AND REQUIREMENTS

4.1. Uranium resources

Uranium resources of the Czech Republic as of 1.1.1997 shows Table I.

TABLE I. URANIUM RESOURCES IN THE CZECH REPUBLIC

Category	Cost ranges	
	< \$ 80/kg U	<\$ 130/kg U
RAR	6 630	30 220
EAR-I	1 180	18 960
EAR-II	5 480	8 480

Eighty-one per cent of the known uranium resources (RAR + EAR-I) are tributary to existing production centres in Rozná, Hamr and Stráz, remainder occurs in Brzkov and Osecná-Kotel deposits. No new areas favourable for the discovery of resources have been identified in the last ten years. EAR-II are associated with the Rozná, Brzkov and Hvzzdov deposits. The speculative resources are believed to exist in the Stráz block, Tlustec block and Hecmánky region, all in the Cretaceous basin of the Northern Bohemia.

4.2. Production capability

The restructuring of the Czech Republic’s uranium industry carried out since 1989 includes a major reduction in production capability. Since 1989, the following mines were closed: Olší (1989), Vítkov II (1990), Okrouhlá Radoun (1990), Brevnište (1990), Príbram (1991), Dylec (1991), Zadní Chodov (1992) and Hamr (1995).

Currently, only two mines remain in operation: the Rozná underground mine in Western Moravia, and the Stráz ISL facility.

The closure of the mines listed above was accompanied by a decrease in uranium production from 2500 t U in 1989 to 604 t U in 1996.

4.3. Requirements

Installed nuclear generating capacity will be increased in 2000 to 3516 MWe (Net.) and annual reactor-related uranium requirements will increase to 700 t U in 2000 and following years. The whole uranium requirements for next ten years are expected to be covered by domestic production.

5. FUTURE PRODUCTION POSSIBILITIES

Future production centre could be reactivated at Brzkov deposit. Brzkov is a vein type deposit with known resources in the RAR and EAR-I categories. It is located in the western part of the Moldanubian of Moravia. The mine was closed but could be reopened under more favourable market conditions.

Based on a prefeasibility study, elaborated in 1996, the Hvzzdov deposit with EAR-II in sandstones of Northern Bohemian Cretaceous Basin is not economically viable for the exploitation in the near future.

The Osecná-Kotel sandstone-type deposit in the Northern Bohemian Cretaceous Basin with RAR and EAR-I resources is also under consideration for mining after 2005. But complex hydrogeological conditions will make developing and mining of these resources at cost below $ 130/kg U difficult.

6. ENVIRONMENTAL ASPECTS OF URANIUM PRODUCTION

Mining and milling of uranium ores in the Czech Republic led to substantial impacts into the environment, the removal of which will require a long-lasting remediation procedure.

The main environmental impacts to the biosphere caused by uranium mining and processing facilities include the following:

– waste dumps with an aggregate volume of over 46 million m^3
– surface tailing ponds totalling 584 ha
– approximately 600 ha disturbed by the ISL operation at Stráz deposit
– contamination with chemicals used in the ISL operation of about 186 million m^3 Cenomanian and 80 million m^3 Turonian groundwater [6].

The total area affected by uranium mining and milling in the Czech Republic involves approximately 19 km^2. The removal of impacts into the environment will continue for many years later then 2000 and will need considerable financial resources.

7. CONCLUSIONS

The Uranium industry in the Czech Republic developed after the World War II into a significant branch of industry with the peak of production of about 3000 t U in 1960. Due to the excess supply in the uranium market and the termination of uranium export to the former Soviet Union, the uranium production in the Czech Republic declined substantially after 1989. The restructuring of the Czech uranium industry was carried out and recent national strategy balances uranium production with domestic reactor related uranium requirements.

Nowadays, parallel with the continuing reduction of uranium production, the decommissioning and restoring activities are becoming the main programme of the state enterprise DIAMO. Since 1993 all decommissioning and restoring measures are funded from the state budget of the Czech Republic.

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THE CURRENT URANIUM EXPLORATION ACTIVITIES OF THE POWER REACTOR AND NUCLEAR FUEL DEVELOPMENT CORPORATION (PNC), JAPAN

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Abstract

As of November 1996, Japan's total installed commercial nuclear power generation capacity was 42 GW(e), accounting for 34% of total electric energy generation. By 2010, Japan intends to have an installed electricity generation capacity of 70.5 GW(e). This will increase the country's demand for nat Ural uranium from 7,700 t U in 1994 (13% of the world consumption) to 13,800 t U in 2010 (17%-19% of the world projected consumption). However, Japan's known uranium resources at Ningyo-Toge and Tono deposits, are estimated at roughly only 6,600 t U. The Long-term Programme for Research, Development and Utilization of Nuclear Energy (adopted in 1994) calls for diversification through long-term purchasing contracts, independent exploration and involvement in mining vent Ures, with the objective of ensuring independence and stability in Japan's development and utilization of nuclear energy. The Power Reactor and Nuclear Fuel Development Corporation (PNC) has been commissioned to carry out the task of independent exploration. PNC is carrying out exploration projects in Canada, Australia, USA and China targeting unconformity related type deposits with an eye to privatizing them. Currently about 40,000 t U of uranium resources are held by PNC. PNC has been carrying out the following related activities: (1) Reference surveys on uranium resources to delineate the promising areas; (2) Development of uranium exploration technology; (3) Information surveys on the nuclear industries to project long-term supply and demand; (4) International Cooperation programme on uranium exploration with Asian countries.

1. INTRODUCTION

Nuclear Programme

As of November 1996, Japan had 51 operable reactors with a total installed commercial nuclear power generation capacity of 42 GW(e), providing approximately 34% of total electric energy generation. Four additional reactors are currently under construction and two more reactors have been planned.

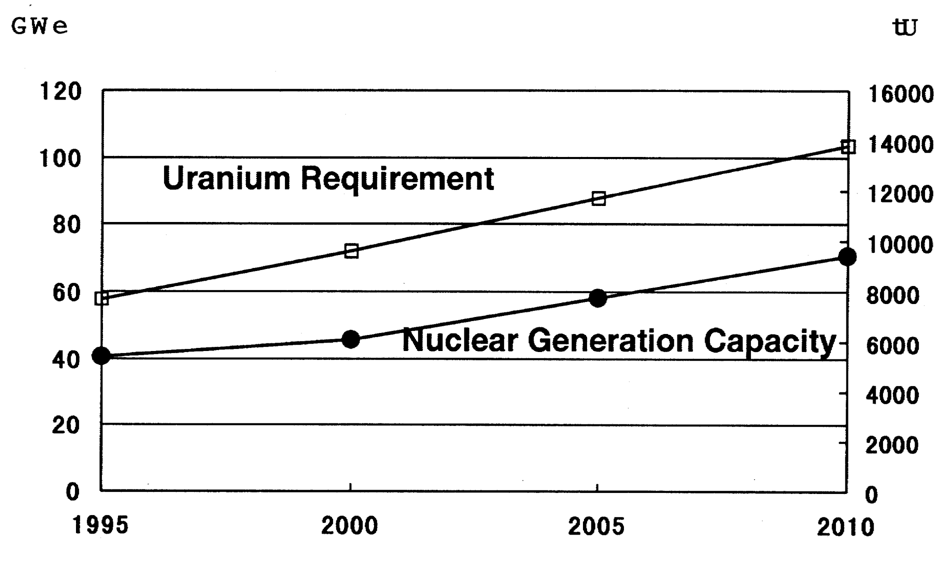

FIG. 1. Projected Japanese nuclear generation capacity and uranium requirement.

Japan plans to expand an installed capacity to 45.6 GW(e) (gross) by the year 2000 and 70.5 GW(e) (gross) by 2010. This will increase the country's demand for nat Ural uranium from 7,700 t U in 1994 (13% of the world consumption) to 13,800 t U in 2010 (17%-19% of the world projected consumption).

Supply and procurement strategy

About 6 600 t U of uranium resources have been detected in Japan. Japan has scarce domestic uranium resources and, therefore, must depend entirely on overseas supplied uranium.

Long-term Programme for Research, Development and Utilization of Nuclear Energy (revised in 1994) emphasized the stable and autonomous use and development of nuclear power in Japan.

In order to assure the steady supply of nat Ural uranium, it has been requested that our resources should be diversified through long-term purchase agreements, independent exploration and joint mining vent Ures, etc. The Power Reactor and Nuclear Fuel Development Corporation (PNC) has been commissioned to carry out the task of independent exploration and then, if successful, share the results with the private sector.

2. HISTORICAL REVIEW OF URANIUM EXPLORATION ACTIVITIES OF PNC

Domestic uranium exploration was commenced by the Geological Survey of Japan in 1954. In 1956 the Atomic Fuel Corporation, PNC's predecessor, was established by the government to carry out domestic exploration.

PNC commenced overseas uranium exploration activities in 1966. As Japanese private companies carried out active overseas exploration at that period, PNC's duty was at a grass-roots level of exploration.

In the middle 1980's, most Japanese companies withdrew from uranium exploration. As a result, PNC's duty was expanded to participate in a project at advanced exploration stage. From the late 1980's, PNC concentrated it's activities in known uranium provinces especially in Canada and Australia.

3. CURRENT ACTIVITIES

PNC is conducting its own exploration programmes and related activities (i.e. delineation of the promising areas, development of exploration technologies, information surveys on the nuclear industries to project long-term supply and demand, cooperation programme on exploration with Asian countries).

Uranium exploration

Currently PNC is carrying out exploration projects in Canada, Australia, USA and China. Economical unconformity related type deposits are the main target of our current exploration. Consequently, PNC gives priority to uranium provinces in Canada and Australia.

In Canada, PNC is conducting it's activities in the Athabasca Basin and the Thelon Basin. These are major unconformity related type uranium provinces in Canada.

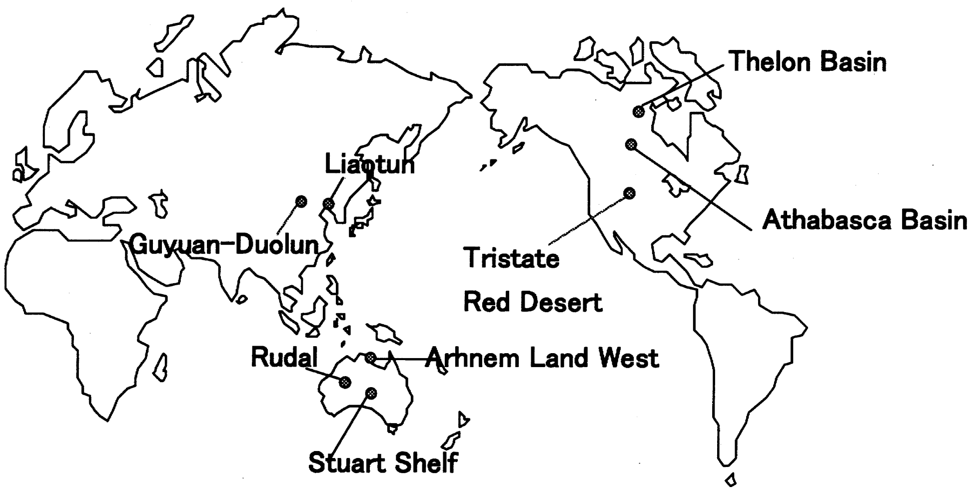

FIG. 2. Exploration activities.

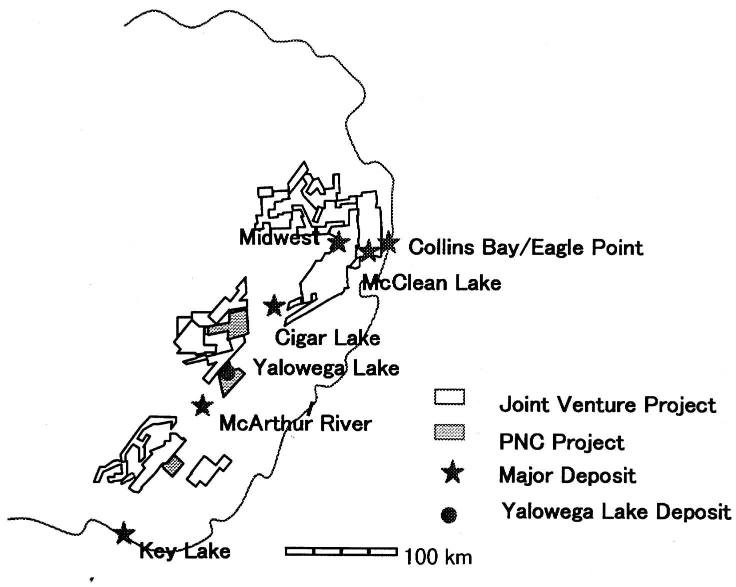

FIG. 3. Activities in Eastern Athabasca Basin.

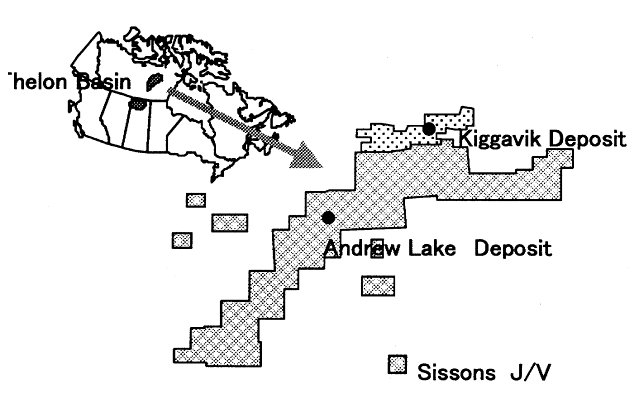

FIG. 4. Activities in Thelon Basin.

In the Athabasca Basin, PNC is participating in 13 joint vent Ure project including the Dawn Lake project and Wally project. PNC also holds 3 of it's own projects. Recently PNC discovered the Yalowega Lake deposit in own Christie Lake project area. The Yalowega Lake deposit is an unconformity related type deposit. The Yalowega Lake deposit is estimated to contain about 10,000 t U_30_8, average grade about 3% U_30_8.

In the Thelon Basin, PNC is participating the Sissons project. The Sissons project is a joint vent Ure project with PNC, Urangesellshaft and Daewoo. This project covers an area south to southwest of the Kiggavik deposit. The Andrew Lake unconformity related type deposit was discovered in this project area. Exploration activities have been carried out targeting unconformity related type deposits.

In Australia, PNC is carrying out exploration in the Arnhem Land, the Rudall and the St Uart Shelf regions. These are typical uranium provinces in Australia.

In Arnhem Land, the uranium deposits of Ranger, Nabarlek and Jabiluka are located. This region is under prospected because of restrictions for exploration activities related to native land tenure. So PNC believes there is still fairly good potential remaining to discover additional deposits.

In 1996, PNC, in joint vent Ure project with Cameco, commenced exploration work, after 8 years of negotiation with the traditional landowners.

In Rudall, PNC is participating in the Rudall joint vent Ure project with CRA Exploration. This project covers the extension area to the Kintyre deposit. Exploration activities have been carried out targeting unconformity related type deposits.

In St Uart Shelf, PNC is participating in the St Uart Shelf joint vent Ure project with Westem Mining. This project area surrounds the Olympic Dam deposit. Exploration activities have been carrying out targeting a deep seated breccia complex type deposit.

In addition to these, PNC holds the Mulga Rock deposit. This deposit is a flat lying sheet shape sandstone type deposit. The uranium resources of Mulga Rock deposit are estimated about 13,000 t U, average grade about 0.1%.

In the United States, PNC is participating in the Tristate joint vent Ure project and holds one project in Red Desert area, Wyoming. Both projects are targeting sandstone type deposits. Tristate project is a joint vent Ure with Geomex, located in the corner of Wyoming, Colorado and Nebraska. Big Red deposit is located in this project area.

Another uranium mineralized zone is located in PNC own project Red Desert area. PNC is carrying it's activities in both projects to evaluate resources.

In China, PNC is participating in the Liaot Ung joint vent Ure project in Liaoning province with China National Nuclear Corporation. This project is targeting unconformity related type deposits.

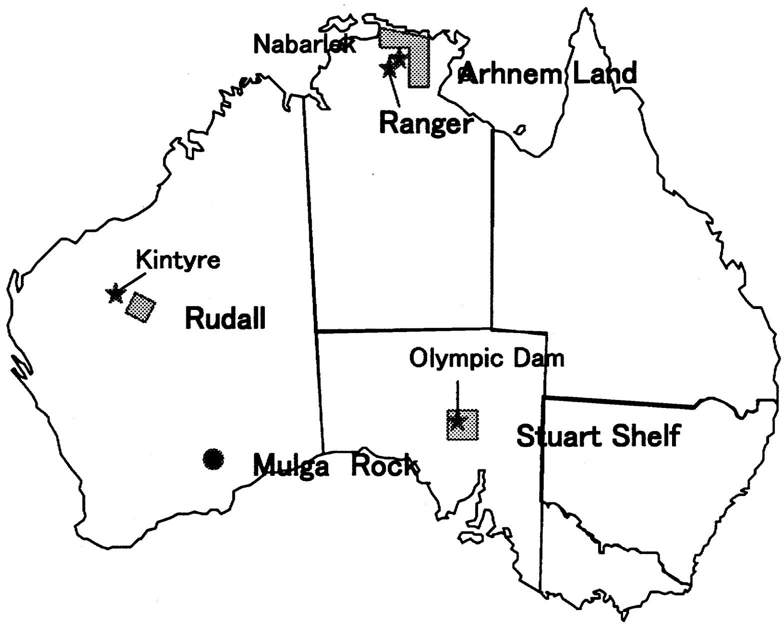

FIG. 5. Activities in Australia.

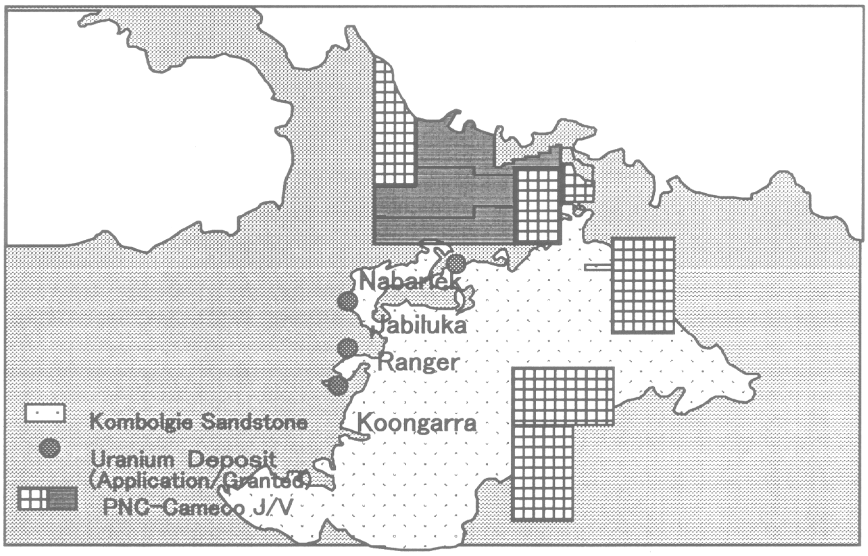

FIG. 6. Activities in Arhnem Land.

PNC is also participating in the Guyuan-Doulun joint geophysical research project with China National Nuclear Corporation in Hebei province.

Fig. 7 shows PNC totally owned deposits and joint vent Ures owned deposits. PNC holds several mineralized zone in addition to these. As a result of our discovery of uranium deposit in Canada, Australia and Africa, our overall interest in uranium amounts to about 40,000 t U.

Uranium potential assessment

Uranium potential assessment is a series of works to locate areas which may host uranium deposits.

By using PNC's knowledge of controlling factors on uranium deposit formation, it is thought possible to statistically process geological and exploration data from around the world to estimate favorable areas to host uranium deposits, even locations and resources of deposits. A Geographical Information System is an appropriate tool to quantify, integrate and visualize geological and exploration data.

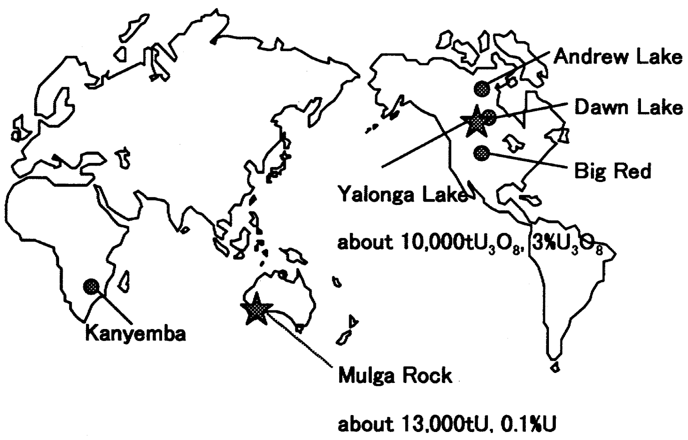

FIG. 7. Deposits owned by PNC & Joint Vent Ure.

There are many issues still to be considered and much on-going works involved in establishing the system. In the fut Ure, with continued progress, we may estimate total world uranium resources by this potential assessment method.

Developing uranium exploration technology

Exploration for deposit exposed at the ground has already been done over. Currently, deep seated "blind deposits" are our main target. PNC is developing geophysical and geochemical exploration techniques for "blind deposits" exploration.

To improve the precision of our geophysical interpretation, PNC has started to develop the multi-data analysis computer system. This system makes it possible to delineate geophysical characteristics of deep seated deposits by processing various different types of geophysical data together.

PNC is also doing research on the phase equilibrium of the clay mineral assemblages around uranium deposits in order to acquire a better understanding of clay and elemental haloes.

Uranium information service

PNC has been collecting information on uranium industries throughout the world, which includes information on resources, mines, environmental issues, related regulations, commercial use of highly enriched uranium and recycling issues.

PNC analyzes these information and projects long-term supply and demand of the world. Fig. 8 shows a example of our supply and demand projection. The mine productions are projected based on data collected by PNC on each deposit/mine. Demand forecast and other source of supply are referred from publications. Our projection indicates that a possible shortage of uranium supply may occur in the early 2020's.

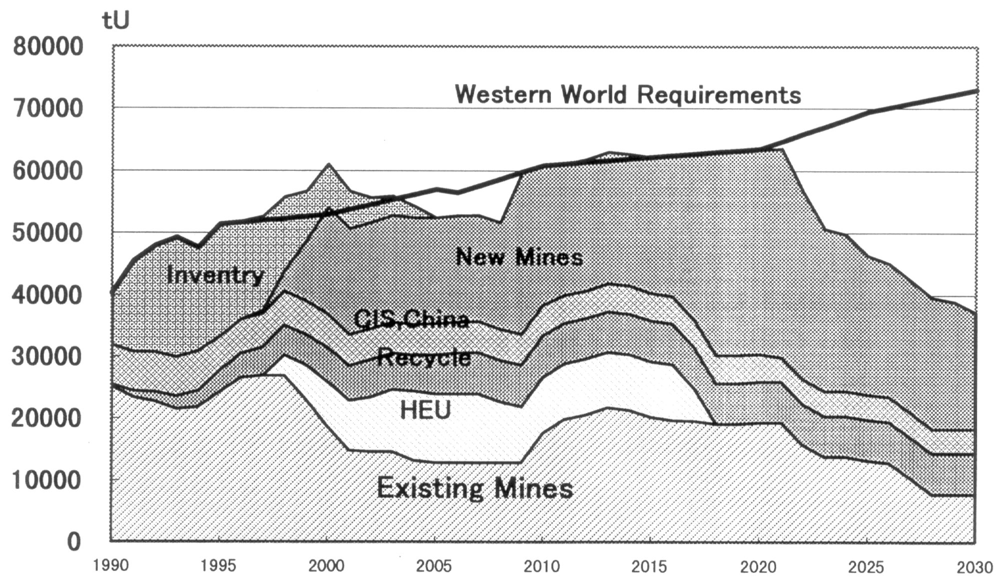

FIG. 8. Projected uranium supply and demand in the western world.

PNC issues Uranium Resources Newsletter and Specified Reports to present necessary information and our analysis to relevant organizations.

International cooperation programme

PNC is carrying out an international cooperation programme on uranium exploration with Asian countries using our own exploration technology and experience. Under this programme PNC annually invites 3 to 5 researchers from Asian countries, while dispatching our own experts to Asian countries.

4. CONCLUSION

In Japan, nuclear generation is the major source of electric supply and is expected to increase the share of generation. Japan will continue to be one of the major uranium consuming countries of the world and Japan will relay entirely for its uranium supply on other countries.

Japan seeks to diverse it's source of supply through long-term purchase agreements, independent exploration and joint mining vent Ures.

PNC is now the only Japanese organization to carrying out the task of independent exploration. To fulfill our responsibility PNC is continuing exploration activities and related activities. PNC is also continuing a international cooperation programme on uranium exploration with Asian countries to support their uranium exploration.

REFERENCE

[1] NAKANO, H., The Current Stat Us and Fut Ure Prospects of Uranium Exploration in Japan, Forum on Uranium Resource Development. Tokyo, (1997).

CHARACTERISTICS OF URANIUM DISTRICTS OF THE RUSSIAN FEDERATION

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Abstract

Uranium deposits are discovered in 15 ore districts of the Russian Federation. They are subdivided into four groups: Streltsovsky district with existing production centre, Stavropolsky district with depleted deposits, three prospective districts and ten reserve districts. The overview of new data on these districts is presented. Streltsovsky district with Priargunsky Production Centre include 19 molybdenum–uranium deposits of structure-bound volcanic type in caldera. The main activities in Stavropolsky district with two depleted uranium deposits are connected with restoration works and wastes rehabilitation. Except Streltsovsky district there are no more deposits in the Russian Federation prepared for uranium production. At the same time some uranium deposits of Vitimsky, Zauralsky, and West-Siberian districts are prospective for new development of production centres. They belong to the sandstone type, related to paleovalley or basal channel, and are suitable for ISL operation. The deposits of the other districts are considered to be reserve and considered unprofitable for uranium production at present and in the nearest future. The biggest of them is Aldansky district with gold-uranium deposits in potassium metasomatites in areas of Mesozoic activation of Archean cratons. Central Transbaikalsky, Yeniseisky, Yergeninsky, Onezhsky, Ladozhsky, Bureinsky, Khankaisky, Volgo-Uralsky reserve districts include mainly small-size deposits of vein, volcanic, surficial and metasomatite types with low uranium grades.

1. INTRODUCTION

After the USSR disintegration there left 60% off all Nuclear Power Stations capacities and only 26% of Known Uranium Resources on the Russian territory. Russian nuclear power plants demand and export supplies are provided by accumulated uranium stocks and by uranium produced from the deposits of Streltsovsky district in the Eastern Transbaikal region. Considerable part of the produced uranium is being exported. To 2010 the stocks may be exhausted due to increasing capacities of nuclear power plants and possible increasing of export because of rising prices for uranium. Thus the problem of new development in uranium resources and production is urgent for the Russian Federation.

Uranium deposits were discovered in 15 ore districts which are distributed mainly in the southern part of the Russian Federation. The vast areas to the north of 60° parallel remain practically untouched by exploration. These districts can be subdivided into four groups (Table I):

1. Streltsovsky district with existing production centre,
2. Stavropolsky district with depleted deposits,
3. Three prospective districts (Vitimsky, Zauralsky, West-Siberian) include deposits with “Known” resources recoverable at costs of $80/kg U or less, which are prospective for the development of new uranium production centres,
4. Ten reserve districts (Aldansky, Central Transbaikalsky, Yeniseisky, Yergeninsky, Onezhsky, Ladozhsky, Volgo-Uralsky, Bureinsky, Khankaisky, Chukotsky) include deposits of high cost uranium resources which may have economic potential for the future production.

TABLE I. URANIUM DISTRICTS OF THE RUSSIAN FEDERATION

Uranium Districts of Russia Table. 1

Districts	Grade U,%	Principal deposit type (ore setting)	Host rocks (lithology)	Strati-graphy*	Shape of ore bodies	U mine-rals **
District with existing production centre						
Streltsovsky 19 deposits (2depleted, 4-large, 7-mid., 6-small)	0,2	Volcanic (Mo-U in caldera structure controlled)	felsite, rhyolite, dacite, basalt, conglomerate	Up.Jur.-L.Cret.	stockwork, vein, tabular	P,C,B,G
			granite, marble	PZ_3-PR_1		
District with depleted deposits						
Stav.:polsky 2 small, depleted	0,1	U vein-stockwork	rhyolite, mudstone	Quat.	vein, lens	P,G
Prospective disricts						
Vitimsky 10 dep.(2-mid., 8-small)	<0.1	Sandstone basal channel (U-REE in paleovalleys)	sandstone, sand, clay, conglomerate	Tert.	ribbon, lens, tabular	P,C
Zauralsky 2-mid,1-small,1-deplet.	<0.05	Sandstone basal channel (Sc-REE-U in paleovall.)	sandstone, sand, siltstone	Up.Jur., Quat.	tabular, lens	P,C
West-Siberian 1- mid., 3 - small	<0.15	Sandstone basal channel (U in paleovalleys)	sand, clay	Up.Jur.-L.Cret.	tabular, lens	P,S
Reserve districts						
Aldansky 9 dep.	<0.1	Metasomatite (Au-U in K metasomatites)	gneiss, granite	Early.AR	vein, stockwork	B
Central Transbaikalsky						
1-mid., 2-small	0,2	U vein	granite	M.-Up.Jur	vein	G
1-mid., 4-small.	<0.1	Volcanic (Mo-U in cal-dera structure controll.)	sandstone, dacite, rhyolite	M. Jur.-L.Cret.	tabular, vein, lens	P.C
2-mid.; 3-small	<0.1	U sandstone	sandstone,conglom.	L.Cret	tabular	P,C
3-small	<0.1	As-U vein	granite, diorite	M-Up.PZ	vein	P
Yeniseisky						
2- mid.	<0.2	U sandstone	sandstone, siltstone	Up.Dev.	tabular	P,S
4-small	< 0.1	Volcanic (Mo-U in caldera structure controlled)	felsite, tuff, rhyolite		lens, stockwork	P,C
Ergeninsky 13dep.(1-mid.,12-small)	<0.1	Lignite (U-REE in clay with bone detritus)	clay, fish bone detritus	Cenoz.	tabular	P,S
Onezhsky 5 small	< 0.1	Metasomatite (U-V in carbonate-mica albite metasomatites)	siltstone, shist, dolomite, sandstone	PR_1	stockwork, vein, tabular	P,C
Ladozhsky						
1-mid., 1- small.	0,1	U unconformity (?)	sandstone	Riphean	lens, tabular	P,C
Bureinsky 9 small	< 0.2	Volcanic, vein-stockw. .(Mo-U in caldera)	felsite, rhyolite	K_{1-2}	vein, stockwork	P.C.G
Khankaisky	<0.1					
3 small		Mo-U vein	rhyolite	D	vein	P.C
1 small		Surficial (U paleovaleys)	sandstone	KZ	lens, ribbon	C,S
Volgo-Uralsky		Surficial				
2 small	<0.2	(U in paleovalleys)	clay, sand	Up.Perm.	lens, tabular	C,P
2 small	0,03	(U-bitumen in sediments	limestone	L.Perm.		
2 small	0,01	(U epigenetic in lignite)	lignite	Quat.		
Chukotsky 4 small, 1 depleted	0,1	Volcanic (Mo-U in cal-dera structure controll.)	volcanite, terrigene sediments	Jur.	vein, stockwork	P

* - Stratigraphy: L-Lower, M-Middle, U-Upper, AR-Archean, PR-Proterozoic, PZ-Paleozoic, MZ -Mesozoic, Dev-Devonian, Perm.-Permian, Jur-Jurassic, Cret-Cretatious, Tert-Tertiary, Quat-Quaternary

** - Principal uranium minerals: P- pitchblende, C- coffinite, B- brannerite and U-Ti phases, G- supergene minerals, S- sooty pitchblende

The data on the main uranium districts and resources of the Russian Federation became available after the well known paper "Uranium Resources of the Union of Soviet Socialist Republics" at IAEA Technical Committee Meetings in August 1991 [1]. Since that time there were numerous publications in Russian geological editions and several presentations at IAEA Technical Committee Meetings [see references]. The idea of this paper is to summarise and to make the overview of new data on uranium deposits of the Russian Federation.

2. DISTRICT WITH EXISTING PRODUCTION CENTRE

Priargunsky Mining-Chemical Complex in Eastern Transbaikal region is currently the only uranium production centre in the Russian Federation. It processes the monometallic uranium and polymetallic molybdenum–uranium ores of Streltsovsky district deposits, which are classified as structure-bound volcanic type [1,2,3,4]. The average U grade is 0.18%. There are 19 deposits in the district (Fig. 1): 17 deposits are situated in volcanic rocks and sediments (13 of them are in stratified effusives of sheet facies and 4 in effusives of neck facies) and 2 large deposits in the basement rocks (dep. Antei in granite, dep. Argunskoye in granite and marble). The principal ore control factor is structural. The type of host rocks does not exert influence on ore grade [5].

Since the beginning of uranium mining in 1970 ten deposits have been brought into operation and only two deposits are depleted by open pit operation. Most deposits have been explored underground and conserved now.

Relatively high grade ores (over 0.3%U) of *deposit Antei* are the main object of current mining. Vein-like ore bodies are localised within two sub-parallel steeply dipping faults 1 km long and 350–1400 m from the surface. The upper borderline of Antei is flat dislocation in the structure eluvium of granites directly under the dacites of Streltsovskoye deposit. The latter include 20% of the district total resources.

The uranium production is provided mainly by traditional sulphuric acid leaching at the hydrometallurgical plant and a small amount is produced by heap leaching. The possibility of increasing production with low grade ores is being considered using heap leaching and in place leaching methods of ore processing. Ore bodies from the upper complex of the section in sediments and felsite with pitchblende, molybdenite-pitchblende and supergene mineralization are considered to be most favourable for these methods [6].

3. DISTRICT WITH DEPLETED DEPOSITS

Stavropolsky district include two depleted uranium *deposits: Beshtau and Byk*. Uranium mineralization is presented by oxidized sulphide-pitchblende veins and stockworks in xenoliths of bituminous sediments within the apex of granite porphyry and rhyolite bodies [1].

These deposits have been exploited by two underground mines since 1950, which were closed in 1975 (Beshtau mine) and in 1990 (Byk mine). From 1965 to 1989 ore bulk was processed not only by traditional sulphuric acid leaching at the milling plant, but also by in place leaching and heap leaching. From 1980s to 1991 ore bulk from Vatutinskoye U deposit (Ukraine) and from Melovoye U deposit (Kazakstan) was also processed at the Lermontovsky milling plant. After 1991, when U production has been stopped, apatite flotation concentrate is being processed at the milling plant.

Currently the main activities are connected with the environmental issues in the rehabilitations of wastes. Rehabilitation of mining wastes dumps of mine 1 (deposit Beshtau) at the surface of 36 ha is mainly completed. Rehabilitation of waste rocks of mine 2 (deposit Byk) at the surface of 18 ha is underway and planned to be finished in 1999. The project of milling complex (buildings and territories) remediation is at the planning stage. Rehabilitation and decommissioning of milling tailes pond at the surface of 118 ha has been started in 1996 and planned till 2005. The radiation survey of the region at the surface of 3200 ha was conducted in 1996.

4. PROSPECTIVE URANIUM DISTRICTS

The resources of Streltsovsky district deposits and uranium stocks are not sufficient to provide the requirements of the Russian Atomic industry and export commitments after 2010. Currently most of world uranium production is provided by very profitable deposits with high-grade ores (Canada) and by deposits suitable for in situ leaching (Kazakstan, Uzbekistan).

Deposits of Vitimsky, Zauralsky and West-Siberian districts are considered to be most prospective for new uranium production centres development in the Russian Federation. They are presented mainly by small and middle-size valley type sandstone deposits (sandstone basal channel type by IAEA classification) with low-grade ores, which are favourable for in-situ leaching operation. Deposits of Vitimsky and Zauralsky districts have been already described at IAEA-TCM [7] and in the “Red Book 1993” [2], that is why their description is excluded here.

4.1. West-Siberian district

The district is situated in south-western edge of Siberian platform. Deposits are located in the Upper Jurassic–Lower Cretaceous and Paleogene-Neogene platform sediments in an area of more than 5.000 km^2. Their geological setting is very much similar to deposits of Zauralsky district [2,7,8].

Malinovskoye deposit is the biggest one in West-Siberian district [9]. It is located about 100 km north-east from town of Kemerovo. Paleovalley is of meridian trend, 50 km length, 1–3 km width, 70m and 300m depth respectively in the mouth and in the source part. Cambrian volcanic–sedimentary rocks with granite and diorite intrusions and Devonian terrigene and terrigene–volcanic sediments with post Devonian granite and syenite intrusions constitute the basement of paleovalley (Fig.2). The average thickness of Mesozoic–Cenozoic alluvial sediments, which fill the paleovalley, is 300 m.

The productive horizon with U mineralization is presented by grey alternating sand, gravel, clay and siltstone, which are enriched by coal and organic material, especially in the lower part of the section (Fig.3). It is covered by overlying strata of Lower Cretaceous red clay 50–110 m thickness. The U ores are localised at the depth 100–300m from the surface in united sheet-like strata up to 50m. thickness, which consists of tabular-, lens- and roll-like ore bodies up to one km in length, 100–300m wide. Uranium grades are 0.013–0.139%, sometimes up to 1.32%. Principal U mineral is sooty pitchblende, minor pitchblende, coffinite. The ores have favourable technological properties for ISL mining: clay fraction less then 20% (average – 17%), low-carbonate content (CO_2-0.5%), recovery is 40–97% (average–76%), filtration factor is 0.65–17 m/day.

The presence of Malinovskoye deposit provided an evidence on the broad uranium potential of the south-eastern part of the West-Siberian platform margin.

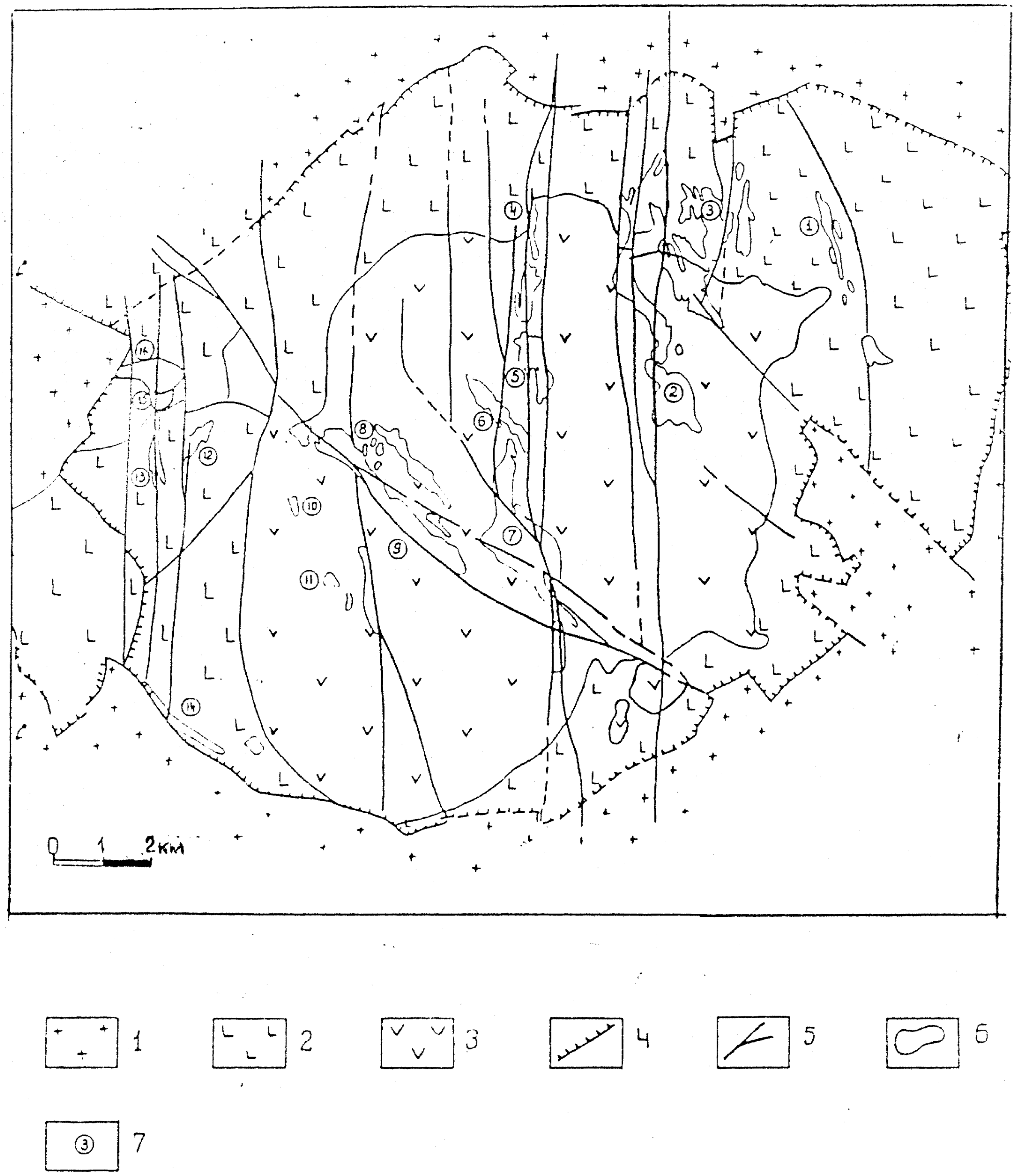

FIG. 1. Schematic geologic map of Streltsovsky district.

Legend: 1) Paleozoic granite; 2) Upper Jurassic volcanics and sediments of lower complex; 3) Lower cretaceous volcanics and sediments of upper complex; 4) Caldera boundary; 5) Fault zones; 6) Ore bodies projection;7) Deposits: (1) Shirondukuevskoye, (2) Streltsovskoye, (3) Antei, (4) Oktyabrskoye, (5) Martovskoye, (6) Lutchistoye, (7) Malo-Tulukuevskoye, (8) Tulukuevskoye, (9) Yubileinoye, (10) Vesenneye, (11) Novogodneye, (12) Pyatiletneye, (13) Krasnyi Kamen, (14) Yugo-Zapadnoye, (15) Zherlovoye, (16) Argunskoye.

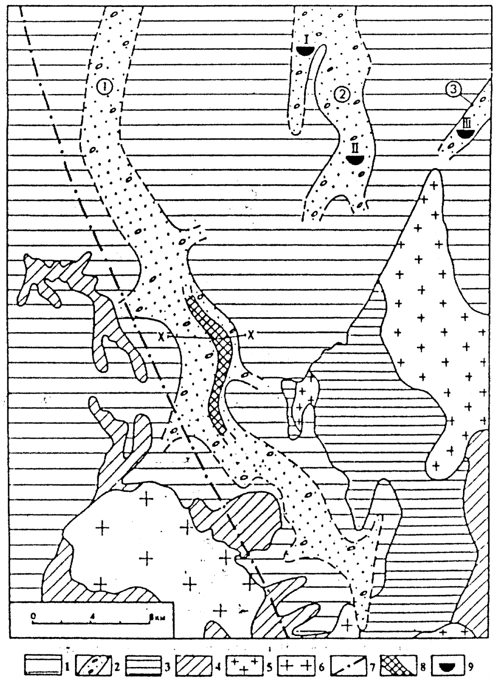

FIG. 2. Schematic geological map of Malinovskoye deposit area (after P.S. Dolgushin).

Legend: 1) Sedimentary complex of West Siberian platform; 2) Mesozoic alluvial productive facies of paleovalleys; 3-6 Rocks of the basement: 3) Devonian volcanics and sediments (red sandstone, siltstone, mudstone, effusives, tuffs), 4) Cambrian volcanics and sediments (porphyrite, sandstone, slates, limestone), 5) Mesozoic granitoid, 6) Pre-devonian granitoid; 7) Kuznetsko-Alatausky fault; 8) Malinovskoye deposit, 9) Uranium occurrences.

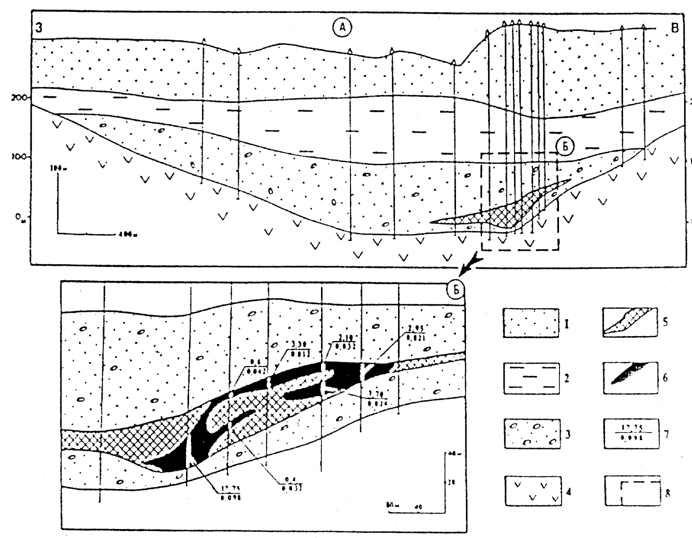

FIG. 3. Cross sections of Malinovskoye deposit (after P.S. Dolgushin).

Legend: 1) Lower and middle cretaceous kaoline clay, sand; 2) Lower cretaceous clay; 3) Lower cretaceous -upper Jurassic productive horizon of grey sand, gravel; 4) Porphyrite of the basement; 5) Ore body, 6) Commercial ores; 7) Parameters; numerator-thickness, m: denominator-U grade, %.

5. RESERVE URANIUM DISTRICTS

There are 10 reserve districts in the Russian Federation. They include numerous deposits which are unprofitable for uranium production at present and in the nearest future due to economic reasons.

5.1. Aldansky district

Aldansky district is situated in southern Yakytiya in the central part of Aldansky shield. It is the biggest reserve district of the Russian Federation [10,11]. Geological setting of the district include three levels of formations (Fig. 4):

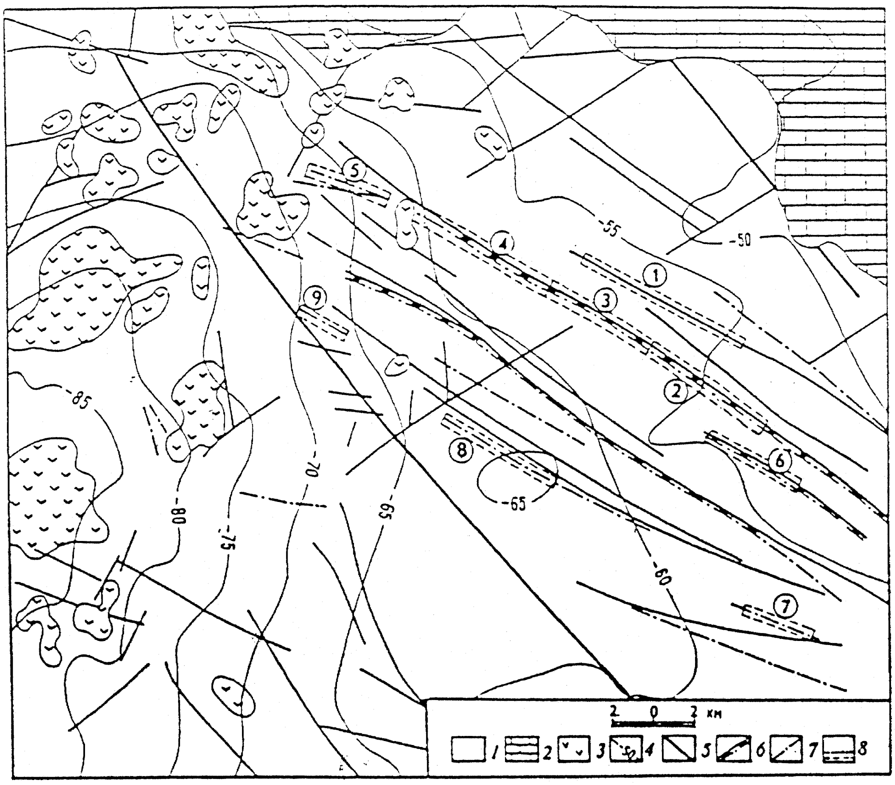

FIG. 4. Geological map of Aldansky uranium ore district (after E.V. Akhapkin).

Legend: 1) Archean crystalline basement (gneiss, granite, schists); 2) Cambrian platform mantle (limestone, dolomite); 3) Mesozoic intrusive subvolcanic complex; 4) Isoanomaly of gravitation field, m. gal; 5–7) Types of faults: 5) Ancient, 6) Ancient renewed in Mesozoic, 7) Mesozoic; 8) Ore parts of faults; Figures in circle-uranium deposits: (1) Severnoye, (2) Druzhnoye, (3) Kurung, (4) Elkonskoye Plateau, (5) Elkon, (6) Vesenneye, (7) Agdinskoye, (8) Snezhnoye, (9) Intersnoye (2–5 deposits of Yuzhnaya zone).

- Early Archean gneiss, granite, migmatite, schist compose the crystalline basement,
- Vend — Lower Cambrian platform mantle up to 700 m thickness is presented by limestone and dolomite,
- products of intensive Jurassic tectonic-magmatic activation presented by sediments and volcanics, which fill closed fault troughs, and by extrusion of laccoliths, stocks, sills of subvolcanic intrusions of alkaline complex.

Gold mineralization is typical for the district. It is presented by stratiform concentrations in the basal layers of closed fault troughs and by placers.

Uranium deposits are related to Elkonsky horst (the upstanding block of Archean granite-gneiss basement) which is intruded by Jurassic alkaline rocks and crossed by the faults of different age. These faults can be divided into three groups:

– ancient Early Proterozoic faults,
– renewed faults with overprinting of Mesozoic tectonites and metasomatites upon ancient faults,
– young Mesozoic faults, which develop within unbroken Archean rocks.

Uranium mineralization is related to young and to renewed faults.

Mesozoic activation led to intensive pre-ore pyrite- carbonate- feldspar metasomatic alteration extending along faults for tens of metres into the gneiss wall. Subsequent repeated crush and brecciation of potassic metasomatites inside faults precede uranium ore formation. Such tectonic sutures make up the complex of sub-parallel linear vein-like stockworks 500–700 m long and commonly up to 10m thick. The thickness of separate sutures is several centimetres. Uranium mineralization is presented by brannerite, which is usually transformed in amorphous aggregate of U-Ti dioxide phases. Ore textures — brecciated, knotty, cancellated with uranium mineralization in the cement. Molybdenum and gold are regarded as by-products. The absolute age of ores is 150–130 mln.y., the temperature of their formation 200–230°C.

Most uranium deposits are localized within Yuzhnaya zone, which is presented by 30 km long ancient tectonic suture, which have been renewed in Mesozoic (Fig. 4). Its central part can be considered as one gigantic deposit, consisting of deposits Druzhnoye, Kurung, Elkon, Elkonskoye Plateau with numerous echelon-like linear stockworks. The upper borderline of ores is situated commonly at the depths of 200–500 m but the most productive ore chimneys predominate at a depth more than 1 km. The average U grade is 0.15%. The resources belong to 80–130 $/kg U cost category. Deposits Kurung, Druzhnoye, Elkonskoye Plateau have been explored by underground mines, the rest — only by bore holes from the surface.

Complicated economic, geographical, mining and technical conditions and rather low quality of ores makes the development of this district unprofitable in the nearest future but it could be of future interest due to the considerable gold resources.

Other reserve districts include mainly small and middle size deposits of vein, volcanic and sandstone types with low U grades. They are not yet considered to be the sources of uranium production.

5.2. Central Transbaikalsky district

Central Transbaikalsky districts include 16 deposits of three principal types [1,4,12] (Fig. 5). Their genesis is connected to the Mesozoic and Cenozoic tectonic-magmatic activation, which occurred in various geological situations. Their resources could be considered as the potential addition to the base of Priargunsky Production Centre.

Volcanic type is presented by 5 U- Mo deposits in caldera composed by Upper Jurassic–Lower Cretaceous volcanic rocks (similar to some stratiform deposits of Streltsovsky district).

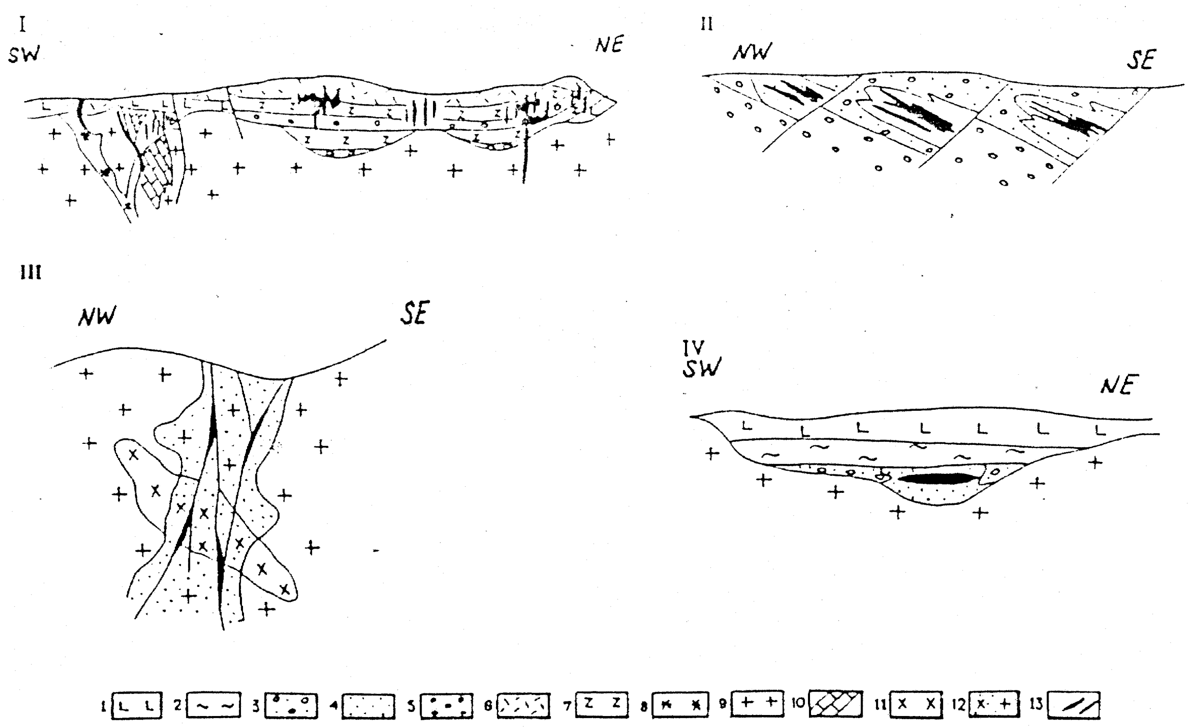

FIG. 5. Schematic sections of uranium deposits of Transbaikal region (after M.D. Pelmenev). I) Streltsovskoye ore field, II) Imskoye deposit, III) Gornoye deposit, IV) Khiagdinskoye deposit.

Legend: 1) Basal; 2) Siltstone-sandstone strata; 3) Red gravel and conglomerate; 4) Grey gravel and conglomerate; 5) Conglomerate; 6) Rhyolite; 7) Dacite; 8) Syenite-porphyry; 9) Granite; 10) Dolomite; 11) Diorite; 12) Clay-ceolite alteration, 13) Uranium ore bodies.

Olovskoye deposit is the biggest of the volcanic type. Mineralization occur in tabular stratiform bodies along interbeded contacts in volcanics and sediments of Upper Jurassic-Lower Cretaceous age. They are presented (from below to up) by conglomerate, gravel, sandstone, siltstone, rhyolite, tuff (Fig. 6) [13]. Biotitic granite and granodiorite constitute the basement. Vertical range of ore mineralization is from 10 to 120 m. Deposit consist of 90 ore bodies in 24 ore strata. Its length is 9 km, width to 600 m (average 200–250 m). More than a half of total resources are localised in lenses (to 20 m thick, first hundred meters long, first ten meters wide) in terrigene sediments and a third part of resources in ribbon-like bodies (first meters thick, more than 1 km long, 100–300 m wide) in the top and bottom of rhyolite and dacite tuff. Uranium mineralization is represented by pitchblende, coffinite in association with pyrite, native arsenic, carbonates, clay minerals. The age of ores is 102–110 mln.y.

Imskoye deposit is the example of 5 stratiform sandstone type U deposits in step faulted grabens, filled with molasse-like Cretaceous sediments [14]. The sediments are presented by the strata of conglomerate and gravel of proluvial facies, sandstone and siltstone of alluvial, limnetic and boggy facies. Their thickness is up to 1500 m. Proterozoic and Paleozoic granite and metamorphite constitute the basement of the graben (Fig. 7). Ore bodies of stratiform tabular and lens form are situated mainly in gravel with granite pebble and to a minor extend in sandstone. Host sediments are enriched with lignite, plant detritus and pyrite. The productive horizon is overlaid by 50–350 m cover. Uranium mineralization is represented by thin disseminated uranium oxides and sooty pitchblende in association with carbon substance and sulphides.

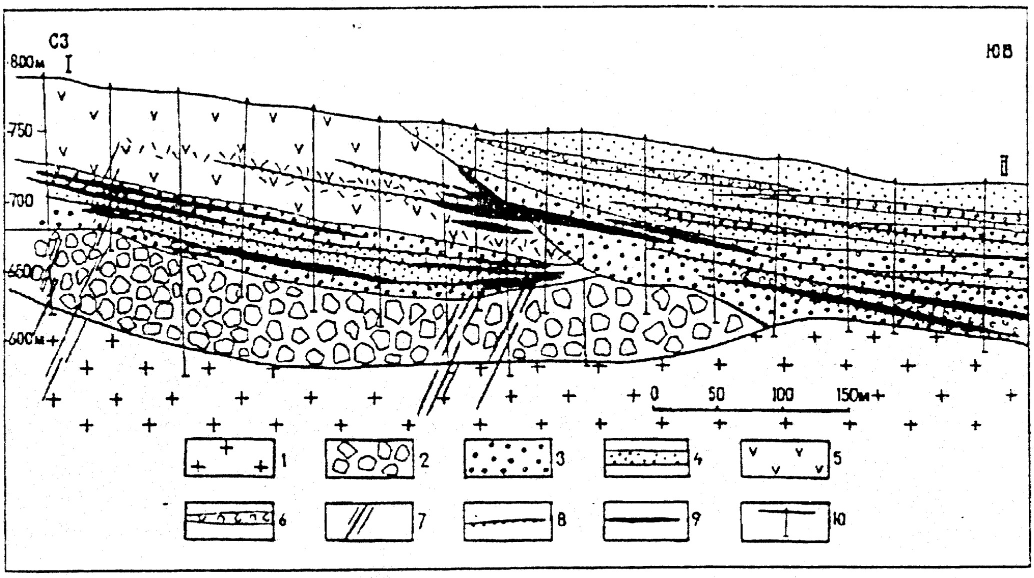

FIG. 6. Geologic cross-section of Olovskoye uranium deposit (after V.E. Vishnyakov).

Legend: 1) Granitoid and Metamorphites of the basement (lower structural stage); 2–6) Volcanics and sediments of upper structural stage): 2) Rubbly-clumpy conglomerate, 3) Heteropebbled conglomerate, gravel, 4) Sandstone, siltstone, 5) Rhyolite ignimbrite, 6) Rhyolite-dacite tuff; 7) Subvertical faults and jointing zones; 8) Gently pitching conformable interlayer faults; 9) Ore bodies; 10) Bore holes.

Gornoye deposit is a typical example of 6 vein deposits in highly radioactive Jurassic granite (Fig. 5) [15]. Ore bodies are located in 10 fault zones of north-north-east trend, which are developed in a tectonic fault wedge between two regional faults of meridian and north-east trend. Their length is usually first km, and thickness is to ten meters. Host rocks within these zones are intensively broken down and altered by quarts-clay-zeolite metasomatites. Separate veins-like ore bodies usually have a length up to first hundreds m and thickness to first m. Uranium grade is about 0.2%, sometimes to several %. The lower boundary of ores is at the depth 700m. Uranium mineralization is represented mainly by zeolite-beta-uranotil association. The age of ores is 40–14 mln.y.

5.3. Yeniseisky district

Resources of Yeniseisky district are presented mainly by two middle-size sandstone type stratiform deposits Primorskoye and Ust-Uyuk in Upper Devonian sediments of Minusinsky basin.

The section of *Primorskoye* deposit is formed in alluvial-lake Upper Devonian sandstone, siltstone, claystone [16]. Ores host is in thin (first metres) layers of grey sediments with the large amount of organic carbon (0. n-n%). The lateral extension of the ores is from 1 km^2 to 15 km^2. There are two types of ore bodies — irregular tabular and lens form in plan in essentially clay limnetic facies and ribbon-like form in the sand-clay sediments of channel complexes. Uranium grade is relatively high, from 0.05 to 2% (average 0.2%). Ore mineralization is represented mainly by thin-disseminated coffinite, with minor pitchblende. The absolute age of ore is 340–370 mln.y. Ore bodies of *Ust-Uyuk* deposit differs by ribbon and roll-like form and lower U grades.

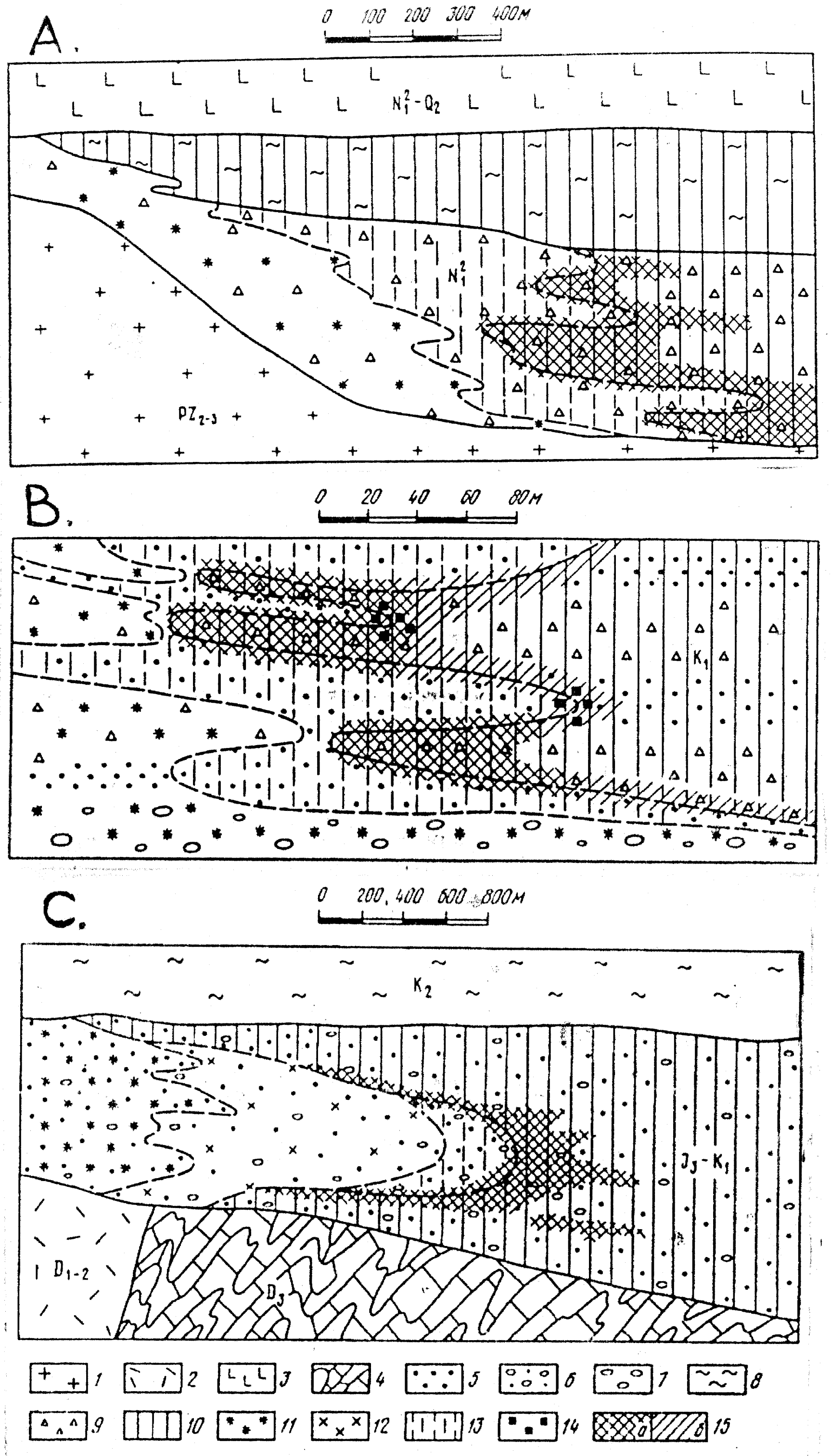

FIG. 7. Schematic geologic sections of deposits: A) Imskoye (Central Transbaikalsky distr.), B) Khiagdinskoye (Vitimsky distr.), C) Bobrovolnoye (Zauralksy distri.);

Legend: 1) Granite of the basement; 2) Persilic effusives; 3) Basalt sheet; 4) Limestone; 5) Sandstone; 6) Gravel-sand alluvial sediments; 7) Granite-pebble conglomerate; 8) Red clay sediments; 9) Pattum; 10) Primary grey sediments; 11) Mottled oxidized sediments; 12) Zone of redeposited Fe oxide; 13) Bleached sediments; 14) Accumulations of Neogenic Fe sulphides; 15) Uranium ores: a) high grade, b) low grade.

5.4. Yergeninsky district

The district is located within Kalmytskaya Autonomic Republic of Russia with the town Elista in the centre of it [17]. Its size is about 70 × 90 km. The district is situated in the northern part of Skifskaya platform within Karpinsky ridge. It has a cosidementational geological history of marine basin, which was more definitely displayed in Paleogene. Deposits consist of uraniferous fossil fish bones mineralization hosted in pyritic clays. They are also classified as organic phosphorous type. Tabular ore bodies with low U grades (0.05–0.07%) are localised within various "fish strata" of Upper Oligocene, which are similar to deposits of Prikaspysky district in Kazakstan [1]. Their dimensions are from hundreds meters to tens km long. Thirteen deposits, 37 ore occurrences and more than 30 mineralization manifestations are divided into 6 ore fields.

Stepnovskoye deposit with 20.000 mt U resources is the biggest in the district. It is located in the S-W part of the district at the depth 170–700 m and is characterised by following dimensions: 11 km length, 0.4–2.5 km width, 3–6 m thickness. The geological setting is very much similar to well-known Kasakstanian deposit Melovoye [1]. There are high contents of pyrite in the ores the average is 16% to as high as 25% in some strata. Other mineralization is characterized by plant relicts, phosphorites, dolomite, ankerite, barite.

A low thickness of ore strata (to 1 m) is typical for most deposits of the district, except Stepnovskoye (3–6m). The composition of the ores is presented in Table II.

5.5. Onezhsky district

Onezhsky district include some small metasomatite type deposits in the area of the Baltic shield, north-west part of the Russian Federation. They are considered to be unique due to considerable vanadium resources of high quality (av.grade –2.9%) [18]. Mineralization is polymetallic with high concentrations of gold, palladium, platinum, copper and molybdenum, which are regarded as by-products [19]. The deposits are localised within Onega epicratonnal trough filled with volcanic rocks, sediments and metamorphites of Lower Proterozoic (schungite, siltstone, slate, sandstone, dolomite, tuffites) in the zones of fold-faulted dislocations. Ore bodies are located within steeply dipping faults filled by cataclasites. Ore mineralization is situated in the zonal metasomatites aureoles upon host rocks (from periphery to the centre): pre-ore albitites, glimmerites, syn-ore mica-carbonate metasomatites. The latter are connected with the main U-V resources. Uranium mineralization is resented mainly by pitchblende and vanadium by vanadian flogopite, which are related to the aureoles of mica-carbonate metasomatites upon albitized slates, siltstone and sometimes dolomite. The age of ores is 1740 ± 40 mln.y. Primarily these deposits were related to unconformity type but according to some recent data their genesis could be regarded as infiltrational (similar to sandstone roll type deposits) in the areas of ancient weathering crusts [20].

5.6. Ladozhsky district

After the discovery of Canadian and Australian unconformity-contact deposits the exploration aimed on evaluation of unconformable contact of altered by lateritic weathering Archean basement and overlying Proterozoic sediments took place in the Russian Federation within the Baltic shield. The discovery of *Karhu* deposit in the Ladozhsky district, which is related to unconformity type in the basal layers of Riphean mantle, was the first result of these activities. Uranium mineralization is located mainly in the surface of arkose stratum upon the weathering crust of Archean basement rocks and to a minor extend in the basement rocks and in the upper basal sandstone. The principal uranium mineral is pitchblende in association with Fe, Zn, Mo, Cu sulphides. Syn-uranium alteration is presented by chloritization, carbonatization. Average uranium grade is 0.1% but could reach as high as 0.5% at 7 m thickness and even 8%. Dimensions of ore bodies are 300–500 m, thickness 2–7 m.

TABLE II. COMPOSITION OF THE ORES OF ERGENINSKY DISTRICT DEPOSITS (AFTER STOLYAROV A.S. [17])

Ore field/number of deposits	Average content, %							
	P_2O_5	**S.pyr.**	**Al_2O_3**	**U**	**ΣTR_2O_3**	**Sc***	**Re***	**Mo**
Stepnovskoye/1 dep.	4.8	16.0	7.5	0.05	0.23	18	1–4	0.024
Shargadykskoye/2 dep.	5.7–13.6	15.4–16.	5.3–6.9	0.03–0.05	0.2–0.38	17–19	0.2–1.4	0.013
Bagaburulskoye/4 dep.	15.–17.8	7.7–9.0	3.5–8.0	0.08–0.16	0.52–0.7	21–23	0.2–1.7	0.01
Centralnoye/2 dep.	3.9–6.6	5.–12.8	8.1–8.8	0.03–0.06	0.15–0.33	13–20	0.2–2.2	0.022
Kharabulukskoye/1 dep.	10.6	6.3	8.6	0.08	0.45	25	0.2–1.0	0.06
Yashkulskoye/2 dep.	6.7–7.0	12.5	8.2–10.	0.03	0.18–0.32	14–16	0.2–1.1	——

*Content in n × 10–4

The geological position of this district is considered to be favourable for new deposits discovery, including the deposits of unconformity type in Pre-Riphean structures and of exogenetic-epygenetic (sandstone) type in Vend- Paleozoic sedimentary complexes.

5.7. Bureinsky district

Bureinsky district includes 5 small deposits of volcanic type in Cretaceous rhyolite and felsite, which are similar to deposits of Streltsovsky district, and 4 small deposits of vein type in Upper Paleozoic rocks altered by albitization and pyrite-chlorite-hydromica metasomatites.

5.8. Khankaisky district

Khankaisky district includes 3 small deposits of vein type with low U grades (<0.1%): *Sinegorskoye and Fenix* deposits are located in Devonian rhyolite with quartz-sericite-hydromica alteration adjacent to leucogranite; ore bodies of Lipovskoye deposit are located within albitized cataclasm zones (up to 50 m thickness) in skarned Cambrian carbonate-terrigene rocks adjacent to Devonian granite.

Rakovskoye deposit belong to sandstone basal channel type. Ribbon-like ore bodies (to 1 km in length, to 100 m wide and 5–10 m in thickness) are located in lignite-bearing basal sandstone above granite basement. Mineralization is represented by coffinite and sooty pitchblende.

5.9. Volgo-Uralsky district

Volgo-Uralsky district includes six small deposits and numerous occurrences of exogenetic type in lignite, terrigene and carbonate sediments in south-eastern part of the Russian platform [21].

Sandstone type deposits in paleovalleys, filled with Upper Permian sediments, are represented by syngenetic *Cherepanovskoye deposit* with low grades (<0.03%) ores in black clay, and by epigenetic *Vinogradovskoye deposit* in permeable sands with relatively high grade ores (0.2%). Uranium ores contain Mo(0.005–0.5%), Sc(10–100 g/t), Ag(1–80 g/t). Ore bearing sediments contain organic substance and disseminated pyrite. Ore bodies with >0.01% grades are of tabular and ribbon-like form, up to 3 m thick, 100–200m wide, and hundreds of meters in length. The principal mineral is coffinite, which is usually disseminated in organic substance and in pyrite.

A lot of *Repyovskoye* occurrences and deposits of U-bitumen type are discovered in limestone and dolomite of Upper Carbonaceous age, covered by Middle Jurassic clay sediments. Ore lenses form roll-like bodies. Uranium grades are 0.01–0.4% (average 0.32%). The uranium mineralization is represented by pitchblende, coffinite, nyngioite associated with bitumen substance (asphaltite, kerite). Bitumen genesis is considered to be from oil and uranium syngenetic with bitumen [21,22]. The admixtures of V(0.01–0.6%), Ni, Mo(to 0.05%), Se(to 0.09%) are noted in the ores. Mining of this deposit by underground method is not presently profitable and by ISL is not effective due to carbonaceous host rocks.

The third group includes occurrences and two deposits *(Babaevskoye, Mayachnoye)*, which are associated with lignite-bearing formation and recent peat. Low U grade (0.01%) and small resources (<1000 t) are typical of them.

These examples confirm the potential favourability of the the Russian platform for uranium deposits.

5.10. Chukotsky district

This part is located in the north-eastern part of the Russian Federation and includes some small separate deposits of volcanic type in Mesozoic volcanites and in lignite-terrigene Jurassic sediments. The level of their exploration is very small and the prospects of mastering are almost impossible.

6. CONCLUSION

Numerous uranium ore districts of the Russian Federation include only one uranium producing centre on the basis of Streltsovsky district deposits. Most of the above-mentioned districts relates to reserve category and are unprofitable for exploration and production in the immediate future. However, taking into account trend of the growth of world uranium prices, the complex grading of the ores of some districts, as well as the possibility of new progressive mining and processing methods using (including in situ leaching), the prospects of the commercial exploration of new districts appear more optimistic.

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INDUSTRIAL TYPES OF URANIUM DEPOSITS IN KAZAKHSTAN

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Abstract

The main industrial uranium deposits of Kazakhstan that can be commercially mined, are located in two ore regions and are represented by two types of the uranium deposits. The first region is named Chu-Syrdarya (75.6% of total resources of Kazakhstan) and is located in the South of Kazakhstan and this one is the largest in the world among the regions of the deposits connected with the bed oxidation zone, localized in the permeable sediments and amenable for in-situ leach mining. The second region is named Kokshetau (16% of total resources) and is located in the North of Kazakhstan at the north edge of Kazak Shield and is characterized by the vein-stockwork type of deposit. Other industrial deposits (8.4% of total resources) are grouped in two regions that have been determined and are retained as reserves for economical and ecological reasons. These are: Pricaspian region with the organic phosphate type of uranium deposits; and Ili-Balkhash region with mainly the coal-uranium type. There are 44 industrial uranium deposits with resources ranging from 1000 t to 100000 t U and more in each of them, in all, in Kazakhstan. Seven of them are completely mined now. Total uranium resources in Kazakhstan are determined at 1670000 t U.

1. INTRODUCTION

Uranium mining in Kazakhstan is at present being carried out by in-situ leaching (ISL) method in the South of the Republic. Conventional mining that had been intensively carried out to the beginning of 1990s in the North and South of Kazakhstan, has now stopped. In the South of Kazakhstan the most profitable deposits are presently being mined and in the North of Kazakhstan stoppage of the mining operation was due to the economic position of the Republic and the relatively low quality of the ores. The average grade of uranium ores in those deposits does not exceed 0.1–0.3%. Nevertheless, up to date preservation of the industry infrastructure that has up to 2500 t U per year production capacity, under improved economic conditions in both Kazakhstan and the world uranium market, mining of these deposits could be quickly reactivated. Therefore, the region in the North of Kazakhstan continues to be regarded as a significant region with industrial uranium resources.

Discoveries of uranium deposits in Kazakhstan have a long and interesting history that started in 1951 with the discovery of Kurday deposit that have continued to recent years.

The surface of the Kazakhstan territory is characterized by the combination of the outcrop folded structures and the areas which are covered by the different friable sediments from Triassic period to the present (Fig. 1). The thickness of these sediments varies from several metres to thousand or more metres in areas of structural depression.

Folded structures are well exposed and well investigated using different exploration methods. Structural depression were intensively investigated using geophysical methods and drilling during the last decades and is considered thoroughly investigated for uranium deposits.

Various geological conditions in Kazakhstan provided the possibility for the discovery of different types of uranium ore occurrences that totaled to several thousands in the entire territory of Kazakhstan. All occurrences were investigated with the use of geophysical, geochemical, mining and drilling techniques. As a result, more than 50 uranium deposits from

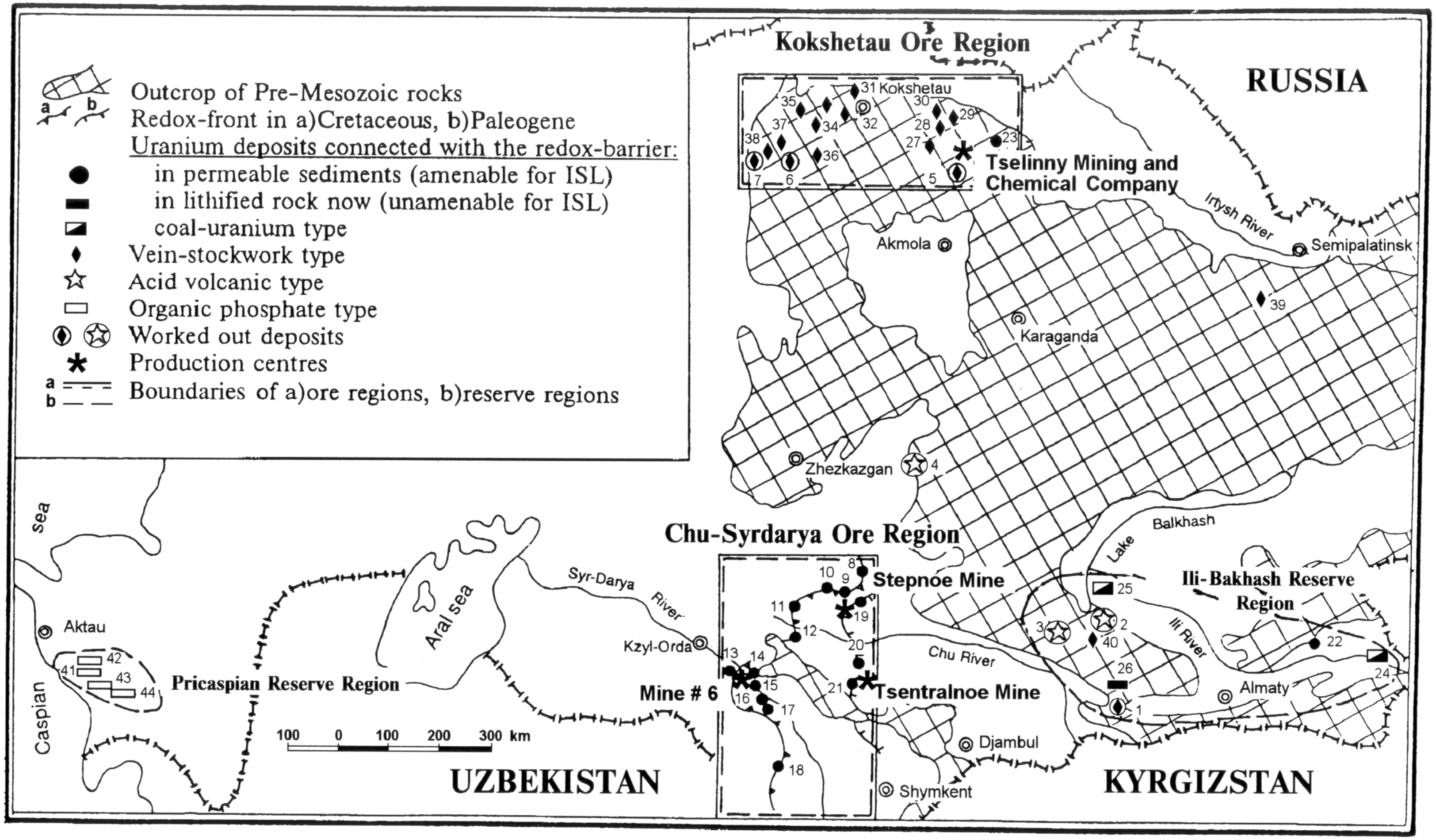

FIG.1. Uranium Deposits and Ore Regions in Kazakstan

Deposits: 1-Kurday, 2-Botaburum, 3-Kyzylsay, 4-Djidely, 5-Manybay, 6-Balkashino, 7-Ishimskoe, 8-Zhalpak, 9-Akdala, 10-Mynkuduk, 11-Inkay, 12-Budyonovskoe, 13-Irkol', 14-North Karamurun, 15-South Karamurun, 16-North Harasan, 17-South Harasan, 18-Zarechnoe, 19-Uvanas, 20-Moyunkum, 21-Kanzhugan, 22-Sulushokinskoe, 23-Semizbay, 24-Koldjat, 25-Nizhne-Iliyskoe, 26-Kopalysay, 27-Zaozyornoe, 28-Agashskoe, 29-Shatskoe, 30-Glubinnoe, 31-Slavyanskoe, 32-Chaglinskoe, 33-Grachyovskoe, 34-Kosachinoe, 35-Fevralskoe, 36-Vostok, Zvyozdnoe, 37-Viktorovskoe, 38-Kamyshovoe, 39-Ulken-Akzhal, 40-Dfusandalinskoe, 41-Melovoe, 42-Tomak, 43-Tasmurun, 44-Taybogar.

small to unique ones were discovered in Kazakhstan. Seven of them are completely mined out now. Thirty seven industrial uranium deposits with resources from 1000 t to 100 000 t U, or more, in each are the base of the uranium resources in Kazakhstan. Total uranium resources in Kazakhstan including discovered and speculative are determined of 1670000 t U. In this case, the known (RAR+EAR I) resources are about 850000 t U.

Commercial resources are allocated in the sediments of different ages from Paleogene to Paleozoic and more ancient. In this case, the most part of the resources, 68.4%, is found in the Cretaceous friable permeable sediments. In the Paleogene, 10.8% resources are concentrated in the same friable and permeable sediments. Impermeable Jurassic rocks have 7%, while Paleozoic rocks have 13.8% resources. Of these, 78.4% uranium resources of Kazakhstan are amenable for ISL and other 21.6% are suitable for conventional mining.

2. ORE-FORMATION PROCESSES AND TYPES OF URANIUM DEPOSITS IN KAZAKHSTAN

Uranium occurrences and industrial deposits are forming as a result of different processes and formation of the uranium mineralization are detected in the wide spectrum of endogenic and exogenic oregenesis. Without going into details of whole variety of the ore occurrences, we have concentrated on the processes of the forming of the industrial uranium deposits.

Processes of endogenic oregenesis formed two industrial types: acid volcanic and vein (more exactly-vein-stockwork).

Acid volcanic deposits are located in South of Kazakhstan (Botaburum and Kyzylsay) and also in the central part (Djidely). These deposits have been completely mined out at this time.

The group of vein-stockwork deposits are more numerous. These deposits are found in both South of Kazakhstan (Kurday and Djusandalinskoe) and especially in the North, where they have formed a very important ore region. Smaller vein-stockwork deposit Ulken-Akzhal (about 2000 t U) is located separately in the East of Kazakhstan.

Exogenic processes are widely noted in the territory of Kazakhstan where they have formed different occurrences and deposits connected with the oxidation-reduction geochemical barrier. In the arid climate condition of Kazakhstan numerous uranium occurrences were formed in different settings. The formation of industrial deposits were developed only in the oxidation of young Cenozoic bed that was developed due to Paleogene artesian aquifers, where as in the Cretaceous and Jurassic sediments they were formed on the redox-front only. It needs to be noted that at the same geochemical barrier in the top parts of the coal beds of Jurassic sediments, the industrial uranium ores could be formed as a result of an influence of the oxidation of ancient Mesozoic soil. In this case, it was possible that the formation of the uranium deposits be classified as deposits of the coal-uranium type.

The belt of depression structures located in the South of Kazakhstan (south of the Aral Sea-Lake Balkhash), is the area where bed oxidation zones and ancient soil oxidation zones occurred. These depression structures are artesian basins with infiltration regime. In the South, they are in contact with mountain system Tyan,-Shan, acting as water supplying area for the aquifers of the depression structures. The bed oxidation zones are developed primarily in the Chu and Syrdarya depressions (in the region of Chu River and Syrdarya River) where 14 large and unique uranium deposits were discovered (Fig. 2). Only one industrial deposit connected with the bed oxidation zone in Cretaceous sediments is found in the Eastern part of Kazakhstan in Ili and Balkhash depressions (in region of Ili River and Lake Balkhash). However, here too deposits of coal-uranium types in Jurassic sediments were also noted.

A very interesting genesis is considered for the Kopalysay deposit. It is agreed that this deposit is also associated with the oxidized bed zone but this one is found in ancient sediments of Lower Silurian age. The oxidized bed zone has perhaps been developed in the Upper Silurian or some later time. Then, the host rocks and ore bodies underwent recrystallisation and eventually transformed to the hard impermeable rocks that are now not amenable for ISL. It is interesting to note that the Kopalysay deposit is the single example of the ancient oreforming epigenesis in Kazakhstan.

The more unique genetic example is noted in the deposits of the Pricaspian region where the ores are located in the Oligocene beds along with the numerous detritus of fish bones. These ores have the diagenetic nature and have been determined as an organic phosphate type.

Thus, only four types of uranium deposits form the industrial resources in Kazakhstan, despite the presence of different and numerous occurrences of uranium mineralization. These are: sandstone type, connected with zone of oxidized beds (78.4% of total uranium resources), vein-stockwork (15.4%), coal-uranium (4.5%), organic phosphate (1.7%).

Undoubtedly, the uranium resources from the first two types of deposits are of major importance and form the two main industrial uranium regions of Kazakhstan known as Chu-Syrdarya and Kokshetau.

3. ORE REGIONS OF KAZAKHSTAN

Metallogenic zoning of Kazakhstan territory has been frequently investigated by many researchers for the preparation of metallogenic provinces, zones and other subunits. This zoning was used successfully for prognosis mapping and definition of further efforts to carry out the search and exploration of uranium both in Kazakhstan and in other regions. In this article the ore regions, their industrial importance and the appropriate timing for their exploitation are discussed. These decisions were made possible by the knowledge gained from adequate research that has been carried out in Kazakhstan. It is most probable that additional uranium resources in Kazakhstan will be discovered in the above mentioned regions.

3.1. Chu-Syrdarya region (Fig. 2)

The region is located in the South of Kazakhstan and includes exclusively the sandstone deposits connected with bed oxidation zones. Chu-Syrdarya region is located at the edge of a huge platform and, beginning from Cretaceous, this region was in the form of a large alluvial plain. Sedimentation on this plain is connected to the activity of the large paleochannels. At the beginning of Upper Cretaceous the continental conditions gave way to marine conditions with the formation of the gray-green clay horizon with a thickness of up to 150 m. This horizon is the regional upper confinement and creates the favourable conditions for the bed oxidation zones development in the Cretaceous-Paleogene sediments as in the common hydraulic system.

Bed oxidation zones have a regional nature and extend from the mountain system of Tyan-Shan, that are located in the South, to beyond the borders of the Republic, and to the north-

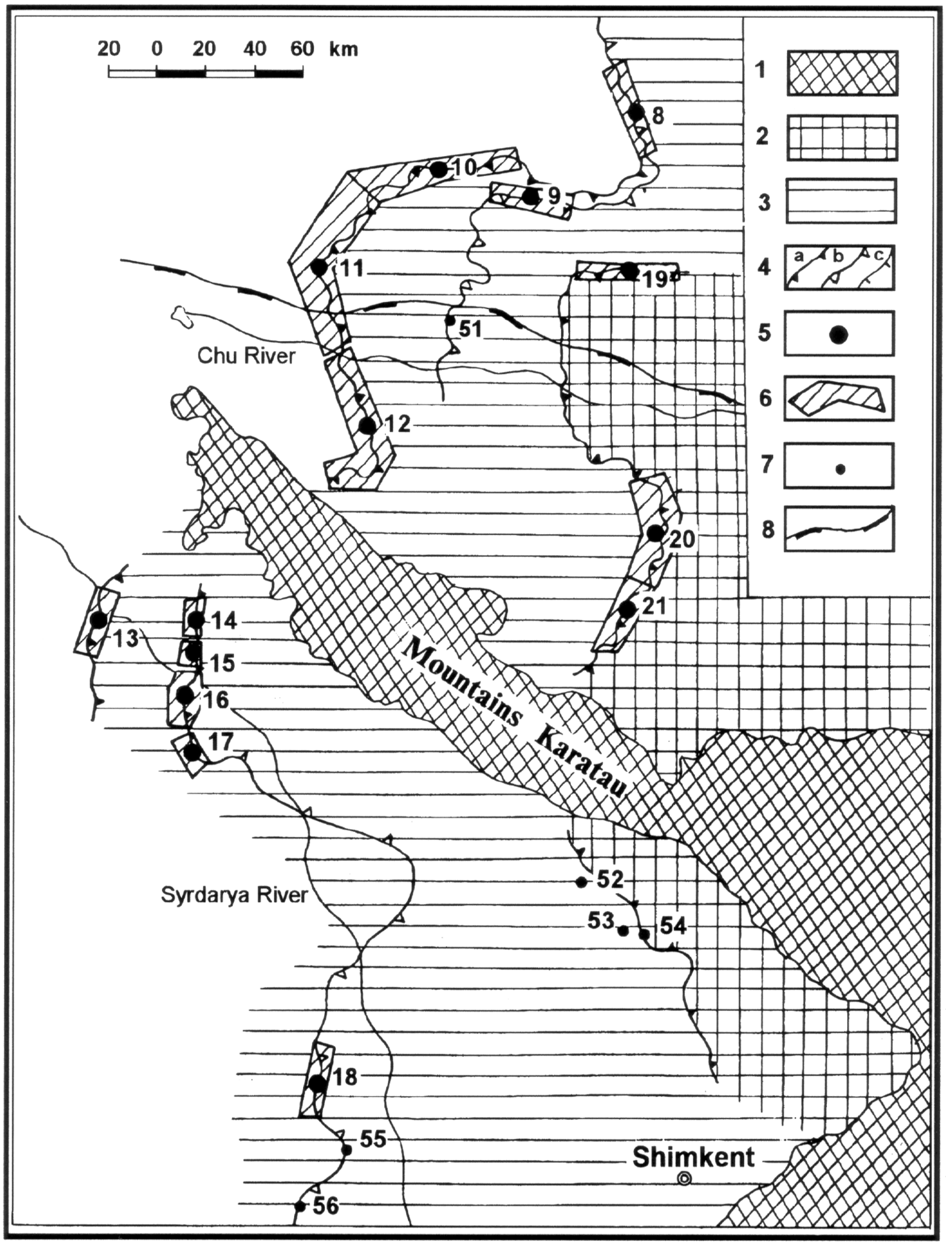

FIG.2. Distribution of uranium deposits in the Chu-Syrdarya ore region in Kazakstan

1-Outcrop of Pre-Mesozoic rocks, 2-Area of the bed oxidation zone development on whole thickness of Cretaceous-Paleogene sediments, 3-Area of the bed oxidation zone development in Cretaceous sediments only, 4-Redox-front a)in Paleogene sediments, b)in Zhalpak horizon of the top of upper Cretaceous, c)in Mynkuduk-Inkuduk horizon of middle part of upper Cretaceous, 5-Industry uranium deposits amenable for ISL, 6-Ore-fields of the industry uranium deposits, 7-Small non-industry uranium deposits, 8-North boundary of the artesian water.

Industrial deposits: 8-Zhalpak, 9-Akdala, 10-Mynkuduk, 11-Inkay, 12-Budyonovskoe, 13-Irkol,' 14-North Karamurun, 15-South Karamurun, 16-North Harasan, 17-South Harasan, 18-Zarechnoe, 19-Uvanas, 20-Moyunkum, 21-Kanzhugan
Non-industrial deposits: 51-Sholak-Espe, 52-Kyzylkol, 53-Lunnoe, 54-Chayan, 55-Zhautkan, 56-Asarchik

west direction up to 500 km. At the end of these zones in the redox-front area, uranium deposits are formed. It is postulated that uranium ores began to form at the beginning of the Oligocene time and were still forming up until recently.

The region encloses the territory of the two depressions — Chu-Sarysu and Syrdarya that are divided by the Karatau mountains. The lifting of Karatau started only recently and after the formation of regional bed oxidation zones therefore the recent hydrogeological conditions has insignificantly influences on the distribution ore bearing redox-fronts.

Bed oxidation zones are developing throughout the whole thickness of friable Cretaceous-Paleogene sediments of the region. The thickness of the permeable part of the series reaches 350–500 m. The permeable ore bearing series could be divided into the 9 ore subhorizons with commercial ores.

The ore bodies have the form of rolls or bed bodies of rolls wings. The average thickness of the ore bodies ranges from 4 to 8 m and sometimes reaches 20–30 m. The uranium content could be 0.03–0.08% and sometimes up to 0.1% or more. The major uranium minerals are nasturan and coffinite. Some deposits have Se, Re, V and Sc in commercial grade. These ore bodies have up to 10–15 km in lateral extend and have been determined down to the depth of 100 to 800 m. Approximately as many as 68% of resources are located in the artesian aquifers. The ores have high permeability (up to 5–8 m per day and more) and high recoverability. The properties of the ores combined with the assumed increased water temperature with depth might give to the possibility of commercial profitable ISL mining operation for the ore bearing redox-front at deeper than 800 m.

Total resources of the region represents 75.6% of the total resources of Kazakhstan.

3.2. Kokshetau ore region

The Kokshetau region is located in the North part of the Kazak Shield and includes more than 20 uranium deposits, 16 of which have more than 1000 t U each. All deposits are of the vein-stockwork type except the Semizbay deposit that has the ores associated with redox-front and amenable for ISL mining. Three of these deposits have now been mined out.

Uranium deposits are located in the different geological structures and in different host rocks. But all deposits are characterized by the association of uranium ores with fault structures and a series of metasomatic alterations of the rocks that had been led to formation of vein-stockwork ore bodies.

Ores of this type are characterized by not very high grades (0.1–0.3%). Deposits include from 1000 t U to 10000–20000 t U. The largest deposit is the Kosachinoe deposit that contains 96000 t U with an average grade of 0.1%. This deposit is being explored now.

Total resources of the region represents 16% of the total resources of Kazakhstan. Taking into consideration that the industrial base of Tselinny Mining and Chemical Company, which has a capacity of up to 2500 t U per year, is in place, the region can become a good base of the uranium industry in Kazakhstan.

3.3. Ili-Balkhash ore reserve region

The region is located in the district of Ili river and Balkhash Lake and includes the deposits of different types. Two coal-uranium deposits named Koldjat and Nizhne-Iliyskoe (70% of total resources of the region) and Sulushokinskoe deposit (26% of resources) which is associated with bed oxidation zone and that is amenable for ISL mining, are the main deposits of the region. The vein-stockwork Djusandalinskoe deposit and Kopalysay deposit which is associated with ancient bed oxidation zone are not amenable for ISL mining.

The Sulushokinskoe deposit could be mined under the present economic condition. With regard to the coal-uranium deposits, they have very complicated mine-geological conditions and are located in the recreation area which has a complicated hydrological environment and could not be mined without applying specially designed and costly conservation measures. Therefore, these resources are kept as reserve.

Total resources of the region represents 6.7% of the total resources of Kazakhstan.

3.4. Pricaspian ore reserve region

Uranium mining in the Pricaspian region, on the unique organic phosphate type deposit with low grade of uranium, is stopped now due to economic reasons. However, considering the significant contents of the rare earth elements in the ores, the region might have some importance. Resources of the region represents 1.7% of the total resources of Kazakhstan.

4. SUMMARY

The numerous uranium ore occurrences of different types have been discovered in Kazakhstan through 50 years of investigative history. The enormous industrial uranium resources of Kazakhstan are presented mostly (93.8%) by two major types. There are deposits of sandstone type or subtype which is associated with the bed oxidation zone in Cretaceous-Paleogene permeable sediments and the vein or vein-stockwork subtype with ore formation in the fault structures that appeared in the different Paleozoic and more ancient rocks.

The above mentioned deposit types are found in two main uranium ore regions in Kazakhstan. These deposit types dictates the two mining methods that should be used for their exploitation. The deposits associated with bed oxidation zones found in the Chu-Syrdarya ore region with ISL mining method and the deposits of vein-stockwork type found in the Kokshetau ore region with conventional mining.

The future of uranium industry in Kazakhstan for a long time will be dependence on the uranium mining in these two regions. Therefore, the ISL mining will continue to provide more than 80% of the total uranium production in Kazakhstan.

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SOUTH AFRICAN URANIUM RESOURCES — 1997 ASSESSMENT METHODOLOGY AND RESULTS

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Abstract

The first commercial uranium production in South Africa started in 1953 to meet the demand for British/US nuclear weapons. This early production reached its peak in 1959 and began to decline with the reduced demand. The world oil crisis in the 1970s sparked a second resurgence of increased uranium production that peaked in 1980 to over 6,000 tonnes. Poor market condition allied with increasing political isolation resulted in uranium production declining to less than a third of the levels achieved in the early 1980s. South Africa is well endowed with uranium resource. Its uranium resources in the RAR and EAR-I categories, extractable at costs of less than \$80/kg U, as of 1 January 1997, are estimated to 284 400 tonnes U. Nearly two thirds of these resources are associated with the gold deposits in the Witwatersrand conglomerates. Most of the remaining resources occur in the Karoo sandstone and coal deposits.

1. INTRODUCTION

The Earth and Environmental Technology Division (EET) of the Atomic Energy Corporation of South Africa Ltd., (AEC) is responsible for the assessment of South Africa's uranium resources and production capability on an on-going basis. These assessments are carried out with the close cooperation of the mining companies, whose assistance is acknowledged and greatly appreciated. The results of this ongoing assessment are compiled to ensure confidentiality and reported to the International Atomic Energy Agency (IAEA) every two years for publication in *Uranium Resources, Production and Demand.*

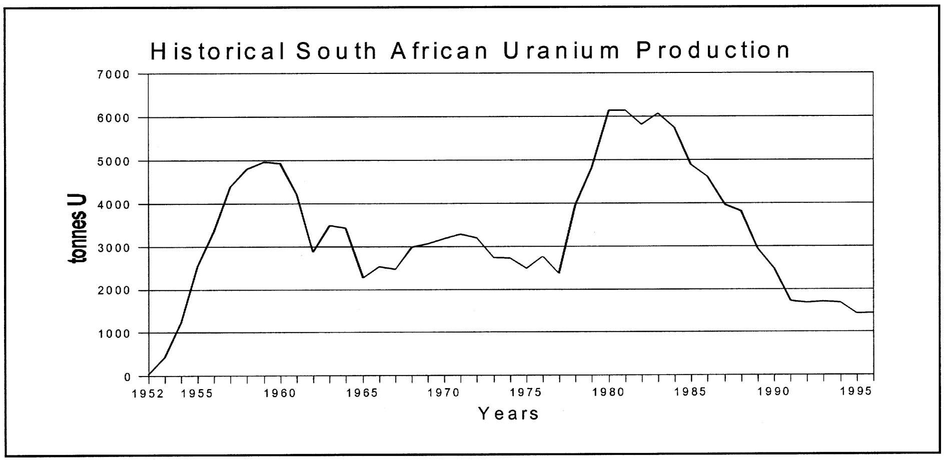

FIG. 1. Historical South African uranium production.

South Africa has been an important player in the international uranium market since its inception in the early 1950s. In the mid 1940s South Africa's potential for uranium production came under scrutiny for the first time when a joint British/US team visited the country to investigate the reported presence of uranium in the Witwatersrand gold mines. The presence of significant amounts of uranium was established and this was followed shortly in 1953 by the establishment of the first commercial uranium plant in South Africa. Production expanded rapidly to accommodate the military needs of the Western World for their nuclear weapons programmes (Figure 1). By 1959 these needs began to decline as did South Africa's uranium production. The world oil crisis in the 1970s sparked a surge in the price of uranium and South Africa's mining industry was quick to react to the increased demand with production more than doubling in 5 years. The uranium price peaked in 1979, then fell dramatically over the next 3 years. This was reflected by a steady fall in South African uranium production from 1981. The 1980s were characterised by plant closures and declining production capability, which continued into the 1990s. Poor market conditions allied with increasing political isolation resulted in uranium production declining to about a third of the levels achieved in the early 1980s.

Since 1967 the AEC has been monitoring and assessing the country's uranium resources and production capability. In addition exploration activities and uranium production are also monitored. The AEC plays no active role in the commercial uranium industry in South Africa but from time to time has engaged in research activities aimed at better defining the controlling factors of uranium mineralisation in various environments. These activities have been carried out in conjunction with researchers at various academic institutions and the results released to the private sector.

2. GEOLOGY OF SOUTH AFRICA'S URANIUM OCCURRENCES

Uranium in South Africa is hosted in a variety of geological environments, of which only four are of real significance currently. These will be touched on only briefly as they have been reported on extensively elsewhere. Of major importance are the gold deposits of the Witwatersrand quartz pebble conglomerates which have significant uranium as a by-product. The mineralisation is hosted in reefs composed of coarse detrital sediments ranging from conglomerates to coarse sandstones. They are found in seven major goldfields extending around the northeastern to southwestern rim of the Witwatersrand Basin and account for the majority of South Africa's uranium production. Grades are low, generally lower than 0.05% U_3O_8, but the ubiquitously associated economic gold mineralisation make them economically viable. Almost all of the gold mines have uranium resources but these are often too low grade to warrant extracting the uranium. These resources are mined in conjunction with the gold but the uranium is not extracted and is dumped onto the tailings dams. These tailings dams can constitute significant low cost, easily accessible uranium resources if care is taken not to dilute these uraniferous slimes. Another factor to consider is the use of cemented slimes as backfill in mined out areas of the mine which effectively sterilises this potential resource.

The sandstone and coal hosted deposits of the Karoo Supergroup are the only other important uranium resource base in South Africa. They contain about one quarter of the total uranium resources in the country. The sandstone hosted deposits are generally small and erratic in nature, occurring in palaeochannel sandstones, with grades of up to 2% U_3O_8, but with average grades of about 0.1% U_3O_8. Molybdenum occurs as an accessory element which could be extracted as a by-product. The AEC recently completed an intensive stratigraphic and palaeontological study of these deposits which indicated that there exists a considerable potential for the discovery of further deposits. The coal hosted deposits are more extensive and continuous, but generally have lower grades, averaging about 0.05% U_3O_8.

South Africa has a number of intrusive alkaline complexes of various ages, two of which are known to contain uranium mineralisation. The Pilanesburg complex in the Northwest Province hosts a variety of exotic elements including uranium but low grades have resulted in little interest being shown in it. The Phalaborwa Igneous Complex in the Northern Province has major copper, phosphate and vermiculite mines. The copper mineralisation is hosted by carbonatite and has very low grade uranium associated with it in the form of uranothorianite. It is only the large scale of the operations which allow the uranium to be extracted economically. This is the only uranium producer in South Africa outside the Witwatersrand Basin.

Monazite in heavy mineral sands along the east and west coasts of South Africa contains low concentrations of uranium. The sands are being exploited for their ilmenite, rutile, zircon and monazite contents but the uranium is not being extracted. Other environments which host uranium mineralisation are younger surficial sediments in northwestern Cape, granitic gneisses in Namaqualand and marine phosphate nodules off the southwestern coast of South Africa. None of these will be of any economic interest in the foreseeable future.

3. EXPLORATION

No exploration for uranium as a primary target has taken place in South Africa for over a decade. All work in the Karoo Basin ceased in the early 1980s and in the Witwatersrand Basin gold has always been the primary target for exploration activities. The almost universal relationship between gold and uranium mineralisation in the Witwatersrand Basin has resulted in additional uranium resources being discovered during gold exploration. In the late 1980s gold exploration in the Witwatersrand Basin was at a high tempo, but a stagnant gold market since then has resulted in a severe curtailment of exploration programmes with little drilling taking place. This situation is unlikely to change without a substantial improvement in the gold market. Similarly a marked improvement in the uranium market appears necessary to stimulate interest in uranium exploration outside the Witwatersrand Basin, because of the low grades and small size of the potential targets.

4. URANIUM RESOURCES

South Africa is well endowed with uranium resources and has been ranked in the top five nations in this regard for many years. A major proportion of these resources occur as a by-product of gold mineralisation and South Africa is in the unique position of being the only major uranium producing nation which produces all its uranium as a by-product to the exploitation of other mineral commodities. The size of a large part of the resource inventory is thus dependent on factors external to the uranium market, but it has the fortunate effect of allowing South Africa to tailor its output to the prevailing market conditions, but. The by-product nature of the uranium mineralisation also imposes certain constraints on how the resource inventory is estimated.

4.1. Assessment procedure

The definitions and terminology used for South Africa's uranium resource assessment are those as used for the IAEA publication, *Uranium Resources, Production and Demand*. Interested readers are referred to the latest edition for further information.

The resource estimation procedure is carried out on a property-by-property and a reef-by-reef basis and consists of five stages (Figure 2).

Budgetary and staff constraints prevent the AEC from gathering raw data and conducting resource evaluation estimates itself. All companies operating in South Africa furnish full particulars of their exploration activities with regard to uranium and provide the AEC with estimates of their uranium resources, both for active mining operations and prospects, under conditions of strict confidentiality. The reporting of resource estimates is done on standardised forms to ensure uniformity of the data and discussions. These resource assessments are conducted on the basis of a US dollar/rand exchange rate set as the 1st January of the year of assessment. In the case of the Witwatersrand gold deposits a gold price is also specified as this has a direct bearing on the size of the associated uranium resources.

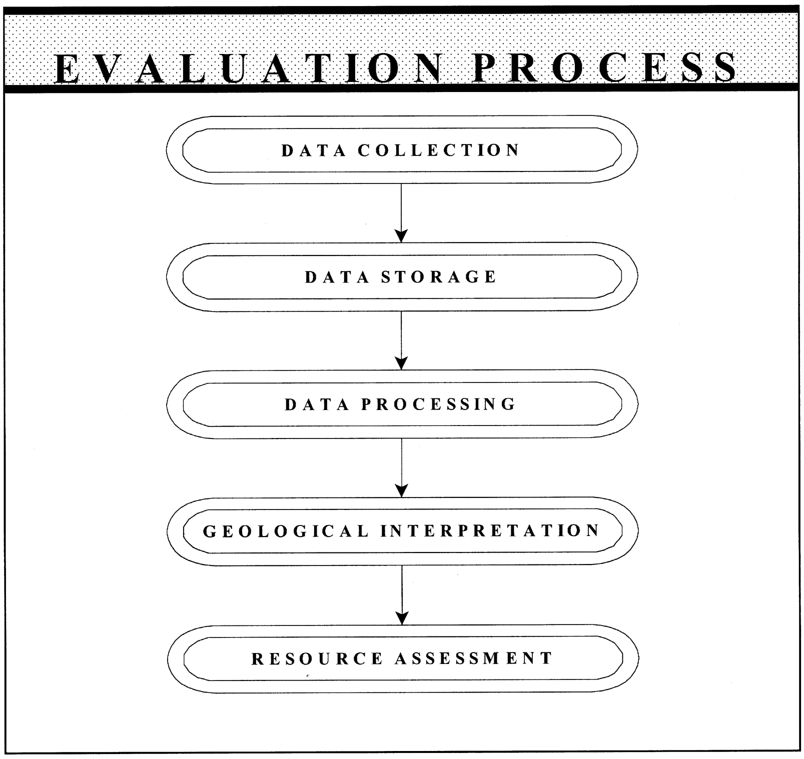

FIG. 2. Uranium resource evaluation process.

The data received from the mining and exploration companies are stored in a computerised database to facilitate data manipulation. The database is structured to allow the selective extraction and manipulation of specific information as required in the estimation process.

The resource estimates supplied by the companies are assessed in terms of the known geological setting of the resource as revealed from the exploration reporting and discussion with the personnel involved. The estimates are also compared with the previous estimates of the resource, and in the case of active mines, with past production records. Discrepancies and anomalies are referred back to the relevant company for discussion with the evaluation personnel and possible revision. When the resources returns have been finalised, the estimates are compiled to yield a national uranium resource inventory which can be used to project production capabilities and allow planning of the country's energy strategies.

A number of factors need to be considered during the resource assessment process with respect to their cost categorisation, particularly where the uranium mineralisation occurs as a by-product.

4.2. Cost categorisation

Uranium resources in South Africa fall into three categories based on their relationship with associated mineralisation, if any. It may be the primary mineralisation, as is the case in the Karoo deposits; it may be a co-product, in the case of some of the Witwatersrand reefs; or most commonly, it occurs as a by-product. The method of determining the cost categorisation of the uranium resources is different in each case.

Where uranium is the primary product, the process is relatively straight forward. First a US dollar/rand exchange rate is determined as the uranium price is denominated in US dollars and working costs are calculated in rands. The tonnage and grade of the deposit estimated using one of many ore reserve estimation techniques depending upon the amount of information available and the characteristics of the mineralisation. These range from normal and lognormal mean, through various distance weighted and trend surface techniques through to kriging. The former are usually applied in prospect situations, but the trend in South Africa is, more and more to use kriging, especially on the mines where large data sets and access to low cost computing power are available. Mining and metallurgical process losses are estimated and the cost categorisation is determined from the working costs (including all forward costs) and the estimated recovery grade.

In the case where one or more other extractable minerals are present, but neither the uranium nor the other minerals are economic, the uranium would be a co-product. Here the grade and tonnage of the deposit are determined as before, but the cost categorisation of the uranium becomes a function of the revenue generated by the other minerals. This revenue is offset against the total estimated working costs and the residual shortfall is used to determine the cost category of the uranium.

Uranium becomes a by-product where the primary mineral being exploited is economically viable by itself. The grade and tonnage of the orebody is then constrained by the market conditions of the primary mineral and the working costs required to extract it. The extractable uranium is thus only that which falls within the boundaries of the primary mineral's orebody. The cost of extracting the uranium is then only the incremental cost of metallurgical treatment of the milled ore to extract the uranium, as the mining and milling costs are borne by the revenue generated by the primary mineral. This is the case with the majority of the Witwatersrand gold deposits and enables the profitable exploitation of otherwise uneconomic uranium resources. Hence the gold price as well as the exchange rate are of critical importance in determining the size and the cost categorisation of the uranium resources. The magnitude of South Africa's uranium resource base is thus also very dependent on the state of the gold mining industry. This is in a depressed state at present with threats of curtailment of operations at certain sections of some mines. It remains to be seen how the industry weathers these threats which it has survived in the past, but problems of low productivity and high working costs need to be addressed.

For the 1997 South African uranium resource assessment, the gold price was set at US$370/oz Au and the US$/rand exchange rate at US$1 = R4.70.

4.3. 1997 Assessment results

South Africa's uranium resources as at 1 January 1997 in the RAR and EAR-I categories, extractable at costs of less than \$80/kg U are estimated to be 284 400 tonnes U. The Witwatersrand conglomerates and slimes account for 73% of the total or 207 900 tonnes U, with the Karoo sandstone and coal deposits making up most of the rest (Table I). Other than these two main depositories the other deposits only contribute just over 1% of the total resources.

There is little change in this estimate when compared with that made two years ago, with only a 9% increase in the RAR and EAR-I categories, extractable at costs of less than \$80/kg U. This is to be expected because very little exploration has been carried out in the Witwatersrand Basin and none outside the Basin. However a more substantial increase in the resources could have been expected because the gold price in rand terms rose by 24%. This increase was almost completely offset by a 21% increase in estimated workings costs. Figure 3 shows the changes in cumulative resource estimates for the RAR and EAR-I categories exploitable at costs up to \$130/kg U for the last five reporting periods.

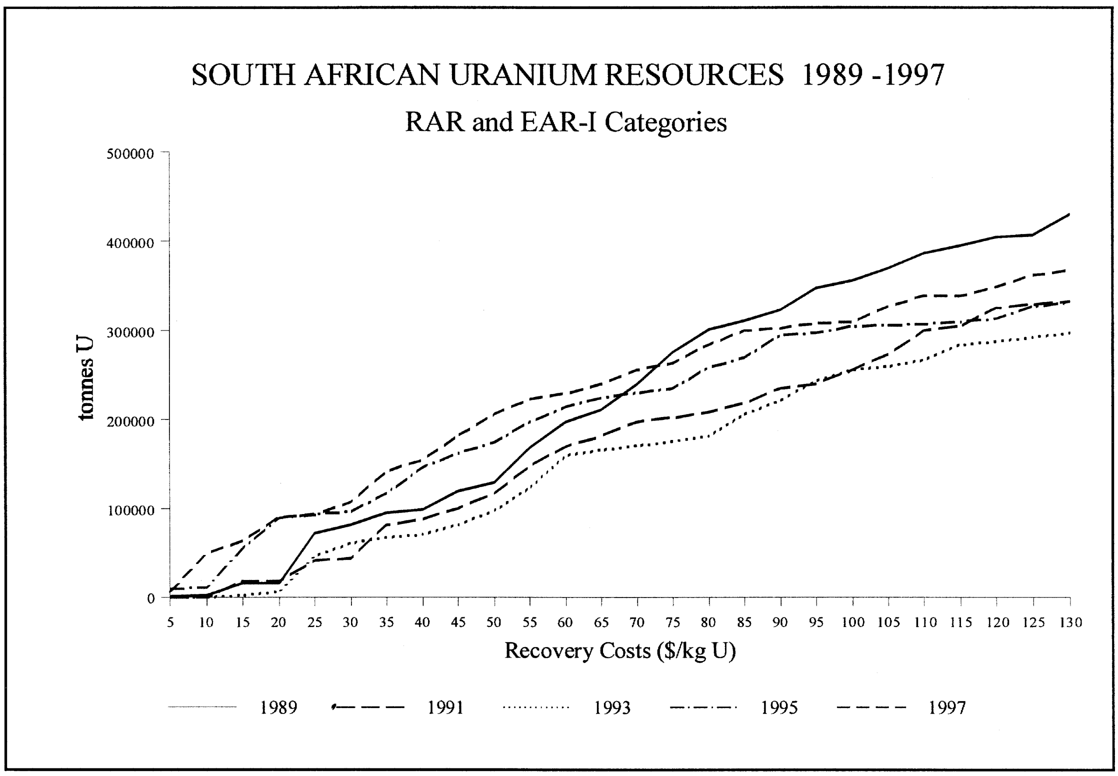

FIG. 3. South African cumulative uranium resources.

These fluctuations are a function of changes in the gold price, exchange rate and working costs as little or no exploration took place during this time. South Africa's physical uranium resource base has remained relatively static for the last decade but individual deposits have been moved from one cost category to another depending on the factors mentioned above. This situation is likely to persist in the future until the gold and/or uranium markets improve, which would stimulate exploration resulting in the addition of new resources to the national inventory.

TABLE I. SOUTH AFRICAN URANIUM RESOURCES AS AT 1 JANUARY 1997

Deposit Type	RAR			EAR-I			Total RAR+ EAR-I <\$80	Total RAR+ EAR-I <\$130
	<\$40	<\$80	<\$130	<\$40	<\$80	<\$130		
Witwatersrand Conglomerates	93300	47900	24300	41700	11200	1900	194100	220300
Witwatersrand Tailings	4000	9800	16400				13800	30200
Karoo Sandstone	1500	19700	2100	2700	4200	800	28100	31000
Karoo Coal	11700	27600	8600		5100	1700	44400	54700
Surficial		700				400	700	1100
Alkaline Complex		2100			1200		3300	3300
Total 1997	110500	107800	51400	44400	21700	4800	284400	340600
Total 1995	107500	97200	53900	39400	16400	19400	260500	333800
Difference %	+2.79	+10.9	-4.64	+12.69	+32.32	-75.26	+9.17	+2.04

5. CONCLUSIONS

The South African uranium industry has been in a parlous state for the last decade, as evidenced by declining plant closures and declining production. Exploration for uranium has virtually ceased for several years, except for serendipitous discoveries resulting from gold exploration. Current uranium market conditions make any resurgence of interest unlikely in the short term. It is only the by-product nature of the uranium mineralisation which has allowed the current producers to continue uranium production operations.

Intensive exploration in the Karoo during the 1970s and in the Witwatersrand Basin established a large uranium resource inventory which has only been marginally depleted by mining operations. The magnitude of the resources are dependent on the vagaries of the \$/R exchange rate and the gold price, but in spite of continuing upward pressure of working costs they remain a significant proportion of the world’s total. The South African mining industry’s past performance indicates that, given improved market conditions, it would be capable of increasing production substantially in a short period of time to take advantage of an increase in demand.

URANIUM FAVOURABILITY AND EVALUATION IN MONGOLIA (PHASE II), RECENT EVENTS IN URANIUM RESOURCES AND PRODUCTION IN MONGOLIA

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Abstract

Uranium exploration in Mongolia covered a period of over 5 decades. The main results of these activities were the discoveries of 6 uranium deposits and about 100 occurrences as well as numerous favourable indications. Sizable resources are found mainly in deposits of the sandstone, volcanic and alkaline intrusive types. Of these, the first two are considered to be of economic importance. Uranium production in Mongolia started in 1989 with the exploitation of volcanic type uranium deposits of the Mongol-Priargun metallogenic province, known as the Dornot Mine. Due to political and economic changes in the country and neighbouring areas of the Russian Federation, this uranium production was terminated in 1995. A new plan to restart production at the Mardai-gol deposits as a joint venture between Mongolia, the Russian Federation and a US company is being considered.

1. URANIUM EXPLORATION

Historical review

Uranium exploration in Mongolia started immediately after World War II with investigations of other various mineral deposits. During 1945–1960, number of occurrences of uranium were discovered in the deposits of brown coal in the Eastern Mongolia.

Between 1970 and 1990 under the bilateral government agreement of the Mongolian Peoples Republic and the USSR specialized geological works were conducted by Geological Reconnaissance Expedition of Ministry of Geology USSR During that period full airborne gamma-spectrometric surveys of scale 1:25,000–1:50,000 on the territory of the country over 420,000 sq.km. or 27% of the territory; of scale 1:200,000 over 450,000 sq.km. or 28% of the territory and of scale 1:1,000,000 over 224,000 sq.km. or 14% of Mongolian Altai and Hangai mountain and Gobi desert region were conducted. The territory along the border with People's Republic of China and Central Mongolian mountain area or 30% of the territory was left out of these surveys.

Metallogenical investigation of scale 1:500,000 over 500,000 sq.km area and more detailed geological exploration of scale 1:200,000–1:50,000 over 50,000 sq.km area of territory of Mongolia were completed. All these works included 2,684,000 m surface drilling, 3,179,000 cube.m. surface trenching and 20,800 m underground exploration.

Based on results of these explorations, the territory of Mongolia was classified into four uranium bearing metallogenical provinces: Mongol-Priargun, Gobi-Tamsag, Hentei-Daguur and Northern Mongolia (Fig. 1). Each of these provinces differ by their geological structure, type of uranium deposits, association of minerals and mineralization age.

- Mongol-Priargun metallogenic province is located in Eastern Mongolia and spatially coincides with the same named a continental volcanic belt tracing along the extension some 1,200 km at the wide — ranging width 70–250 km, from Mongolian Altai to Lower-

Priargun. This territory mostly includes deposits and occurrences of fluorite-molybdenum-uranium association caused by volcano-tectonic activization. Distinct uranium mineralization districts of Northern-Choibalsan, Berkh, and of Eastern and Central Gobi are included in this area. The Dornod ore knot of Northern Choibalsan area includes uranium deposits of Dornod, Gurvanbulag, Mardai and Nemer as well as polymetals and fluorite.

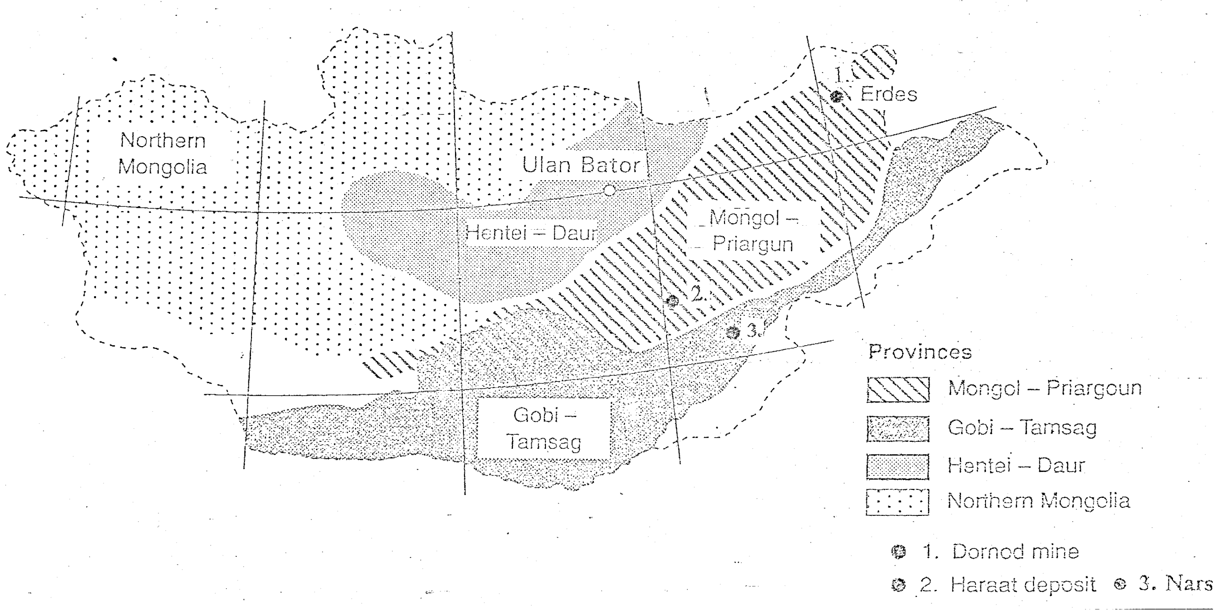

FIG. 1. Uranium metallogenic provinces and deposits of Mongolia.

- Gobi-Tamsag metallogenic province covers 1,400 km long and 60-180 km wide territory on the southern Mongolia and characterized by numerous uranium occurrences in grey and motley coloured terriginous sediments related to stratum oxidation and restoration. The district units a perspective uranium in the southern part of the same named basin with the deposit named Nars and numerous occurrences as well as perspective uranium-bearing basins like Tamtsag, Sainshand, Zuunbayan and others.

- Hentii-Daguur metallogenic province is 700 km long and 250 km wide territory which includes Hangai and Hentii mountains. In this area uranium occurrences of light colored granite fragments can be found. Uranium occurrences of Janchivlan ore knot can be of interest within this area.

- Northern Mongolian metallogenic province is the biggest and 1,500 km long and 450 km wide area in the Northern and Western Mongolia. This province is comparatively old in its geological structure and is characterized by variety of minerals such as uranium-thorium-rare earth elements related with alkaline mineralization, uranium-thorium in metasomatosis, pegmatite, and magmatic and uranium host rock type of silicon schist. This area is very interesting for exploration and research because of wide variety of origins and geological structure of uranium mineralization and will hopefully attract in the future lots of scientists.

All these metallogenic provinces have ore knots, basins, ore areas each of which is listed in the enclosed table of Uranium Resources. The table shows names of deposits, host rock type, reserves and resources.

Recent and on-going activities

Currently uranium exploration is conducted by the following organizations:

1. "Uran" company, a state owned enterprise dealing with for research and explorations carried out by the Main Directions of Geological Explorations on the Territory of Mongolia.
2. "Gurvansaikhan" company, a joint Mongolian-Russian-American venture, is dealing with explorations, evaluations and research of Choir, Hairkhan, Undurshil, Ulziit and Gurvansaikhan basins. This company will start mining from 1998.
3. "Koge-Gobi" company, joint Mongolian-French venture, is dealing with explorations, evaluations and research of Sainshand, Oshiin Nuur, Nyalga and Tamsag basins. This company will start mining from 2003.

Uranium expenditures and drilling statistics

	1995	1996	1997 (expected)	
Industry Expenditures (US$ x 1000)	1,400	2,440	3,100	
Government Expenditures (US$ x1000)	250	120	35	
Total expenditures (US$ X 1000)	1,650	2,560	3,135	
Industry surface Drilling in Meters		40,000	41,500	52,000
Number of Industry Holes Drilled	1,000	1,035	1300	

The Government of Mongolia supports and encourages uranium geological explorations and planning to conduct geological survey on 32,000 sq.km., explorations on 40,000 sq.km. and detailed explorations on 4,000 sq.km. of territory for the period till 2005 (See Figure 2).

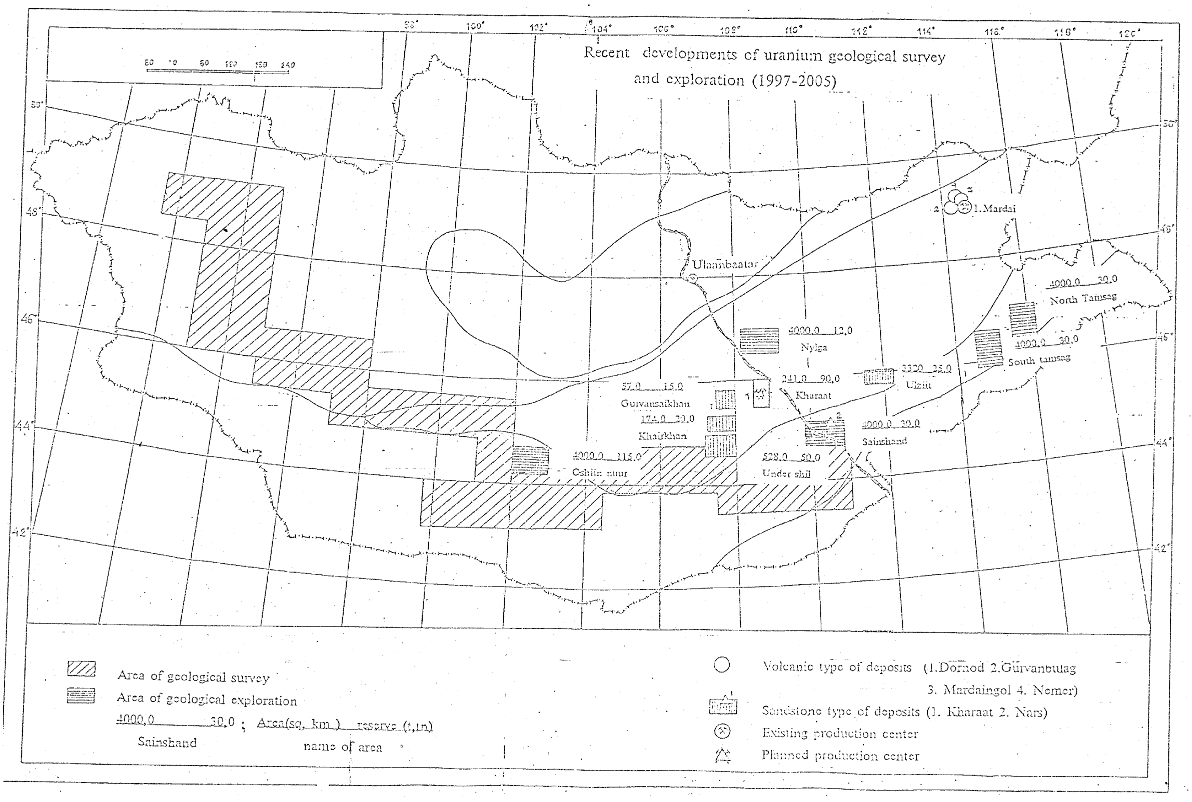

FIG. 2. Recent developments of uranium geological survey and exploration (1997–2005).

2. URANIUM RESOURCES

As a result of uranium specialized geological surveys and explorations of 1970–1990, 6 uranium deposits, about 100 occurrences and over 1000 mineralized spots, radioactive anomalies were revealed on the territory of Mongolia.

The following is an evaluation of uranium reserves and resources calculated using mathematical statistical method and based on known of criteria of mineralized regions, radio-geochemical data and tectonic map.

The uranium resources are divided into the following types according to the host rock lithology: (Table I)

TABLE I. URANIUM RESOURCES OF MONGOLIA

Metalo-genic provinces	Metallogenic zones and ore districts	Name of area	Host rock type	Total of resources	Share of				
					Reserves		Resources		
					C1	C2	P1	P2	P3
I. Mongol-Priargun metalogenic province	1. North Choibalsan	I.1.1. Dornot ore knot	3	70	31	20	6	13	
		I.1.2. Ugtam ore knot	3	5				5	
		I.1.3. Turgen ore knot	3	5				5	
		I.1.4. Engershand ore knot	3	5				5	
		I.1.5. Soumyn nuur basin	2	5				5	
	2. Berkh	I.2.1. Ulziisaikhan hill ore knot	3	15				10	5
		I.2.2. Batnorov ore knot	3	12				7	5
	3. Dornogoby Eastern Goby	I.3.1. Bor-Undur ore knot	3	5				5	
		I.3.2. Khongor ore knot	3	7				7	
		I.3.3. Ulaan nuur (Red Lake)o.kn.	3	15				15	
		I.3.4. Shivee ore knot	3	3				3	
		I.3.5. Choir basin	2	90		8	8	54	20
		I.3.6. Nyalga basin	2	12				6	6
		I.3.7. Tavansuvee basin	2	20				20	
	4.Dund -Goby	I.4.1. Mushgia khudag ore knot	3	16				6	10
		I.4.2. Ulziit mont. ore knot	3	20				10	10
		I.4.3. Ongiin gol basin	2	115				50	65
	5. Outside of areas	I.5.1. Matad ore knot	3	5				5	
		I.5.2. Ulziit basin	2	25				15	10
		I.5.3. Choibalsan basin	2	5				5	
		I.5.4. Gurvansaikhan basin	2	15				10	5
II. Goby-Tamsag		II.1. Sainshand ore area	2	30			3	12	15
		II.2. North Sainshand basin	2	30				7	23
		II.3. Zuunbayan basin	2	50				20	30
		II.4. Undurshil basin	2	50				20	30
		II.5. Tamsag basin	2	60				10	50
		II.6. Ail ore knot	3	10				5	5
		II.7. Outside of area		270					270
III.Khentii Daur		III.1. Central ore area	4	30			4	10	16
		III.2. Janchivlan ore knot	4	10				10	
		III.3. Chuluut ore knot	1	30				10	20
		III.4. Outside of area		80					80
IV. North Mongolian		IV.1. Buteel mount.range ore area	7	15				5	10
		IV.2. Khubsugul ore area	8	20					20
		IV.3. Ar-gol ore area	6	30				5	25
		IV.4. Tsagaan shivee ore area	6	35					35
		IV.5. Mongol Altai ore area	5	50				5	45
		IV.6. Dundgorkhi ore knot	5	5				5	
		IV.7. Tashaat deluu ore knot	5	5				5	
		IV.8. Bayankhongor ore area	8	40					40
		IV.9. Tuva ore area	6	30					30
		IV.10. Khangai ore area	6	15					15
		IV.11. Kharaatsag mount. ore area	6	5					5
		IV.12. Lakes' basin	2	100					100
Total				1470	31	28	21	390	1000
Percentage				100	2.1	1.9	1.4	26.6	68

	Host Rock	Age	Resources (1000 tU)
1.	Uranium association in palaeovalleys,	N-Q	30
2.	Sandstone type.		
	Unconsolidated oxidised porous sandstone.	K-Q	607
3.	Volcanic type. F-Mo-U association.	J_3-K	183
4.	Granitic type. Shatter zones of leucogranites	K_1-Q	40
5.	Uranium association in shatter zone of		
	granitoids and metamorphits.	PR_3-T	60
6.	Alkaline rock type. U-Th-TR association.	PZ_2-PZ_3	115
7.	Metasomatite, migmatic, pegmatic type.	PR_3	15
8.	Flinty shist (shale) type.	PR_3	60

3. URANIUM PRODUCTION

Historical review

"Erdes" uranium mining enterprise was established under the bilateral Mongolian- Soviet inter-government agreement at Mardai group of deposits. In 1989 this enterprise started its uranium mining. Mined uranium ores were transported by railroads to Krasnokamensk in Chita region for processing at a mining-chemical factory. Unfortunately, political and economic transformation in the country during that time caused the suspension of uranium mining in 1995.

Uranium Mining

Years	Ore Tons	Grade %	Uranium Metal kg
1989	79,882	0.117	93,566
1990	91,154	0.098	89,253
1991	100,724	0.1	100,639
1992	98,209	0.118	105,225
1993	52,321	0.104	54,275
1994	63,378	0.114	72,114
1995	13,919	0.145	20,187

Currently, "Central Asian Uranium", Mongolian-Russian-American joint venture is doing its preparations to operate the group of Mardai deposits.

Planning review

The following is uranium production plan based on plans of uranium exploration and mining organizations on the territory of Mongolia.

Uranium production plan (in Tons)

Years	Central Asian Uranium	Gurvansaihan	Kojegobi	Total
1998	150	100		250
1999	250	200		450
2000	300	200		500
2001	300	400		700
2002	300	400		700
2003	350	400	100	850
2004	400	400	200	1,000
2005	400	400	300	1,100

4. NATIONAL POLICY RELATED TO URANIUM

Currently, State Great Hural (Parliament) of Mongolia is discussing the draft amendments to the Law on minerals. The following points are the preferred concepts of this Law at this time:

- equal opportunities for national and foreign investors for obtaining licenses to explore and mine minerals
- simple, open and efficient procedures for issuing exploration and mining licenses
- to provide special rights for a holder of a mining license to mine every mineral found on the licensed territory as well as rights to sell, to loan and to inherit the license
- royalty for mineral mining should be set at 2.5% of sales income with no regard to commodity type
- to open new opportunities such as short depreciation period for investments to mining enterprise in order to provide safe and quick payback and or possibility to conclude stable contracts with the Government.

In addition, the Draft Amendment Law include many other provisions, to support investors in mining and geology and to provide favourable conditions for them. I would firmly suggested that those who are interested, to get acquainted with the Revised Law as soon as it is adopted. We, in Mongolia and myself, will be happy to assist anybody interested to obtain a copy of the law.

The Mongolian government is attaching great importance to the mining of uranium deposits which will positively influence the improvement national economy. It has developed a special programme on uranium and is committed to implement this programme. The programme covers the following policies and guidelines:

- Geological explorations and mining of uranium deposits, processing and marketing of uranium ores on the territory of Mongolia is in the focus of the government; the direction here is to reduce Mongolian government investment and to encourage more foreign investment.
- To conduct surveys on potential hazard of uranium geological explorations and mining and to protect the environment, people, fauna and flora from it.
- To develop intensive and effective cooperation with international organizations involved in the prospecting, mining and sale of uranium and other raw materials for nuclear energy.

- To develop all the necessary regulations, instructions and recommendations for activities related to uranium
- To start uranium geological surveys of areas of sandstone type of deposits or occurrences on the territory of Mongolia
- To study possibilities of extraction of uranium from phosphate and coal deposits and to seek alternative resolutions
- To train national personnel for uranium studies and productions, to introduce advanced technology and instruments and tools of high precision
- To set up a government enterprise responsible for monitoring and coordination of uranium exploration and production, as well as for development and implementation of the Government policy and strategies in the field of uranium explorations based on mobilization of efforts of national specialists.

The programme defines actions and activities necessary for training national personnel for uranium prospecting and productions, for introduction of advanced and efficient technology and for supply of high capacity equipment and instruments and tools. The programme also lists achievements in this field and gives high appreciation to the technical assistant project of the International Atomic Energy Agency.

CURRENT URANIUM ACTIVITIES IN PAKISTAN

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Abstract

The rocks of Siwaliks group in Pakistan, extending from Kashmir in the east through Potwar Plateau, Bannu Basin and Sulaiman range up to the Arabian Sea in the west have been extensively explored for uranium. The Dhok Pathan Formation, which is younger member of the middle Siwaliks has been aeroradiometrically surveyed and extensively prospected on foot. A large number of anomalies were encountered in Kashmir, Potwar Plateau, Bannu Basin and Sulaiman range. While exploratory work in Sulaiman range and Bannu Basin yielded a few workable deposits, none of the anomalous areas yielded an ore grade concentration in Potwar Plateau. As conventional exploration activities in Potwar Plateau did not yield any ore grade concentration therefore a resource potential evaluation programme through geological modeling was started under the guidance of an IAEA expert. The volcanic material found in the middle Siwaliks is considered to be the main source of uranium and siliceous cement in the sandstones. These findings have considerably increased uranium potential in Siwaliks. The tectonic deformation during and after the deposition of Siwaliks is considered to be the main reason for mobilization of uranium, while permeability barriers and upward movement of oil products may provide trappings for the mobilized uranium. Through this survey south western part of Potwar Plateau being relatively less deformed is considered to provide conducive environments for concentration of uranium. Low grade uranium concentrations have also been discovered in carbonatites in northern part of Pakistan. Preliminary exploration in Sallai Patti carbonatite through drilling supplemented by trenching, pitting and aditing, subsurface continuation of surface concentrations has been confirmed. The ore contains about 200 ppm of uranium and 3 to 4% phosphate in addition to magnetite, rare metals and rare earths. It has been demonstrated on laboratory/pilot scale that the concentrations of uranium and phosphate can be upgraded up to 150 times and 10 times respectively through application of wet magnetic and wet gravity concentrations methods. Considerable potential of uranium exists in this carbonatite.

1. INTRODUCTION

The rocks of Siwalik group in Pakistan have been a target for uranium exploration since the discovery of first radioactive anomaly in these rocks in Dera Ghazi Khan district. These rocks of Miocene to lower Pleistocene age are exposed from Kashmir in the east through Potwar Plateau, Bannu Basin, Sulaiman Range and extend upto the Arabian Sea in the southwest (Fig. 1). The group basically comprises sand - shale interlayering with occasional development of conglomerate of channel lag and terrace deposits.

Siwaliks have been divided into lower, middle and upper Siwaliks on the basis of lithology. The lower Siwaliks are dominantly bright coloured (shades of red, orange) shales with minor sandstones followed by massive sandstone and alternating beds of shale and sandstone in the Middle Siwaliks. These are finally succeeded by coarser facies comprising grit, conglomerate, boulder beds and subordinate shales of upper Siwaliks. The sandstones in the Middle Siwaliks (subdivided into Nagri and Dhok Pathan Formations) are mainly sub-graywackes and lithic arenites. The fine grained facies of Nagri fall into clay/siltstone category whereas those of Dhok Pathan include mudstone, siltstone with rare clay.

The rock exposures of Dhok Pathan Formation, which hosted the first discovery have been aeroradiometrically surveyed and extensively prospected on foot. As a result, a large number of uranium anomalies were encountered in Dhok Pathan Formation in Kashmir, Potwar Plateau, Bannu Basin and Sulaiman Range. Further west, where the character of Siwaliks changes from continental to marginally marine and argillaceous material dominates, no radioactive anomaly was found. Subsequent to exploratory work a few workable deposits of uranium were outlined in Sulaiman Range and Bannu Basin. Potwar Plateau, has however so far not yielded any uranium ore body. Major part of the uranium outlined at various locations in Sulaiman Range (Fig. 2) has been mined out while the ore bodies outlined at Nangar Nai are being tested for mining through in situ leach mining method.

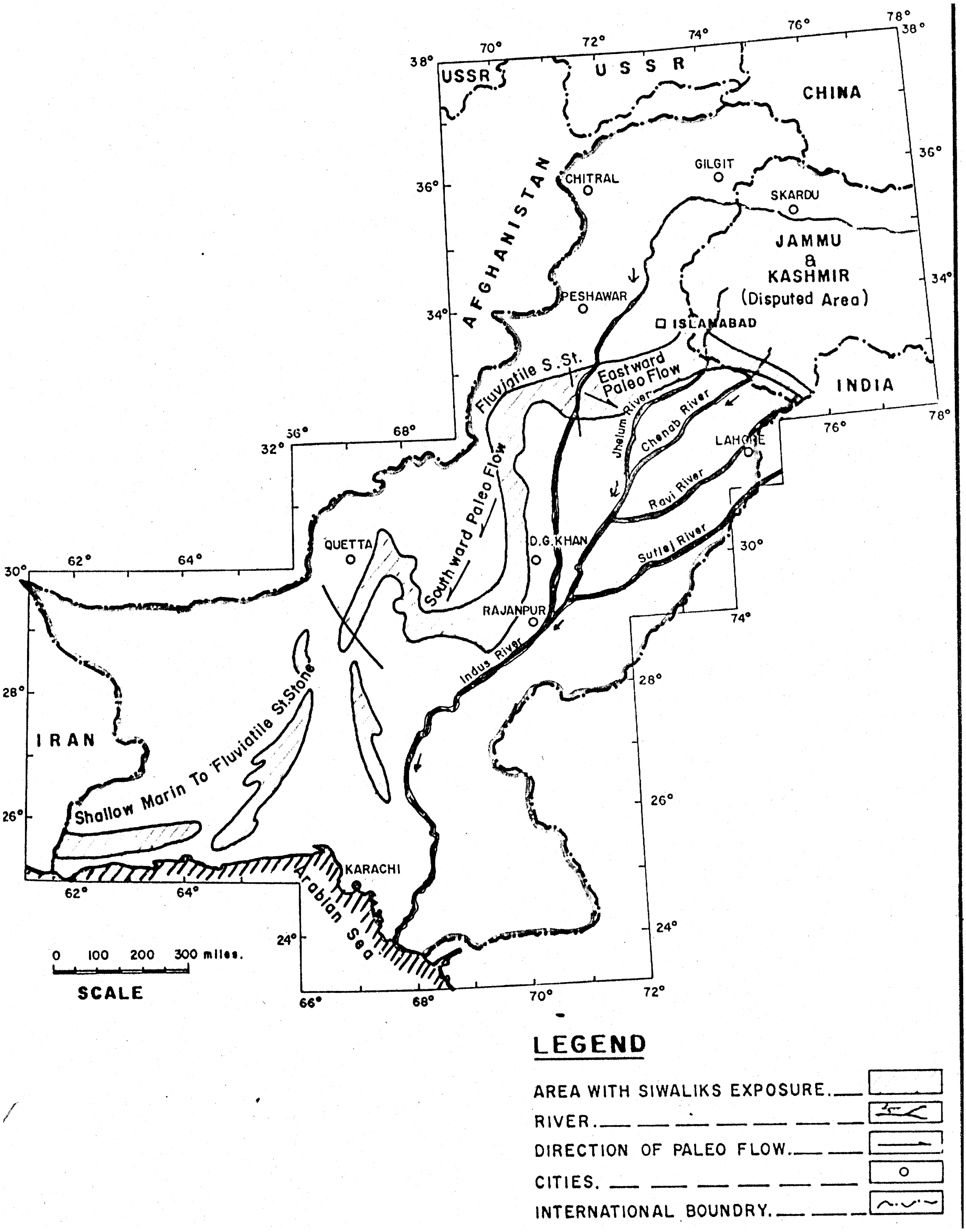

FIG. 1. Map of Pakistan showing Siwaliks exposures.

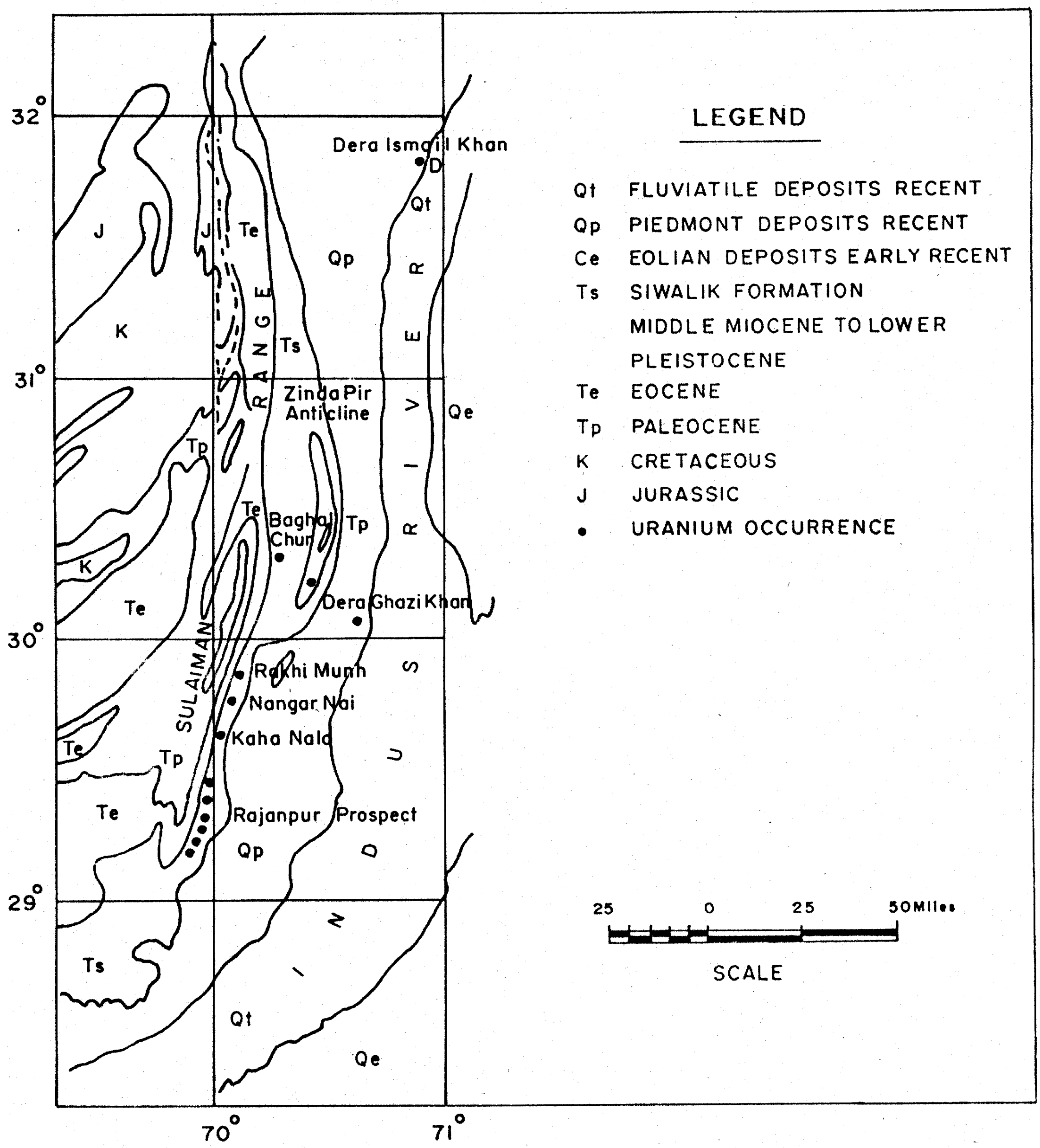

FIG. 2. Geological map Sulaiman range.

2. URANIUM IN BANNU BASIN

The tectonics of the area seems to have played the key role in the genesis of uranium ore bodies in Bannu Basin. The basin has experienced repeated upheavals, accompanied by successive lowering of water table. This has caused the leaching of uranium after each upheaval, which has been reprecipitated below the present water table. The confined geohydrological regime helped the preservation of uranium below the water table. This is evident in Figure 3 in which radioactive halo is shown above the present ore grade concentration.

The ore zones bear very low radioactive signature as compared with the contained chemical uranium. Thus there is a strong disequilibrium in favour of uranium, indicating a very young emplacement age.

The uranium ore bodies outlined in Bannu Basin are hosted by poorly consolidated sandstones. Their exploitation through conventional mining methods was considered impracticable and hazardous due to bad ground conditions and influx of large quantity of water. Alternatively, application of ISL technology was studied which was found to be feasible due to a host of strata characteristics such as high permeability, ore bodies being below water table etc; debarring negative factors such as dips, structural imperfections and for the most part absence of the bottom confining shale. Subsequently, ISL tests were conducted on a number of 5 spot patterns for a period of 4 years and basic ISL parameters were determined to form a basis for start of semi-commercial scale operations in mid 1995. R&D is continued alongside to fine tune the operations with a view to improve recovery and reduce production costs.

The ISL mining technique employs 5 and 7 spot well pattern. Ammonium bi-carbonate and hydrogen peroxide are used as lixiviant and oxidant respectively. These are injected at atmospheric pressure. Production of leach liquor is obtained using submersible pumps. System operates at low pH to forestall mobilization of calcium. The lateral excursion is controlled through maintaining injection and production in balance and is regularly checked through monitor boreholes.

3. EXPLORATION

Till few years back, the exploration in Siwaliks sandstones and other terrains was based on physical activities, comprising various radiometric surveys and follow up of the radioactive/uraniferous exposures through mapping, pitting, trenching, drifting and ultimately drilling to locate the subsurface continuations of the mineralization exposed at the surface. Within last 8 to 10 years the scope of exploration activities has been expanded and the use of non-radiometric geophysical techniques such as Magnetic, Electromagnetic and Resistivity have been introduced. Radon Surveys (SSNTD.ROAC etc.) are also used as a supplementary technique to detect the buried source of radioactive emanations. But again these methods have so far been applied in the areas already known to host uraniferous concentrations.

4. PLATFORM SURVEY OF POTWAR PLATEAU

Potwar Plateau area, in spite of conventional exploration activities at a number of sites with widespread surface radioactivity, yielded no uranium mineralization and most of the work at various sites remained inconclusive, due to difficulty in properly selecting and testing of prospective area in an active collision zone environment and shallow data handling.

In order to upgrade the technical skill of the local geoscientists and to overcome the deficiencies in exploration methodology, a resource potential evaluation programme through geological modeling generally referred to as Platform Survey was started under the guidance of an IAEA expert.

Potwar plateau was selected for the platform survey because it has excellent molasse outcrops, spreading over 15,000 sq. kilometers, which though hosted a large number of radioactive anomalies (Fig. 4), but did not yield any workable uranium concentration through conventional type of exploration.

Simultaneous with determining the potential of uranium in the area, the project was aimed to build up the expertise of local geoscientists in conclusive evaluation through successive cycles of data collection, synthesis, followed by interpretation and evaluation.

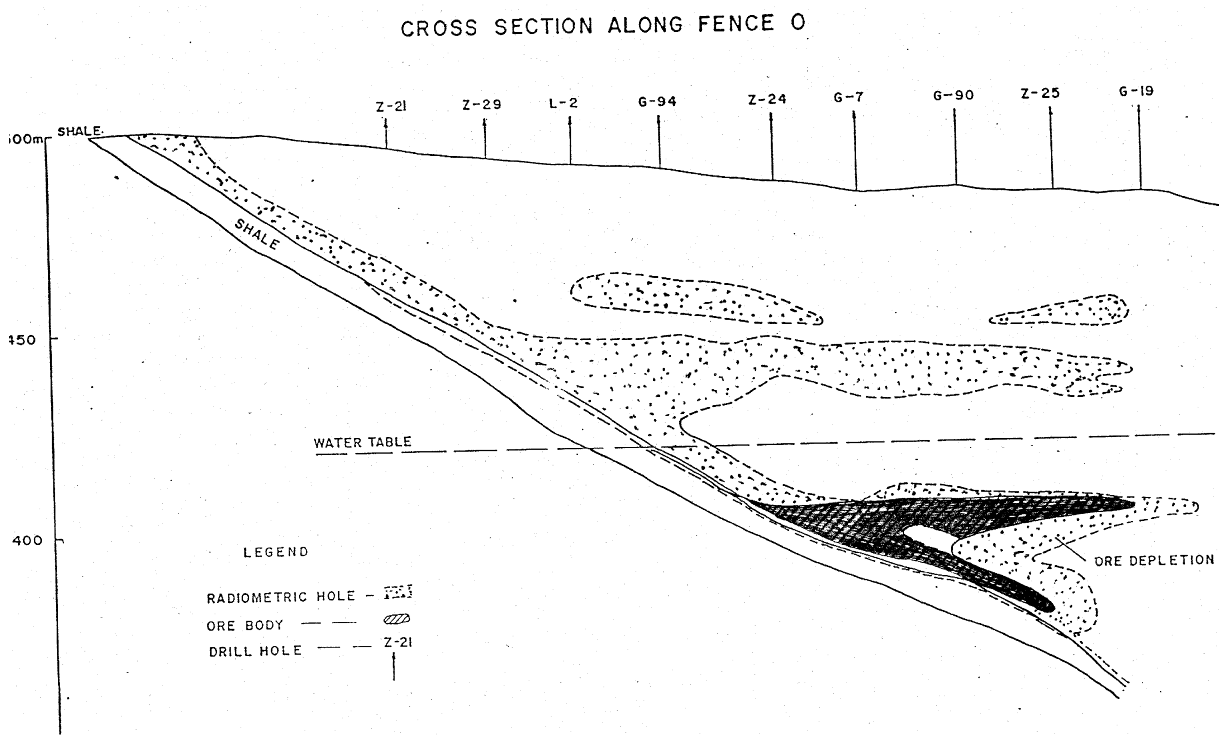

FIG. 3. Cross section along fence O.

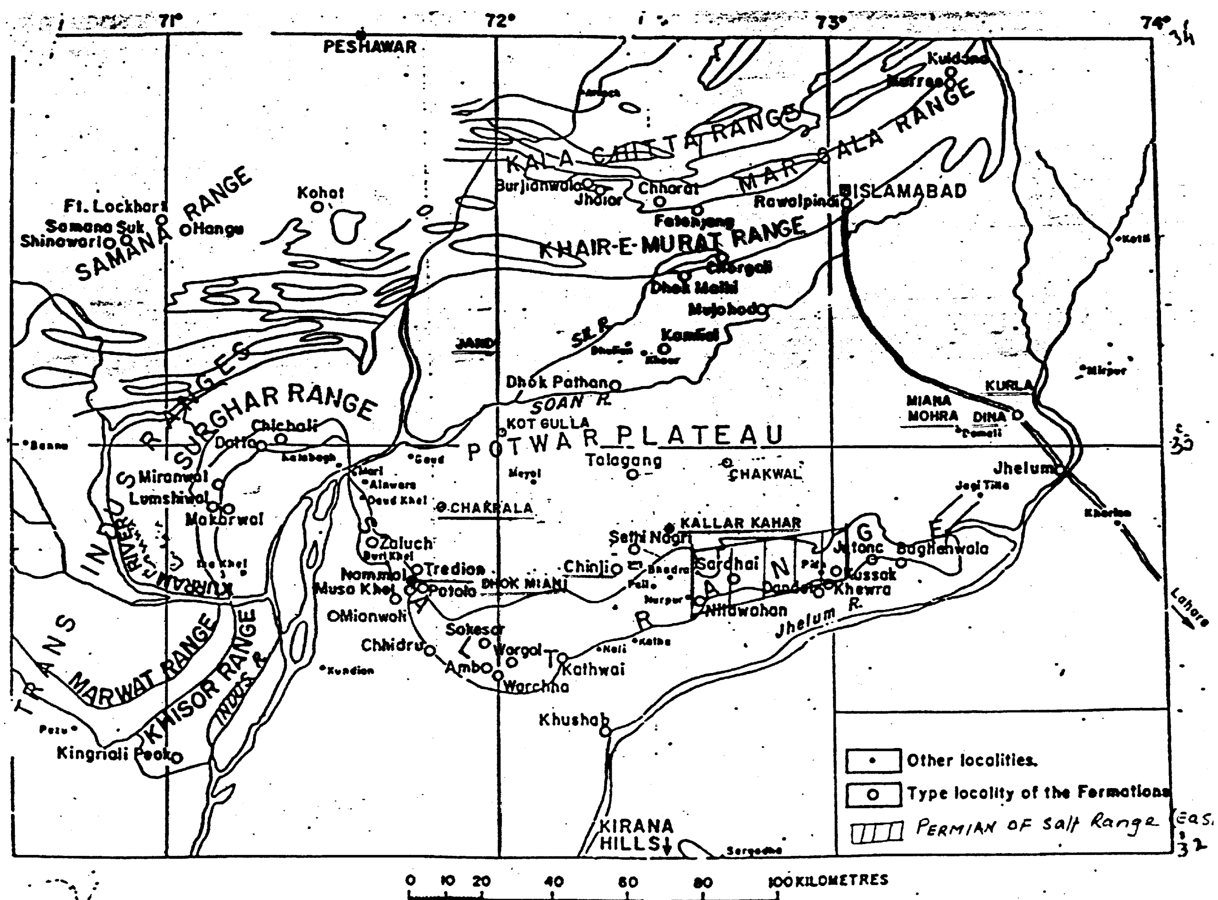

FIG. 4. Distribution of molasse outcrops in Potwar Plateau.

4.1. Methodology for platform survey

All the related information available in the literature was collected and was illustrated in the form of comprehensive maps and charts depicting sedimentology, paleo-environment, tectonics, radiometry and hydrogeochemistry of the area. For this purpose the Potwar Plateau was divided into four subregions roughly taking NS lineament falling along 72°45'E and NE-SW flowing Soan river as dividing line. While large scale sedimentry features and details of tectonics were identified through study of literature, imagery interpretation and additional field work, scanty data on petrochemistry was supplemented with systematic rock sampling. Systematic rock sampling along 14 sections covering the middle Siwaliks, distributed across Potwar Plateau was carried out to substantiate the data base. The location of these sections is marked on the map in Fig. 5. The samples collected were analysed for mineralogical composition, heavy minerals contents, U_3O_8, U^{+6} U^{+4}, eU, Fe^{+2} and Fe^{+3}, C_{org} and C_{inorg}. The nature of clay minerals was also determined with XRD.

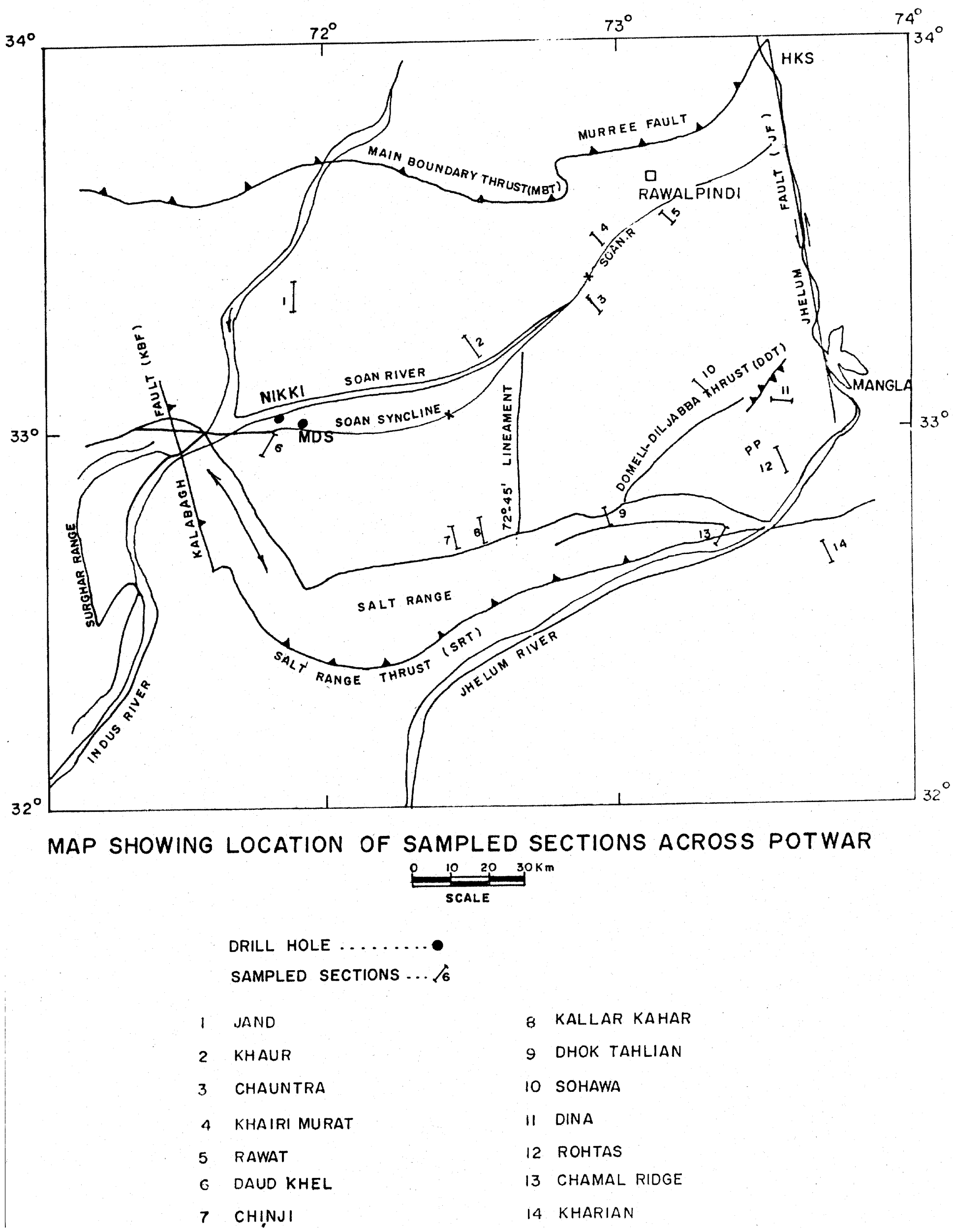

FIG. 5. Map showing location of sampled sections across Potwar.

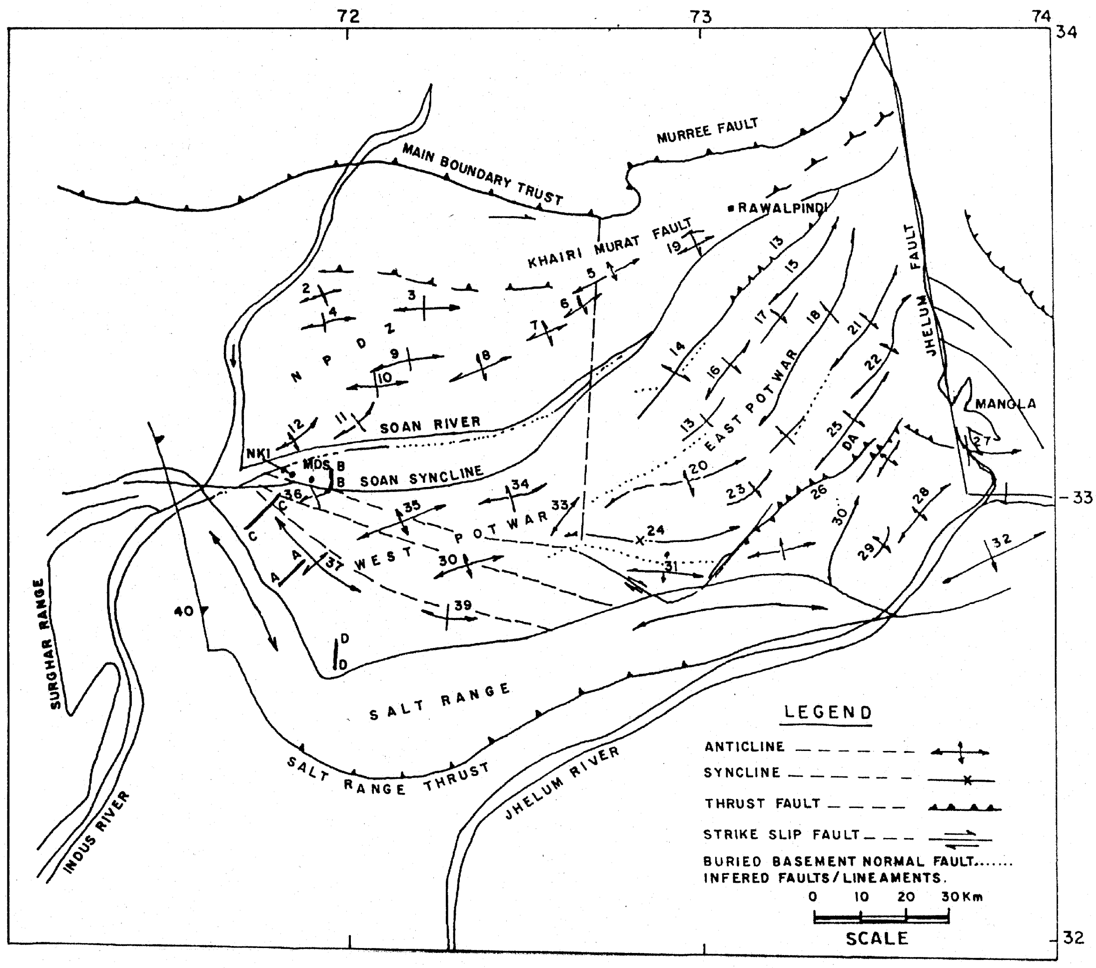

FIG. 6. Structural map of Potwar Plateau (modified after Khan & Pennock).

The petrochemical data was processed to identify variations in nature of provenance, depositional environments, diagenetic changes, evolution of uranium and their time space distribution.

4.2. Tectonics

Structurally the Potwar Plateau consists broadly of a number of faulted anticlines and synclines (Fig. 6) superimposed on the main Soan Syncline trending ENE to WSW roughly co-linear with the Soan River. The LANDSAT imagery interpretation identified the north-south trending long linear features which represent the surface expression of basement related faults. It is observed that the northern and eastern part of Potwar Plateau has attained a higher degree of deformation, as compared to southwestern part of Potwar Plateau. Both in the eastern and northern parts, tight folds generally breached at the anticilinal crest, are common, while in the southwestern part, there is much lesser number of linears/faults and folds are incipient and also much gentler.

4.3. Mineralization

The synthesis of collected data followed by its interpretation/evaluation has provided a better grasp of the overall present geological environment allowing to study the reported anomalies and their time-space distribution and their significance/weightage.

4.3.1. Source of uranium mineralization

Evidence of synsedimentary volcanism has been collected from Potwar Plateau. In the middle Siwaliks, syn-sedimentary volcanism has been a quite frequent feature both in sand and clay facies and its evidence is found in the form of pellets, irregular concretions, bentonitic pockets, ash layers of volcanogenic silt (angular grains in silty matrix) and a siliceous cement in the sandstone.

Pyroclastic layers upto several meters thick have been identified in two drill holes at several levels within the Nagri and Dhok Pathan Formation. These findings have considerably increased the initial uranium stock potential of these members of Siwaliks.

4.3.2. Uranium mobilization/concentration

Syn to post sedimentary tectonic deformation is considered as the main reason for uranium movement whereas the upward migration of oil products is regarded as the main reductant and permeability barriers are two main factors responsible for trapping of uranium mineralization.

The remote sensing imagery and fragmentary field data reveal that the sub region is criss crossed by dense net work of extensive, diverging and discontinuous lineaments marking out the major basement faults with degree of surface expression varying from negligible to flexuring or breaking. The brittle and tensional tectonic style now documented for South West Potwar is likely to provide more channel ways, remobilization medium as well as uranium trapping fronts.

The main parameters considered for evaluation of uranium distribution and potential of Middle Siwaliks of Potwar Plateau subregions are:

i) Uranium source
  Silica cement considered to be released by the devitrification of volcanic glass.
  K-feldspar content of the sediments
  Significant magmatic content
  Volcanic Rock Fragments.
ii) Uranium remobilization
  Alteration as indicated by Fe^{+2}/Fe^{+3} ratio
  Porosity/Permeability
  Uc/eU ratio as indicative of uranium leaching
  U in sandstone/U in shale ratio
iii) Trapping of uranium
  Redox Status inferred by Fe^{+2} /Fe^{+3} ratio
  Reducing Color of sandstone (grey, green etc)
  Uc/e U ratio
  U in S.St/U in shale ratio

The data collected along the sections and two boreholes is graphically represented in Fig. 7.

4.3.3. Results of platform survey

Comparative study of 12 parameters on source, mobilization and trapping selected from the petrochemical data confirms that the southwestern Potwar Plateau is relatively of more interest. Even in this area, three out of six formations are more likely to develop an environment conducive to complete the uranium cycle.

The platform survey thus sets an example in exploration strategy. Through this work an area of 15000 sq. km of Potwar Plateau was narrowed down to 2000 sq. km for detailed prospection in southwestern part. This has been further narrowed down to about 400 sq. km for detailed studies to locate subsurface zones of interest.

5. URANIUM ACTIVITIES IN NORTHERN AREAS

Uranium prospection and exploration activities have also been carried out in ignometamorphic rocks of northern areas of Pakistan which include granites, graphitic metapelites and carbonatites.

5.1. Geology

Northern Pakistan can be subdivided into three broad geological domains from south to north (Fig. 8). These are:

1. The Indo Pakistan Plate
2. Island Arc Assemblage
3. Eurasian Plate.

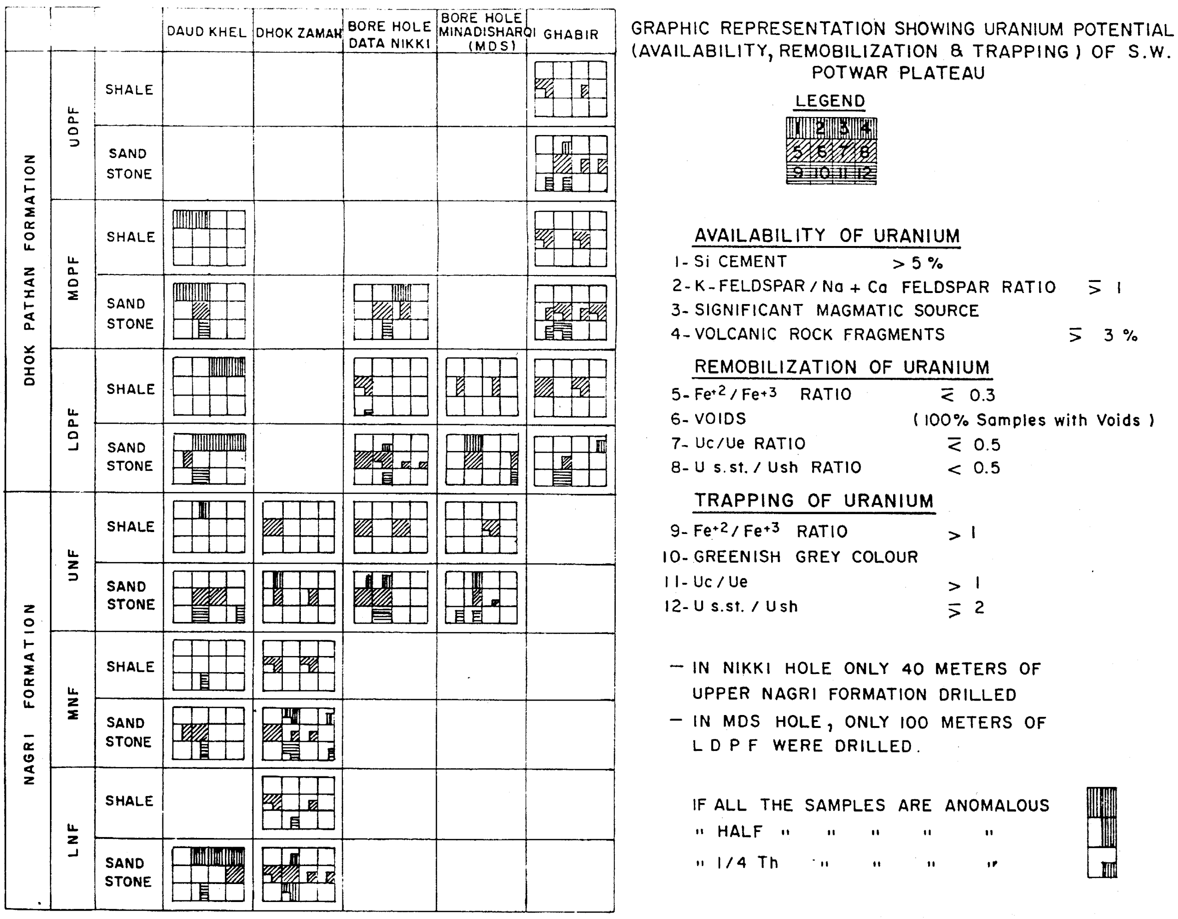

FIG. 7. Graphic representation showing uranium potential (availability, remobilization 8, trapping) of S.W. Potwar plateau.

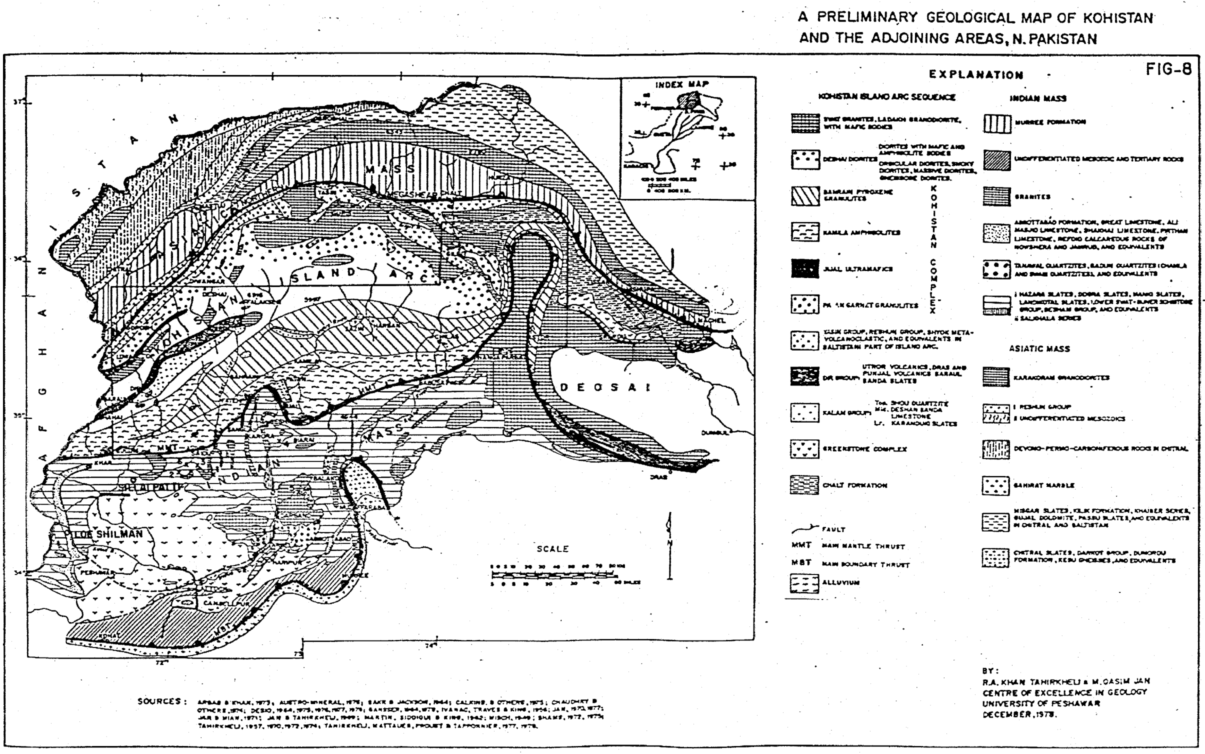

FIG. 8. A preliminary geological map of Kohistan and the adjoining areas, N. Pakistan.

These three units are separated by two major regional structural elements known as Main Mantle Thrust (MMT) and Main Karakarum Thrust (MKT).

The present tectonic picture of Northern Pakistan shows that the Indo Pakistan Plate to the south subduct along MMT under the Island Arc Assemblage which in turn subduct under the Eurasian Plate to the north along the other suture zone i.e. MKT.

The lithological assemblage belonging to Eurasian Plate include metasediments comprising pelitic and calcareous rocks and Karakorum Granodiorite Group consisting of granodiorite, granite pegmatite and aplites.

The lithological assemblage between the two suture zones comprises of 30-40 km. thick zone of metasediments, calc alkaline intrusive and volcanic and ultra mafic rocks. The sequence has been regarded as a complete cross section of a fossil island arc abducted on to the Indo Pak Plate.

The lithological assemblage belonging to Indo Pak Plate consist of metasedimentary, sedimentary, igneous and metaigneous rocks. The metasediments are composed of metapelites and psammites showing progressive increase in metamorphism towards MMT from chlorite to sillimanite schist and gneiss.

The igneous rocks mostly comprise granite and granite gneiss, along with alkaline rocks, which include alkaline granites, syenites, nepheline syenites and carbonatites.

Extensive prospection has been done scanning the terrains of metapelites as well as granites. Although a large number of radioactive anomalies have been discovered in these rocks but there has not been much success in locating any significant uranium concentrations.

5.2. Uranium in carbonatites

During routine prospection activities some of the carbonatites have been found to be radioactive. The main source of radioactivity is pyrochlore mineral. In mid seventies, a carbonatite body in Loe Shilman area was explored through drilling and large samples were obtained through trenching and aditing in the area for pilot scale processing. The anomalous zones within the carbonatite were however too scattered and of small dimensions, therefore exploratory work was discontinued.

Another carbonatite body occurs near Sallai Patti Village in Malakand Agency (Fig. 8) which in parts is radioactive. Preliminary analysis indicated the presence of uranium in the rock samples, which also contained rare metals, rare earths, phosphate and to a lesser degree magnetite, Geological investigations were therefore undertaken to determine the trend and size of the radioactive zones in the carbonatite body and to evaluate it's potential for exploration as a multimineral prospect.

5.2.1. Geological setting of Sallai Patti Carbonatite

The geological setting of Sallai Patti carbonatite is shown in Fig. 9. It is a sheet like body and has intruded along the fault running in N.W. direction between granite and schist. The dip of the carbonatite body is low to moderate in the western part and moderate to vertical in the eastern part. The carbonatite body varies from 2 to 30 m in width and on the surface extends for about 12 km. West ward extensions have not been checked so far.

There is another parallel and elongate body, partly covered under the alluvium towards east of main carbonatite body. This body is 2 to 7 m thick and is intruded within the schists. This body joins the main carbonatite body in the eastern and western parts of the area. This body of carbonatite has almost vertical dips.

5.2.2. Exploration in Salli Patti Carbonatite

Surface radiometric maps of two selected blocks of the carbonatite body were prepared to understand relationship of uranium mineralization to lithology and structure. The maps indicated that roughly 25% of the carbonatite body is radioactive and has potential for further subsurface exploration.

Subsurface exploration on these two blocks was subsequently undertaken and diamond core drilling was initiated in a bid to correlate surface radiometric data with the subsurface data. Fifty holes up to a depth of 90 meters were drilled. The data obtained from the drill holes established the subsurface continuation of radioactivity which showed a systematic pattern of distribution along well defined zones.

Uranium mineralization in the area has been found to have a definite structural control which can be traced both along the strike as well as dip of the carbonatite body.

A reconnaissance diamond core drilling programme of relatively deeper boreholes was thereafter carried out along the entire length of the carbonatite body to see the behaviour of uranium mineralization with depth. Six boreholes were as such drilled, depth of which ranged from 140 to 350 meters. All the boreholes were logged radiometerically. Core samples were analysed for determination of chemical uranium values. Results show that uranium mineralization continues with depth, thus considerably enhancing the workable volume of the carbonatite body.

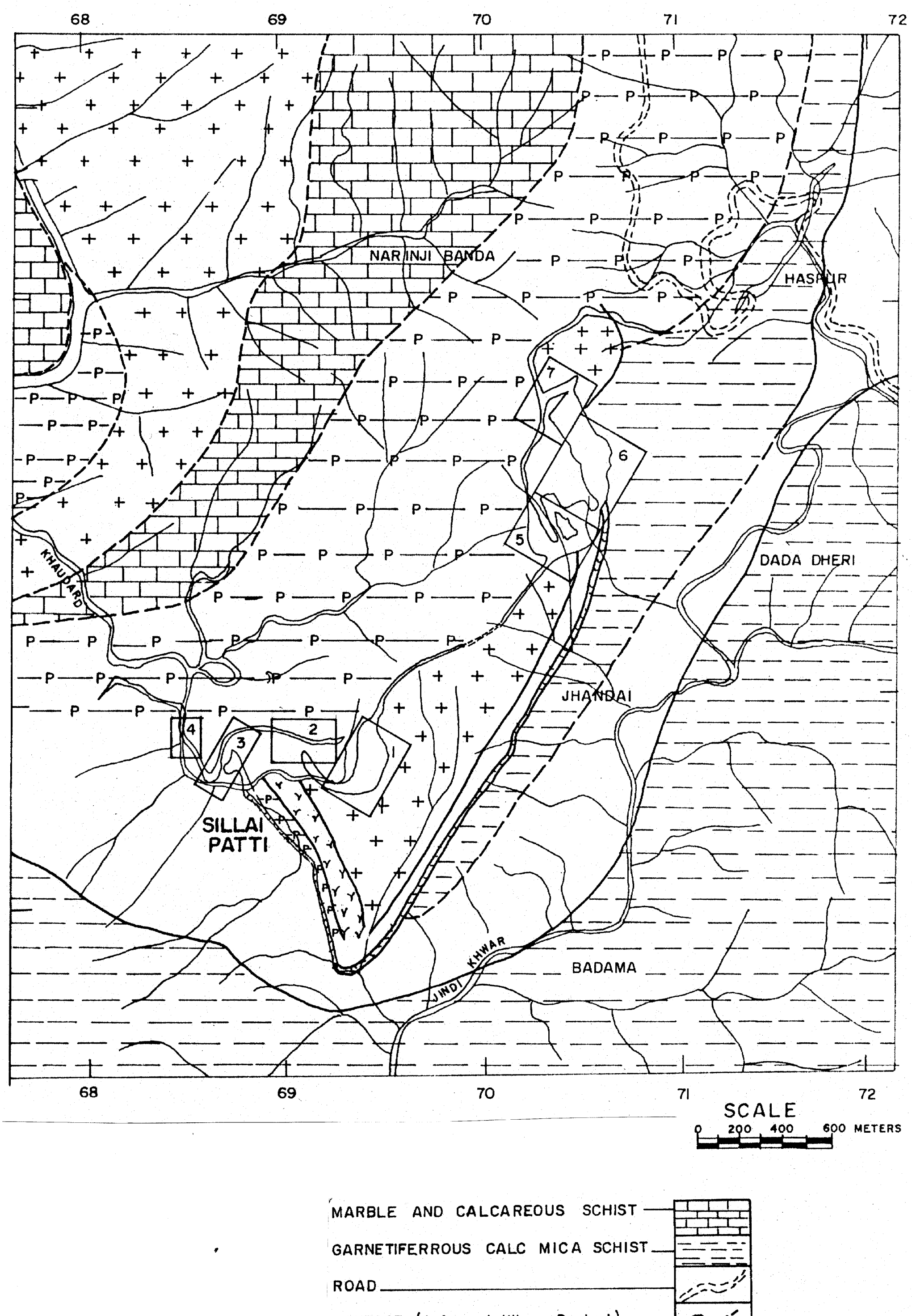

FIG. 9. Geological map of Sillai Patti area.

5.3. Uranium resource evaluation

The surface behaviour of the radioactive zone has been found to continue in the subsurface. Therefore in order to determine the uranium potential, the carbonatite body was divided into seven arbitrary blocks, and in each block channels were cut across the mineralized zones at a regular interval of about 50 meters. Samples collected from each channel and all the channel samples from one block were then mixed and further sampled to represent the whole block. Then all the samples from all the seven blocks were mixed to represent the entire carbonatite body. Results of these analyses are presented in Table I. The resource potential of this carbonatite body could be a thousand tons uranium at an average grade of 0.02% U.

5.4. Beneficiation studies

The chemical and mineralogical analyses of the Sallai Patti carbonatite is as follows:

PYROCHLORE	0.4%
Uranium	200 ppm
Rare metal	600-800 ppm
APPATITE	7.1%
Phosphate	3% P_2O_5
REE	0.2%
MAGNETITE	5.0%
Fe	3.0%
CALCITE	70%
$CaCO_3$	68%

As is evident from the analyses of ore that the uranium content in the carbonatite is rather low. Beneficiation studies for upgrading of uranium were therefore, conducted on laboratory scale as well as on pilot scale, which has indicated that the ore is amenable to upgrading by physical concentration methods like wet magnetic separation, wet gravity separation and froth floatation. The preliminary results indicate the recovery percentage of different fractions, and attainable upgrading ratio as below:

Mineral Concentration	Assay	UGR	Recovery
Pyrochlore	3% U	150.0	78.75%
Apatite	30% P_2O_5	10.0	70.00%
Magnetite	71% Fe	19.7	95.00%
Calcite	95% $CaCo_3$	1.4	83.00%

Thus the uranium content can be upgraded up to 150 times before subjecting it to chemical processing. Pyrochlore concentrate containing upto 3% U can be processed for recovery of uranium. Similarly using froth flotation techniques, phosphate (P_2O_5) can also be upgraded from 3% to 30% which is the acceptable grade for use in the manufacture of fertilizer.

TABLE I: CHEMICAL ANALYSES OF CHANNEL SAMPLE IN SALLAI PATTI CARBONATITE

Sr. No.	Sample No.	U_3O_8 (ppm)	P_2O_5%	Fe%
1.	SPB-1/1	113	3.35	2.54
2.	SPB-1/2A	146	4.06	4.63
3.	SPB-1/2B	21	3.88	2.65
4.	SPB-1/3	133	3.88	1.90
5.	SPB-1/4A	396	4.93	2.48
6.	SPB-1/4B	127	4.58	3.35
7.	SPB-1/5	125	3.35	2.93
8.	B-1	183	3.97	2.40
9.	SPB-2/1A	159	3.79	3.91
10.	SPB-2/1B	114	3.53	4.63
11.	SPB-2/2A	55	3.79	3.13
12.	SPB-2/2B	159	4.58	4.94
13.	SPB-2/3A	82	4.41	2.97
14.	SPB-2/3B	368	3.52	3.91
15.	SPB-2/3C	1633	4.23	4.47
16.	SPB-2/4A	204	5.29	4.47
17.	SPB-2/4B	204	3.88	4.84
18.	SPB-2/5A	84	2.99	4.56
19.	SPB-2/5B	95	3.52	4.34
20.	SPB-2/6A	408	3.47	3.13
21.	SPB-2/6B	245	3.35	5.19
22.	SPB-2/7	52	2.73	1.89
23.	SPB-2/8	91	2.99	1.91
24.	SPB-2/9	163	2.64	2.14
25.	B-2	327	4.06	4.97
26.	SPB-3/1	585	8.53	12.75
27.	SPB-3/2A	340	3.62	11.47
28.	SPB-3/2B	281	3.11	10.25
29.	SPB-3/3A	64	4.38	10.56
30.	SPB-3/3B	359	4.38	5.69
31.	B-3	281	4.47	11.63
32.	SPB-4/1A	604	3.79	4.56
33.	SPB-4/1B	91	1.89	4.50
34.	SPB-4/2A	359	3.79	3.83
35.	SPB-4/2B	264	4.29	5.50
36.	SPB-4/3A	91	4.80	6.31
37.	SPB-4/3B	32	4.60	3.45
38.	SPB-4/4A	48	2.61	4.85
39.	SPB-4/4B	59	4.52	19.31
40.	SPB-5/1	427	3.73	4.13
41.	SPB-5/2	233	3.41	2.93
42.	SPB-5/3A	194	2.76	2.80
43.	SPB-5/3B	119	3.16	3.85
44.	SPB-5/4	60	0.73	10.05
45.	B-5	155	2.59	3.88
46.	SPB-6/1A	272	3.97	3.53
47.	SPB-6/1B	233	4.54	2.13
48.	SPB-6/1C	143	0.73	5.31
49.	SPB-6/2	194	0.92	5.28
50.	SPB-6/3	893	10.13	3.56
51.	SPB-6/4	505	4.06	2.51
52.	B-6	388	4.05	2.58
53.	SPB-7/1	544	5.07	9.98
54.	SPB-X	271	3.32	3.88

6. DISCUSSION

Pakistan has undertaken conventional exploration in sedimentary and ignometamorphic rocks. Initially, workable concentrations of uranium were discovered, which were mined-out to meet the internal requirement for power generation. Realizing the shortcomings of the conventional exploration techniques, we have undertaken re-evaluation of all the geological formations considered to be favourable for occurrence of uranium, through platform surveys in order to establish the availability of source of uranium, its mobilization and location of trappings.

This approach initiated under the guidance of IAEA expert has proved very useful. It has helped in upgrading the technical capabilities of local geoscientists to undertake formation evaluation studies in other area of the country with more confidence. Previously in spite of several known uranium anomalies in the Potwar Plateau, no significant break through was achieved. The platform survey of the area has indicated that South Western Potwar is relatively more favourable for uranium resource. Semi detailed investigations in the south west Potwar has yielded some significant surfacial information to supplement the findings of Platform survey. Moreover, the economic significance of the Nagri Formation has also been established for the first time in addition to the previously known Dhok Pathan Formation. Nagri Formation will now be checked all across the country for its uranium potential.

Besides Siwaliks, there are other favourable formations present in Pakistan, amongst which metapelites exposed in Kashmir and northern areas are important. Work has already been started to understand the significance of the widely spread radioactive anomalies with chemical uranium at a number of places. Thus Pakistan has a very large volume of rocks which could host uranium deposits, but their discovery is difficult due to constant uplifting which activate the destructive processes of leaching of the precipitated uranium concentrations.

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PRODUCTION OF URANIUM IN NAVOI MINING AND METALLURGY COMBINAT, UZBEKISTAN

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SUMMARY

Under the conditions of constantly increasing level of development of the nuclear power, it is inevitable that the uranium stockpiles accumulated to 1985 will soon be depleted. This consideration underlies the development concept of uranium production in the Navoi Mining and Metallurgy Combinat, Uzbekistan. Because this product has become a source of hard currency revenues for the Republic, there will be a significant increase in the processed ore and output of uranium oxide within the next few years.

Uranium production in the Navoi Mining and Metallurgy Combinat represents a full-cycle operations ranging from geological survey through hydrometallurgical processing resulting in the output of uranium concentrate in the form of uranium protoxide-oxide (U_3O_8). The NMMC uranium operations include the Hydrometallurgical Plant and three facilities accomplishing ISL mining facilities.

A successful start on the development of the Uchkuduk deposit by ISL method in the 1960s gave rise to scientific and production approach for development of other uranium deposits of the infiltration bedded (sandstone) type. Uranium recovery by ISL has become a separate mining branch within the 30-year period of its history and the contribution of this branch in uranium production has steadily grown. Since 1995 all uranium produced by Navoi Mining and Metallurgy Combinat is attributed to ISL.

During this evolution period of the ISL method, a whole range of systematic scientific research and practical works were carried out covering improvement of process flowsheets, equipment, operational methods and techniques for particular mining conditions at those specific sites.

In co-operation with design and scientific research institutions, a significant number of scientific researches, test works, design and engineering projects were achieved in order to create optimal conditions for ISL mining and further processing of pregnant solutions by sorption as well as to appropriately equip the mining sites and processing facilities.

During these periods, three principle flowsheets were tested and introduced at the ISL sites of the Navoi Mining and Metallurgy Combinat: sulfuric acid scheme, acid & bicarbonate scheme, weak acid scheme. Out of these three, the sulfuric acid and weak acid schemes have been more intensively developed.

The commercial scale operation of the new method of leaching, using as a leach the ore body water saturated with air, and practically free of reagents, resulted in the reduction of the mining cost and laid the foundation for environmentally friendly operational method.

Optimal parameters of the ISL process have been established including method of processing the pregnant solutions by sorption and the arrangement of the appropriate equipments; methods of well construction which is efficient for any particular conditions and ways to restore their productivity during the course of exploitation, a new production well grid arrangements in connection with hydrological and geological conditions of horizons under development, and an effective lifting equipment for pregnant solutions; methods for extraction of rhenium from ISL solutions as a by-product; and the recovery of scandium oxides from wastes after the hydrometallurgical treatment of the ISL solutions.

Under the transition to market-oriented economy the major effort of the Combinat is focused on reducing the cost of uranium production by the implementation of an up-to-date innovations in ISL technology. We are in the process of re-equipping our drilling facilities by replacing out-of-date and depreciated major equipment.

A new plant has been commissioned for the production of PVC casing pipes necessary for the completion of production wells thus covering the requirements of the entire ISL complex for the near future and for many years to come. Based on modern control and measurement instrumentation we introduce automated control systems for ISL process with broad communication transfer system allowing the integrated information exchange.

Introduced are the systems for automated design of ISL process preparation, which realize computer aided geological support and design of block mining procedure as well as operative planning of recovery and mining preparation works and metal transfer accounting during the course of operations. The park of logging stations is at the moment in the process of being changed to microprocessor computer-aided complexes to provide automated services during geophysical investigations of wells. For the deposits with complicated radiological condition we widely apply the direct method of uranium determination based on instant neutron fission which has increased the efficiency of logging.

The large number of uranium reserves in the Kyzylkum province lay the basis for the plan to significantly increase the uranium oxide production. The realization of the above mentioned innovations makes it possible to significantly intensify the ISL operations performance in the Navoi Mining and Metallurgy Combinat and ensure high revenues from uranium sales at the world market.

STATUS OF URANIUM IN BRAZIL

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Abstract

Uranium exploration in Brazil was started in 1952 by the Brazilian National Research Council. This led to the discovery of the first uranium deposits in Poços de Caldas and Jacobina. These activities was later continued by the National Energy Commission/Comissão Nacional de Energia Nuclear (CNEN), formed in 1962. The founding of NUCLEBRÁS at the end of 1974 marked the increasing effort of the country's uranium exploration programme. At this time only the Poços de Caldas deposit was known with measurable resources. Due to the reorganization of the Brazilian nuclear programme in 1988, all uranium exploration in the country was stopped. By then, eight areas with uranium reserves has been identified. Brazil uranium resources in the RAR category at ≤ $80/kg U cost range are estimated to be 162 000 tonnes U, out of which 56 100 tonnes are in the ≤ $40/kg U cost range. Additional resources in the EAR-I category and the cost range ≤ $80/kg U are in the order of 100 200 tonnes U. The first production of uranium in Brazil, at the Osamu Utsumi mine (Poços de Caldas deposit), started in 1982. Because of escalated costs and reduced demand, this activity was put on stand-by status between 1990 and 1992. The mine was restarted in 1993, but was stopped again in October 1995. The cumulative production of the mine to 1996 was 1241 tonnes U. The Lagoa Real deposit is currently being prepared as a new producing mine.

1. URANIUM EXPLORATION

Historical review

Systematic prospecting for radioactive minerals, begun in 1952 by the Brazilian National Research Council, led at that time to the discovery of the first indications of uranium at Poços de Caldas (Minas Gerais State) and Jacobina (Bahia State).

This phase of activities depended initially on foreign know-how. In 1955 technical co-operation agreements were signed with the government of the United States of America for the reconnaissance of Brazil's uranium potential. In 1962 the recently created National Nuclear Energy Commission/Comissão Nacional de Energia Nuclear (CNEN) sought the collaboration of the French Centre d'Etudes Nuclèaires (CEA) in organizing its Mineral Exploration Department.

In the 1970s more financial resources were made available for radioactive mineral prospecting exclusively through the CNEN. With the founding of NUCLEBRÁS in December 1974, the Brazilian government's efforts received an impetus in the basic part of the nuclear programme, namely, the exploration development and mining of uranium deposits.

When, in December 1975, Brazil and Germany signed the Agreement for Co-operation in the Field of Peaceful Uses for Nuclear Energy, the Osamu Utsumi mine, in Minas Gerais, was the only uranium deposit known and measured.

As a result of its efforts NUCLEBRÁS has identified eight areas with uranium reserves, namely, Poços de Caldas plateau, Minas Gerais; Figueira - Paraná; Quadrilátero Ferrífero-Minas Gerais; Amorinópolis - Goiás; Rio Preto/Campos Belos - Goiás; Itataia - Ceará; Lagoa Real - Bahia; Espinharas - Paraíba. (investigated by NUCLAM).

Due to the reorganization of the Brazilian nuclear programme in 1988, all uranium exploration activities were stopped in 1991.

Recent and ongoing activities

Following the reorganization of the Brazilian nuclear programme in 1988, the uranium activities were delegated to a special organization known as Urânio do Brasil S.A., which was organized as a subsidiary of Industrias Nucleares do Brasil (INB), the holding company responsible for the planning, programming and execution of the nuclear fuel cycle. Due to management adjustments, all the dependent companies were incorporated and presently there is only Indústrias Nucleares do Brasil S.A. taking care of the whole fuel cycle activities.

During the period 1990 up to 1992, the uranium production was in stand-by status. The restart of production took place in the late part of 1993 and stopped again in October 1995, with the production of 277 ton of U_3O_8.

Nowadays the uranium production in Poços de Caldas mine is in stand-by status.

In 1998, the uranium mining project Lagoa Real, in Bahia, should be in phase of operation, with a production forecast of 300 tons of uranium concentrate per year-an amount which will not only satisfy the demands of Angra I Nuclear Power Plant, but also Angra II, when this starts operating. A modular mining - industrial project, Lagoa Real will carry an initial cost of implementation of US$ 23 million with the objective of mining the uranium contained in 33 anomalies (points of high concentration of uranium) around the mineral province, located in the area known as the Polígono das Secas (Poligon of Droughts), Center-South of Bahia, in the Municipalities of Caetité and Lagoa Real.

Discovered in 1977, Lagoa Real has reserves of 100,000 tons of uranium concentrate. Initially, anomalies numbers 13 and 8 will be mined, called respectively the Cachoeira Mine and the Quebradas Mine, producing 300 tons of uranium yearly by open pit mining, for a period of 15 years. During the implementation phase, the project will create 500 direct jobs and will absorb 200 workers when it starts operation.

The ore from Lagoa Real will be processed using the method of in pile leaching. The uranium concentrate will be extracted using organic solvents. This process eliminates the phases of milling, agitating and filtering, reducing in about 40% the investments needed for implementation and operating of the undertaking, comparing to conventional leaching.

During the last two years all the feasibility studies were concluded and the INB decided starts the implementation of the project in 1997.

Known conventional resources (RAR and EAR Category I)

The conventional resources are located in the following deposits:

– Poços de Caldas Plateau (Osamu Utsumi Mine)

There are three principal types of uranium mineralization at Osamu Utsumi Mine, which are superimposed on one another at certain locations:

- Primary mineralizations connected with hydrothermal phenomena;

- Primary mineralizations connected with chimneys of volcanic breccias;

- Secondary mineralizations connected with weathering phenomena.

The hydrothermal primary uranium mineralization is characterized by argillization phenomena and by the presence not only of uranium, but also of pyrite, fluorite, molybdenum and, in smaller quantities, zirconium and thorium. It occurs in orebody "A" of the Osamu Utsumi Mine in the form of systems of large and small veins which can have thicknesses of up to 5 m and be at depths of as much as 300 m.

The primary mineralization in breccias is connected with the phenomena of pulsations in volcanic chimneys. It occurs in body "B", which accounts for about 70% of the deposit. It has essentially the same constituents as the hydrothermal primary mineralization.

The secondary mineralization is connected with the phenomena of leaching and oxidation of the uranium nearer the surface by the infiltration water, transport and redeposition along the oxidation- reduction front. It occurs in body "E" and in the upper parts of bodies "A" and "B" of the Osamu Utsumi Mine. It can be subdivided into two types: (a) sub-horizontal mineralization connected with the oxidation reduction front, and (b) mineralization in nodules remaining in zones deeply altered by weathering.

Figueira deposit

By establishing a reference calcareous horizon at the top of the basal part of the Rio Bonito Formation it was possible to characterize three stratigraphic units:

- Unit A, the sequence between the top of Itararé and a carbonaceous siltite, including coal;
- Unit B, the sandy sequence which extends to a siltite below the calcareous horizon;
- Unit C, comprising siltite and limestone.

The uranium mineralization is located in the sedimentary sequence between the coal seam in unit A and the calcareous horizon in unit C. It is associated with sandstones carbonaceous, siltites and coal seams. In sandstones the uranium mineralization is found in the form of uraninite between the interstices of quartz, grains cemented by a calcareous cement; in carbonaceous siltites and coal the uranium mineralization occurs in the form of organo-mineral complexes.

Quadrilátero Ferrífero - Minas Gerais

- Gandarela and Serra das Gaivotas Deposits

The Gandarela syncline is located in the central part of the Quadrilátero Ferrífero, where the thrusts were in the east-west direction. Tear faults, in the perpendicular direction, are abundant, with variable displacements and angles. The eastern fringe of the syncline has the largest surface expression.

The sedimentation in Gandarela syncline is typically fluvial with palaeo-current directions from north-east to south-west.

Of economic importance are the oligomictic metaconglomerates from the basal section of the Moeda Formation which show uranium mineralization, especially the horizons connected with a paleodrainage of approximately N45°E direction. The conglomerate pebbles are almost all quartz, rarely quartzite. It is a relatively immature conglomerate with an abundant quartz sericite matrix of light green colour, generally quite pyritic with mineralization of uraninite and pitchblende.

In some areas the sericitic pyritic matrix shows at least three types of pyrite, one finely distributed in the matrix, generally with uranium; another, in large masses of the pebble type, rounded oval in shape, occurring mainly in association with gold secondarily with uranium; and a third being well-crystallized idiomorphic pyrite having no direct relation with the mineralization.

Amorinópolis deposit, Goiás

The Iporá-Amorinópolis area where the uranium mineralization occurs is located in the so-called Amorinópolis horst. The area was subjected to tectonic movement of tensile nature which caused gravity faults and injection of alkaline materials.

The uranium mineralization of the Amorinópolis deposit is of two types, a primary one with uranium of valency +4, and a secondary one with uranium of valency +556. The primary mineralization is composed of dark minerals, pitchblende (uraninite) and coffinite. The secondary one consists mainly of autunite and sabugalite, which are alteration products of the primary mineralizations.

The uranium mineralization is controlled essentially by the physico-chemical conditions of the host arkosic sandstone and the hydrodynamic flow of the solutions.

Itatatia deposit, Ceará

The uranium mineralization of the Itatatia deposit is associated with apatite or collophane. Typical apatite occurs in generally idiomorphic millimetre crystals, filling fractures and pores of feldspathic rocks (episyenites), gneisses, marbles, and calco-silicate rocks or even in breccias. Even collophane or apatite of the second generation do not always show definite crystalline forms; in some cases, however. There are botryoidal and can occur, filling pores, fractures of rocks and breccia zones and also large-size cavities in marbles. In the last case, the uraniferous calcium phosphate is of massive aspect. Minerals most frequently associated with the phosphates are calcite quartz and chalcedony.

Two main types of mineralization were confirmed in the area:

- Massive collophanite filling cavities in limestone;
- Collophanite disseminated in marble, vacuolar feldspathic rock and gneisses (impregnation).

The mineralization of collophanite intercalated with marble is restricted to a limited area, in the form of a lens in sub-vertical position to a known maximum depth of 100 m, while that of collophanite disseminated in feldspathic rocks, marble and gneisses (impregnation) is more irregular and apparently does not form continuous layers.

Espinharas deposit, Paraíba

The uranium mineralization occurs in dykes of feldspathic rocks enclosed in gneisses in an area of about 1,2 km^2. It is related to metasomatic phenomena of the sodic type (albitization). The mineralized rock is composed of 80 to 90% feldspars, some biotite and smaller quantities of apatite and carbonates. Its grain-size varies from very coarse pegmatite to microcrystalline. In the proximity of dykes the enclosing rock (amphibolitebiotite gneiss) is infiltrated by feldspathic material.

Various radioactive minerals, including uraninite, have been observed. The primary radioactive minerals were for the most part fully altered, forming unidentifiable secondary minerals at the surface.

Lagoa real deposit, Bahia

The uraniferous anomalies of Lagoa Real Deposit, are found in a zone Archaean basement consisting of cataclastic granitoids, augen gneisses, microcline-gneisses, granodiorites and albitites.

This zone is about 80 km long and varies in width from 30 to 50 km. To the south, east and north there lays large areas of low relief which are underlaid mainly by gneisses and greenshists of Archaean or Low Proterozoic age. Along its western margin, the massif is frequently faulted against the metasediments and metavolcanics of the Espinhaço Super Group. The region may have been subjected at least to three tectonic cycles during which the rocks were rejuvenated. These include the Guriense (3,000 m.y. +), Transamazonian (1,800-2,100 m.y.) and the Brazilian (1,800 500 m.y.) cycles.

The microline-plagioclase-augen gneisses are the host to the albitites which often are mineralized. They always exihibit strong cataclasis and granoblastic texture.

The uranium mineralization occurs in albitites. They are characterized by the presence of sodic plagioclase (albite) and aegerine-augite. The country rocks are invariably microline - ortho-gneisses. The foliation of these gneisses is essentially parallel to the regional trend, which within the massif inscribes an arch. The fractures which also follow the strike are often cataclastic and their dip directions, as well as that of the foliation, are helicoidal from south to north. The mineralized bodies of metasomatic albitites surrounded by microline gneiss are fusiform and likewise accompany the regional structural trends. The length of these varies from 20 to 100 times the width.

The uranium enrichment is of brazilian age which is supported by absolute age dating (U/Pb) of uraninite at 820 m.y. Solutions rich in sodium chloride and methane (found in fluid inclusions) ascended pre-existing fracture planes and zones of weakness within the microcline gneisses causing sodium metasomatism and the formation of the albite-pyroxene-rocks. The uranium was mobilised and concentrated as fine disseminations in the mafic bands of sodic pyroxene.

The uranium mineral is uraninite. β-uranophane can be observed on fractures planes at surface. The grades of U_3O_8 are quite high and may reach 3.50% in exceptional cases. The average grade of the mineralized zone is about 0.3 to 0.2% U_3O_8. The concentrations of thorium are low (100 ppm).

Similar deposits and metalogenetic models have been described by Kazansky and Laverov (1977) in the USSR

Besides the evident structural ore control uranium also follows a lithological control as it is restricted to albitites.

But there is no mineralized albitites mineralogicaly and chemical similar to the mineralized ones. The only conspicuous difference is the greater proportion of mafic minerals in mineralized albitites.

Uraninite is associated with fine bands of mafic and opaque minerals (aegirinaaugite, amphibole, biotite, garnet, epidot and magnetite).

During albitization of gneisses there is a relative loss of SiO_2 and K_2O and a gain in Na_2O_3, Al_2O_3 and Fe.

Oxygen isotope analyses of quartz, albite and magnetite from gneisses and albitites indicates that the metassomatic fluids were of ground-water nature.

REASONABLY ASSURED RESOURCES*
(Tonnes U)

Cost Ranges

<$40/kg U	<$80/kg U	<$130/kg U
56 100	162 000	162 000

* As in situ resources.

ESTIMATED ADDITIONAL RESOURCES - CATEGORY I*

(Tonnes U)

Cost Ranges

< $40/kg U	< $ 80/kg U	< $130/kg U
0	100 200	100 200

* As in situ resources.

All of the above known resources recoverable at below $40/kg U as well as those recoverable at costs below $80/kg U, are tributary to existing and committed production centres.

Undiscovered Conventional Resources (EAR Category II and Speculative Resources)

The Rio Cristalino Project is located in south east part of Pará state, and eleven anomalies were detected until 1984, when the evaluation with the use of detailed radiometric, topographic and geological mapping, trenching and exploration drilling were stopped.

Uraniferous anomalies were found in a association with quartzites/metaarkosic rocks and metasandstones. The primary uranium mineralization occurs envolving grains of quartz and feldspar on the metaarkosic rocks. The uranium mineral is uraninite. Chemical analyses in samples collected in the first ground-check of these anomalies, had shown values up to 6,1 % of U_30_8.

At the moment, INB is developing a programme of re-evaluation in this area. The estimates of undiscovered uranium, resources and speculative resources are summarised in the following tables.

ESTIMATED ADDITIONAL RESOURCES - CATEGORY II*

(Tonnes U)

Cost Ranges

< $40/kg U	< $ 80/kg U	< $130/kg U
0	120 000	120 000

(Tonnes U) *As in situ resources

SPECULATIVE RESOURCES*

Cost Range		Total
$ 130/kg U	Unassigned	
0	500 000	500 000

* As in situ resources

Unconventional uranium resources

The identified unconventional uranium resources are, as indicated below, hosted in marine phosphates and carbonatites.

UNCONVENTIONAL AND BY-PRODUCT RESOURCES*

Deposit	Location	Deposit type	Tonnes U	Grade (ppm)	Production Centre
Olinda	PB	phosphate	28 000	120-140	for P205
Araxa	MG	carbonatite	13 000	80	for Fe-Nb
Gandarela	MG	quartz pebble conglomerate	2 000	250	----

* As in situ resources.

URANIUM PRODUCTION

Historical Review

When, in December 1975, Brazil and Germany signed the Agreement for Cooperation in the Field of Peaceful Uses for Nuclear Energy, the Osamu Utsumi mine, in Minas Gerais, was the only uranium deposit known and measured. The Mining and Milling Industrial Complex of the Poços de Caldas Plateau (CIPC), which started production in 1982, was owned by the state owned company Nuclebras until 1988. At that time Brazil's nuclear activities were restructured. Nuclebras was liquidated and its assets transferred to Uranio do Brasil S/A. With the dissolution of Uranio do Brasil in 1994, the ownership of uranium production is 100 per cent controlled by Industrias Nucleares do Brasil, a state owned company.

Between 1990 and 1992, the production centre at Poços de Caldas was on stand-by status, because of escalated production costs and reduced demand.

Production restarted in 1993 and stopped again in October 1995, in function of a political decision to implement the Lagoa Real Project.

Between the 1981 and 1995, the cumulative uranium production was 1241 t U.

Historical Uranium Production

(tonnes U contained in concentrate)

Production Method	Pre-1994	1994	1995	1996	Total through 1996	Expected 1997
Conventional Mining -Open-pit	964	124	125	0	1241	0
Total	964	124	125	0	1241	0

STATUS OF PRODUCTION CAPABILITY

Poços de Caldas Plateau

During 1994 and 1995, uranium oxide was produced at Poços de Caldas Plateau - mining/milling operations.

Nowadays the uranium production in Poços de Caldas mine is in stand-by-status. Subsequent production is expected to come from the Lagoa Real deposit, or alteratively, from the Itataia deposit, where uranium could be recovered as a co-product with phosphate. The technical details of these current and future production centres are summarized in the following table.

Lagoa real project

A production facility with a capacity of 300 t U_3O_8 year is planned to start operation in 1998 at Lagoa Real. It will be sustained by known resources recoverable at costs of up to U$ 40/KgU.

At the present moment it was concluded the Environmental Impact Statement and the Public Hearings is scheduled for July 4th. The start of construction is foreseen for the beginning of August 1997.

OWNERSHIP STRUCTURE OF THE URANIUM INDUSTRY

The current ownership in the Brazilian uranium mining industry is 100 per cent Government represented by the State-owned company Indústrias Nucleares do Brasil. This company controls the Poços de Caldas operating company, referred to as Complexo Mínero-Industrial do Planalto de Poços de Caldas (CIPC).

URANIUM PRODUCTION CENTRE TECHNICAL DETAILS
(As of 1 January, 1997)

Name of production Centre	Poços de Caldas	Lagoa Real	Itataia
Production centre class	Existing	Committed	Planned
Operational status	Stand-by	Feasibility	Feasibility
Start-up date	1982	1998	N.A.
Source of ore			
- Deposit names	Cercado Mine	Cachoeira	Itataia
- Deposit type(s)	Collapse Breccia Pipe	Metasomatic	Phosphorate
Mining operation:			
- Type	OP	OP/UG	OP
- Size (Tonnes/ore/day)	2 500	350	N.A.
- Average mining recovery (%)	80	80	N.A.
Processing plant			
- Type	AL/SX	HL/SX	SX
- Size (Tonnes ore/day)	2 500	350	N.A.
- Average process recovery (%)	90	90	N.A
Nominal production (tU/year)	425	300	350
Plans for expansion	No	No	N.A.
Other remarks	Stand-by status	---	---

NATIONAL POLICIES RELATING TO URANIUM

The reorganization of nuclear activities in Brazil took place in mid 1988. The fuel cycle related activities, formerly the responsibility of Nuclebrás, were transferred to the newly created company, Indústrias Nucleares do Brasil (INB), while related R-D (research and development) activities are being conducted by the Comissão Nacional de Energia Nuclear - (CNEN), which reports to the President of the Republic. CNEN is also responsible for licensing and regulation of nuclear activities.

Brazil's uranium supply policy is that all requirements will be met by INB's domestic production.

The policy regarding stockpiling of uranium provides for a minimum stock of fertile and fissile materials equal to one year forward demand plus a safety margin of 10 per cent.

Nowadays Angra II final assembling is underway and the comissioning of the unit is expected to take place at the end of 1999, which was the main fact concerning nuclear activities in Brazil. It is expected to be the missing driving force need for stabilization of the parameters governing at planning and investments in the nuclear fuel cycle in this country.

BHIMA BASIN, KARNATAKA, INDIA
URANIUM MINERALISATION IN THE NEOPROTEROZOIC

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Abstract

Based on the geological analogy of known uranium mineralisation in other Proterozoic basins of India, the Bhima basin in northern Karnataka, covering an area of 5200 sq km, was taken up for uranium exploration. An integrated approach involving exploration techniques such as terrain analysis using satellite imageries, jeep-borne radiation survey, regional hydrogeochemical sampling and ground radiometric surveys were used. In addition gamma-ray logging of borewells drilled for water have enabled delineation of subsurface mineralisation at Gogi. Uranium mineralisation is associated with: (1) altered phosphatic limestone along the cherty limestone-shale boundary as at Ukinal, (2) brecciated non-phosphatic limestone as at Gogi, and (3) basic enclaves in the basement granites, as at Gogi East. Uranium occurs essentially as adsorbed phase on limonite and absorbed in collophane in the phosphatic limestone as at Ukinal. Mineralisation at Gogi is characterised by intense fracturing and brecciation apparently related to E-W trending Kurlagere-Gogi fault and is essentially low temperature (c.200°C) hydrothermal nature represented by coffinite (thin veins and globular aggregates) along with pitchblende, pyrite (both framboidal and euhedral), pyrrhotite, haematite and anatase. Mineralisation is both syngenetic — remobilised as in the phosphatic limestones (Ukinal) and epigenetic hydrothermal (Gogi). The spatial relation of the unconformity, basement faults, and uranium — bearing basic enclaves within the basement points to the importance of the unconformity as a surface for fluid transport and fixation in conducive hosts. Presence of labile uranium in the basement granites with significant groundwater anomalies (up to 309 ppb U) enhances such possibilities.

1. INTRODUCTION

Proterozoic basins of India constitute one of the major thrust areas in exploration programme aimed at discovering high grade uranium reserves in India [1]. This is particularly true with the proving of a uranium deposit at Lambapur and other significant occurrences in the Cuddapah basin that are being evaluated [2]. Based on these experiences uranium investigations in the Bhima basin were formulated and accordingly an integrated approach with several exploration techniques was adopted. A synthesis of available geological information on stratigraphy, structure, lithology, and radiometric data of the earlier surveys in the basin [3] were utilised in formulating such an exploration strategy. As a first step, terrain analysis based on the satellite imagery data, jeep borne radiation survey and regional hydrogeochemical sampling were initiated. During the ground radiometric checking along the northern slopes of a hill near Ukinal village in Shahapur taluk in Gulbarga district, Karnataka surface radioactivity in cherty limestone fragments in soil covered areas close to the limestone — purple shale contact was recorded. The radioactivity could be traced intermittently for a length of 200 m and samples assayed upto 322 ppm U_3O_8 with <2 ppm Th. This anolmalous zone was found to be restricted to the altered phosphatic limestone occurring in a narrow linear zone extending for over 2.5 km along the limestone–shale contact.

Gamma ray logging of some of the borewells (drilled for water) was also taken up to confirm the depthward continuity of the surface mineralisation. This technique proved to be the most rewarding in bringing to light uranium-mineralised bands upto 0.136% U_3O_8 for 6.4 m, at a shallow depth of 40 m. Gamma-ray Logging of such borewells was also helpful in identifying mineralised area where there is no surface manifestation.

The paper deals with the geological setup and petromineralogy of the different types of uranium mineralisation in the Bhima basin. It also describes the exploration methodologies that were adopted in the reconnoitory stage, as well as during the detailed follow-up. Brief attempts are also made on the genetic aspects of the mineralisation.

2. GEOLOGY OF BHIMA BASIN

Bhima basin (Figure 1) is one of the smaller Proterozoic basins in India having an exposed extent of 5200 sq km disposed in a sigmoidal fashion over a stretch of 160 km in NE-SW direction covering parts of the states of Karnataka and Andhra Pradesh. The northern extensions of this basin are concealed under thick cover of Deccan traps of Upper Cretaceous–Eocene age. The southern boundary of the basin exposes the crystalline basement consisting of Archaean granite-greenstone terrain and younger granitoids of unknown age. The basin is made up of mainly limestone and shale with thin but fairly continuous arenite and conglomerate bed at the base exposing the unconformity contact at several places along the southern margin.

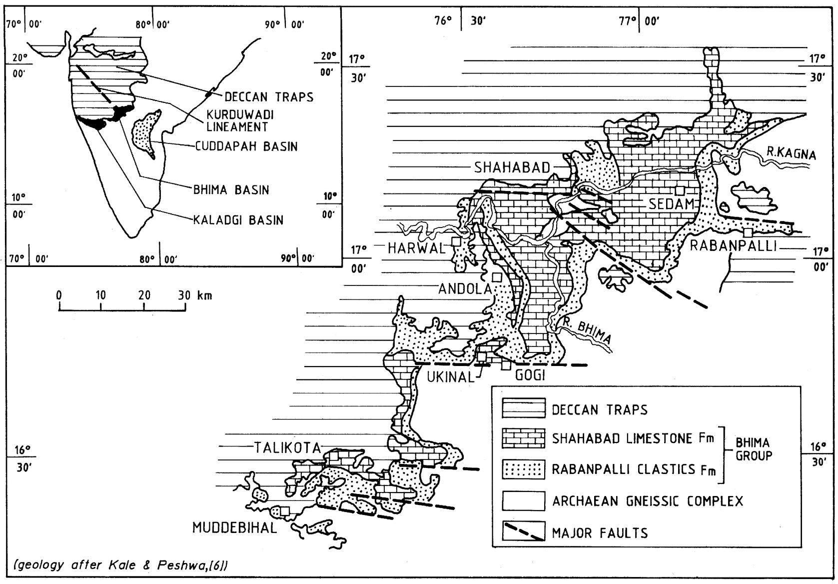

FIG.1. Geological map of the Bhima basin showing the locations of Gogi and Ukinal.

There is a general agreement that the Bhima sediments were deposited during the Late Proterozoic period. Based on the litho-structural similarity, the Bhima and Kurnool sediments are considered to be homotaxial but having independent evolutionary history [4]. Mishra et al. [5] have presented a historical account of the work carried out in the basin and classified the Bhima Group into two sub-groups viz. the Lower Sedam and Upper Andola sub-group with a para-unconformity in between. The sub-groups have been further divided into five Formations and twelve Members together accounting for about 270 m of stratigraphic thickness. Recently Kale and Peshwa [6] proposed a re-grouping of these rocks into Lower Rabanapalli clastics and Upper Shahabad Formation having a gradational contact due to vertical and lateral facies variation. They attribute around 150 m stratigraphic thickness for these sediments.

The lithostratigraphic classifications proposed by Mishra et al. [5] and Kale and Peshwa [6] are given in Table I.

Sediments of the Bhima Group are essentially horizontal except at places where they are structurally disturbed due to faulting and folding. Two major faults viz. Gogi-Kurlagere fault at the limestone-granite contact and Deventegnur fault within the Shahabad limestone have been recognised by Mishra et al. (opcit). However, as many as seven major faults transecting the basin have been identified by Kale and Peshwa (opcit).

Present studies show good agreement with the account of stratigraphy given by Kale and Peshwa (opcit) except for the thickness of the sedimentary column. There are a number of major and minor faults recognised in the basin and close to the basin margins, marked by linear zones of tilted and brecciated beds. Very few faults have depth penetration affecting both the basement and the sediments (eg. Gogi-Kurlagere fault).

TABLE I. LITHOSTRATIGRAPHIC CLASSIFICATION OF THE BHIMA GROUP

	# Mishra et al. [5]	Kale and Peshwa [6]
	5. Harwal-Gogi Formation	B) Shahabad Limestone Formation (includes #2 & #4)
Andola Sub Group	4. Katamadevarhalli Formation	Grey micritic impure limestone
	3. Halkal Formation	Dark blue-grey massive limestone
	(iii) Fissile Shale Member	Variegated, siliceous and cherty limestones
	(ii) Orthoquartzite Member	Blue-grey, blocky micritic limestones
	(i) Chertpebble Conglomerate Member	Flaggy, impure cherty/agrillaceous) limestones
	------------Para-unconformity------------	
	2. Shahabad Formation	
		------------Facies change------------
		A) Rabanpalli Clastics Formation (includes #1, #3 and #5)
Sedam Sub Group	1. Rabanpalli Formation	(d) Ekmai Shale Member (ferruginous& calcareous shales)
	(v) Purple Shale Member	(c) Kasturipalli Glauconitic Member
	(iv) Green/yellow Shale Member	(b) Kundrapalli Quartzarenite Member
	(iii) Siltstone Member	(a) Adki Hill Conglomerate Member
	(ii) Quartzitic Member	
	(i) Conglomerate/Grit Member	

3. EXPLORATION METHODS

Uranium exploration programme in Bhima basin was conceived by taking into consideration the available geological data on (i) the earlier radiometric information on Bhima basin [3] (ii) Srisailam sub-basin of Cuddapah Supergroup wherein a significant uranium deposit was identified [4] and (iii) Kaladgi basin [7]. Accordingly an integrated approach of exploration methods such as satellite image analysis and aerial photo interpretation, jeep borne radiation survey and regional hydrogeochemical sampling was adopted to narrow down the target area.

3.1. Satellite image analysis and aerial photo interpretation

Regional lithostructural analysis was carried out through visual interpretation of Landsat TM transparencies 145-048 and 145-049 (FCC bands 3,4,7) using large format optical enlarger and PROCOM-2. Aerial-photo studies on 1:60000 (approximately) were restricted to areas close to Kurlagere-Gogi fault. The trend lines observed over the Bhima basin vary from E-W to NNW-SSE to NE-SW. Over the Peninsular Gneissic Complex (PGC) terrain, the dominant structural trend is NNW-SSE which conforms to the structural trend lines of Dharwars. The satellite data over an area of 10000 sq km between co-ordinates 16°20'–17°35'N and 76°15'–77°40'E and aerial photo interpretation over 750 sq km was carried out [8] and three areas were selected as first order priority targets.

(i) Kurlagere-Gogi fault: intersections of NE-SW lineaments and E-W faults are noticed at many places between Gogi and Malla
(ii) Intersection of NE-SW to ENE-WSW and E-W fractures/lineaments with Wadi fault to the NW and SE of Allur
(iii) E-W Tirth fault south of Talikota

3.2. Jeep borne radiation survey

An integral gamma jeep scintillometer, Model JS-14 with a time constant of one second, was utilised during the jeep radiation surveys. A 3" × 3" NaI (Tl) crystal coupled with photomultiplier tube was used as detector. The detector was fitted at 1.5 m height from the ground, hence the approximate detecting ability of the instrument works out to about 10 m. Vehicle speed during the survey was maintained at 20-25 km/hr.

3.3. Hydrogeochemical sampling

In addition to jeep radiation survey, a number of hydrogeochemical samples were collected mainly from tubewells and analysed for uranium, conductivity, pH and other anions and cations. Samples showing higher than threshold values (14 ppb U) were found along major faults passing through the basin and the basement rocks. The faults were therefore recognised as one of the guiding criteria in narrowing down the target areas.

3.4. Other exploration methods

Ground radiometry, solid state nuclear track detection (SSNTD), trenching and pitting, and shielded probe logging are some of the other techniques used extensively in selected areas.

3.5. Gammaray logging of borewells

Available borewells in the area were logged by using total gamma counts. This confirmed subsurface ore grade mineralisation at Gogi. The mineralised intercepts were later confirmed by spectral logging of the borewells.

3.6. Exploratory drilling

Exploratory core drilling has been taken up recently in the area to get information on lighology, depth continuity, nature and controls of mineralisation.

4. URANIUM MINERALISATION

Three distinct types of uranium mineralisation are seen in the rocks of the Bhima basin and its environs. These are associated with (i) altered phosphatic limestone (ii) brecciated non-phosphatic limestone and (iii) the basement granitoids.

4.1. Mineralisation in altered phosphatic limestone

The best exposed area of this occurrence is seen near Ukinal (16° 45' 45"N; 76° 39' 59"E). The mineralisation, of varying dimensions, is traceable discontinuously over a distance of 2 km (Figure 2) along cherty limestone–shale boundary. It is less commonly seen near the basement granite and along minor faults.

Similar mineralisation is also identified near Dharsanapur, Gogi West along the E-W trending Kurlagere-Gogi fault and near Ramthirth along the southern part of Wadi fault.

Radiometric analysis of representative samples and their P_2O_5 contents are given in Table II. It can be seen from Fig. 3 that there is a positive correlation between U_3O_8 and P_2O_5.

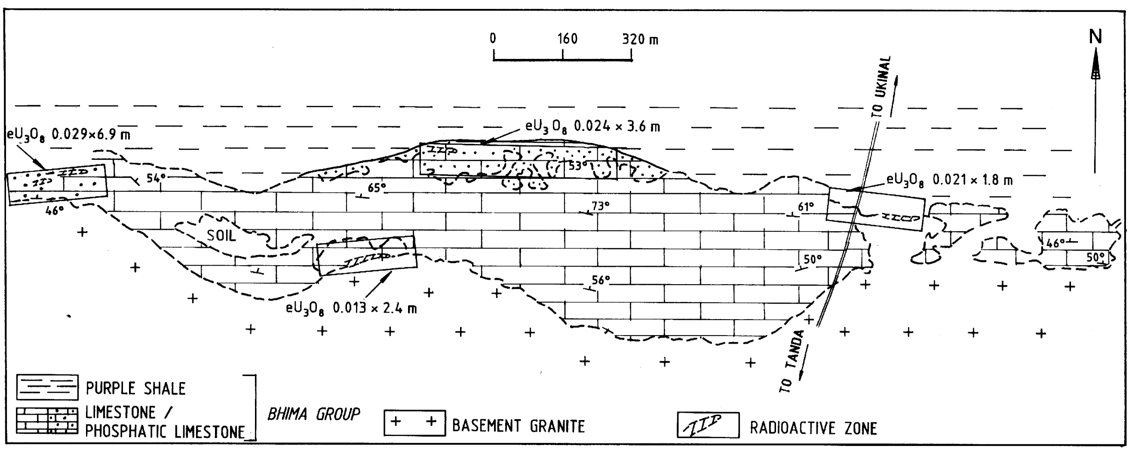

FIG.2. Geological map of the Ukinal area.

TABLE II. U_3O_8 and P_2O_5 CONTENTS OF RADIOACTIVE SAMPLES

Locality	eU_3O_8 (Wt %)	P_2O_5 (Wt %)
Ukinal	0.084	28.35
	0.080	29.52
	0.051	22.39
Dharshanapur	0.060	10.50
Gogi west	0.041	11.84
	0.053	20.81
	0.029	12.11

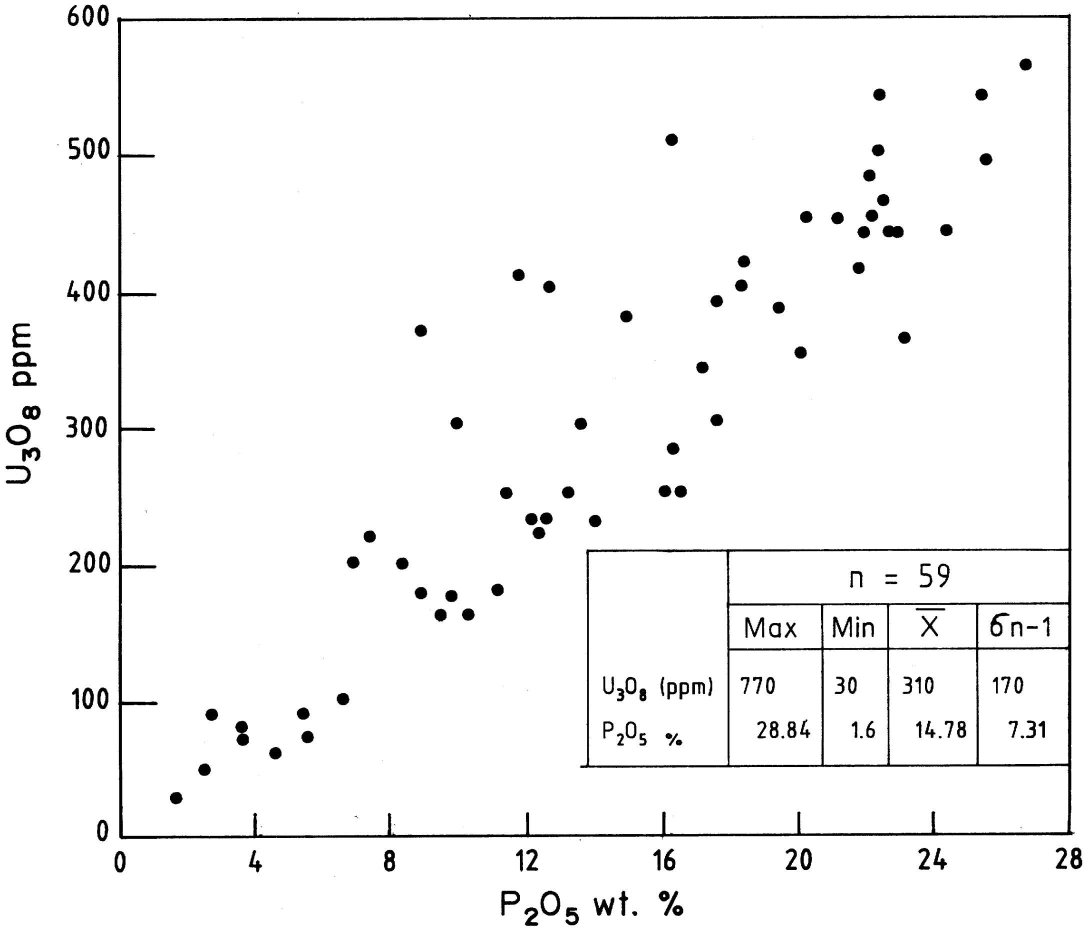

FIG.3. U_3O_8 vs P_2O_5 plot for the radioactive limestones of the Ukinal area.

Based on petrographic examination the mineralised rock has been identified as phosphatic chert, phosphatic limestone and phosphorite. A few large grains of apatite are present. Collophane is present as sub-rounded and lensoidal shaped large patches cemented by chert at places. It is surrounded by micrite and sparry ferroan calcite. Limonite occurs in the phosphatic rock as cavity fillings and intergranular spaces. The manganese oxide appears as spherulitic bands along with accessory psilomelane, haematite, pyrite and ultrafine pitchblende (?).

Radioactivity is mainly due to adsorbed uranium on limonite, absorbed uranium in collophane, labile uranium along grain boundaries and to a small extent due to the presence of ultrafine pitchblende (?).

The major, minor and trace element data of the mineralised rock is given in Table III.

4.2. Mineralisation in brecciated non-phosphatic limestone

Near Gogi (16° 45'N; 76° 45'E) uranium mineralisation is hosted by non-phosphatic brecciated limestone which occurs close to the granitic basement contact. It is exposed along a 400 m long and 50 m wide zone (Fig. 4) which is characterised by intensely fractured and brecciated dark grey limestone. The E-W trending Kurlagere-Gogi fault passing through this mineralised zone takes a NE swerve south of Gogi lake and again attains easterly trend north of Gogi village.

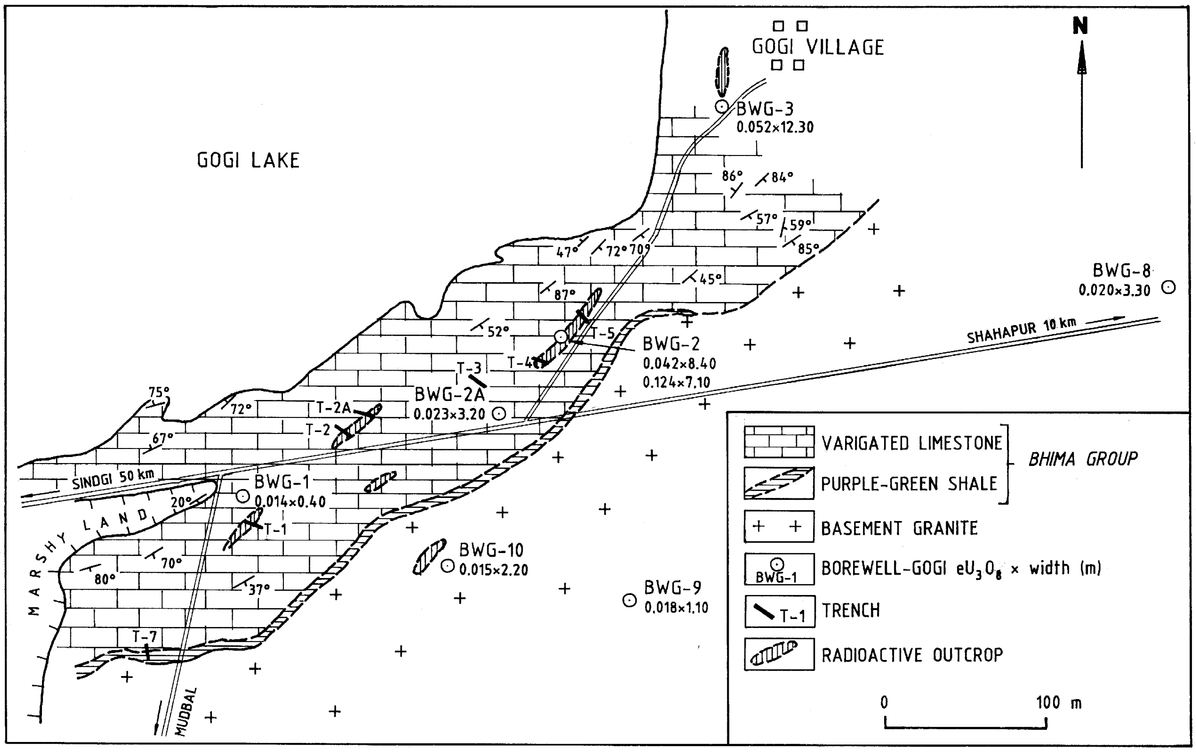

FIG. 4. Geological map of Gogi Lake area showing surface radioactivity, trenches and borewells logged.

TABLE III. MAJOR, MINOR AND SOME TRACE ELEMENT DATA ON URANIFEROUS PHOSPHATIC LIMESTONE, UKINAL AREA, GULBARGA DISTRICT, KARNATAKA

Major oxides	Wt%	Trace elements	PPM (Average of 24)
SiO_2	27.27	Ti	1211
TiO_2	0.04	V	38
Al_2O_3	0.66	Mn	398
Fe_2O_3	1.38	Co	35
FeO	< 0.05	Ni	61
MnO	0.41	Cu	33
CaO	39.01	Y	39
MgO	1.02	Pb	66
Na_2O	0.18		
K_2O	0.07		
P_2O_5	25.64		
U_3O_8	0.077		

TABLE IV. U_3O_8 and P_2O_5 CONTENTS OF RADIOACTIVE SAMPLES OF GOGI AREA, BHIMA BASIN

% eU_3O_8	%P_2O_5
0.191	0.23
0.081	0.10
0.070	0.02
0.079	0.07
0.161	0.06

U_3O_8 and P_2O_5 values from the mineralised zone (Table IV) do not indicate any correlation between them.

The mineralised rock is fine grained compact, buff, grey and brown in colour. The cavities contain fluorite which gives bluish purple fluorescence under ultravoilet light. Calcite in the limestone is of a ferron variety. The calcite grains are turbid, containing impurities of limonite and pyrite. Limonite is also present as irregular patches and along grain boundaries with haematite. The ore minerals identified are pyrite (framboidal and euhedral), coffinite, pitchblende, pyrrhotite, haematite and anatase.

The radioactivity is attributed mainly due to coffinite that occurs as a discrete mineral in the form of thin veins and globular aggregates (Fig. 5) in close association with pyrite and pitchblende. Pitchblende shows replacement relationship with coffinite (Fig. 6). This replacement may be due to breakdown of coffinite into pitchblende + quartz + material of unknown composition [9]. The major, minor and trace element data of the mineralised rock is presented in Table V.

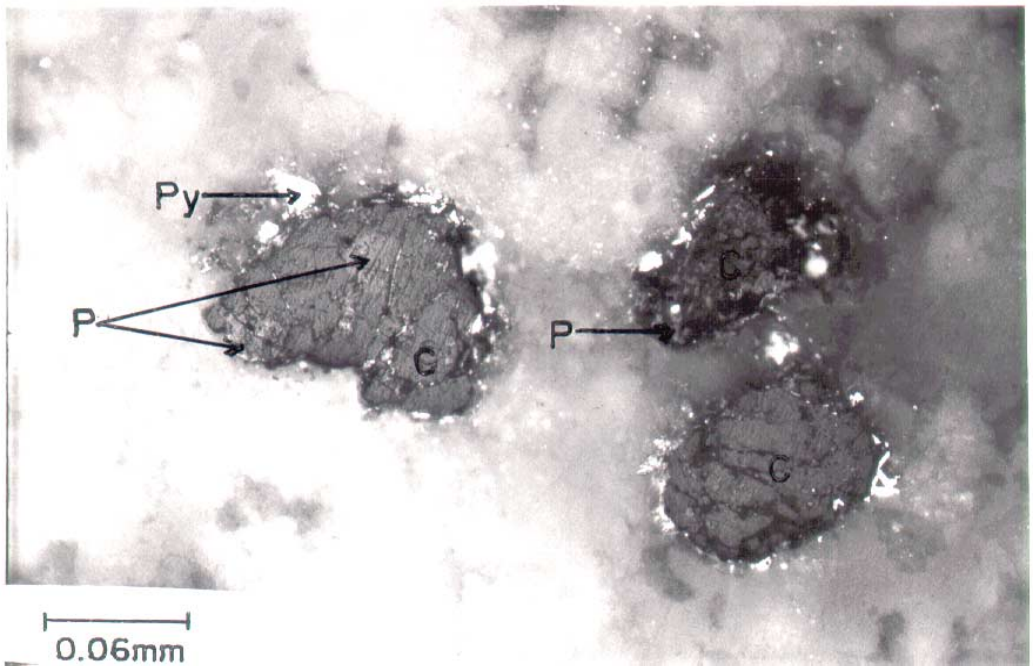

FIG. 5. Globular aggregates of coffinite (C) being replaced by pitchblende (P) and in association with pyrite (Py. White), reflected light, 1N.

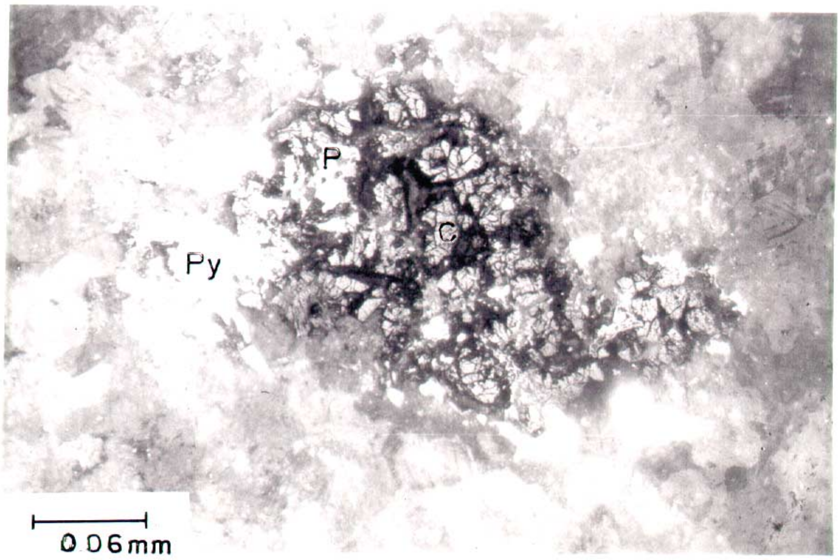

FIG. 6. Fractured coffinite (C) replaced by pitchblende (P) filling some of the fractures. Note the intimate association of coffinite and pitchblende with pyrite (Py, white), reflected light, 1N.

TABLE V. MAJOR, MINOR AND TRACE ELEMENTS DATA ON BRECCIATED URANIFEROUS LIMESTONES–GOGI AREA

Element	1	2	3	4	5	6	7	8	9
All Values are in %									
SiO_2	6.64	5.33	11.64	4.51	2.63	33.28	8.08	59.04	1.04
Al_2O_3	2.08	1.85	2.27	1.68	1.21	1.69	1.75	0.43	1.42
TiO_2	0.32	0.35	0.10	0.10	0.05	0.21	0.08	0.05	0.08
Fe_2O_3	39.98	33.94	0.70	3.20	0.71	3.25	0.77	4.69	0.72
FeO	0.18	<0.05	1.00	0.11	0.14	0.25	0.29	0.50	0.50
MnO	0.32	0.45	0.13	0.42	0.28	0.35	0.24	0.02	0.19
CaO	21.01	26.85	35.70	50.00	52.14	33.36	48.84	18.52	57.74
MgO	0.63	0.45	8.60	0.38	0.48	0.42	0.65	0.23	0.52
Na_2O	0.54	0.50	0.56	0.63	0.58	0.34	0.58	0.28	0.54
K_2O	0.35	0.11	0.25	0.20	0.11	0.16	0.34	0.21	0.18
P_2O_5	0.24	0.08	0.23	0.10	0.02	0.07	0.06	0.06	0.11
LOI	26.20	28.62	37.21	38.52	40.62	26.60	38.10	14.80	37.21
U_3O_8	0.029	0.012	0.138	0.065	0.063	0.034	0.053	0.138	0.010
All values are in ppm									
Mo	194	122	10	10	240	<10	<10	19	<10
V	224	766	20	100	158	304	94	390	146
Y	9	25	14	47	12	24	8	7	9
Zr	100	76	68	80	72	54	82	22	72
Cu	29	36	12	30	165	50	26	212	62
Co	31	41	33	38	36	52	33	38	31
Ni	50	51	29	31	27	45	35	47	31
Pb	239	344	493	440	434	1161	366	1208	275

4.3. Mineralisation in basement granitoids

This mineralisation is associated with the basement granites bordering the Bhima basin close to the non-conformity contact. Basic enclaves occurring within the granitoids record high order radioactivity. Two such lensoidal occurrences exposed at Gogi are referred to as Gogi East anomaly. Radiometric assay of selected samples range from 0.02 to 0.3% U_3O_8.

Radioactivity is attributed to a U-Ti complex and no discrete uranium mineral has been identified in these rocks. The granitoids in general analyse higher content of uranium ranging from 10 to 110 ppm.

5. DISCUSSION

The geological processes responsible for the formation of the Bhima basin followed by the sedimentational history have been studied in recent years [5,6]. Bhima basin is considered to be a product of trans-tensional tectonics, resting on the undulating crystalline basement. The sigmoidal nature of the Bhima-Basement contact is significant and is attributed to the "pull apart" mechanism [10]. Mishra et al. [5] emphasised the role of epeirogenic uplift and isostatic adjustment resulting in faults with their normal attributes like rolls, drags and even warps. Although there have been limited studies on these faults, there are sufficient field evidences to conclude that at least a few of them, particularly the reverse faults, penetrate the sedimentary column and extend well into the basement granites. Faulting also appears to have been activated periodically i.e., during pre-, syn-, and post- sedimentation periods. The basic dykes emplaced along these weak planes have also been affected by the faulting/fracturing subsequently.

The basement granitoids peripheral to the Bhima basin contain anomalous concentration of uranium ranging from 10 to 110 ppm. Much of the uranium is in labile form as evidenced by anomalous values (upto 308 ppb) in ground water. Fracturing and development of foliation characteristically seen in the granites clearly point out their involvement in the reactivation processes. The fluids generated during the process resulted in the concentration of ore grade uranium mineralisation along the fault zones, such as at Gogi and other places.

Gogi area

Since specular hematite, coffinite and pitchblende are low temperature minerals, the temperature of formation of uranium mineralisation here appears to be low (200°C). Comparing the mineral assemblage of pyrite, coffinite, pitchblende and calcite in the limestone under study with experimental studies [11], it can be deduced that the mineralisation took place at an Eh. of -0.1 to -0.3 volts and pH of 7.5 to 8.0. The globular aggregates and vein like form of coffinite and veinlets of pitchblende indicate that the mineralisation is of hydrothermal type.

Ukinal area

The association of uranium with phosphatic limestone and phosphorites at Ukinal along the fault zones is conspicuous. The relation between phosphorite and uranium is well known [12]. The presence of glauconite indicates shallow marine environment of deposition of normal salinity under slightly reducing condition in area of low sedimentation [13, 14].

6. CONCLUDING REMARKS

The salient features of the mineralisation described in this paper, though preliminary, have several important implications. Epigenetic, low temperature hydrothermal coffinite mineralisation at Gogi is essentially fault controlled in the peripheral parts of the basin. Mineralisation occurs at shallow depth of about 50 m from the surface. The fact that the basement granites peripheral to the Bhima basin are fertile with 10–110 ppm of uranium, a large part of it appears to be in labile form considering the hydrogeochemical anomalies of wells located in the area. A closer understanding of this mineralisation would open up larger areas for exploration in the peripheral parts of the Bhima basin, especially those with the faulted margin. Gamma-ray logging of the bore wells drilled for water in this context should be of immense value, as it is found to be in areas without any surface expression of mineralisation.

The mineralisation that is intimately associated with phosphatic rocks and phosphorites may prove to be strata bound with larger tonnage. Considering the fact that we have both higher abundances of P_2O_5 (upto 30%) and U_3O_8 (upto 0.08%) in these rocks, there is a strong possibility that these may become commercially viable than conventional uranium-phosphorous associations.

The uranium mineralisation that is associated with the basic enclaves in the basement, though not significant at present, points to the fact that the unconformity surface, as expected, has acted as channel way to the uraniferous fluids, derived from the basement granite with labile uranium as well as from the sedimentary column, though this may not be significant. Fault zones intersecting such enclave rich granitoids or mafic rich parts that have been altered, could provide conducive hosts. Thus, not only the fault bound contact zones become important, but also those covered by sediments towards the basin interior. Considering the fact that the overall thickness of the Bhima basin is less, exploration efforts can be relatively less costly in areas that are not covered by Deccan Traps.

Finally, the basin margin, fault bound, brecciated limestone hosted (with minor SiO_2 and MgO) coffinite mineralisation does add a new variant to the long list of uranium deposit types. Such a feature enhances the optimism of those seeking uranium in new, hitherto unknown terrains.

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INVESTIGATION OF THE CHARACTERISTICS OF SANDSTONE TYPE URANIUM DEPOSITS IN THE PATAGONIA REGION: RECENT ADVANCES

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Abstract

In the years 1995 and 1996, additional 16,300 m of drilling was carried out in the Cerro Solo area, Province of Chubut, Patagonia Region. This led to the improvement of the resource estimate of the main orebodies, in tonnes of recoverable uranium at costs of up to $ 80/kg U to the following: reasonable assured resources: 2,200 t U; estimated additional resources (C.I): 900 t U. Additionally, the gathering of specific information gave consideration to the possibility of recovering molybdenum as a byproduct, as well as allowing laboratory tests that provided better understanding on the uranium leachability. Moreover, the derived the geological model will help and facilitate the exploration of the Eastern Slope of the Sierra de Pichiñán District, and the regional research programmes in the San Jorge Gulf Basin as a whole. CNEA current priority in relation to the country's uranium resources, is the adoption of a policy that will permit the offering of the final feasibility study of the known orebodies and its exploitation to the private sectors.

1. INTRODUCTION

Information on recent events in the development of uranium deposits in the Patagonia Region was published in different reports, some of them by the IAEA [1,2,3,4,5]. The Cerro Solo Project, is an ongoing evaluation project on a tabular sandstone type uranium deposit, lying 50 to 130 m deep in fluvial sediment belonging to the Cretaceous Chubut Group. The deposit is located in the Province of Chubut, 400 km West of Trelew City, 630 m.a.s.l.

At the same time of the exploration of the favourable formation at a local scale, a regional scale programme was also being considered. In this report some of the results of the investigations carried out by the multidisciplinary team in the area will be described.

2. PRESENT STATE OF THE STUDIES

Follow up drilling programmes performed in the 1980s indicated the presence of mineralization in different target sites within a selected area (180 sq. km, named Eastern Slope of the Sa. de Pichiñán District) of a paleochannel that initiates the deposition of the Chubut Group.

The orebodies that make up the Cerro Solo deposit were delineated after 1990. Different grid systems of drilling were used in accordance to the objectives of study whether it is for geological characteristics or to obtain reliable resource estimates. A 300 ha area was covered with around 600 drillholes; the main orebody is located within 90 ha of the studied area. A 25 × 25 m closer grid that was carried out to better define the geological characteristic and resource estimation of the orebody used 136 drillholes. In most of the drillholes only cuttings were recovered. A total of 25 holes were cored to allow special studies on the chemical composition of the ore and on the behaviour of uranium minerals in leaching experiments.

For the exploration of the entire District, about 10,000 m of drilling were carried out in different sectors that were selected for their particular geological features. Through this work, new favourable areas were noted [6]. The same studies were used to establish the uranium favourability of the San Jorge Gulf Basin as a whole, and in the estimation of the endowment of specific geological units [4]. Through this process, specific project was formulated to select exploration targets at regional scale [2].

3. UPDATED RESOURCE ESTIMATION

Improved knowledge on the mineralization characteristics of the Cerro Solo deposit provided a more reliable resource estimate of 3,100 t U, in the up to $ 80/kg U category of the IAEA system (70% Reasonable Assured Resources, 30% Estimated Additional Resources). This figure was estimated from the main orebody, using conventional verified by geostatistics methods. In addition, the marginal mineralization around the deposit almost double the above mentioned tonnage, mostly in the EAR I Category [7].

As of January 1997, uranium resources in the Cerro Solo area is shown in the following tabulation. These figures are expressed in tonnes of recoverable uranium, this means, losses due to mining and ore processing were already deducted.

Reasonable Assured Resources (RAR)		Estimated Additional Resources Category I - E A R - I	
Cost ranges		Cost ranges	
< $ 80/kg U	< $ 130/kg U	< $ 80/kg U	< $ 130/kg U
2,200	2,800	900	3,000

The mineralization in the main orebody is represented by lenses of 50 to 500 m long with an average thickness of 3 m and frequent high grade and thickness variations. If only a high percentage of the resources is to be mined, the average grade of the mined ore can be increased from the 0.3% to 0.4-0.5% U.

Of more important consideration is probably related to the potential of the entire 180 sq.km area Eastern Slope of the Sa. de Pichiñán District, both taking into account the mineralization located close to the main orebody and from the wide grid drilling and other known favourable criteria of the paleochannel. The hypothetical or EAR II resources of the entire district has not been formally estimated, but in the authors opinion it would be around 2-3 times the present estimated resources.

4. ABOUT THE CHEMISTRY OF THE ORE

4.1. Uranium leachability

Six drillholes were cored in preselected positions of the mineralized horizons with the aim of studying the general behaviour of the ore with the consideration the probable line of processing that will be required. This was followed by a number of laboratory assays. These works were part of the evaluation programme completed in 1996.

Representative samples from the core were selected taking into account taking into account the grade and the position in the deposit. These samples were then divided into 2 high grade samples that were treated in different combinations of oxidation and temperature conditions commonly carried out in a conventional mill; sulfuric acid solution was used in leaching. Results of these experiments are noted in the following table:

Sample number	U grade (ppm)	U recovery (%)	Mo grade (ppm)	Mo recovery (%)
13.040	2643	96.3	1147	67.5
13.041	5822	95.4	3166	55.4

It can be concluded that under the condition of these laboratory experiments, a good recovery of uranium can be obtained. Related to Mo, giving a 61.4% average recovery, it can be considered as a moderate recovery if this method of treatment is to be used.

Another 2 samples, in this case low grade, were ground up to 3 cm maximum size and put into a 5 kg column each and be treated, imitating acid heap leaching conditions. The results were as follows:

Sample number	U grade (ppm)	U recovery (%)	Mo grade (ppm)	Mo recovery (%)
13.038	932	67.3	484	26.7
13.039	681	74.3	200	47.4

As expected, the recovery of both elements are lower than in the previously described test. For uranium, it may be considered as acceptable. However, the recovery of molybdenum is low to very low. The behaviour of sample 13.038 is presently being investigated focusing on its mineralogical composition [8,9].

4.2. Presence of molybdenum

Representative number of assays carried out on the drill cores, indicate an important molybdenum concentration which is in close relation with the uranium mineralization. Both phenomena appear to be associated with the enrichment of organic material in the sediments.

Present data available provide just a qualitative estimation on the molybdenum grade in the deposit, that may be indicated as U/Mo ratio. It varies between 2 and 3, meaning a tendency of a relatively higher Mo concentration that might provide the possibility of its recovery as a byproduct.

5. THE GEOLOGICAL MODEL

5.1. Importance of mineralogical composition of the host formation

Based upon the description of the drillholes cutting at every meter, complemented with the analysis of geophysical logs using on lithological gamma, a better understanding was gained on the control of mineralization at the specific levels of the lithological column, particularly in relationship with its mineralogical composition. Grain size and the presence of organic material are important factors. Furthermore, the importance of the provenance of the clasts was also established [10, 11]. The general description of the established stratigraphic column is shown in Fig. 1.

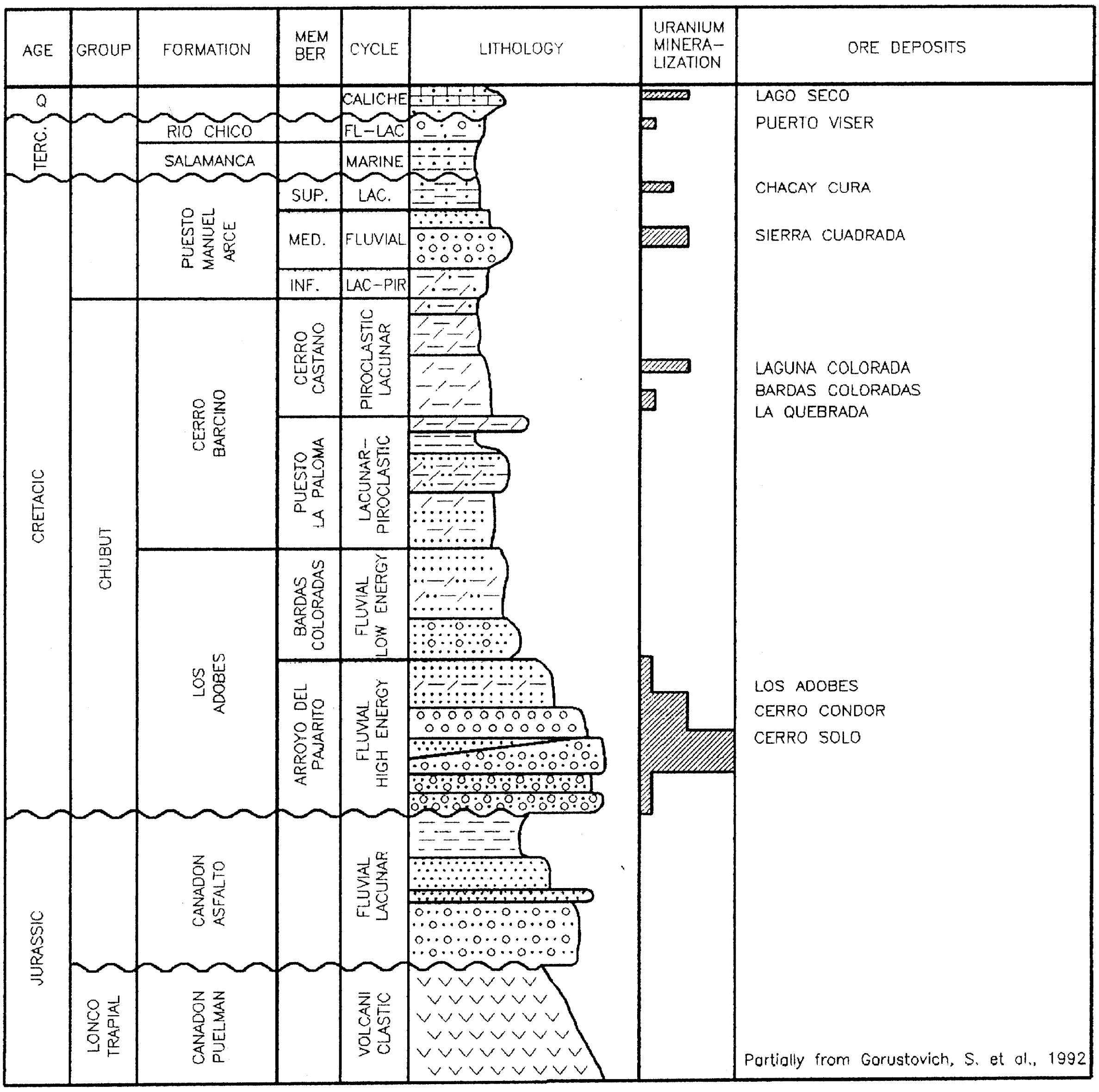

FIG. 1. Summary of Cretacic stratigraphic units, Correlation with uranium mineralization.

From mineralogical composition and provenance, the Arroyo del Pajarito Member of the Los Adobes Formation, that hosts the uranium deposits, may be divided into two zones: mesosiliceous in the basal portion and acid in the upper part. Related to the clast composition, the first is made up of dacites, rhyodacitic ignimbrites and minor andesites, while the second is of rhyolitic volcanic rocks like tuffs, ignimbrites and less abundant of porphyritic volcanites.

The above mentioned description provides the characteristics of one sector of the deposit. The features of the main orebodies in the southern sector, that was studied with more detail, gave a representative characteristics of the entire deposit as summarized below:

- the basal level of the formation filled the ancient reliefs, showing highly variable thickness. It contains scarce organic material and it lacks uranium mineralization.
- the upper level lies between subparallel planes, the lower one separates it from the basal section, and the one on top forms the boundary with the tuffaceous Cerro Barcino

Formation. It contains abundant organic material in its composition and forms as hosts of most of the uranium mineralization in the area.

Some other features that were identified as a particular characteristics of the southern sector, are:

- the orebodies are located in the acid section close to the contact with the basal section.
- the closer the orebodies to the border of the paleochannel, the higher the grade. That is, the higher grade orebodies are associated with the highs in the ancient relief of the fluvial system.

The description of the southern sector is shown in the schematic sections in Fig. 2, and an example of interpretation of the control factors are shown in Fig. 3.

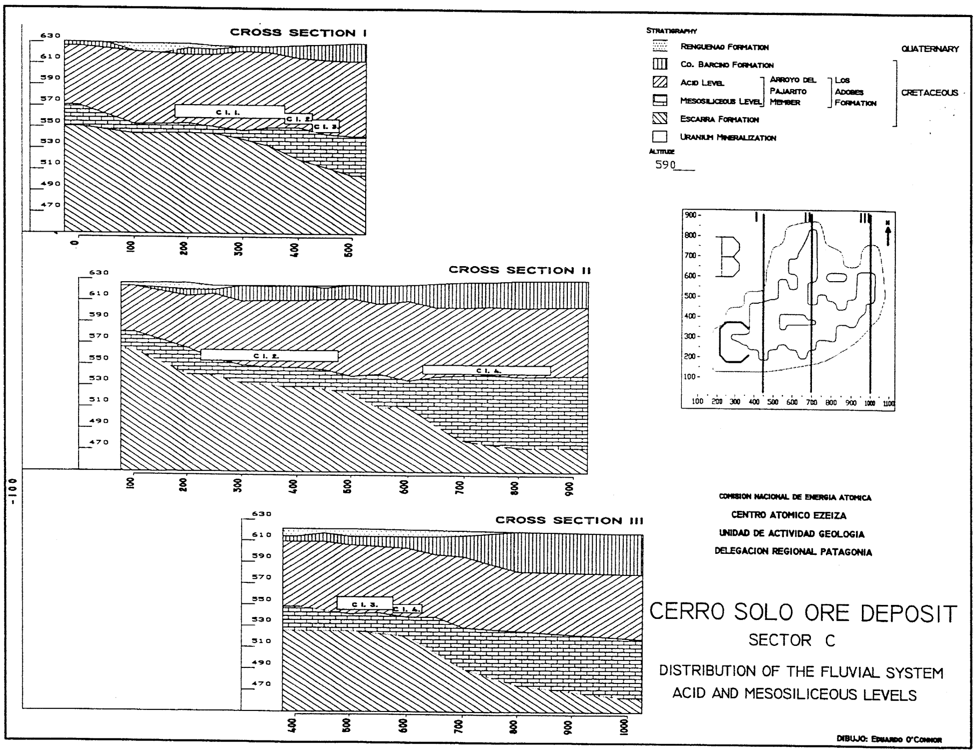

FIG. 2. Cerro solo ore deposit Sector C, Distribution of the fluvial system acid and mesosiliceous levels.

It can be generally stated that the orebodies is in close association with sandy lenses of the predominantly conglomeratic high energy sediments.

A general summary on the host rock characteristics and its relationship with the uranium mineralization is shown in Table I.

5.2. Provenance of the fluvial system

On the provenance of the minerals, it is obvious that the basal section came through the destruction of the Jurassic Lonco Trapial Group, that lies in the central region of the San Jorge Gulf Basin. The composition of this Group is as follows: andesites, basalts and intermediate volcaniclastics; the first and second types are predominant in the ore deposit area.

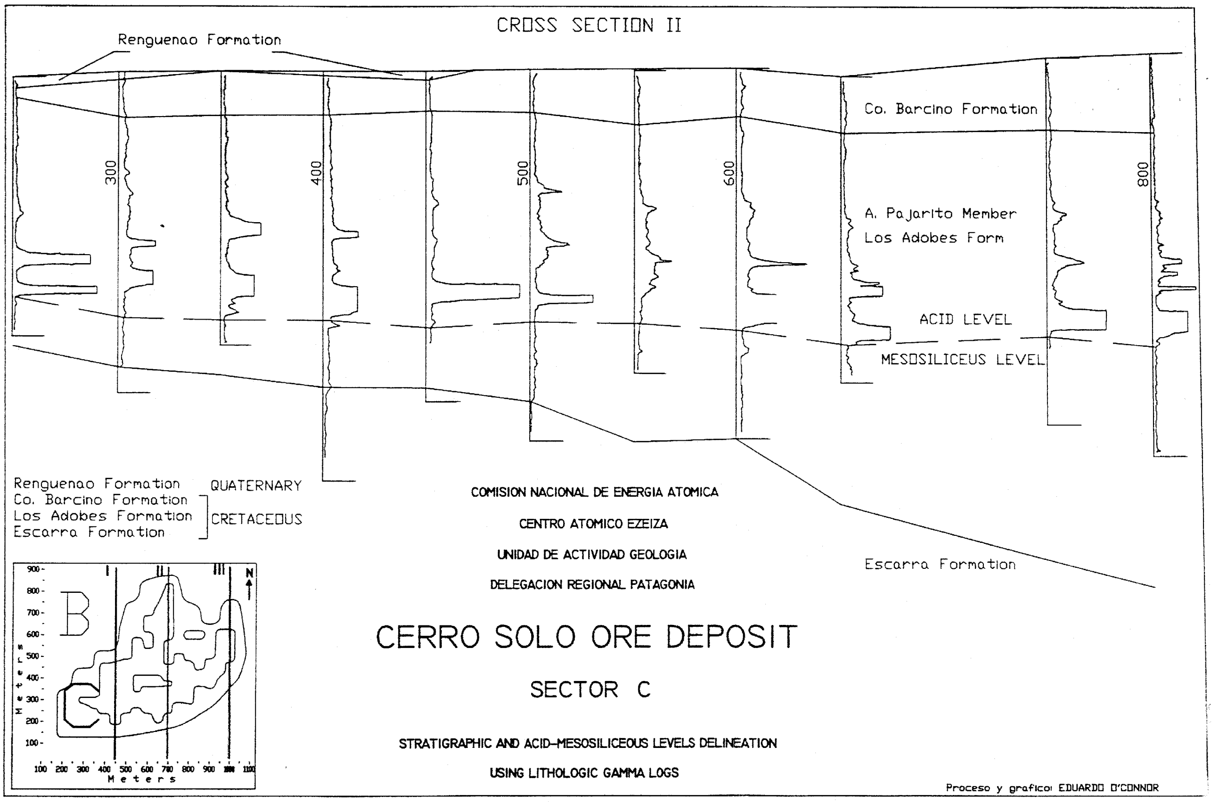

FIG. 3. Cerro solo ore deposit Sector C, Stratigraphic and acid-mesosiliceous levels delineation, using lithologic gamma logs.

TABLE I. RELATIONSHIP BETWEEN MINERALIZATION AND GEOLOGIC PARAMETERS

CLASTS PROVENANCE			STRATIGRAPHY	PREDOMINANT CLASTS COMPOSITION	OXIDATION STATE	GENERAL CHARACTERISTICS
STRATIGRAPHY	ROCK TYPE	SOURCE TYPE				
MARIFIL FORMATION	ACID TUFFS IGNIMBRITES RHYOLITES	REGIONAL	LOS ADOBES FORMATION (ARROYO DEL PAJARITO MEMBER)	ACID	OXIDATED	LACK OF MINERALIZATION
					REDUCED	SCARCE ORGANIC MATERIAL SCARCE CALCITE LOW GRADE MINERALIZATION ABUNDANT ORGANIC MATERIAL ABUNDANT CALCITE HIGH GRADE MINERALIZATION (SECTOR C) MAXIMUM PERMEABILITY LEVEL FINE SANDSTONE, HIGHER PERCENTAGE
LONCO TRAPIAL FORMATION (PAMPA DE AGNIA MEMBER)	DACITES RHYODACITIC - IGNIMBRITES	AREAL		MESOSILICEOUS		LACK OR LOW GRADE MINERALIZATION PRESENCE OF CALCITE WITHOUT ORGANIC MATERIAL
	ANDESITES BASALTS	LOCAL	ESCARRA FORMATION	BASIC	OXIDATED	WITHOUT MINERALIZATION ABUNDANT CALCITE ABUNDANT CLAYS LACK OF ORGANIC MATERIAL

An important characteristic of this economic basement is the faulted blocks structure, with graben like lows, filled predominantly with foothill sediments, detritical flows, sedimentary breccias and paraconglomerates (Escarra Formation). The mesosiliceous section of the Arroyo del Pajarito Formation represents the last filling of this small basins, with fluvial characteristics, high energy and low sinuosity, that indicates the expansion of the flood areas.

The acid section’s provenance is related to the ignimbritic rhyolitic plateau that covers the eastern part of the San Jorge Gulf Basin (Marifil Formation, Jurassic). Apparently when the alluvial systems heads reached this region, the composition of the Chubut Group’s sediments changed accordingly. At the same time climate changes could have originated the organic material enrichment in this section, making it more favourable for uranium mineralization.

5.3. About uranium favourability of the basin

From the point of view of the uranium favourability, the geologic-economic model that was developed through the Cerro Solo's investigation provided a useful guide to the exploration of the San Jorge Gulf Basin as a whole, considering that the Chubut Group is widely distributed in this area, covering a total area of 170,000 sq. km (68,000 sq. miles).

Figure 4 represents a map, that indicates the known and inferred development of the fluvial and the tuffaceous systems of the Chubut Group. It also shows the position of the main deposits and group of anomalies that have been studied to some extent [3, 4, 5].

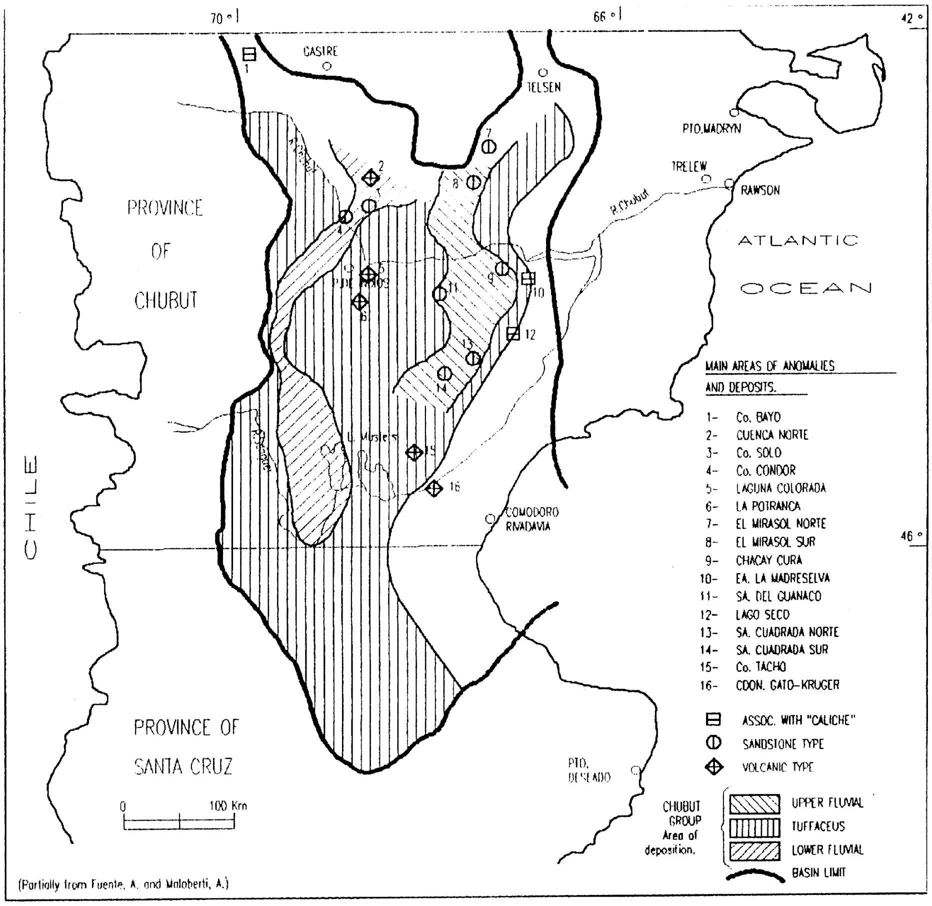

FIG. 4. Main areas of anomalies and deposits.

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McARTHUR RIVER PROJECT, SASKATCHEWAN, CANADA

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Abstract

The McArthur River uranium deposit contains an estimated 416 million pounds at an average grade of 15% U_3O_8. Cameco, on behalf of joint venture partners Uranerz and Cogema, plans to develop an underground mine with ore to be transported 80 kilometres for processing at the Key Lake mill and tailings facility. The planned production of 18 million pounds per year will be achieved by mining only 125 tonnes of ore per day. This allows for a high degree of engineering control of the extraction process to ensure the health and safety of employees and protection of the environment. Three remote mining methods have been considered: raiseboring, box hole boring, and remote box hole stoping. All three are compatible with grouting or freezing to control water flow and ground conditions. Raiseboring has been selected as the primary method in the first phase of production. Crushing and grinding will be carried out underground and thickened slurry will be pumped to surface. Public review of the environmental impact statement was completed in 1996, the review panel issued a favourable report in March, 1997 and government approvals were received in May, 1997. Subject to receipt of licenses and permits, production is planned in 1999 when it will replace the depleted mine production from Key Lake.

1. INTRODUCTION

The development of the McArthur River and Cigar Lake mines will represent a new generation of large, very high grade, underground uranium mines in Saskatchewan. Subject to approvals and licensing, production from these mines is planned in 1999 for McArthur River and 2000 for Cigar Lake. This will replace production from Key Lake which will be depleted, and from Rabbit Lake, to be depleted a few years later. These developments are important for the Canadian uranium production industry and for Cameco which is the largest owner and will be the operator of both mines. This paper describes recent activities and the current status at one of these, the McArthur River project.

McArthur River is in the eastern part of the Athabasca Basin in northern Saskatchewan. It is located about 70 kilometres northeast of Key Lake and 40 kilometres southwest of Cigar Lake. In the case of both McArthur River and Cigar Lake the ore will be transported by road to off-site mills; McArthur River ore will be milled at Key Lake and Cigar Lake ore at the JEB mill at McLean Lake (see Fig. 1). The McArthur River project is owned by Cameco 55.844%, Uranerz 27.922% and Cogema 16.234%.

2. GEOLOGY

The large and high-grade Saskatchewan uranium deposits occur at or close to the unconformity which separates the generally flat-lying, unmetamorphosed middle Proterozoic sandstones of the Athabasca Group from folded and metamorphosed lower Proterozoic and Archean rocks beneath. At McArthur River this unconformity is at a depth of 500 to 600 metres. The mineralization at McArthur River is associated with a northeast-trending, southeast-dipping zone of reverse faulting along which the unconformity is displaced vertically 60 to 80 metres. The individual faults tend to be rather narrow in the basement rocks, expanding to form extensive zones of mylonitization, fracturing and brecciation in the overlying sandstone. The lower Proterozoic basement rocks at McArthur River include significant quartzite units. The alteration is characterized by intense silicification of the sandstone with weak development of clay alteration. This is in contrast with the strong bleaching and clay alteration generally found around other Athabasca deposits. The mineralization is largely pitchblende without the associated cobalt-nickel-arsenic minerals which are present at Key Lake and Cigar Lake.

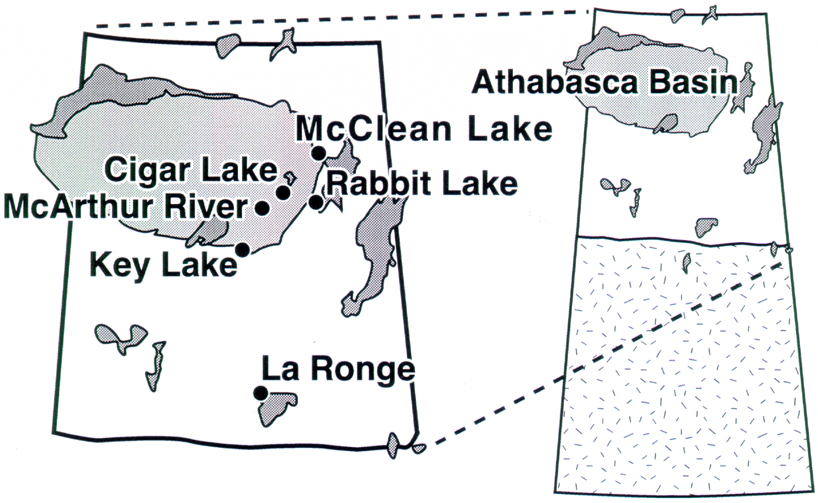

FIG. 1. McArthur River location map.

3. SURFACE EXPLORATION

The McArthur River deposit was discovered in 1988 following eight years of systematic exploration in the area [1]. The discovery history was typical of Athabasca Basin exploration methods but made more difficult by the great depth to the unconformity. Glacially transported, mineralized sandstone boulders were discovered in the general area and, following several years of investigation, some of these boulders were traced to subeconomic mineralization at the unconformity. Improvements to large-loop time-domain electromagnetic methods allowed the definition of graphite in the basement fault structure which controls the location of the ore. Drilling confirmed this structure and discovered subeconomic mineralization five kilometers to the southwest of the McArthur River orebody. The recognition of favourable alteration patterns in drill holes helped guide the exploration drilling to the orebody.

The discovery of McArthur River in 1988 was followed by four years of core drilling from surface which outlined high grade uranium mineralization over 1.7 kilometers of the fault structure. The mineralization was found to occur in both sandstone and basement rocks with the best mineralization, consisting of massive or almost massive pitchblende, generally occurring near the unconformity on the upthrown side of the fault zone.

Approximately 60 drill holes were completed during this period of which 37 holes intersected ore material. Based on this information a resource of 260 million pounds at an average grade of 5% U_3O_8 was estimated in 1991. This estimate was based generally on single drill holes spaced 50 or 100 metres apart along much of the ore structure, only one complete drill section, and a few holes 25 m apart in the strike direction. A particular problem was the range of influence that could be attached to very high grade intersections. Seventy per cent of the estimated resource was based on only seven drill holes, and eighteen per cent was based on a single hole which graded 43% U_3O_8 over 25 metres. Accordingly, conservative assumptions were adopted regarding continuity of the high grade material. Figure 2 shows the pattern of surface exploration holes in the southern part of the ore structure at the end of surface exploration in 1992 and the reserve blocks indicated from underground drilling in 1995. Following completion of this drilling it was decided to discontinue drilling from surface and undertake an underground exploration program which would provide the detailed information about the shape of individual orebodies, properties of the wall rocks, and hydrology that was necessary to design mining methods.

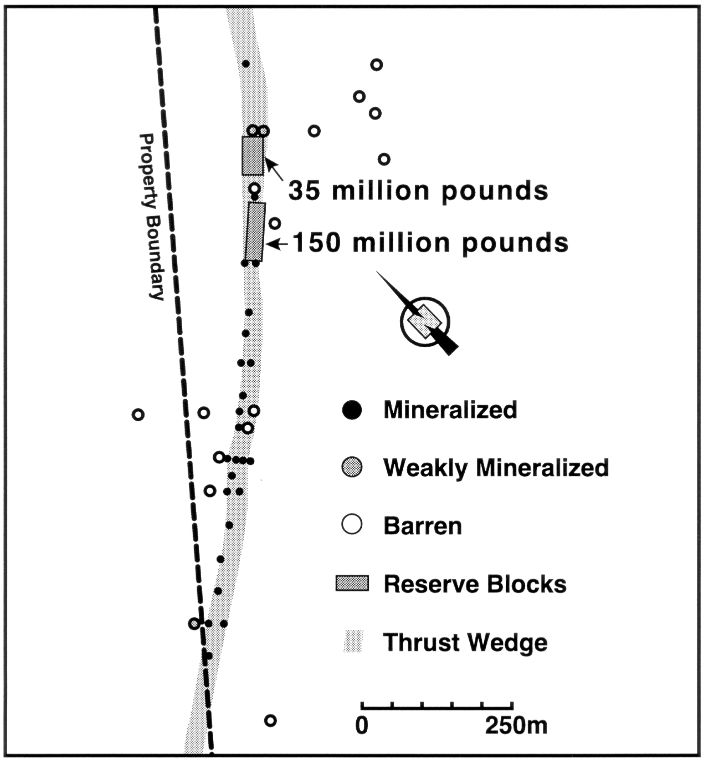

FIG. 2. Surface drill holes and underground reserve blocks.

4. UNDERGROUND EXPLORATION

Following the approval and licensing of the underground exploration programme, shaft sinking commenced in 1993. By July of 1994 the shaft had been sunk to 550 metres and horizontal development started on the 530 metre level. During the next 12 months approximately 900 metres of level development were completed and about 10,000 metres of core drilling to better define the orebody and geotechnical characteristics of the surrounding rocks.

Two important results were achieved by the underground exploration programme: a significant new orebody was discovered, and it was learned that ground conditions, water inflow and radiation could be controlled by conventional techniques.

4.1. Reserves and geology

Based on about 110 holes drilled in fans from drill bays spaced 30 metres apart (Fig. 3), reserves of 397,000 tonnes grading 18.7% U_3O_8 for a total of 188.7 million pounds contained U_3O_8 were estimated. This represents a more than six-fold increase over the original estimate from surface holes for this 300 metre section of the orebody. Part of this increase results from the finding of greater continuity of high grade mineralization than was assumed in earlier estimates but most of the addition is in a new orebody about 100 metres long, 20 metres thick and averaging 60 metres in height which contains about 150 million pounds of U_3O_8 at an average grade of 15 to 20% U_3O_8. This orebody extends almost 50 metres below the unconformity, which was not expected, and as a result the shaft had to be deepened to 684 metres.

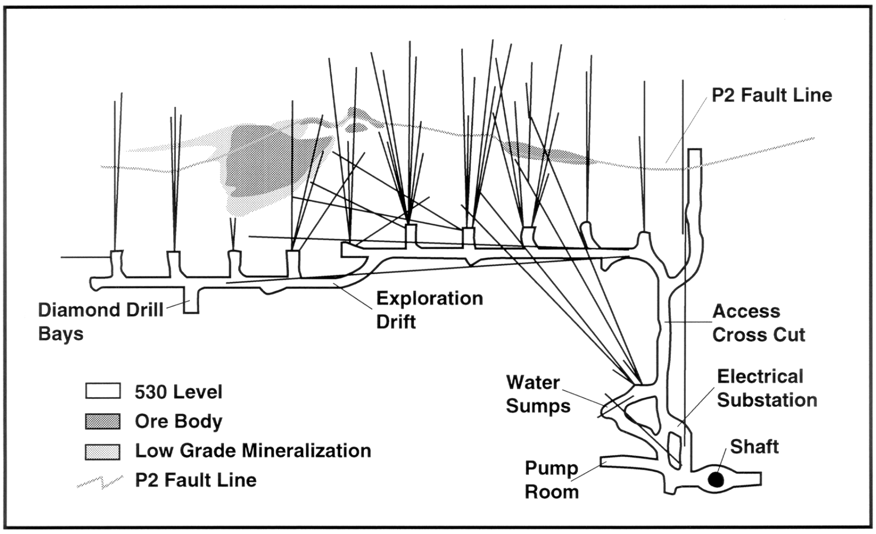

FIG. 3. Underground exploration plan. Drill sections are 30 metres apart.

It is apparent from the drill sections such as Fig. 4 that the new, high-grade footwall ore is located where a thick unit of basement quartzite is in contact with paragneiss, thus providing a strong competency contrast in this area. It has been suggested as well that the concentration of ore near the "nose" of the wedge on the hangingwall side results from fault refraction at the unconformity. The underground drilling has provided a great deal of new and detailed geological information which is currently under study, and which will provide a better understanding of this remarkable deposit with, hopefully, new ideas for further exploration.

The estimated resource at McArthur River based on the underground drilling plus the original surface drill holes is 416 million pounds at an average grade of 15% U_3O_8. In preparing this estimate, no assumptions were made about finding new reserves beyond those indicated from the surface drilling. In fact, the nature of the mineralization and limited data available from surface drilling make it possible that losses may be expected in other areas. That said, the estimate from surface holes is considered to be reasonably conservative with scope for an overall gain in reserves in future underground drilling into new areas of the deposit.

4.2. Results related to mining

The underground programme also provided information that allowed the mine design to proceed with confidence that radiation, water and ground conditions can be controlled for the protection of workers and the environment. Cross cuts and drifts approximately 4.5 metres wide by 4.1 metres high were excavated largely in basement rocks and, although geotechnical conditions varied, ground conditions were found to be competent and were controlled by conventional support techniques of bolting, screening and as necessary, shotcrete. Ground water in the basement rocks was minimal and not radon bearing.

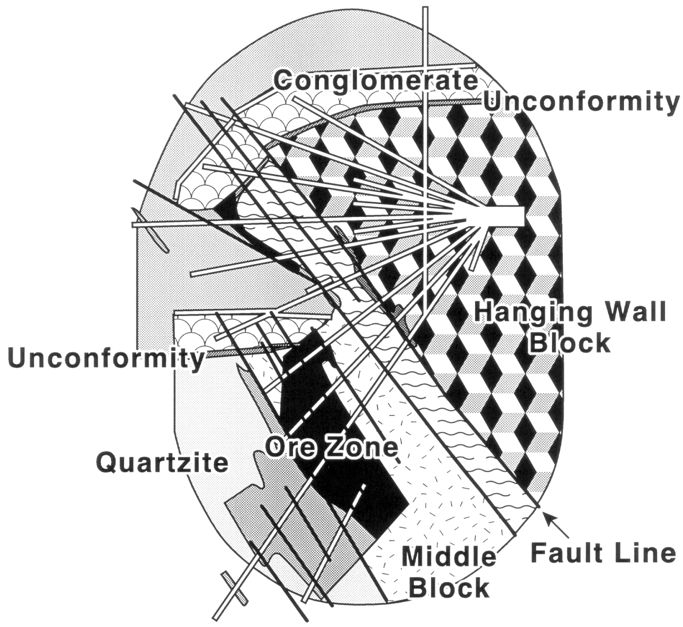

FIG. 4. Underground drill section

The detailed analysis of drilling results and drill core also provided information about geotechnical conditions in the orebody and surrounding rocks. Water was encountered from fractured sandstone during drilling. This was controlled by drilling through a gate valve and grouted stand pipe at each hole, and by grouting water-bearing fractures as they were encountered. Any released water was controlled by graded concrete floors and a separately-ventilated water containment system.

The ventilation system and radiation control measures taken were very effective, resulting in successful completion of the program with no radiation excursions.

5. MINING METHODS

Planning to select mining methods was carried out concurrently with the underground exploration program. The basic design criteria included non entry mining, remote control production equipment, total containment of the ore stream from extraction to delivery to the mill, a primary ventilation system with a secondary exhaust system to control radon gas, and mining methods consistent with grouting and/or freezing to limit inflow of water and improve ground conditions near the orebodies.

Three mining methods which are compatible with the design criteria were considered. These are raiseboring, boxhole boring, and remote boxhole stoping. The raiseboring method was selected as the primary method to be used in the first phase of mining.

Raiseboring requires tunnels above and below the orebody. A pilot hole is drilled from the upper to the lower tunnel, a reaming head is attached, and the raisebore machine then pulls the reaming head up through the orebody (Fig. 5). The raise diameter ranges between 2.4 and 3 metres. Chips typically the size of road gravel fall to the bottom of the raise into a chute which leads to an underground ore processing system. Byproduct dust is controlled by water sprays and dust scrubbers. The chute provides gamma radiation shielding and is connected to the secondary exhaust system.

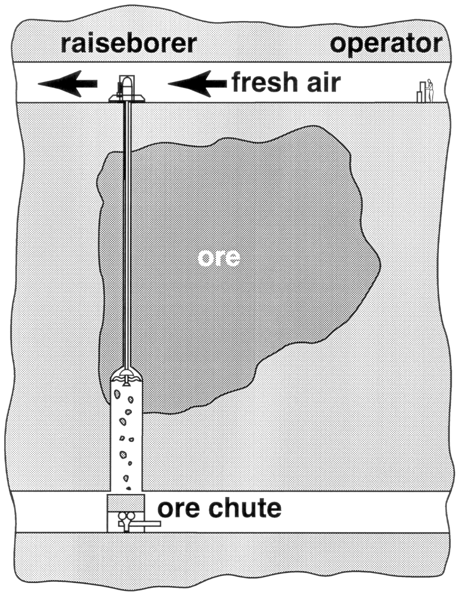

FIG. 5. Raiseboring.

The hole created by raiseboring is then backfilled with concrete. Based on tests carried out at another uranium mine in Saskatchewan it is expected that by overlapping the raises, with accurate drilling of the initial pilot holes, up to 95 per cent of the ore will be extracted.

While raiseboring will be the primary mining method, it may not be appropriate for all orebodies. Boxhole boring will be used where it is difficult to establish a tunnel above the orebody. Boxhole boring is similar to raiseboring except that the reaming head is pushed up through the ore from below.

Remote boxhole stoping is another method that may be used. It is a combination of boxhole boring with drilling and blasting which may be used to reduce the number of raises required to extract a given volume of ore.

6. FREEZING

Since shaft sinking began at McArthur River in 1993 ground water has been encountered and controlled using conventional cement grout injection techniques. An alternative technique which provides equally if not more effective results is to freeze water-bearing ground.

Freezing has been used in numerous mining and tunnelling applications including Athabasca uranium projects and for sinking shafts in a number of Saskatchewan potash mines. The technique involves creating a frozen, impermeable barrier by circulating chilled brine through strategically-placed boreholes. This barrier prevents the flow of water into mine openings and in most instances will also improve the ground conditions.

7. VENTILATION

The ventilation will consist of a primary system driven by high capacity surface fans to provide a flow of fresh air, and a secondary, ducted exhaust system to control contaminated air. This ducted air may, in some locations, contain dust from operations and in these cases the air will pass through water scrubbers to remove contaminated dust.

As soon as licenses are issued work will begin on a second shaft located approximately 300 metres from the main service shaft. This second shaft will serve as the primary exhaust. It will also have an enclosed compartment which will supplement the fresh air supply and also provide a second exit from the mine. Ventilating air capacity on completion of the second shaft will be 280 cubic metres per second. As the mine is developed a third shaft will be located approximately 850 metres from the main service shaft. This shaft will then become the main exhaust from the mine and fresh air capacity will increase to 450 cubic metres per second.

The ventilation system is designed to ensure worker protection. This is done by ensuring that each working area receives only fresh air, locating access and service drifts in the fresh air supply, exhausting sources of contamination by a secondary system, elimination of dust near its source, and by ensuring that short-circuit flow is from fresh to exhaust air. Computer modelling of radiation exposures indicates that during operation, workers should have combined doses which are less than one-quarter of the proposed dose limits (Fig. 6).

8. ORE PROCESSING

Crushing and grinding will be done underground with each process stage carried out in a chamber mined for that purpose. In addition to fresh air ventilation each piece of equipment will be connected to the secondary ventilation exhaust system.

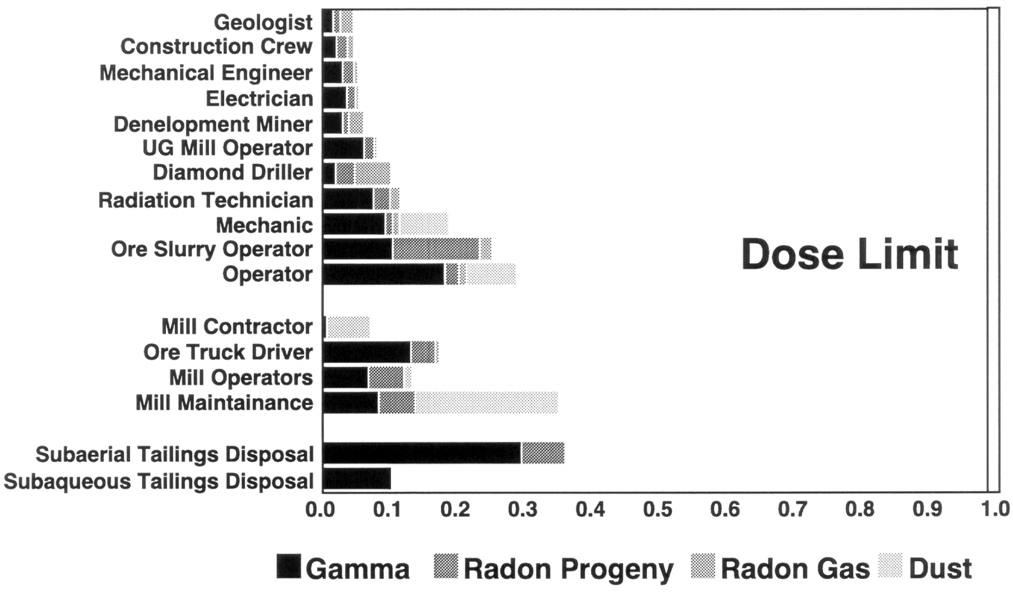

FIG. 6. Predicted annual radiation exposure.

Ore from the raisebore machine passes through a chute onto a roll crusher, then to a cone crusher, and through a surge bin to the grinding circuit. These processes are carried out with water to control dust and airborne contaminants. After grinding, some water is removed in a thickener and the thickened slurry is pumped to a loading facility on surface.

The ore is then moved by truck about 80 kilometres to Key Lake in containers specially designed for this purpose. The container design is based on containers used by Cameco for transportation between uranium refining and conversion facilities in Ontario. The containers, constructed of 30 millimetre steel and enclosed within a steel frame will be strong and shielded from radiation.

On arriving at Key Lake the ore will go to a new receiving plant which will provide for remote-controlled handling of containers, vehicle and container washing, ore slurry storage, and a pump to move the slurry to ore blending areas.

9. MILLING

The McArthur River ore will be milled at the Key Lake operation. The Key Lake mill currently produces 14 million pounds U_3O_8 per year and will be expanded to produce 18 million pounds per year.

Ore from McArthur River will be received at Key Lake and then diluted with crushed and ground low grade waste rock remaining from the Key Lake mining operation to obtain an average blended grade of about 4% U_3O_8. This blended millfeed can be handled with only minor changes to the present milling method, and the blending also eliminates the future liability of mineralized waste stored on surface.

10. TAILINGS MANAGEMENT

Tailings from the McArthur River ore will be placed in a new tailings management facility in the mined-out Deilmann pit. Following the study of various alternative designs, this facility was placed in operation at the beginning of 1996. The Deilmann facility will have two stages. Stage one employs subaerial deposition and a "pervious surround" or drainage envelope system like that used successfully at the Rabbit Lake mine. Stage one will be used for the last five years of tailings from Key Lake. Stage two, for the McArthur River tailings, uses subaqueous injection of tailings from a floating barge into previously deposited tailings. The facility is designed to develop a high-density, low-permeability tailings deposit and then make use of the natural flow of ground water through permeable sandstone and overburden sand, resulting in a very low flow through the tailings without the need to construct a pervious envelope. Among other advantages this system will make more efficient use of the pit volume for potential future expansion of reserves at McArthur River (Fig. 7).

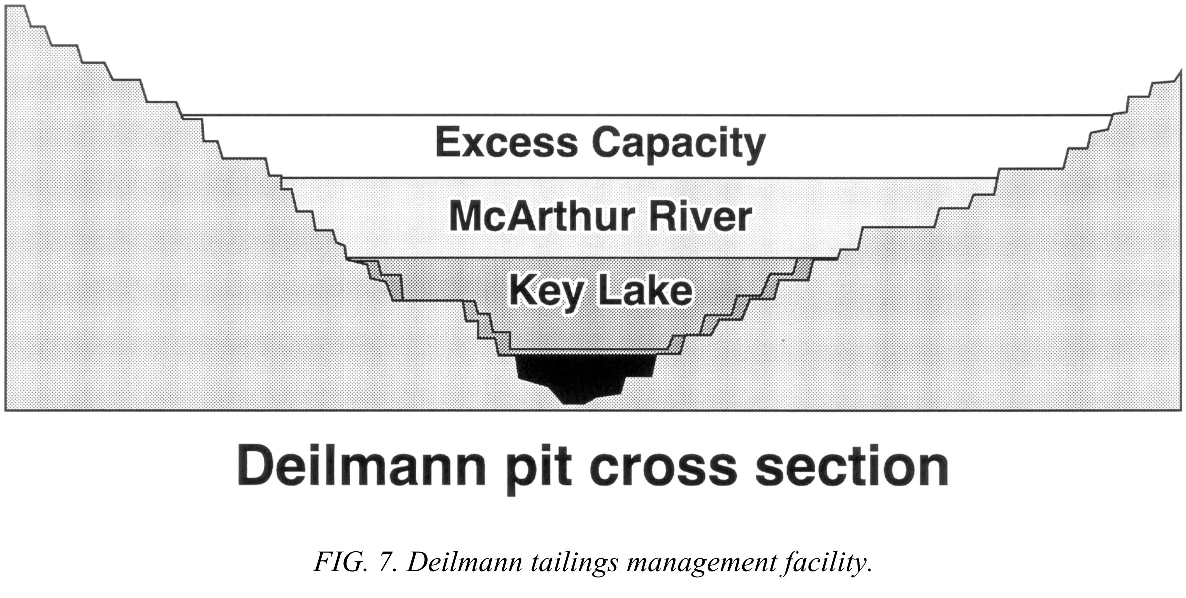

FIG. 7. Deilmann tailings management facility.

11. CONCLUSIONS

Following completion of the underground exploration programme a preliminary feasibility study was prepared and an environmental impact statement was submitted to the regulatory authorities in December, 1995. Public hearings were held late in 1996, a favourable report by the review panel was received in February, and the government approvals in May, of 1997. Construction will commence as the various necessary permits are received, with production scheduled in the second half of 1999.

The McArthur River project is one of the most promising uranium developments in the world. It combines large reserves of superior ore grades that can be mined safely using existing technology with environmental management practices that can meet the most stringent guidelines.

ACKNOWLEDGEMENTS

This paper is based largely on internal documents prepared by the staff of the McArthur River project [2 and others]. I have drawn particularly on the work of Brian Jamieson, Doug Beattie, Stan Frost, Larry Richardson and Brian McGill. I am grateful to them and in particular to Brian Jamieson, project general manager who reviewed the paper.

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RECENT DEVELOPMENTS IN AUSTRALIA'S URANIUM MINING INDUSTRY

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Abstract

Uranium is produced at two mining/milling operations in Australia — Ranger in the Alligator Rivers Region of the Northern Territory, and Olympic Dam in South Australia. In 1996, Ranger produced 4138 tonnes (t) U_3O_8 from stockpiled ore mined from Ranger No. 1 Orebody. The capacity of the Ranger mill is being expanded to 5000 tonnes per annum (tpa) U_3O_8 to coincide with the commencement of mining from No. 3 Orebody in mid-1997. The Olympic Dam copper-uranium-gold-silver deposit is the world's largest deposit of low cost uranium. The operation currently has an annual production of 85 000 t copper, 1700 t U_3O_8 and associated gold and silver. WMC Ltd proposes to expand annual production to 200 000 t copper and approximately 4600 t U_3O_8 by end of 1999. The environmental impact of the expansion is being assessed jointly by both Commonwealth and South Australian Governments. A draft Environmental Impact Statement (EIS) was released in May. Since its election in March 1996, the Liberal/National Party Coalition Government has made a number of changes to the Commonwealth Government's policies relating to uranium mining, including removal of the former Government's "three mines" policy, and relaxation of the guidelines for foreign investment in Australian uranium mines. These changes, together with an improved outlook for the uranium market, have resulted in proposals to develop new mines at Jabiluka (Northern Territory), Kintyre (Western Australia) and Beverley (South Australia). Energy Resources of Australia Ltd proposes to develop an underground mine at Jabiluka with the ore to be processed at Ranger mill. Initial production will be 1800 tpa U_3O_8 which will increase to 4000 tpa U_3O_8 by the 14th year. The draft EIS was released for public comment in October 1996, and the final EIS is to be released in June 1997. Canning Resources Ltd proposes to mine the Kintyre deposit by open cut methods commencing in 1999 with an annual production of 1200 tpa U_3O_8. Heathgate Pty. Ltd. proposes to develop an in situ leach mining operation at the Beverley deposit with capacity to produce 900 tpa U_3O_8, commencing in the year 2000. Improved market conditions and recent changes to Commonwealth Government policies on uranium mining have encouraged Australian companies to commit to the expansion of existing operations and the development of new uranium mines. Australia's annual production is likely to increase from its present level of 5867 t U_3O_8 (for 1996) to approximately 12 700 t U_3O_8 by the year 2000.

1. INTRODUCTION

Major expansions in production are in progress at both the Ranger and Olympic Dam uranium mining operations. Recent changes in Commonwealth Government policies on uranium mining and milling, together with an improved outlook for the uranium market, have resulted in a number of proposals to develop new mines. These policy changes are briefly outlined. The expansions at Ranger and Olympic Dam operations, and the proposals for new uranium mines are described. These will result in major increases in Australia's uranium production by the year 2000.

2. CHANGES TO COMMONWEALTH GOVERNMENT POLICIES RELATING TO URANIUM MINING AND MILLING

Following its election in March 1996, the Liberal/National Coalition Government removed the former Government's "three mines" policy which restricted the development of new uranium mines in Australia. The current Government's policy is to approve new uranium mines and exports provided they comply with strict environmental, heritage and nuclear safeguards requirements. Where Aboriginal interests are involved, the Government is committed to ensuring full consultation with the affected Aboriginal communities.

Uranium export contracts remain subject to Government approval but are no longer scrutinised for pricing purposes. The previous Government had required exporters to demonstrate that their prices were comparable to those received by other suppliers in the various markets.

In November 1996, the Treasurer announced changes in the Foreign Investment Review Board guidelines relating to foreign investment in Australian uranium mining. "The Government has decided that the foreign investment policy in relation to the uranium sector will be the policy that currently applies to the mining sector generally. This means that foreign investment above the notification thresholds in the uranium sector will be subjected to the well established contrary to national interest test and that no special investment restrictions will apply. The establishment of a new mine involving investment of $10 million or more, or the acquisition of a substantial interest in an existing uranium mining business valued at $5 million or more, requires prior approval and no objections will be raised unless the proposal is considered contrary to the national interest.

3. MINING OPERATIONS

Uranium oxide is currently produced at two mining/milling operations — Ranger and Olympic Dam. Australia's total production for 1996 was a record high of 5867 tonnes (t) U_3O_8 (4975 t U) of which Ranger produced 4138 t U_3O_8 and Olympic Dam produced 1729 t U_3O_8. Total production for 1996 was 34% higher than 1995 as a result of the return to continuous milling and ore processing at Ranger during 1996, and production increases at the Olympic Dam operations following completion of the second optimisation project in mid-1995 and improved recovery rates. Australia is now the world's second largest uranium producer after Canada.

3.1. Ranger

Ranger is an unconformity-related deposit which occurs within the Palaeoproterozoic metasediments of the Pine Creek Geosyncline in the Alligator Rivers region of the Northern Territory (Fig. 1). Energy Resources of Australia Ltd (ERA) commenced operations at Ranger in 1991. Ranger No. 1 Orebody was completely mined out in December 1994 and stockpiled ore is sufficient to maintain milling operations through to 1999. The pit is now used as a repository for mill tailings.

The company has received approval from the Northern Territory Department of Mines and Energy to mine the Ranger No. 3 Orebody. Development work for the open cut commenced in late 1996 and production from this deposit is scheduled to commence in mid-1997. No. 3 Orebody has proven plus probable reserves of 19.9 million tonnes ore with average grade 0.28% U_3O_8, containing 55 700 t U_3O_8. The orebody is within the Ranger Project Area and was included in the original Environmental Impact Statement (EIS) for the Ranger Project which was submitted in 1975.

The capacity of the Ranger mill is currently being expanded from its previous level of 3500 tonnes per annum (tpa) U_3O_8 to 5000 tpa U_3O_8. The tonnages of ore processed will increase from the previous level of 1.3 million tonnes per annum to 2.0 million tonnes per annum. The mill expansion is scheduled to be completed by mid-1997 to coincide with the commencement of mining at No. 3 Orebody. In the event that ERA's current proposal for the development of Jabiluka is approved (permitting processing of Jabiluka ore at Ranger mill), capacity of the mill would be increased further to approximately 6000 tpa U_3O_8.

FIG. 1. Uranium deposits and prospects in Australia.

3.2. Olympic Dam

The Olympic Dam copper-uranium-gold-silver deposit is the world's largest deposit of low-cost uranium. It contains in excess of 30 million tonnes of copper metal, 1 million tonnes of uranium oxide and 1200 tonnes of gold [1].

The orebody occurs within the hematite-rich Olympic Dam Breccia Complex which is a large hydrothermal breccia complex within the Roxby Downs Granite [1,2,3] (Figs. 2,3). The intrusive ages for the Roxby Downs Granite were determined from U-Pb zircon ages to be 1588 ± 4 Ma, i.e. Mesoproterozoic [4]. The deposit is unconformably overlain by approximately 300 metres of undeformed Neoproterozoic and Cambrian marine sedimentary rocks.

There is a variety of breccia types which range from granite breccias through hematite-granite breccias to hematite-rich breccias. Ore grade copper-uranium-gold-silver mineralisation forms a large number of ore zones mostly within hematite breccias.

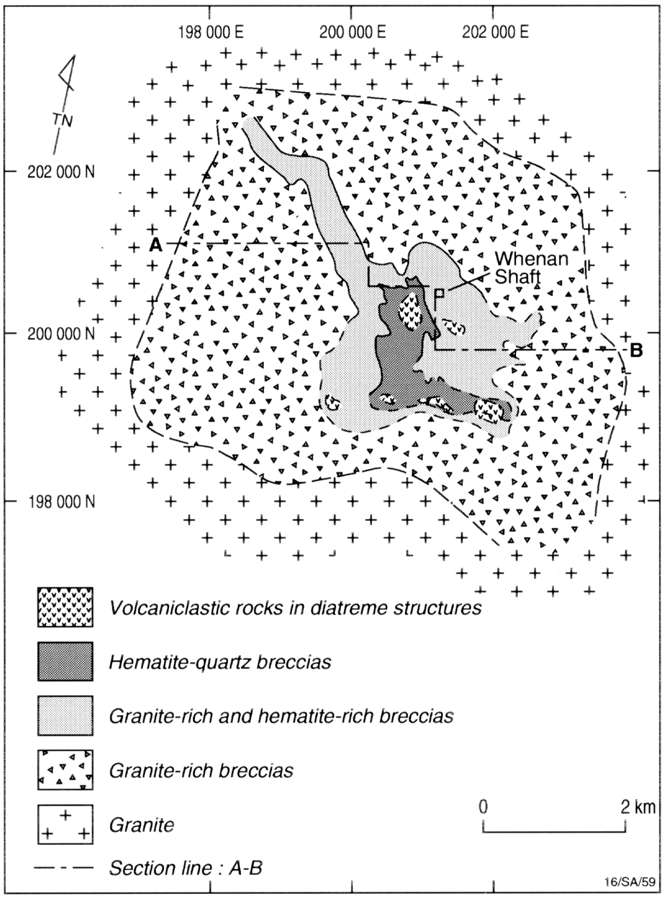

FIG. 2. Simplified geological plan of the Olympic Dam Breccia Complex (modified after Reeve and others, 1990).

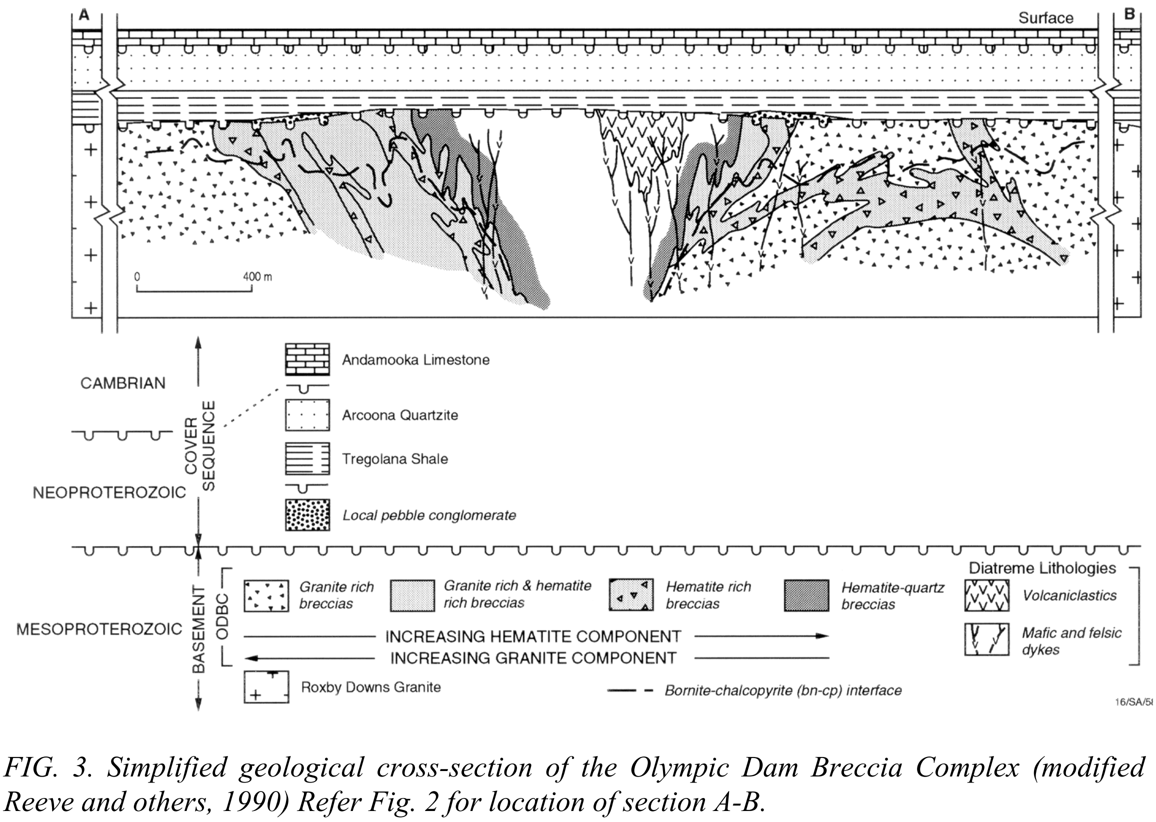

FIG. 3. Simplified geological cross-section of the Olympic Dam Breccia Complex (modified after Reeve and others, 1990) Refer Fig. 2 for location of section A-B.

The principal copper sulphide minerals are chalcopyrite, bornite and chalcocite. Throughout the deposit there is a well developed zonal distribution of the principal copper sulphide minerals (Fig. 3). Chalcopyrite (and pyrite) occur in the deeper and outer parts of the orebody whereas bornite and chalcocite occur in the upper and more central parts. The boundary between bornite-chalcocite mineralisation and chalcopyrite mineralisation (the bn-cp interface) is usually sharp [3]. Grades of 4% to 6% Cu are common in the bornite-chalcocite zones, whereas the chalcopyrite zones are usually less than 3% Cu [3].

Uranium occurs in association with all copper mineralisation. The predominant uranium mineral is uraninite (pitchblende) with lesser amounts of coffinite and brannerite. Ore reserves and resources for the Olympic Dam deposit are summarised in Table I.

TABLE I: OLYMPIC DAM ORE RESERVES AND RESOURCES AS AT JUNE 1996 [5]. NOTE: RESOURCES ARE IN ADDITION TO RESERVES

Reserves/Resources		Ore (Mt)	%Cu	%U_3O_8	Contained U_3O_8(t)
Reserves	Proved	73	2.5	0.08	58 400
	Probable	486	2.0	0.06	297 600
Resources	Measured	0			
	Indicated	1220	1.1	0.04	488 000
	Inferred400		1.3	0.04	160 000

The orebody is mined by conventional large scale underground methods. The processing plant comprises a milling circuit, concentrator, hydrometallurgical circuits, concentrate smelting, copper, gold and silver refining (including copper electro-refining and electrowinning), and uranium precipitation.

The Olympic Dam operation currently has an annual production rate of 85 000 t copper, 1700 t U_3O_8 and associated gold and silver. WMC Limited (WMC) recently announced that the operation is to be expanded and that annual production would be increased to 200 000 tpa of copper, 4600 tpa U_3O_8, 75 000 ounces gold and 950 000 ounces silver. For the processing plant to achieve a sustained production rate of 200 000 tpa copper, the mine would need to supply 8.7–9.2 million tonnes ore per annum, depending on the grade of ore processed. At least thirty stopes would need to be operated in any one year for this rate of production [6]. Based on the current production levels of existing mines, Olympic Dam will rank as one of the world's five largest uranium production centres. The overall capital cost of this expansion was estimated to be A$1.48 billion and it is planned to be completed by the end of 1999.

WMC also announced it would seek the necessary approvals for the project to ultimately expand to 350 000 tpa of copper and associated products, although there are currently no plans to expand beyond 200 000 tpa.

Under the original Indenture Agreement between WMC and the South Australian State Government, the operation had approval to produce up to 150 000 tpa of copper and associated products. The Indenture was amended in 1996 to allow the project, subject to environmental clearances, to produce up to 350 000 tpa of copper. The draft EIS for the project to expand to 350 000 tpa copper was released for public comment in May 1997. The final EIS will be assessed jointly by both Commonwealth and South Australian Government authorities.

Recent exploration drilling has discovered large tonnages of moderate to high grade copper mineralisation along the southeastern margin of the deposit [1]. Drill intersections of up to 84 metres averaging 2.1% copper have been reported. Uranium grades for these intersections are yet to be announced.

4. PROPOSED NEW MINING OPERATIONS

Since the removal of the "three mines" policy in March 1996, the Government has received formal proposals to develop three new uranium mining operations:

– Jabiluka deposit, Northern Territory (ERA Ltd),
– Kintyre deposit, Western Australia (Canning Resources Ltd, a subsidiary of Rio Tinto),
– Beverley deposit, South Australia (Heathgate Pty Ltd, a wholly owned subsidiary of General Atomics, which is a United States company).

4.1. Jabiluka

The Jabiluka deposit is 20 km north of Ranger and occurs within Palaeoproterozoic metasediments of the Pine Creek Geosyncline and lies immediately below the unconformity with the overlying Kombolgie Sandstone (Fig. 4). ERA Ltd purchased Jabiluka from Pancontinental Mining Ltd in 1991 for US$100 million. The draft EIS for the Jabiluka project which was released in October 1996, examines a number of options for the development of the Jabiluka deposit. ERA's preferred option is for an underground mining operation, with the ore to be processed at the Ranger mill. The ore would be trucked for a distance of 20 km to Ranger via a haul road entirely within the lease area. This development option has the least environmental impact [7].

The key aspects of ERA's proposal include:

– no tailings dam and no processing plant at Jabiluka,
– surface facilities will cover only 20 hectares,
– total disturbed land including the transport corridor is estimated at 80 hectares which is much less than other options,
– tailings will be placed in the Ranger open pits which will be rehabilitated at the end of the mine life.

ERA is planning to develop Jabiluka by 1999. It is proposed that initially, 300 000 t of Jabiluka ore would be processed annually to produce approximately 1800 tpa of U_3O_8. It is proposed that the capacity of the operation would expand to 900 000 t ore annually to produce approximately 4000 tpa of U_3O_8 in the 14th year.

Total proved and probable ore reserves for Jabiluka are 19.5 million tonnes ore averaging 0.46% U_3O_8, and containing 90 400 t U_3O_8. The total geological resource (which includes the ore reserves) was estimated to be 28.7 million tonnes ore averaging 0.52% U_3O_8 [7]. These estimates were made using a cut off grade of 0.2% U_3O_8.

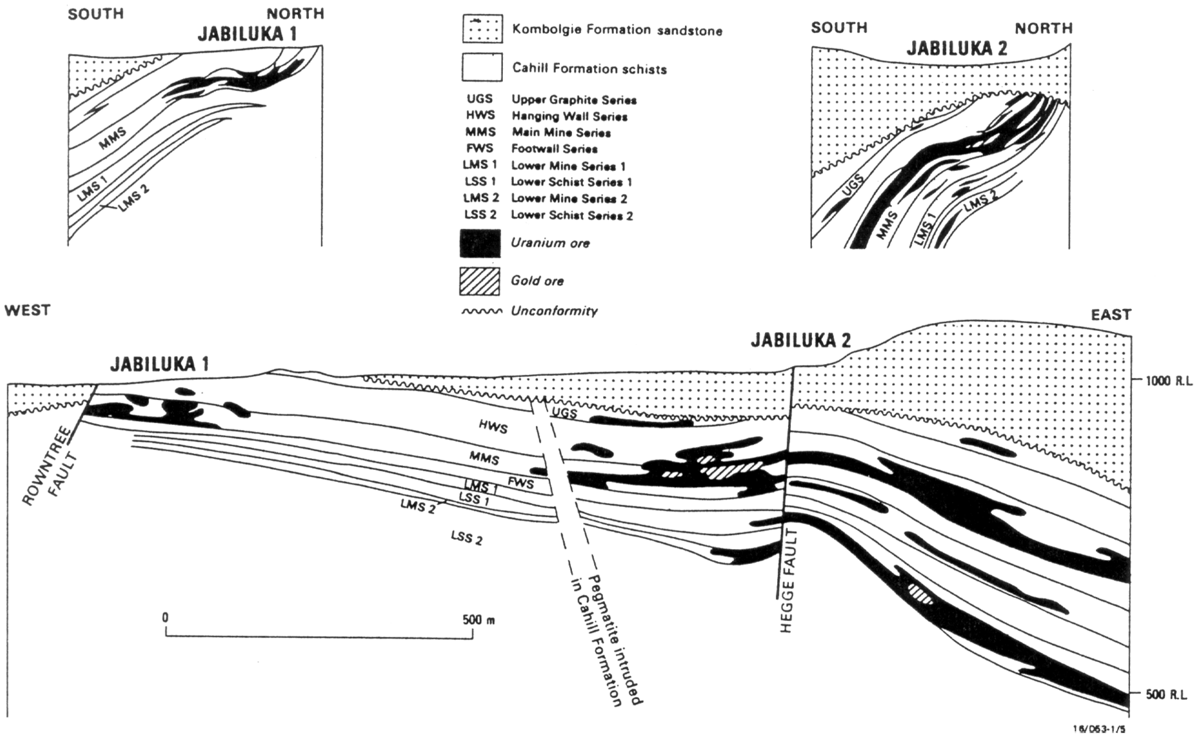

FIG. 4. Cross-section Jabiluka deposit (after Kinhill, 1996).

The final EIS is due to be released in June 1997.

ERA is negotiating with the Traditional Aboriginal Owners for consent to develop Jabiluka according to the company's preferred option. Aboriginal approval already exists for Pancontinental's original concept of a stand alone mill, underground mine and tailings dam on the Jabiluka lease [8].

4.2. Kintyre

The Kintyre deposit is located on the western edge of the Great Sandy Desert in the Eastern Pilbara Region of Western Australia, approximately 1200 km north-northwest of Perth. The project area is located immediately north of the Rudall River National Park.

Kintyre is a Proterozoic unconformity-related deposit which occurs in metasediments of the Rudall Complex and lies immediately below the unconformity with the overlying Neoproterozoic sandstones [9]. Host rocks are mainly chlorite-garnet-quartz schists, chlorite-carbonate-garnet-quartz schist, garnetiferous quartzite (metachert) and metamorphosed carbonate rocks (Fig. 5). Mineralisation occurs as narrow veins of high grade pitchblende within barren host rock. Multiple sets of closely spaced mineralised veins form ore zones.

Canning Resources propose to mine the four orebodies which make up the Kintyre deposit by a number of separate open pits. The ore is suitable for radiometric sorting. Ore processing would be in two main stages:

– a *dry upgrading phase* in which the ore from the mine would be crushed and screened by size. The larger size fractions would be concentrated by radiometric sorting; and the smaller size fraction would be concentrated using ferrosilicon heavy media separation,

– a *wet phase* where the uranium is extracted from the ore in three stages — leaching, iron pre-precipitation and uranium precipitation [10].

Production is planned to start in 1999. Initially the operation would produce 1200 tpa U_3O_8, with the potential to increase production up to 2000 tpa U_3O_8 over a twenty year period. Probable resources were estimated to be 24 500 t U_3O_8, with an additional 11 500 t U_3O_8 of inferred resources [11].

Canning Resources has applied to the Commonwealth and Western Australian State Governments to develop Kintyre. A detailed EIS is being prepared and the final EIS will be assessed jointly by both Commonwealth and Western Australian Government authorities.

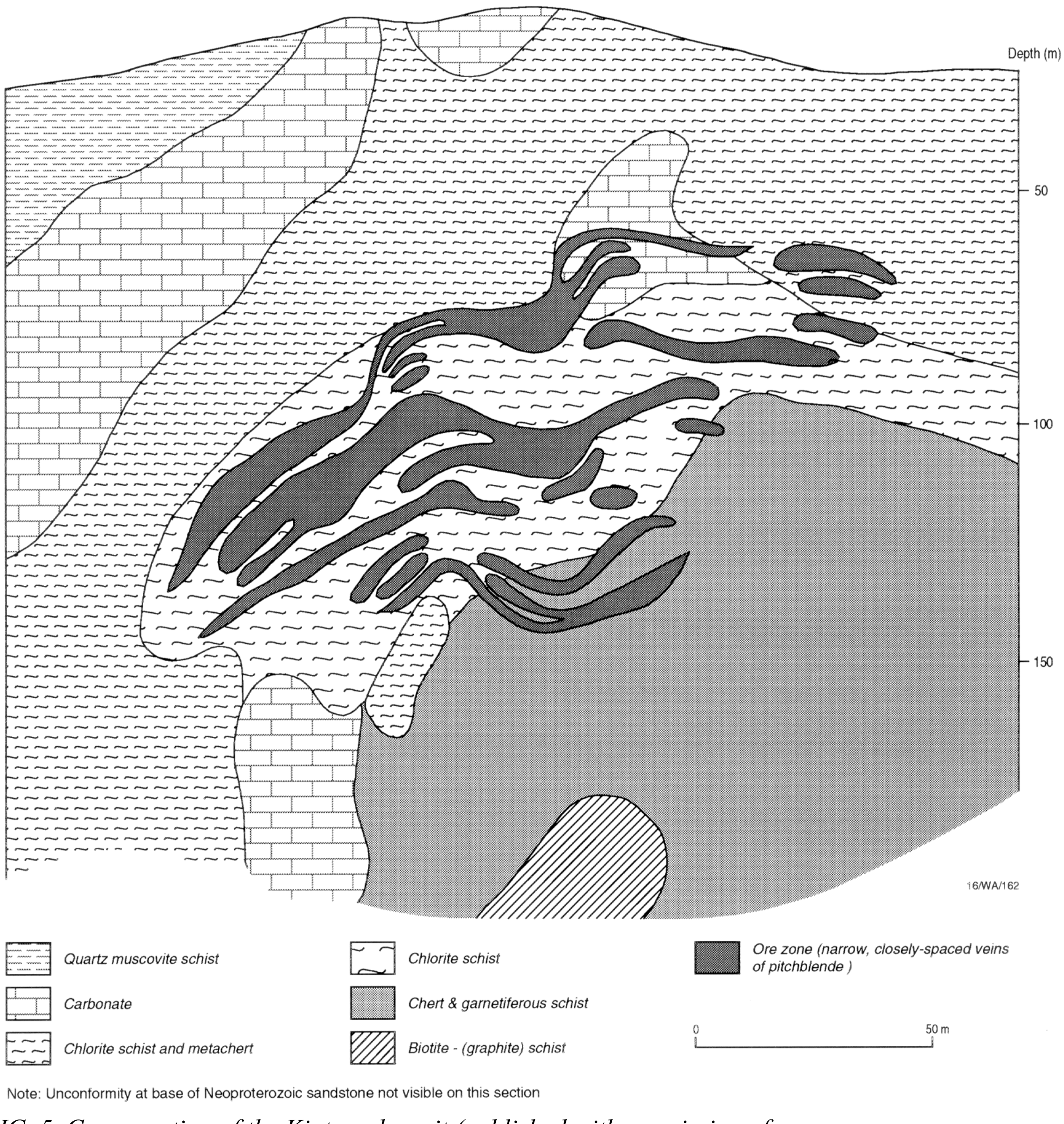

FIG. 5. Cross-section of the Kintyre deposit (published with permission of Canning Resources Pty Ltd).

4.3. Beverley

Beverley is a sandstone-hosted uranium deposit located near Lake Frome, approximately 530 km north-northeast from Adelaide. Heathgate Pty Ltd proposes to develop an in situ leach operation capable of producing 900 tpa U_3O_8 with production commencing in the year 2000. Heathgate considers that the deposit is particularly suited to in situ leaching because of its shape, grade and leachability [12]. Metallurgical and hydrological studies, including aquifer pump tests are currently being carried out.

The deposit comprises several large flat-lying lenses which are between 100 and 150 metres below surface. The deposit has an overall resource of 16 200 t U_3O_8 with an average grade of 0.27% U_3O_8, of which approximately 11 600 t U_3O_8 could be recovered by in-situ leaching [13].

The current proposal, is in the initial phase of a joint Commonwealth/State (South Australia) EIS process.

4.4. Other possible mine developments

Two other possible mine developments are Koongarra deposit in the Northern Territory, and Honeymoon deposit in South Australia. Koongarra is owned by Cogema which is expected to decide before the end of 1997 on whether to proceed with the development of a mining operation. The Honeymoon deposit was recently purchased by the Canadian controlled company, Southern Cross Holdings which is reportedly considering developing an in-situ leach mine by the end of 1998. Southern Cross is partly-owned (35%) by an Australian company, Sedimentary Holdings NL.

5. NATIVE TITLE

In 1992 the High Court of Australia handed down a decision known as the "Mabo Decision". This Court found that the common law of Australia recognised native title to land, that is, the entitlement of indigenous people, in accordance with the traditional laws and customs, to their traditional land. *The Native Title Act 1993* provides a framework for addressing where such native title exists, who holds it and the nature of native title rights in particular cases.

The Commonwealth Government has accepted that there are operational difficulties in the existing *Native Title Act*. It is consulting widely with indigenous people, industry and State Governments, and is preparing amending legislation to ensure that native title processes are workable and to remove uncertainty.

There are currently a number of claims under the *Native Title Act 1993* to existing and prospective uranium mines that have yet to be determined.

The Olympic Dam Project currently has three registered applications for determination. There are also several other applications over all or part of the water borefields and pipeline to the Project [6]. WMC is participating in statutory conferences and meetings convened by the National Native Title Tribunal.

In February 1996, a native title claim covering the Kintyre Project area was registered with the Native Title Tribunal by the Ngolibardue Peoples [14].

The Beverley deposit is held under Retention Leases issued under the South Australian Mining Act. The deposit is located on a pastoral lease (Wooltana) which is subject to a claim by Aboriginal interests in accordance with Commonwealth Native Title legislation [15].

The Ranger, Jabiluka and Koongarra leases in the Northern Territory are on designated *Aboriginal land under separate legislation, the Aboriginal Lands Rights (Northern Territory) Act 1976*. Aboriginal agreements with miners have been negotiated under this Act for each of these projects.

6. CONCLUSION

The abolition of the "three mines" policy means that several new uranium mines are likely to be developed to take advantage of market opportunities. Australia's annual production could increase from the 1996 level of 5867 t U_3O_8 to approximately 12 700 t U_3O_8 by the year 2000 as a result of proposed increases in production at Ranger and Olympic Dam, together with projected production from possible new mines (Jabiluka, Kintyre and Beverley). These increases in production will depend on market conditions.

The chief executive of ERA Ltd, Mr. Phillip Shirvington, recently stated that "Australian uranium miners are enthusiastic about the opportunities for increased production over the next few years. Buoyant market conditions and a supportive Government have encouraged Australian companies to commit to the expansion of existing operations and the development of new mines" [16].

ACKNOWLEDGEMENTS

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THE CROWNPOINT AND CHURCHROCK URANIUM DEPOSITS, SAN JUAN BASIN, NEW MEXICO: AN ISL MINING PERSPECTIVE

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Abstract

The Crownpoint and Churchrock uranium deposits, San Juan Basin, New Mexico are currently being developed by Uranium Resources, Inc. (URI) and its subsidiary Hydro Resources, Inc. (HRI) with an anticipated start-up in 1998. Both deposits will be developed using advanced in situ leach (ISL) mining techniques. URI/HRI currently has about 14,583 t U (37.834 million pounds U_3O_8) of estimated recoverable reserves at Crownpoint and Churchrock. at a cost less than \$39/kg U (\$15/lb U_3O_8). The uranium endowment of the San Juan Basin is the largest of any province in the USA. In March, 1997, a Final Environmental Impact Statement (FEIS) for the Crownpoint and Churchrock sites was completed by the Nuclear Regulatory Commission which recommends the issuance of an operating license. The FEIS is the culmination of a 9 year effort to license and develop the deposits. The Westwater Canyon Member of the Jurassic Morrison Formation is an arkosic, fine to coarse grained sandstone bounded by near basinwide confining clays deposited in a wet alluvial fan environment within the San Juan Basin. The primary, trend-ore deposits are hosted by the Westwater Canyon Member as humate-rich, syngenetic tabular deposits which were subsequently remobilized into roll fronts. Since deposition in the Jurassic, two phases of remobilization have occurred in the basin causing the formation of in situ leach amenable monometallic uranium rolls free of organic debris. Following in situ mining, ground water restoration of the Crownpoint and Churchrock mines is required to provide a water quality consistent with pre-mining baseline conditions. The development of in situ mining offers an environmentally sound and cost-effective method for uranium extraction. URI/HRI anticipates a production of 385–1,156 Tonnes U/year (1–3 million pounds U_3O_8) from the New Mexico properties.

1. STRUCTURAL SETTING

The Crownpoint and Churchrock uranium deposits are located in northwestern New Mexico and are part of the Grants Uranium Region in the San Juan Basin (Fig. 1). The San Juan Basin, regionally part of the Colorado Plateau, is bounded on the north by the San Juan Uplift, to the west by the Defiance Uplift, to the south by the Zuni Uplift, and to the east by the Nacimiento Uplift and the Archuleta Arch. Fig. 2 presents an index map of the five mining districts within the region including the Churchrock, Crownpoint, Smith Lake, Ambrosia Lake, and Laguna districts as well as the locations of the three URI/HRI sites. Historically, the Grants Uranium Region represents the largest of all uranium-bearing provinces in the USA. Crownpoint is located in the central portion of the Chaco Slope and Churchrock is located 30 km to the west, also on the Chaco slope. The location of the three URI/HRI properties is also shown in Fig. 2 and are referred to as Churchrock, Crownpoint, and Unit 1.

2. DEPOSITIONAL FRAMEWORK

The Jurassic Morrison Formation is the single most important uranium producer in the USA and is the host for uranium deposits not only in the San Juan Basin, but also throughout the Colorado Plateau which covers 500,000 km^2 (200,000 mi^2) including portions of Arizona, Colorado, New Mexico and Utah. The deposition of Morrison Formation occurred at a time in which large quantities of volcanic ash provided a source for uranium as the favorable sandstone hosts of the Westwater Canyon Member were being deposited. In the San Juan Basin, sub-aerial alluvial fans draining the Zuni Uplift to the south developed over Recapture Member clays. Following the basin-wide development of the Westwater Canyon Member sandstones, Brushy Basin Member bentonitic claystones and mudstones containing large quantities of volcanic ash were deposited [1, 2, 3, 4, 5, 6].

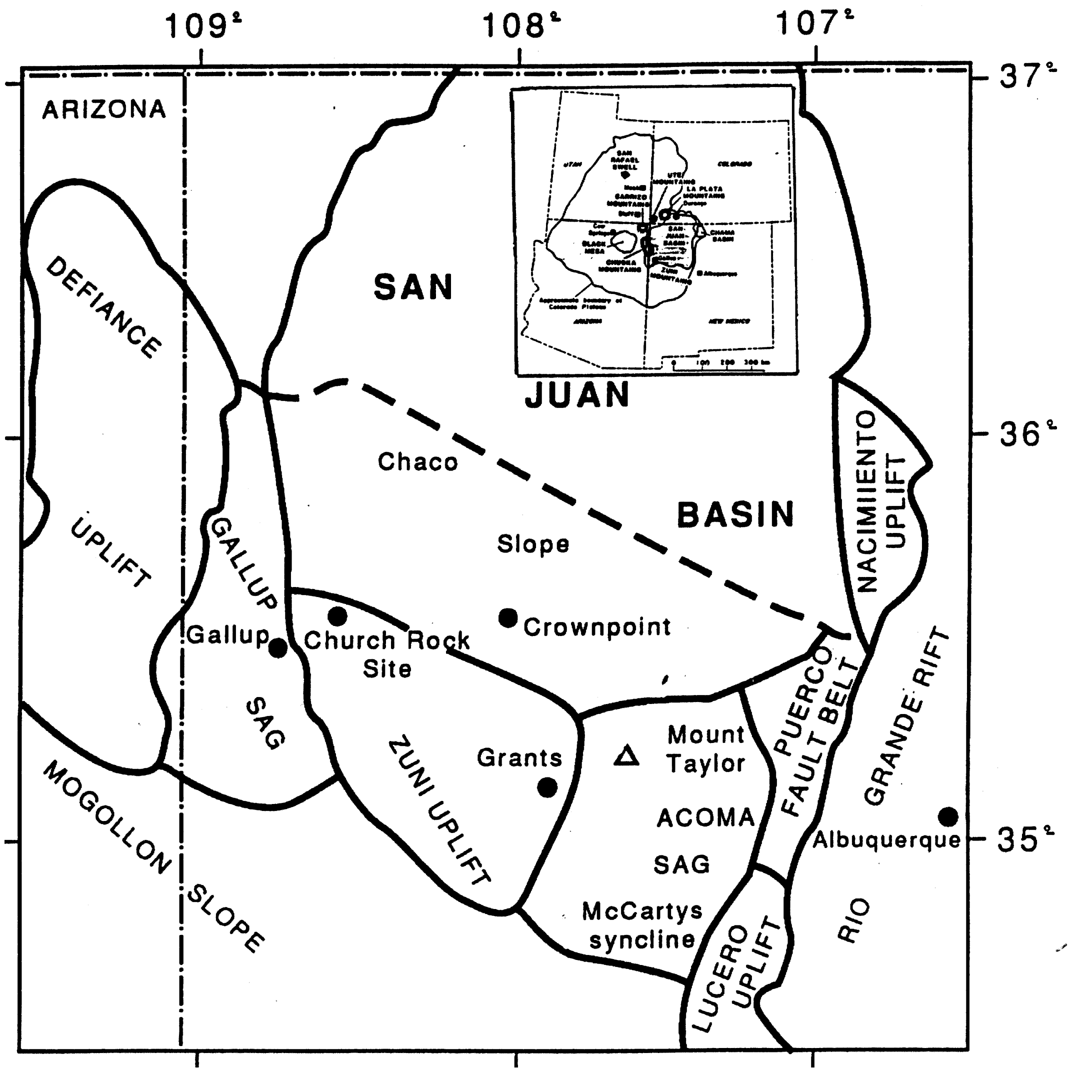

FIG. 1. Location and structural setting of the San Juan basin.

Humate from the sediments was mobilized sygenetically [2, 3] and was reconcentrated into the Westwater Canyon Member sandstones. This provided a reductant for the large quantities of uranium in the Morrison system and gave rise to the humate-rich, tabular “trend-ores” throughout the San Juan Basin. The geometric mean of the total carbon content of the Ambrosia Lake “trend ores” is 0.60% [4]. Background concentrations at Ambrosia Lake is 0.14% [4].

Following deposition of the Morrison, transgressive Dakota seas enveloped much of the western USA depositing beach, barrier bar, and distributary deltaic sediments unconformably over the Morrison Formation. This was followed by deposition of the thick offshore sediments of the Mancos Shale.

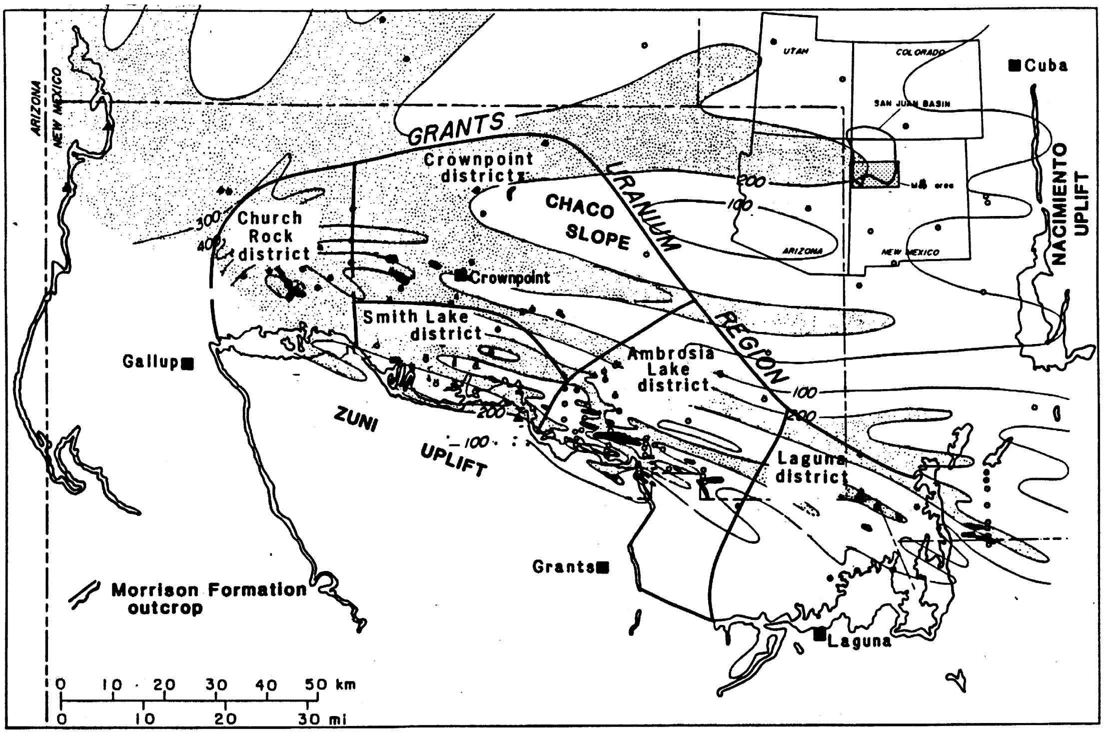

FIG. 2. Grants uranium region depositional framework of Westwater Canyon Member.

Structural re-development of the San Juan Basin during Cretaceous and Tertiary times allowed for the redistribution of the tabular trend ores into the remobilized ores occurring at Crownpoint and Churchrock. This remobilization is responsible for the segregation of vanadium, selenium, and molybdenum from the remobilized ores such as Churchrock [4]. The total carbon is very low [4].

3. LOCATION

3.1. Crownpoint and unit 1

The Crownpoint and Unit 1 sites covers 877 ha (2,192 acres) and is located on Sections 15, 16, 19, 21, 22, 24, and 25 of Township 17 North, Range 13 West and Section 29, Township 17 North, Range 12 West adjacent to the town limits of Crownpoint (Fig. 3). The Crownpoint Trend lies on the central portion of the Chaco Slope to the south of the interior part of the San Juan Basin near the regional redox front at a depth of about 700 m. The Crownpoint trend was discovered in the late 1970s by Conoco and Mobil. Conoco began engineering studies of for a major underground mine in the late 1970s and three deep shafts were completed in 1982.

Unit 1 is located 3.2 km west of the town Crownpoint and covers 512 ha (1,280 acres) in Sections 15, 16, 21, and 22 of Township 17 North, Range 13 West and has very similar geological characteristics to the Crownpoint site. The Unit 1 Site is shown in Fig. 3. This forms a portion of the area leased by Mobil which explored and discovered over 38,500 t U (100 million pounds U_3O_8) within their leases.

Because of the leachable nature of portions of the ore in the area, Mobil completed an in situ pilot operation near what HRI calls the Unit 1 area. This pilot demonstrated the economic viability for ISL production of the Crownpoint ores as well as demonstrating the ability for restoration.

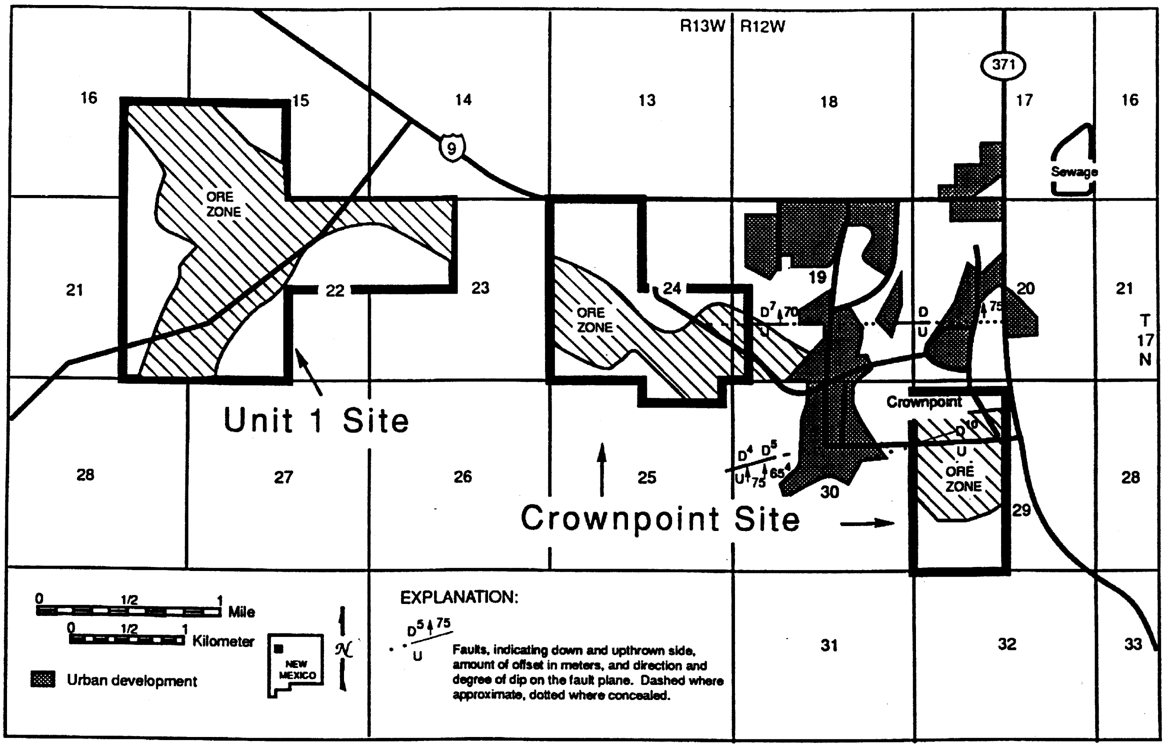

FIG. 3. Crownpoint and Unit 1 site map.

3.2. Churchrock

The Churchrock site is located in the northwest corner of the Zuni Uplift near the boundary of the Chaco Slope and the depth to ore is approximately 250 m. The site is located in Sections 8 and 17 of Township 16 North and Range 16 West and covers an area, as shown in Fig. 4, of 145 ha (360 acres). HRI's mineral rights include 65 ha (160 acres) of patented claims in Section 8, and 80 ha (200 acres) of leases on Section 17. A portion of the Churchrock site in the northeast corner of Section 17 was previously mined for uranium.

4. RESERVES AND PRODUCTION IN THE GRANTS URANIUM REGION

In the Grants Uranium Region, the estimated total endowment of the Westwater Canyon Member is 3.5×10^6 Tonnes U [6]. Cumulative production of uranium from the Grants Uranium Region by January 1, 1997 has been 131,450 t U (341.8 million pounds U_3O_8) [5, 7, 8, 9]. URI/HRI currently has about 14,583 t U (37.834 million pounds U_3O_8) of estimated recoverable reserves at Crownpoint and Churchrock at a cost less than \$39/kg U (\$15/lb U_3O_8). About 40% of all uranium produced in the USA is from the Grants Mineral Belt [5].

5. REGIONAL GEOLOGY

The San Juan Basin has been a regional depocenter since the Paleozoic. Approximately 3,000 m of section are present and range in age from Precambrian to Holocene. Strata from Permian to upper Cretaceous are identified including the Jurassic Morrison formation which hosts most of the uranium deposits in the basin. Formation of minor importance are the Cretaceous Dakota Sandstone and the Jurassic Todilto Limestone. Figure 5 is a cross-section between Gallup and Grants, New Mexico showing the regional relationships of the Jurassic Morrison [1].

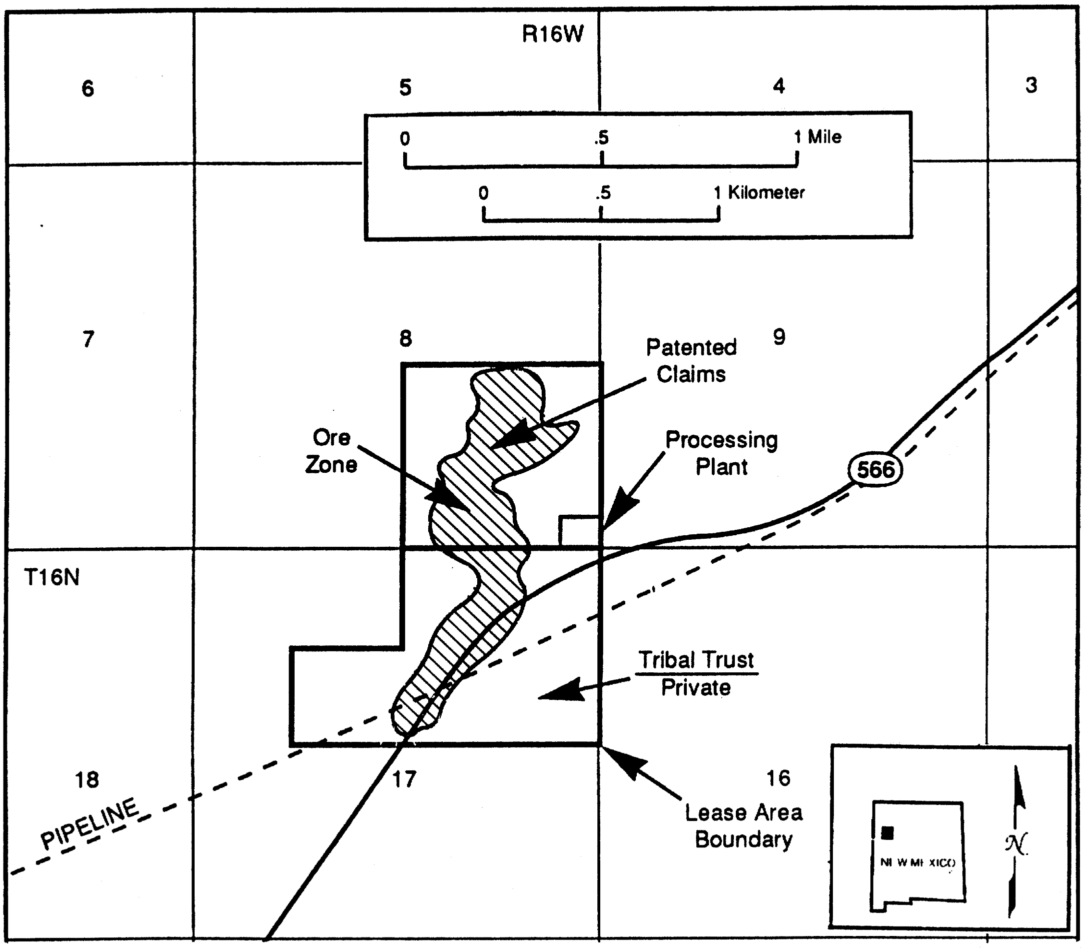

FIG. 4. Churchrock site map.

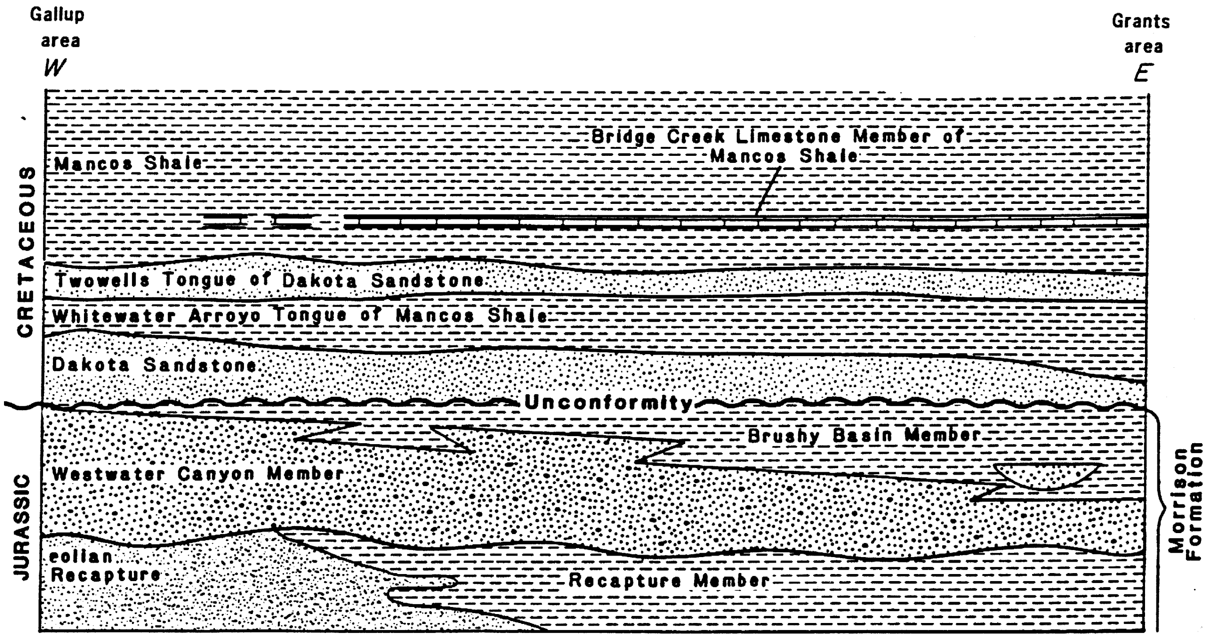

FIG. 5. Cross-section between gallup and grants, New Mexico [1].

5.1. Morrison formation

The Morrison Formation consists of the Recapture, Westwater Canyon, and Brushy Basin Members and may attain a total thickness of about 225 m. A typical section in the Westwater Canyon Member along with a geophysical log is presented in Fig. 6 [1].

5.1.1. Recapture Member

The Recapture Member of the Morrison Formation is composed dominantly of two facies: aeolian and lacustrine. The eolian portion can be up 90 m thick and consists of white, tan, and yellowish-gray, fine- to medium-grained, well sorted, large-scale trough crossbedded

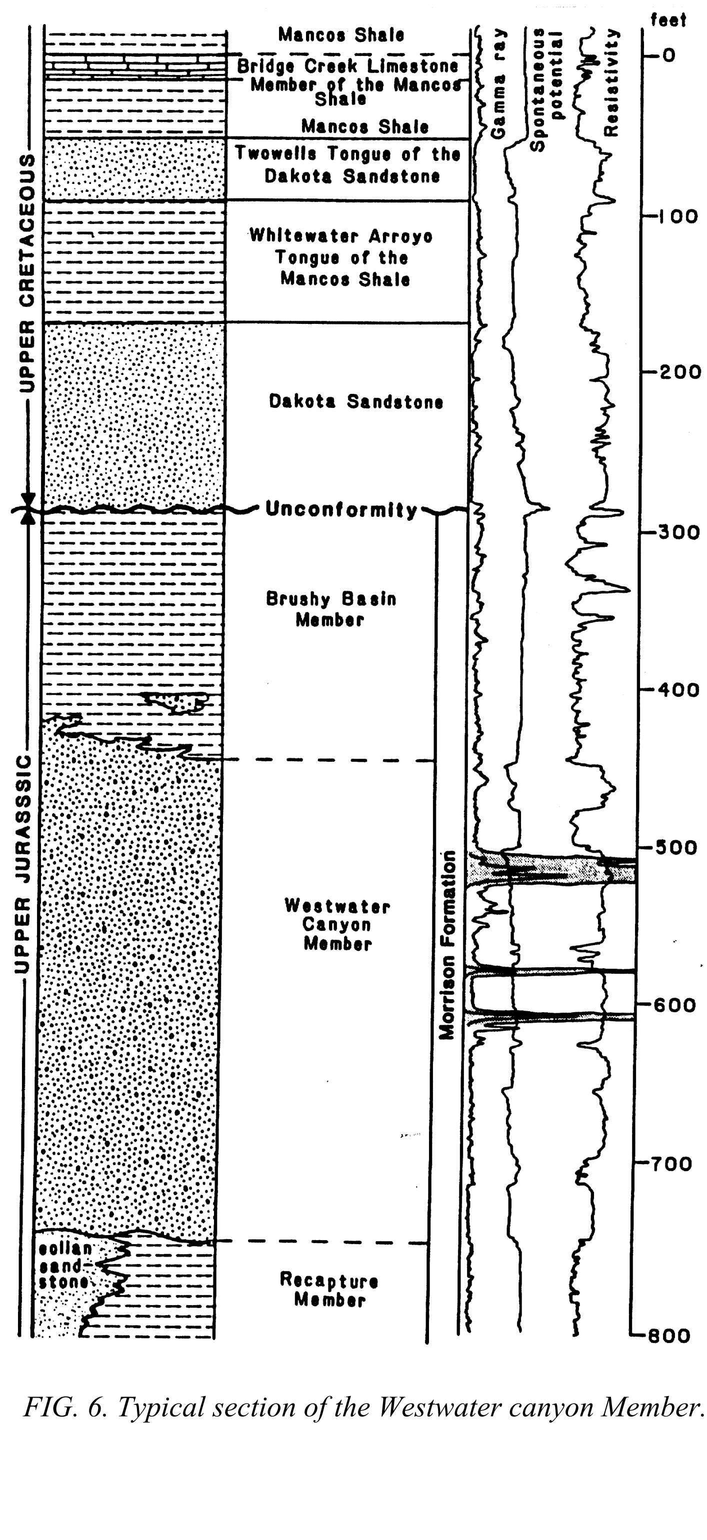

FIG. 6. Typical section of the Westwater canyon Member.

sandstone [1]. The lacustrine facies is an interbedded sequences of alternating red and maroon mudstones and white, light-gray, and reddish-brown, fine- to medium-grained, moderately well sorted sandstone. It ranges in thickness in the San Juan Basin from 0 to 152 m [1].

5.1.2. Westwater Canyon Member

The Westwater Canyon Member is an artesian aquifer with a transmissivity of 3.676×10^{-4} to 3.880×10^{-4} m^2/s (2,556–2,698 gal/day/ft) [8] and is tightly confined by aquicludes of the overlying Brushy Basin clays and underlying Recapture Shale. As described by Kirk & Condon [1], the Westwater Canyon Member is a sequence of vertically stacked and laterally coalesced fine- to coarse-grained, arkosic to felspathic, poorly sorted, sandstone beds interbedded with thin, discontinuous mudstone beds. The color ranges from pink to red, grayish-green, and yellowish gray. The Westwater Canyon Member was deposited in a braided fluvial framework and ranges in thickness from 30 to over 125 m and deposited in a synclinal area between the Mogollon and Uncompahgre uplifts [3]. At Crownpoint, the Westwater Canyon Member ranges in thickness from 72 to 105 m. At Churchrock, the average thickness of the Westwater is 80 m. A shown in Fig. 2, the source of the sediment was from the southwest across the area of the Zuni Uplift.

5.1.3. Brushy Basin Member

The Westwater Canyon Member interfingers locally and regionally with the overlying Brushy Basin Member mudstones which also serve as a regional aquiclude. Locally, the Brushy Basin Member hosts braided fluvial sandstones sometimes referred to as “Poison Canyon”. The Brushy Basin Member is composed of light greenish-gray bentonitic claystone and mudstone and ranges in thickness from 12 to 40 m [1, 8]. At Crownpoint, the Brushy Basin ranges from 20 to 35 m.

5.2. Dakota Sandstone

The Dakota Sanstone unconformably overlies the Morrison Formation and consists of two distinctive units. The lower portion is a paludal shale and mudstone overlying the Brushy Basin Member occasionally containing fluvial sandstone and locally coal. The upper portion of the Dakota is a well-developed white to light-brown, transgressive beach and barrier-bar marine sandstone unit occasionally containing distributary sandstone channels which are occasionally conglomeratic. These channels occasionally scour into the underlying Brushy Basin Member [1]. The thickness of the Dakota Sandstone is up to 60 m.

5.3. Mancos Shale

The Mancos shale was deposited in a transgressive offshore marine environment and is a dark-gray claystone, mudstone and very-fine sandstone system and is up to 600 m thick [1, 8]. At the Churchrock site, the Mancos shale is present at the surface.

6. DEVELOPMENT OF URANIUM DEPOSITS IN THE WESTWATER CANYON MEMBER

Uranium was deposited in the Westwater Canyon Member penecontemporaneously with the deposition of volcanic ash in a humate rich environment. Syngentic concentration of humate and uranium within tabular sandstone masses created the tabular “trend-ore” deposits.

Following structural changes in the basin during Cretaceous times, the trend-ore containing vanadium, molybdenum, and humate was redistributed into secondary "stacked" ore rolls virtually free of organics but containing some molybdenum. A later stage of basin development during Tertiary further redistributed the uranium into monometallic stacked ores. Both Crownpoint and Churchrock are Tertiary stacked-ore deposits.

The Cretaceous and Tertiary remobilized uranium rolls are considered favorable for bicarbonate-oxygen ISL methods currently employed by URI's Kingsville Dome and Rosita plants.

6.1. Regional ore controls

Clear regional controls of the uranium deposits in the San Juan Basin are evidenced by the strong correlation between the regional redox fronts and the location of the ore deposits [1, 2, 3]. This regional redox front is presented in Fig. 7 [1]. The regional redox front is accompanied by discrete zones of hematitic and limonitic alteration within the basin, the hematitic zone being updip of the limonitic zone. Gray, reduced Westwater Canyon Member sandstones occur downdip of the regional redox front. The remobilized ore lies in the limonitic zone downdip of the more intensely oxidized zone of hematitic alteration.

Another important regional and local control for the concentration of uranium is the development of highly transmissive zones in the Westwater Canyon Member fan system which allowed large quantities of uranium bearing solutions to pass through regional redox fronts and be precipitated.

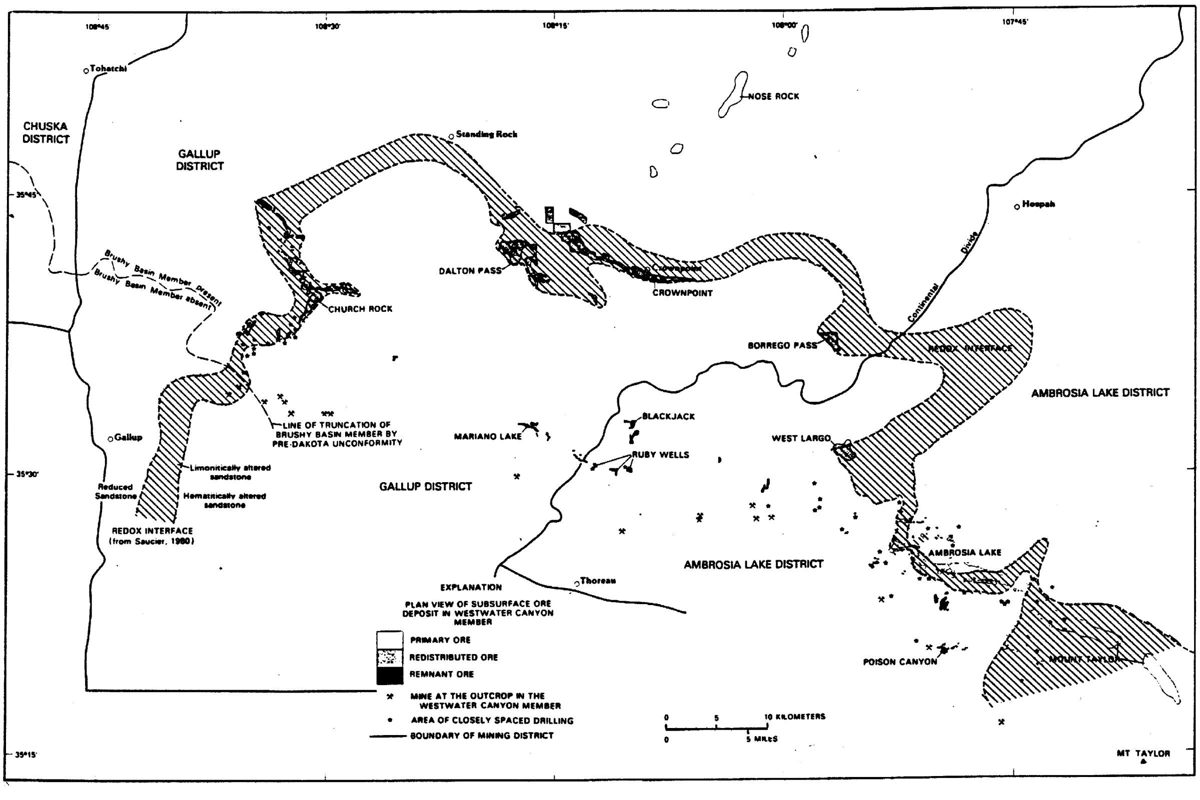

FIG. 7. Regional Redox Interface — From [1].

6.2. Local ore controls

Local ore controls for the individual rolls within the Westwater Canyon Member appear to be the thin, laterally discontinuous clays within the sandstone. As shown in Fig. 8 of the Crownpoint site, multiple, stacked ore bodies are present throughout the Westwater Canyon Member, each within an individual geochemical cell. Accurate interpretation and delineation of these ore rolls is required to design an effective well field.

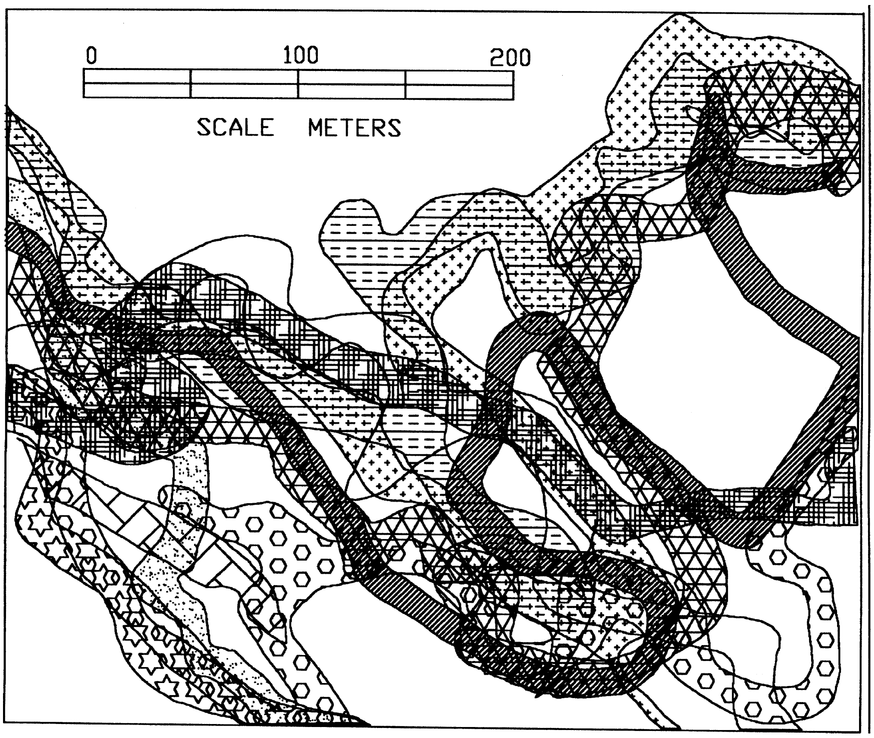

FIG. 8. Stacked roll fronts in the SE¼ of section 24 at Crownpoint.

7. ISL PROCESS

In order to develop the Crownpoint and Churchrock ore deposits, two distinct producing elements are necessary: the Well Field, and the Ion Exchange Plant. The plant consists of ion exchange columns containing resins with an affinity for uranyl carbonate ions. The flow of dilute solutions of uranyl carbonate (about 50–150 mg U/L) from the extraction wells is maintained at a rate of 10,000–20,000 L/m (2,500–5,000 gallons/m) through the plant. This yields between 230 kg U to 4,615 kg U per day (600 to 12,000 pounds of U3O8) for an annual production of 263–1,577 t U per year. Following extraction of uranium, oxygen and complexing agent such as sodium bicarbonate is added and the solution is reinjected. Of course, the true key to ISL development is the well field design.

7.1 Well field design

The well field is the mechanism by which the leaching solutions, or lixiviant, is circulated through the ore body (Fig. 9). Well field design for the in situ leach mines at Crownpoint and Churchrock will include up to 1,000–2,000 injection and extraction wells for each mine site located as close as possible to the ore. Because of the sinuosity of each individual roll front, wells as closely spaced as 10–50 meters will be used to extract the uranium. Each well field will be surrounded by a ring of monitoring wells not more than 120 m (400 ft) from the nearest production well and not farther than 120 m from each other. Leachate migration to the monitoring wells is called an excursion. Excursion controls consist primarily of the initial engineering design of the wellfield, balancing lixiviant flow in the wellfield, and maintaining a slight production bleed of 1% to create a cone of depression around the ore zone. URI has never had an excursion in its operating history.

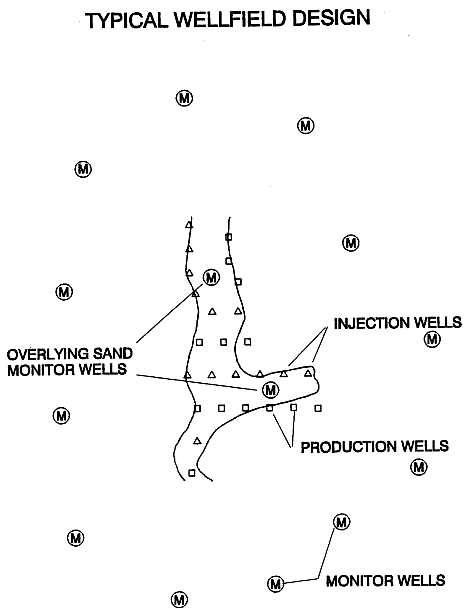

FIG. 9. Typical wellfield design.

8. LICENSING

URI/HRI is currently in the process of obtaining source material license as authorized by the Atomic Energy Act for the Crownpoint, Churchrock, and Unit 1 sites. With the issuance of the FEIS [8] in February, the lengthy re-evaluation by the U.S. Nuclear Regulatory Agency (NRC) [10], the Bureau of Indian Affairs (BIA), and the U.S. Bureau of Land Management (BLM) was completed with a recommendation to issue a combined source and by-product material license from the NRC and minerals operating leases from the BLM and BIA. The FEIS recommended that the license and leases should be conditioned on the commitments made by HRI in the license application and related submittals as well as various recommendations made by the NRC [8]. The FEIS is the culmination of a 9 year effort by HRI to license and develop the deposits. The NRC license will be conditioned on a Safety Analysis Report (SAR) currently being prepared by the NRC and Consolidated Operating Plan (COP) which is currently undergoing review by the NRC.

Other required licenses and conferred rights include the Underground Injection Control (UIC) License, and Surface Discharge Permit, land disposal of treated waste water, and air quality licenses.

8.1. Underground injection control license

In addition to a source material license, URI/HRI has obtained a UIC license from the State of New Mexico Environmental Department. A UIC license allows for the injection of mining fluids into an aquifer for the purpose of extraction of uranium.

8.2. Land application of discharged water

Surface application of treated discharge waters is licensed by the State of New Mexico Environmental Department or the U.S. Environmental Protection Agency depending on the land status.

8.3. Water rights

Water rights in the State of New Mexico is administered through the New Mexico State Engineer. Applications for water rights are required to be published and are subject to a hearing if protested. Water rights may be approved subject to three conditions: That the application (1) not impair existing water rights, (2) not be contrary to the conservation of water within New Mexico, and (3) not be detrimental to the public welfare. URI/HRI is currently in the process of obtaining water rights for the anticipated projects.

8.4. Comparative consumptive water use

Agricultural use of consumed water in McKinley County, New Mexico for 50 hectares (123.5 acres) is compared to the total consumptive water use for all three proposed ISL projects. As can be seen in Fig. 10, the consumed water use for to support 50 ha of all commercial agricultural products is greater than the average use for in situ uranium mining. By comparison, water use for the former Churchrock mines required at least 6 million m^3 (5,000 acre feet) per annum to dewater the mines or at least 36 times the ISL water requirements.

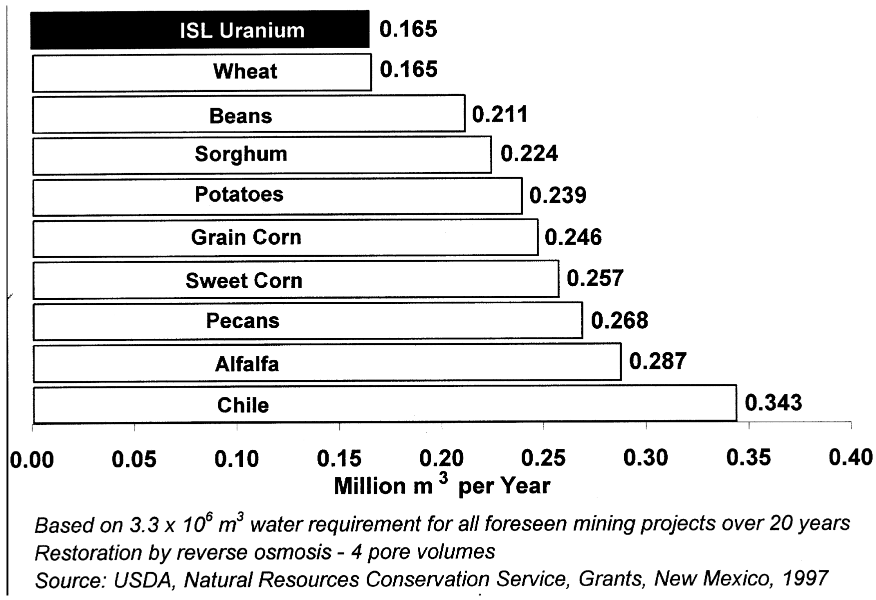

FIG. 10. Comparative consumptive water use 50 hectares of crops and ISL mining.

9. RESTORATION

Based on the experience gained in the industry, three strategies (Table I) are considered in ground water restoration including (a) groundwater sweep (GS); (b) reverse osmosis (RO); and (c) brine concentration (BC) depending on the water budget. Total water use is estimated to be 13–29 million m^3 for groundwater sweep, 3.3–7.7 million m^3 for RO, and 0.03–0.07 million m^3 for BC. This represents the total water requirements for all currently foreseen projects.

TABLE I. WATER REQUIREMENTS FOR CROWNPOINT, UNIT 1 AND CHURCHROCK [8]

Restoration Method	4 Pore Volumes (millions M^3)	9 Pore Volumes (millions M^3)
Groundwater sweep	13	29
Reverse Osmosis	3.3	7.7
Brine Concentrator	0.03	0.07

10. RESOURCE & PRODUCTION BASE OF URI/HRI

10.1. Santa Fe pacific gold corporation agreement

URI/HRI recently signed an agreement with Santa Fe Pacific Gold Corporation in which certain mineral rights were acquired covering 200,000 ha (500,000 acres). These rights were obtained in exchange for 1.2 million shares of URI's common stock and a commitment for $200,000 per year in exploration expenditures for the next 10 years [11, 12]. URI estimates there is approximately 5,700 t U (14.7 million pounds U_3O_8) of proven in-place uranium reserves approximately 3,700 t U (9.6 million pounds U_3O_8) recoverable] that were drilled-out on the acquired land. The potential for further development is very large based on the USGS endowment study of the San Juan Basin completed in 1986 [6]. It is estimated from this study that the endowment at a cutoff grade of 0.10% of the Westwater Canyon Member is 1,392,000 t U (3,280 million pounds of U_3O_8) at ISL minable depths.

10.2. URI/HRI operations and production

URI and its subsidiary HRI currently has uranium production operations in South Texas in the Kingsville Dome and Rosita plants. Production in 1996 amounted to 524 t U (1.36 million pounds U_3O_8) making URI one of the largest domestic producer of uranium in the USA [11].

Based on the recent acquisition of Alta Mesa in Texas, the development of the Vasquez, Texas property, a favorable FEIS for three uranium properties in New Mexico, and recent agreements with Santa Fe Pacific Gold Corporation (SFPGC), the in-place uranium reserves of the company are 34,000 t U (88 million pounds U_3O_8) of which 22,000 t U (57 million pounds U_3O_8) are recoverable [12]. URI/HRI has been extremely active in licensing the Alta Mesa, Texas and New Mexico deposits for production as early as 1998.

ACKNOWLEDGMENTS

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THE McCLEAN LAKE URANIUM PROJECT

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Abstract

The McClean Lake Uranium Project, located in the northern part of Saskatchewan, consists of five uranium deposits, Jeb - Sue A - Sue B - Sue C - McClean, scattered in three different locations on the mineral lease. On 16 March 1995, COGEMA Resources Inc and its partners, Denison Mines Ltd and OURD (Canada) Co Ltd, made the formal decision to develop the McClean Lake Project. Construction of the mine and mill started during summer 1995 and should be finished by mid 1997. Mining of the first deposit, Jeb started in 1996, ore being currently mined. The start of the yellowcake production is scheduled to start this fall.

1. LOCATION

The McClean Lake Project is located in the northern part of Saskatchewan, near the eastern margin of the Athabasca Sandstone basin, approximately 750 km north of the city of Saskatoon (Fig. 1). The nearest operating mine is Rabbit Lake, only 20 km to the Southeast of McClean. Key Lake is about 180 km Southwest, while the new projects of Cigar Lake and McArthur River are respectively 60 and 110 km from McClean, the Midwest deposit being located 20 km to the west [1].

Access is by road and by air to a private commercial airport at Points North Landing, a 30 minute drive from McClean.

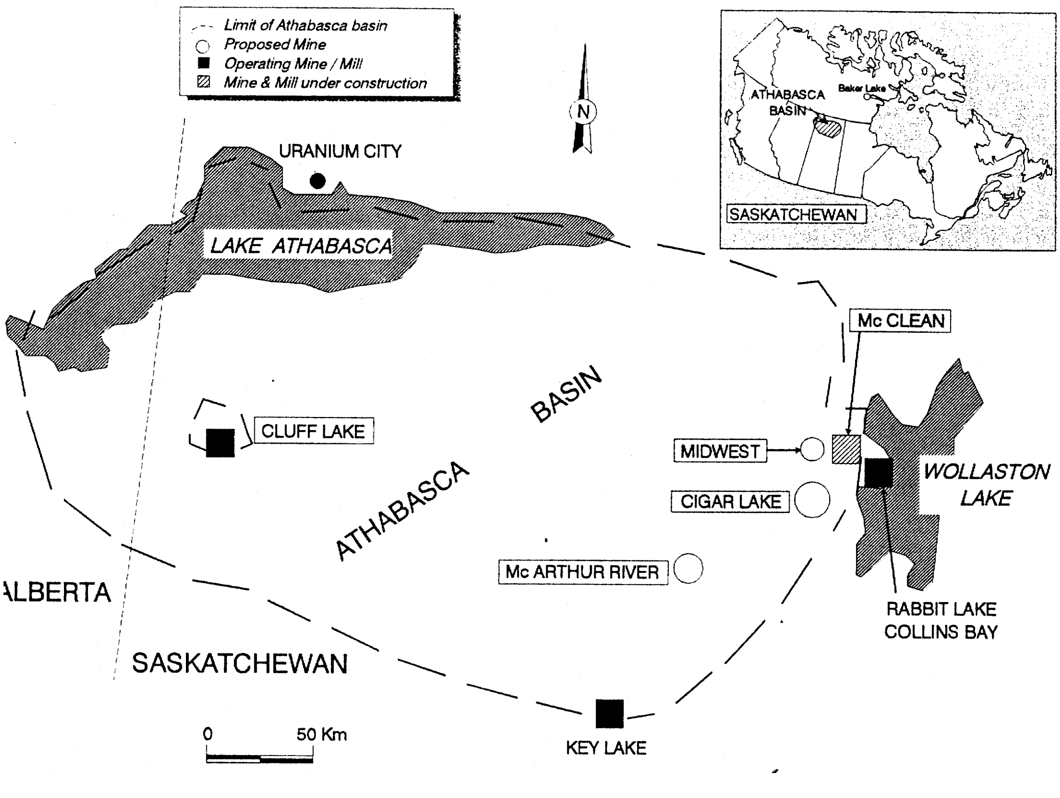

FIG. 1. Saskatchewan uranium deposit.

2. PROJECT HISTORY AND OWNERSHIP

The McClean Lake uranium deposits were discovered in the 1980's by the Wholly Joint Venture, which included Canadian Occidental, Inco and Total Minatco.

In 1990, Total Minatco became the sole owner of the property, which was renamed the McClean Lake project. The project was wholly owned by Total until April 1992, when Denison Mines Ltd and OURD (Canada), which had a consolidated stake of 45% in the Midwest project, and Total executed an agreement, which allowed each party to cross interests in the other's project.

On 23 July 1993, as part of a broader deal, COGEMA acquired all of the uranium assets of Total, and therefore became the sole shareholder of Minatco Ltd. In 1996, Minatco was amalgamated into COGEMA Resources Inc, who is operator of the McClean Project [1].

The resulting ownership structure of the McClean Joint Venture as of 1 January 1997 is:

COGEMA Resources Inc	70%
DENISON Mines Limited	22.5%
OURD (Canada) Cy Limited	7.5%

3. REGIONAL GEOLOGY (Fig. 2)

The McClean area straddles the transition zone between the Mudjatik Domain to the west and the Wollaston Domain to the east, the latter hosting most of the major uranium deposits of Saskatchewan. Approximately one half of the area is underlain by Archean granitic basement rocks. These rocks occur as anticlinal domes and range from granitoïds in the core to foliated granitoïds, gneissic rocks and migmatites on the margins. Mineralogy consists essentially of quartz-feldspar-biotite.

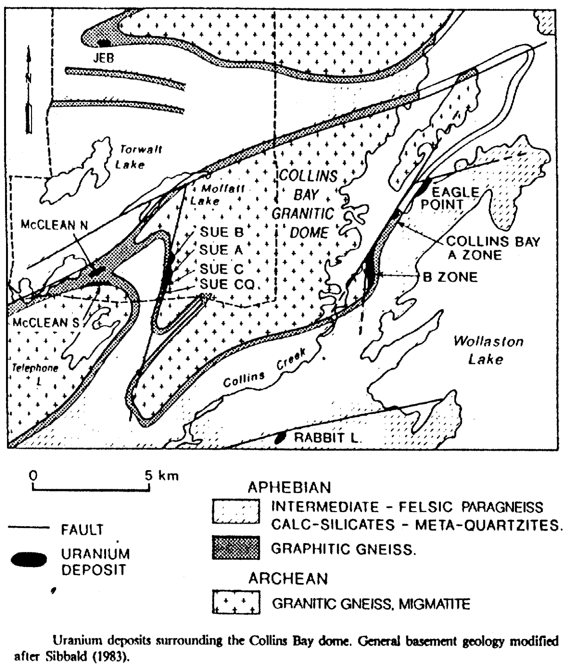

FIG. 2. Uranium deposits surrounding the Collins Bay dome. General basement geology modified after Sibbald (1983).

The granitic domes are unconformably overlain by a thin cover of Aphebian paragneissic rocks, 200 to 300 m thick. The lowermost succession of the Aphebian paragneiss cover contains one to several graphitic units. All the known uranium deposits on the property are associated with these graphitic gneisses.

The basement rocks are unconformably overlain by a flat lying Athabasca sandstone formation of Helikian age. The sandstone cover on the area varies in thickness from 0 to 200 m and is generally overlain by 5 to 30 m of Quaternary glacial till consisting of mixed sand, sandstone and basement boulders.

4. THE McCLEAN URANIUM DEPOSITS

The McClean Lake Project consists of five uranium deposits scattered in three different locations on the mineral lease. They are:

- Jeb in the north
- Sue A, Sue B, Sue C in the south
- McClean, a few kilometres west of the Sue group

These five orebodies are generally related to and positioned close to the unconformity contact between the Athabasca sandstone and the underlying metamorphic gneisses of the basement.

The JEB deposit

On average 18 m of glacial overburden covers the area of the JEB deposit.

Below this overburden a thickness of 75 m of Athabasca sandstone exists. These sandstones are generally quite competent but locally strongly faulted and clay enriched directly above the orebody.

The Aphebian units intersected at the Jeb zone include a package of graphic rocks (intermediate gneisses, calc-silicate gneisses, and pegmatoïds) generally associated with the mineralization an non graphitic units flanking the orebody to the north and south. Structurally the Jeb zone is quite complex with no main system. Instead, a series of four systems, EW-NWSE-NESW and NS, interact together to both limit and or offset the mineralization and create structural traps beneficial for high grade mineralization. Flat lying structures occur at Jeb and delineate zones of weakness with increased hydrothermal alteration and control the mineralization.

Two main types of mineralization exist at Jeb, the most common and the highest grade being that which straddles the unconformity at the sub-crop of the graphitic gneisses and pegmatoïds. This mineralization occurs in the form of pitchblende and uraninite. Grades can be higher than 30% U_30_8.

The second type of mineralization is related to the shear cleavage developed 2-15 m below the unconformity. Grades are lower, but locally can be greater than 10% U_30_8. Significant amounts of nickel in the form of arsenides and sulphoarsenides are dispersed throughout the orebody but also concentrated in the southern flank of the mineralization. The average grade of nickel associated to uranium is 1.0-1.5%.

The Sue A deposit

The Sue A deposit lies between 60 m and 75 m below surface and strikes N12°E. The deposit is 170 m long with a width averaging 15 m to 20 m. Its thickness varies from 1.5 m to 12 m with an average of 9 m. The mineralization is extensively controlled by faulting, resulting in irregular cross-sectional shapes. In general, the deposit is flattened with a westerly dip conforming to the down-dropping of the unconformity. Along strike, mineralization terminates against two sets of faults, northeast and northwest in direction.

The deposit lies on and immediately above the unconformity, in an envelope of massive earth-red clay. Argillic alteration extends almost up to the sandstone sub-crop along fault zones, leaving only scattered sections of silicification in the cap rock. An average of 9 m of glacial overburden covers the sandstones.

Minor amounts of uranium mineralization extend downward into the basement as narrow roots along faults. Less than 2% of the Sue A deposit lies below the unconformity.

The distribution of uranium is confined to a few high grade (> 5% U_30_8) pods, mostly in the south half of the deposit where some 70% of the total uranium is located [2].

The Sue B deposit

The Sue B deposits is located approximately 350 m north of Sue A. The mineralised zone is 90 m long and averages 40 m in width (Fig. 3) but unlike Sue A, the mineralization occurs within two different horizons in the sandstone. The upper horizon contains some 50% of the uranium mineralization. It lies at a depth of about 20 m above the unconformity. Mineralization extends at one point to the subcrop of the Athabasca sandstones, at a depth of 8 m below surface. This upper zone is about 50 m long, 26 m wide and 17 m thick. The lower zone of mineralization lies on and immediately above the unconformity at depths ranging from 60 m to 75 m. In general, the mineralization lies on the western flank of the basement high and follow the down-dropping in steps of the unconformity.

The Sue B mineralization is largely fault-controlled. The upper zone appears as a product of intersecting structures such as conformable and conjugate faults which created a zone of weakness and relatively high permeability.

The Sue B orebody is a medium grade deposit with very little high-grade mineralization. Grades usually do not exceed 5% U_30_8 [2].

The Sue C deposit

The Sue C area lies immediately to the Southwest of the Sue A deposit. The Sue C mineralised vein is a 10 m to 15 m wide N12°E trending subvertical structure dipping 70 degrees to the east (Figs. 4 and 5), paralleling the Archean-Aphebian contact located 100 m to the east. The mineralised zone is 400 m long and averages 40 m in width.

The mineralization is hosted by reverse anastomosing faults, (the Sue C fault), striking N12°E, parallel to the basement lithologies. It is located at the footwall of the graphitic gneiss, in a clay-rich zone as well as in the lower graphitic unit itself. It is typically underlain in sharp contact by massive quartz or silicified paragneiss. A second silicified zone was intersected 30 m west of the ore.

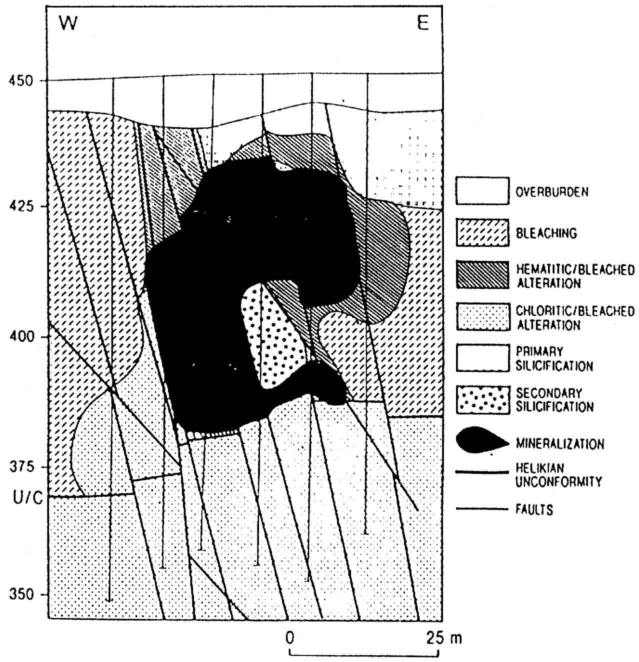

FIG. 3. Sue B deposit alteration pattern and contour of the mineralization at 500 ppm cutoff.

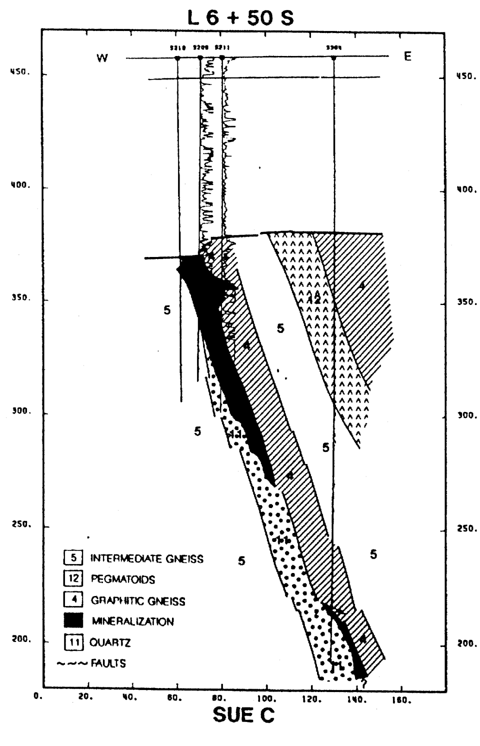

FIG. 4. Sue C deposit.

The mineralization consists of massive pitchblende, pitchblende nodules and veinlets within a white, black or blood-red clay envelope. The mineralization contains minor amounts of arsenides. At the scale of the deposit, the mineralization typically exhibits a vein geometry parallel to the remnant subvertical foliation. On a detailed scale, the high-grade pods are distributed as vertically stacked flat lenses. Therefore the main structural control of the mineralization is the concomitant action of steeply dipping faults and flat-lying shears.

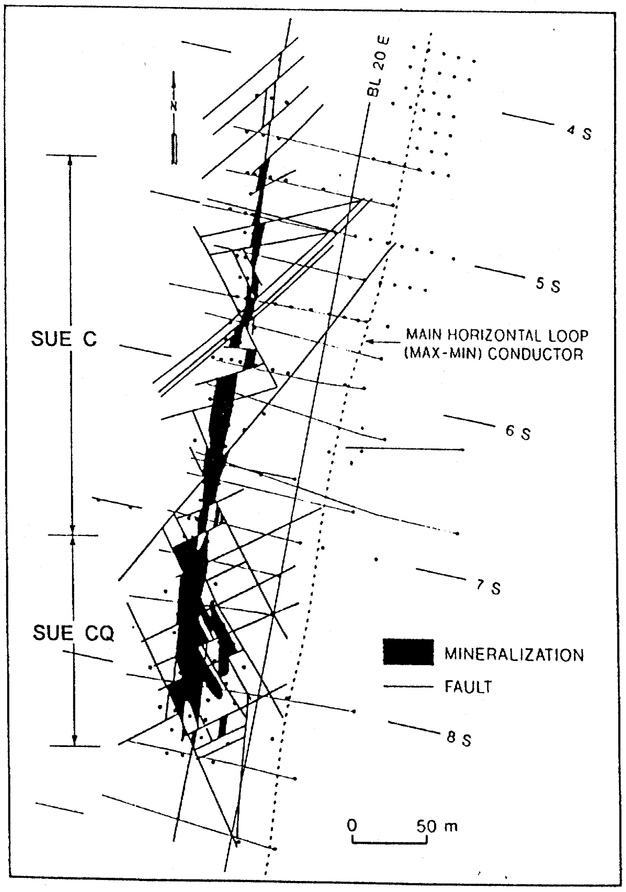

FIG. 5. Sue C — CQ deposits outline of the mineralization at 0.5% cutoff.

The flat-lying shears are associated with a thickening of the silicified zone at depth, thus controlling the downdip limit of the ore. The maximum depth of the mineralization ranges from 115 m in the north to 150 m in the south. The unconformity is typically locates 75 m to 80 m below surface and is disrupted by major reverse faults creating a hump or offsets of up to 40 m. There is no evidence of the mineralization extending upward into the overlying sandstones. Immediately above the ore, the sandstones are strongly argillized (illitization and bleaching) with local hematization.

The continuity of the mineralization in the Sue C deposit is interrupted by major NE and NW faults which have slightly displaced the vein over a few meters. To the South (CQ) the mineralization is discontinuous and of lower grade. The ore is hosted completely within intensely altered graphitic to non-graphitic intermediate paragneiss. The overall mineralised volume is divided into multiple moderately dipping lenses for a total width of 40 m over a strike length of 125 m. The ore does not subcrop, the upper limit being a depth of 120 m, 45 m below the unconformity, and is known to date to a depth of 165 m, 90 m below the unconformity. The bulk of the mineralization consists mainly of pitchblende nodules associated with an ubiquitous red-brown hematitic clay-rich envelope [2].

The McClean deposit

A series of « pods » form two distinct deposits, the McClean North, 800 m long, and the McClean South, 500 m long (Fig. 6).

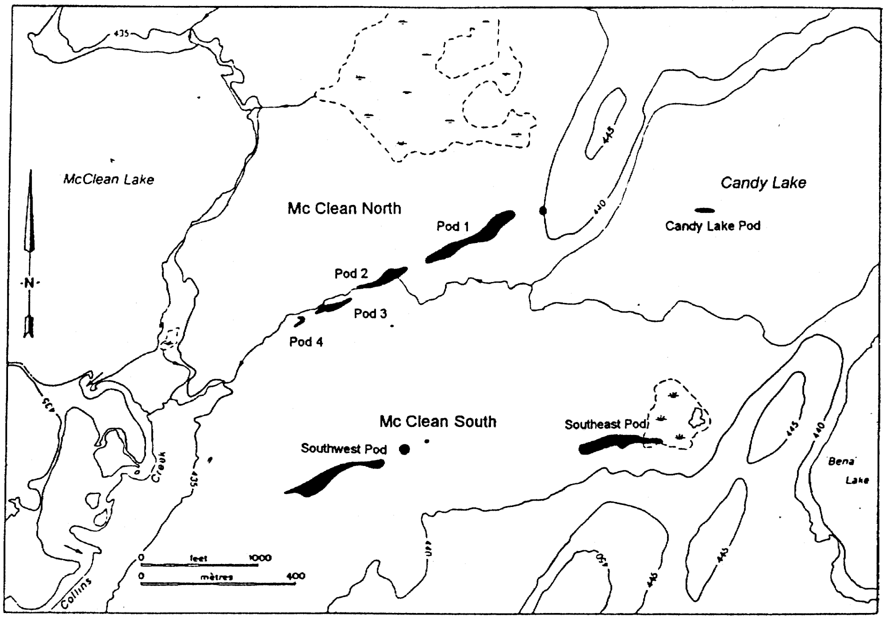

FIG. 6. McClean area — Uranium deposits.

The pods have a « sausage » shape and are 15-45 m wide, 8-25 m thick. The individual pods undulate about the sub-Athabasca unconformity, 40 m above to 40 m below. The unconformity is 170 m below surface. They form thin curved sheets rising from the east within the regolith to reach the unconformity where they thicken.

All the pods overlie graphitic units within the crystalline basement. Fractures and brecciation occur in the regolith and basement adjacent to mineralization, but some of these structures extend beyond ore.

The deposits consist of uranium and iron accompanied by relatively minor concentrations of As, Ni, Co, Cu.

5. RESERVES

The McClean mineral leases contain approximately 20 000 tonnes of uranium (50 million pounds equivalent U_3O_8) and there is a good potential for additional discoveries which would increase the figure significantly.

Mining reserves of the different deposits are given in the following table:

Deposit	Ore (tonnes)	Ore grade (%U)	U content (tonnes U)	Maximum depth (m)
JEB	71 850	2.79	2 003	110
Sue A	55 000	1.26	692	80
Sue B	90 100	0.73	654	80
Sue C	249 900	4.50	11 247	160
McClean	229 300	2.06	4 731	> 200
Total	696 150	2.78	19 327	

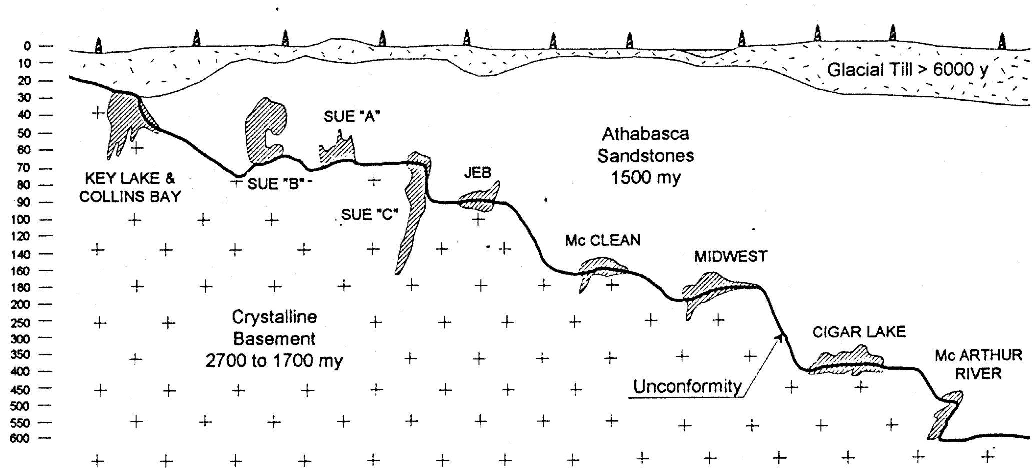

FIG. 7. Depths of known uranium deposits in the eastern Athabasca sandstone basin.

6. MINING

The depth of mineralization (Fig. 7) is obviously a major factor in the choice of the mining method: therefore JEB, Sue A, B and C will be mined by open pit methods. The McClean deposit consists of a series of mineralised pods at depths in excess of 170 m and will be mined from underground.

Stripping of the overburden on JEB deposit started at the end of 1995, followed in 1996 by waste rock mining. Ore mining is currently done and should be finished in August 1997. The ore is stockpiled. Mining activities will then move to the Sue deposits.

7. MILL

The McClean mill is located near the Jeb pit which will be transformed into a tailings depository during the second half of 1997 to receive the tailings from the mill.

The McClean mill has an annual capacity of 6 M lbs U_3O_8 (2300 t U). It will be increased to 24 M lbs U_3O_8 (9200 t U) to process 18 M lbs U_3O_8 from Cigar Lake. This mill will be the largest uranium mill in the world.

The different processes used at the McClean mill are rather conventional by today's standards. However, the mill has to process various categories of ore, originating from several ore bodies, some of them reaching grades up to 30% uranium. Effective radiation protection is therefore critical.

8. JEB PIT: WATER MANAGEMENT AND TAILINGS DISPOSAL FACILITY

The Athabasca Sandstone is completely saturated with water circulating in major fractures. Water inflows in mines, both open pits and underground, are generally large. After being collected in mine sumps and pumped, this water is contaminated and needs to be treated before release to the environment.

For this reason, a ring of 30 dewatering wells is being installed around the JEB pit, in order to intercept groundwater before mining. This water will generally be clean and can be directly released to the environment. Total chemical loading to the environment will also therefore be reduced. In addition, the conditions for the mining equipment in the pit will be much dryer and better, resulting in lower maintenance costs.

These dewatering wills will continue to control the level of the water table when the pit is later operated as a tailing management facility. Thickened tailings will be deposited as a paste under water. This water cover will perfectly shield employees from radiation generated by the somewhat radioactive tailings resulting from the processing of high-grade ore.

9. CONCLUSIONS

The McClean Uranium project is the first new uranium mine developed anywhere in the world since Olympic Dam in South Australia in 1988. By the high quality of its reserves and the good potential for further discoveries this project will allow COGEMA Resources to fulfil its role as the COGEMA group's key producer in the « dollar » currency zone.

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MARKET OUTLOOK FOR AUSTRALIAN URANIUM PRODUCERS

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Abstract

Recent improvements in the uranium market and political changes in Australia presented the uranium producers with their best opportunity in over 15 years. The removal of the well known "three mines policy" by the current government has encouraged Australian producers to develop new development plans. With the expansion of the existing operations at Ranger and Olympic Dam, and the potential operations of Jabiluka, Kintyre, Koongara, Honeymoon and Beverley, Australia expects to increase annual production to 11630 t U_3O_8 by the end of the decade. It will then join Canada as a major supplier of uranium to the world's nuclear power utilities in the 21st century. Uranium exploration, which has been virtually nonexistent over the past 15 years, has once again been reactivated. This occurred because of the change in the Government, but also because the Aboriginal groups are once more allowing exploration on their land.

1. INTRODUCTION

In September 1996, Energy Resources of Australia Ltd (ERA) presented a paper to the NEI Uranium Fuel Seminar on the same topic. At that point in time, ERA considered the outlook for uranium producers to the brightest in over 15 years. The two reasons for such optimism were:

– improvements in the market; and
– political changes in Australia.

Despite the recent fall in the spot price, ERA is still confident about the fundamental strength of the uranium market and the need for new projects to come on stream to meet anticipated demand.

Politically, the conservative government headed by Prime Minister Howard continues to be supportive of industry initiatives although no approvals for new mines have yet been granted.

The Labor Party were the architects of the "Three Mines Policy". Recent media speculation suggests their Australian Labor Party (ALP) Conference will drop the Three Mines Policy at its next meeting in January 1998.

2. MARKET OUTLOOK

In 1996, the world's nuclear power stations consumed the equivalent of approximately 75,500 t (166.5 mlbs) of uranium oxide concentrate. This is expected to grow to 78,400 t (172.8 mlbs) by 2000. However, in 1996, world production of uranium was only 42,600 t (94 mlbs), or 56 per cent of reactor requirements. The shortfall between production and demand provides uranium producers with significant opportunities to increase production and market share.

The fall in production since the 1980s is a result of several factors. These include:

– the sell down of excess utility and producer inventories which accumulated during the 1980s as a result of over production and lower than expected growth in nuclear power; and
– the collapse of the Soviet Union resulting in a flood of uranium to the world market.

It has been ERA's consistent view since the early 1990s that the market would recover in the second half of the decade, as occurred in 1996. From 2000 onwards, considerable new uranium production capacity will be brought on line to meet the anticipated growth in demand for uranium. Western World nuclear power stations are forecast to increase their demand for uranium concentrates by about one per cent per annum from 2000. The majority of this growth will come from North Asia, with demand relatively flat elsewhere. ERA's supply and demand forecast is shown in Figure 1. The large gap between demand and current production will be met by expansions of existing operations and new projects.

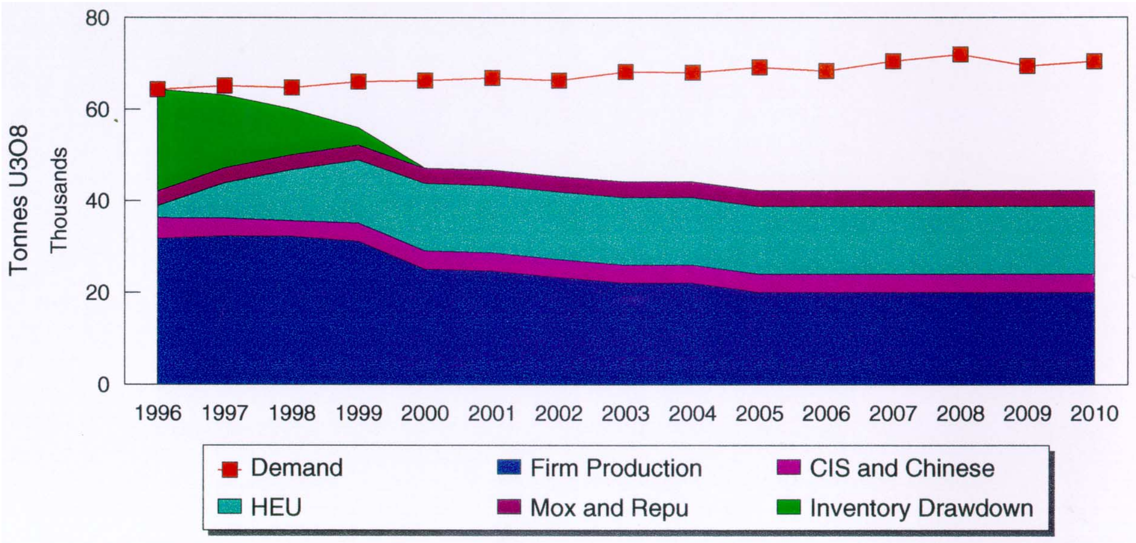

FIG. 1. Market — supply/demand.

Australia and Canada are expected to be the major beneficiaries of the increased demand for mine output. It is forecast that Australia's market share could increase from 8 per cent or 5,831 t (12.8 mlbs) in 1996 to approximately 15 per cent or 11,630 t (25.6 mlbs) by the turn of the century.

3. POLITICAL CHANGES IN AUSTRALIA

In March 1996, Australians elected a conservative government headed by Prime Minister John Howard. This election marked the end of a 13 year rule by the Australian Labor Party (ALP) under Prime Ministers Hawke and Keating.

Upon election to power in March 1983, the Government of Prime Minister Hawke introduced a policy to restrict the sale of uranium from the two mines then in production, Ranger and Nabarlek. This policy was introduced to satisfy factional demands from the left wing union dominated section of the ALP.

An exemption to this policy was granted in late 1983 to Olympic Dam to allow development of this very large copper/uranium mine in South Australia. The State ALP Government lobbied for a concession because of the then ailing state economy. The fact that Olympic Dam is primarily a copper mine had a major influence on the decision.

In 1984, the ALP rewrote its uranium policy naming the "three mines", Ranger, Nabarlek and Olympic Dam as the only mines to operate in Australia. The Government implemented this policy, not through legislation, but by refusing to grant export approval to other potential producers.

In 1988, one of the three mines, Nabarlek, ceased production. However, the government would not allow a "third mine", for example, Jabiluka or Kintyre to commence production to replace production from Nabarlek.

The policy has always been inconsistent and illogical but successive ALP conferences where the party policy platform is set have failed to have the policy removed or changed. The next ALP Conference is planned for 19 January 1998 in Hobart, Tasmania.

The current Liberal Coalition Government allows uranium mining as do the State and Territory Governments where existing and potential uranium mines are located. The government has invited companies to apply to develop new uranium mines subject to strict environmental review procedures.

The large electoral majority of the present Government and the conservatism of the Australian electorate virtually assures it of at least two terms of office. However, the Labor Party has previously stated it will not close an existing operation once in production. This is an assurance of supply to customers for Australian uranium.

4. PLANS FOR EXPANSION — THE MAJOR POTENTIAL PLAYERS

The map of Australia, Figure 2 shows the location of the existing operations, Ranger and Olympic Dam together with the major potential operations, Jabiluka, Kintyre, Koongarra, Honeymoon and Beverley.

FIG. 2. Uranium mines and prospects in Australia.

4.1. ERA — Energy Resources of Australia Ltd

ERA commenced operations at Ranger in 1981. Ranger #1 pit was completely mined out in December 1994 with ore stockpiled to allow the development of Ranger #3. The pit has been prepared as a mill tailings repository with tailings deposition commencing in August 1996.

In May 1996, ERA received government approval for the development of its Ranger #3 pit with total reserves of 55,700 t (123 mlbs) U_3O_8.

Work on Ranger #3 commenced immediately with the construction of a bund wall to prevent water inflows from the adjacent Magela Creek and pre-stripping to provide a water storage area for the 1996/1997 wet season. Figure 3 is an artist's impression of Ranger #3.

1 Ranger #3 shown three years into mining
2 New access road to Ranger
3 Retention Pond #1
4 New haul road to stockpiles and Ranger plant
5 Ranger #1 pit - now converted to tailings repository
6 Final pit outline (stage 3)

FIG. 3. Aerial photograph of Ranger with artist's impression of Ranger #3 in year 3 (1999/2000).

Ranger #3 will be mined by open pit methods with a new fleet consisting of an Hitachi Super EX2500 backhoe configured hydraulic excavator loading four Caterpillar 785B 135 tonne haul trucks. The new fleet is currently undergoing a commissioning and training period prior to the resumption of full scale mining from 1 July 1997.

July 1997 also marks the commissioning of the expanded processing plant at Ranger. The existing mill capacity has been increased to 2 mtpa with the addition of a new ball mill. Other areas of the plant have been upgraded or replaced to enable production of 5,000 t (11 mlbs) U_3O_8 per annum.

Jabiluka #2

ERA has submitted an application to develop the Jabiluka deposit, 22 km (14 miles) north of Ranger. ERA purchased Jabiluka from Pancontinental Mining in 1991 for US$100 million but had been unable to develop the property until recently because of the "Three Mines Policy".

ERA proposes to develop a smaller scale underground mine at Jabiluka compared to the Pancontinental proposal and to truck the ore to Ranger for processing. Figure 4 shows a plan of the Jabiluka area and its proximity to Ranger. Figure 5 shows an artists' impression of the portal facilities at Jabiluka.

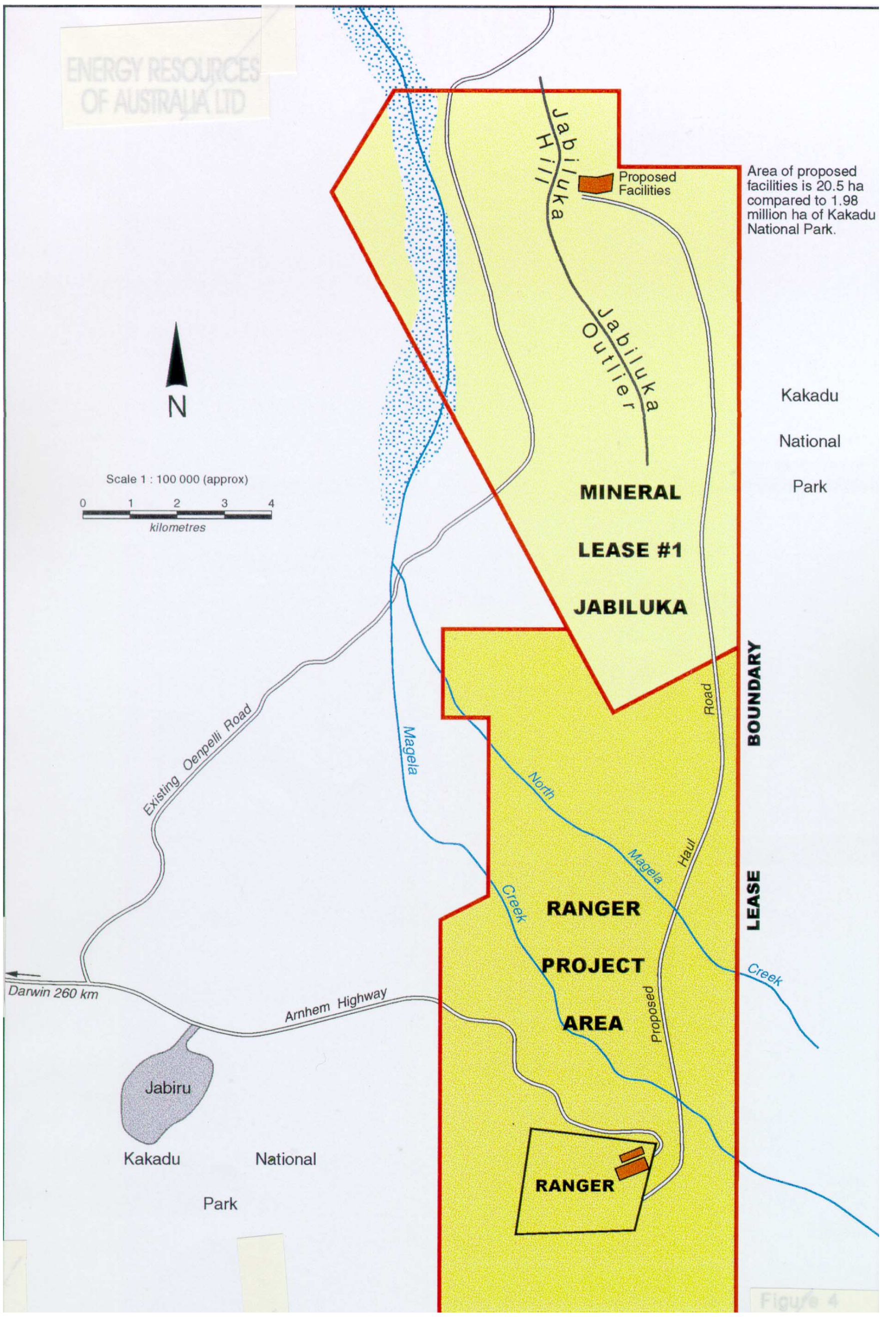

FIG. 4. Plan for the Jabiluka area in proximity to Ranger.

FIG. 5. Artist's impression of the proposed Jabiluka mine site.

As part of the approval process, ERA has completed a Draft Environment Impact Statement (EIS) which was submitted for public comment in October 1996. A supplementary EIS is expected to be submitted to the Government by mid-1997 and notwithstanding opposition from some sections of the community (including certain Aboriginal interests) ERA is confident that EIS approval will be forthcoming shortly thereafter. ERA's excellent environmental record and experience gained over 17 years of operations at Ranger places the Company in a strong position during the review process.

Aboriginal approval will be sought following EIS approval for the "change in concept" proposed by ERA — that is the change in plans from the original approved stand alone mine and mill plans of Pancontinental. There are specific provisions for this in the 1982 agreement between the Northern Land Council and Pancontinental which has been assigned to ERA.

Construction of the decline to access the orebody is planned to commence in May 1998 subject to EIS and Aboriginal approval. The mine is expected to commence production at the beginning of 2000 at the rate of 100,000 t ore per annum increasing in stages to a maximum of 900,000 t ore per annum. The higher grade Jabiluka ore will be blended with Ranger #3 ore, enabling ERA to increase production to 6,000 t (13.2 mlbs) U308 per annum.

4.2. WMC — Western Mining Corporation Holdings Ltd

WMC discovered Olympic Dam in July 1975. This massive copper/uranium/gold/silver mine is the sixth largest copper and the largest single uranium orebody in the world. However, its richness is its size, not its grade.

WMC commenced production in 1988 initially at 1,000 t (2.2 mlbs) U308 per annum. In 1991, an "optimisation expansion" increased uranium production to approximately 1,500 t (3.3 mlbs) U308 per annum and copper production to 66,000 t per annum. Since 1988 Olympic Dam has supplied over 11,000 t (24.3 mlbs) U308 to electric utilities in Japan, Korea, USA and Europe.

In June 1996, WMC announced plans to invest US$1 billion to more than double production from Olympic Dam over the next 5 years. This represents the largest capital expenditure ever undertaken by WMC and brings the total investment at Olympic Dam to US$1.85 billion.

Annual uranium production will increase from 1,500 t (3.3 mlbs) U308 currently to 4,630 t (10.2 mlbs) U308 by 2000 in staged increases from 1997. Copper production will increase to 200,000 t per annum.

To obtain government approvals for the expansion, WMC lodged an Environmental Impact Statement (EIS) in May 1997. The EIS process requires extensive public consultation and input on WMC's expansion plans.

WMC's nine year operating record at Olympic Dam will provide demonstrable evidence that the area can support a significantly expanded operation compatible with good environmental practices.

Figures 6 and 7 illustrate the expanded mine and metallurgical plant layouts before and after the expansion.

4.3. RTZ-RA Kintyre

RTZ-CRA are proposing to develop the Kintyre mine located on the edge of the Great Sandy Desert in the Eastem Pilbara Region of Western Australia, approximately 1,200 km north-northeast of Perth.

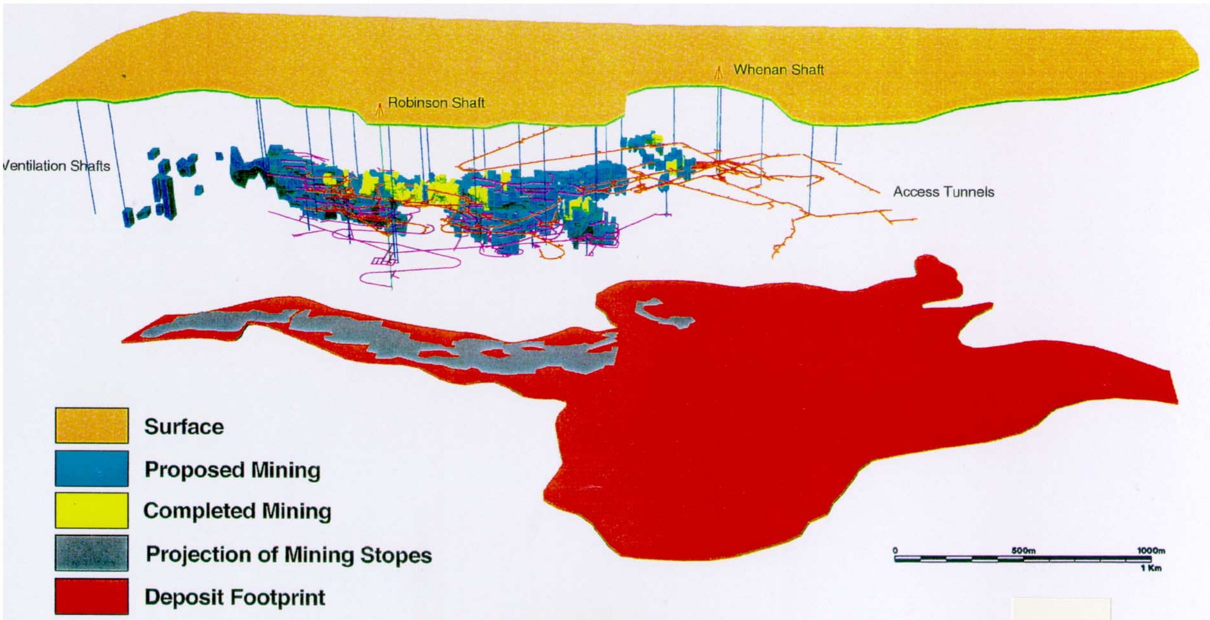

FIG. 6. Olympic Dam, expanded mine layout.

Like Ranger and Jabiluka in the Northern Territory, Kintyre is adjacent to a National Park — the Rudall River National Park. However, the mine will be outside the Rudall River catchment area, and as such plays no part in the eco-system for which the Park was designated to protect. Like all Australian uranium mines, the planning for Kintyre has placed considerable emphasis on protection of the environment.

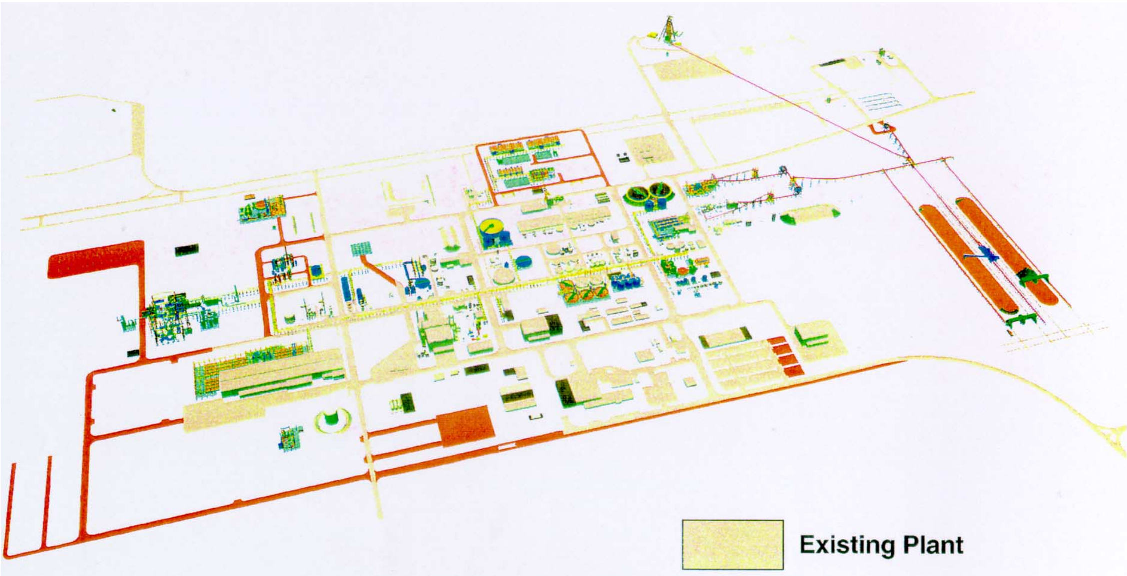

FIG. 7. Olympic Dam, metallurgical plant.

RTZ-CRA plans to commence production in later 1999 at 1,200 t (2.6 mlbs) U_30_8 per annum. The plant will be designed to allow expansion to 1,500 t (3.3 mlbs) U_3O_8 per annum at a later date.

Kintyre will be mined by conventional open pit techniques. The vein type mineralisation of the ore allows radiometric ore sorting prior to traditional acid leach processing. This pre-concentration significantly reduces the ore feed through the plant, reducing the plant size and capital. Operating costs are also improved. RTZ-CRA estimate the capital cost for construction will be approximately US$100 million with a two year construction period. When fully operational, Kintyre will employ 100 people on a fly in fly out basis.

RTZ-CRA has applied to the Federal and State Governments to develop Kintyre. A detailed Environmental Impact Statement (EIS) and Environmental Review Management Programme (ERMP) will be prepared and submitted for public discussion prior to full environmental approval which is expected in 1997.

Kintyre is currently the subject of three native title claims by groups of Aboriginal people that have a traditional association with the Rudall region. These claims are still to be settled by the National Native Title Tribunal. RTZ-CRA is continuing negotiations with the Aboriginal people.

4.4. Cogema — Koongarra

Cogema acquired the Koongarra deposit from Denison in 1995. Koongarra is located about 35 km south of Ranger and it too is surrounded by Kakadu National Park.

In the period 1978-1981, Noranda/Denison completed an Environmental Impact Study which was subsequently approved by the Government.

Denison then proceeded to seek Government approval but this was denied because of the "Three Mines Policy", despite the company having negotiated an agreement with the Northern Land Council and the Traditional Aboriginal Owners.

In 1996, enthusiasm to develop the project was rekindled and Cogema embarked on a new feasibility study to examine the options for the project.

The original project envisaged an open pit mine which would be completed in two years in much the same way as Nabarlek.

The ore would then be stockpiled for later processing utilising a conventional treatment system.

Tailings would be disposed in specially dug pits in impervious weathered schist. A non release water management strategy was to be implemented.

Once all approvals have been received, Koongarra is projected to produce about 1,200 t (2.6 mlbs) U_3O_8 per year. Production could commence in the very early part of the 2000s if everything goes to schedule.

4.5. Honeymoon

The Honeymoon project is located in South Australia close to the NSW mining town of Broken Hill.

Honeymoon has featured prominently in the media recently with the sale of the project to the Canadian based company Southern Cross Resources via a holding company called Sedimentary Holdings NL.

The deposits were previously owned by MIM Holdings Ltd who proposed an ISL operation at the deposit.

In May 1981 the State and Federal Governments granted EIS approval for the project. In November 1981 a small commercial plant, airstrip and camp were constructed and flow testing completed.

With the election of the Labor Government in 1983, export approval was removed and the project was abandoned.

Southern Cross Resources plans to revive the project through additional pilot testing with the objective of establishing commercial production in 1999 at 450 t (1 mlbs) U_3O_8 per annum. The company also owns the nearby East Kalkaroo, Yarramba and Goulds Dam deposits which are also amenable to ISL techniques and will be developed in conjunction with the Honeymoon project.

4.6. Beverley

Beverley is located close to Honeymoon, near Lake Frome in South Australia. Beverley is owned by Heathgate Resources Pty Ud, a subsidiary of the US firm General Atomics.

Beverley is proposed as an ISL operation. A draft EIS was released in 1982 but approval was never granted for production once the Labor Party was elected in 1983.

Heathgate is currently conducting additional drilling on the site to verify the ISL potential of the deposit. Hydrogeological studies including aquifer pump tests and operation of a continuous field leach trial using up to date USA ISL methods will be undertaken in 1997. Preparation of a new EIS has commenced.

The proposed mine will be a fly in fly out operation from Adelaide with a total workforce of about 50 people. Production of 700 t (1.5 mlbs) U_3O_8 per annum have been estimated from about 2000.

An Aboriginal land claim has been made which would delay development. Environmental issues related to water use are expected to receive significant scrutiny during the environmental assessment stage.

4.7. Australia's planned production to 2010

Australia's known planned production to 2010 is represented in Figure 8.

4.8. Ore reserves

Table I lists the ore reserves for each of Australia's uranium mines and the main proposed mines.

TABLE I. ORE RESOURCES/RESERVES

	Ore Million Tonnes	Grade Percent U_3O_8	Contained U_3O_8 Tonnes
ERA			
Ranger #1 stockpiles	5.80	0.26	14,982
Ranger #3	19.90	0.28	55.700
Jabiluka #2	19.50	0.46	90,400
Total	45.20	0.36	161,082
WMC			
Olympic Dam	580.00	0.06	348,000
RTZ-CRA			
Kintyre	n/a	0.2-0.5	35,000
Cogema			
Koongarra	1.8	0.80	14,000
Southern Cross			
Honeymoon	n/a	0.15	6,812
Heathgate			
Beverley	n/a	0.27	11,600

The Uranium Institute's Working Group on Reserves and Resources recently released an estimate of western world reserves mineable at prices less than \$80.000/kg U (\$30.77/lb U_3O_8). The new reserve classification system used by the Ul has been developed to provide a superior understanding of material likely to be available to the market in coming years.

Figure 9 highlights Australia's dominant position in terms of western world reserves, containing 45% of reserves that the Ul expects to be available to the market in coming years.

It must be noted that these figures do not include reserves from NIS countries as the methodology of reserve calculation in these countries fell outside the Ul's guidelines.

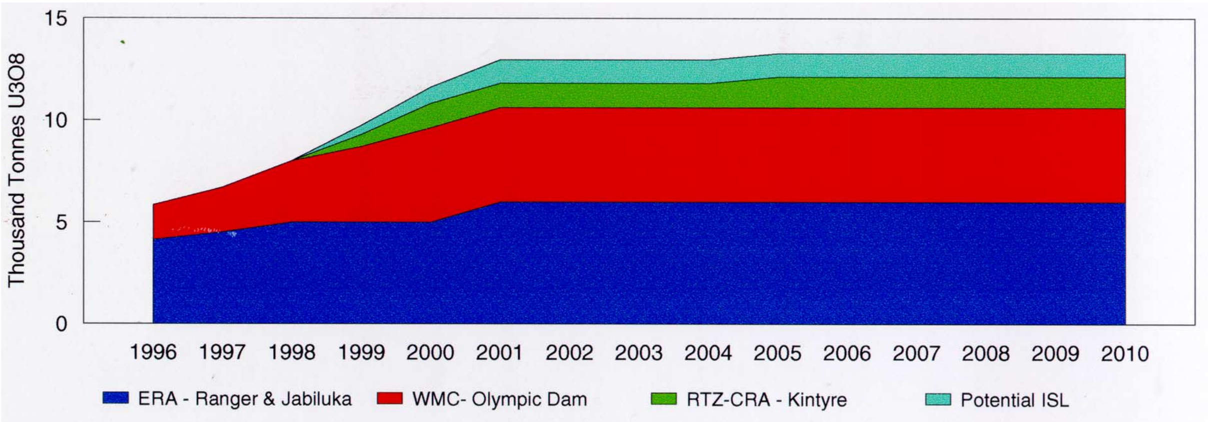

FIG. 8. Australian uranium production.

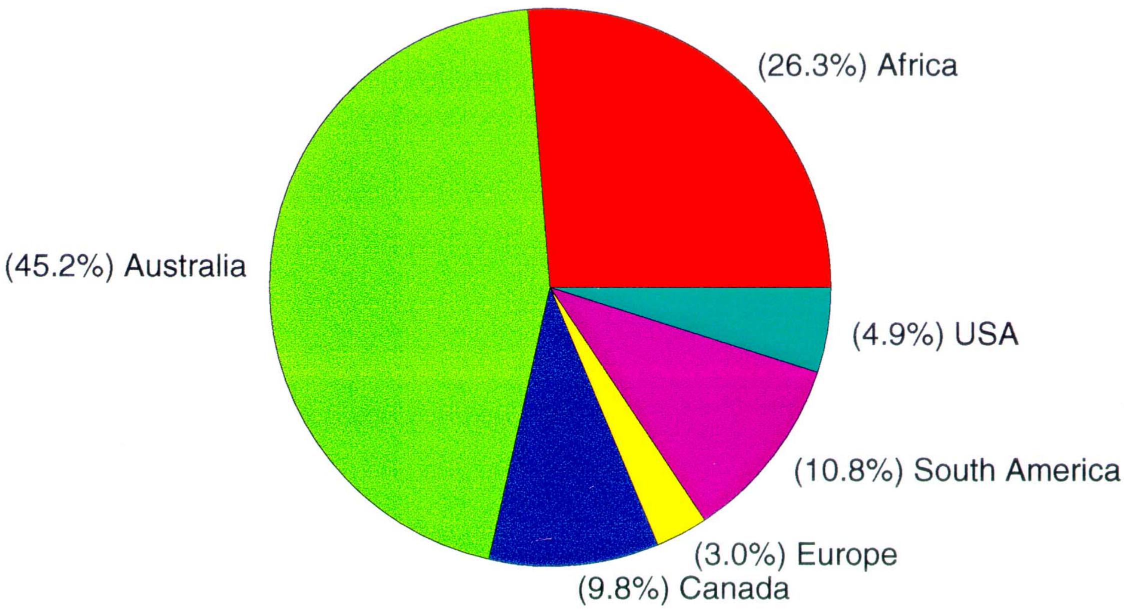

FIG. 9. Uranium reserves Class 1 (Total Reserves < US\$80/kgU).

5. OTHER PLAYERS — LONG TERM

Other potential uranium deposits are shown in Figure 2.

5.1. Yeelirrie

Yeelirrie was discovered by WMC in 1972. The deposit is located about 400km north of the famous goldfields town of Kalgoorlie in Western Australia. The sedimentary deposit has been evaluated to contain a resource of 35 million t at 0.15 % containing 52,000 t U_3O_8.

The mineralisation extends over an area 9km × 1.5km at a depth of 5.5 m below the surface. Mining will be low cost with proposed production of 2,500 t (5.5 mlbs) U_3O_8 per year and 1,000 t per year of vanadium oxide by-product.

An environmental impact statement was produced in 1978 which was subsequently approved by both State and Federal governments. A pilot metallurgical plant was built at Kalgoorlie as part of the feasibility investigations.

With the introduction of the Three Mines Policy, development was abandoned in favour of Olympic Dam. The recent announcement of expansion of Olympic Dam suggests WMC views Yeelirrie as a long term asset to be developed some time after the year 2000.

5.2. Westmoreland

Westmoreland is located in Queensland near the border with the Northern Territory, 400 km north of Mount Isa.

The deposit was originally owned by joint venture partners, Queensland Mines, Urangesellschaft and Hammersley (CRA-RTZ). In 1990 CRA-RTZ took over the exploration work with a view to increasing their equity in the project and in 1996 acquired the remaining equity in the project.

Reserves total 12,000 t U_3O_8 @ 0.166% U_3O_8. The deposit would probably be mined by open pit methods.

5.3. Manyingee/Onslow

This deposit was discovered in 1974 in the northern part of the Carnarvon Basin in Western Australia.

The deposit is owned by Cogema in joint venture with Triako Resources 9.3%. Probable reserves are estimated at 5,000 t U_3O_8 at an average grade of 0.12 per cent.

The deposit has been proven to be amenable to ISL mining techniques following pilot plant testing. Development is not expected in the near term.

5.4.. Ben Lomond

This deposit is located 50 km west of Townsville in Queensland. The deposits are small with reserves estimated at 6,792 t U_3O_8 @ 0.228% U_3O_8. Reserves of co-product molybodenum are estimated at 4,578 t @ 0.149% Mo.

Due to the increased depth, an underground exploration adit was constructed in 1979. 3,500 tonnes of ore were mined to allow bulk sampling and to provide data for the feasibility study.

Proposed mining of the deposit was a combination of open pit (70%) and underground (30%) with annual production of 500 t U_3O_8 and 250 t Mo. The 1984 EIS was approved by the State and Federal Governments, however, development did not proceed because of the Three Mines Policy.

The deposit is owned by Cogema but is currently for sale.

5.5. Other prospects

Other known prospects are listed in the table below.

Project	State	Location	Owner	Reserve/ Resource t (U_3O_8)
Mulga Rock	WA	23km ENE Kalgoorlie	Acclaim exploration	13,000
Oobagooma (ISL)	WA	Derby	Cogema	5,400
Valhalla	QLD	Mount Isa	Summit Gold	10,000
Angela	NT	Alice Springs	Uranium Australia	4,700
Centipede	WA	Wiluna	Wiluna Mines	3,800
Lake Way	WA	Wiluna	Wiluna Mines	3,600
Maureen	QLD	Georgetown		2,900
Bigrlyi	NT	Ngolia Basin	Resolute Samantha	2,700
Lake Maitland	WA	Bronzewing	Skyline Asia	2,400
Angelo River	WA	Ashburton	Acclaim exploration	800
Turee Creek	WA	Ashburton	Acclaim Exploration	225
Paterson Project	WA	East Pilbara	Uranium Australia	---

Source: WA Dept. of Resources Development

6. EXPLORATION ACTIVITY

Over the last 15 years, exploration activity in Australia for uranium has been virtually nonexistent because:

– firstly, the ALP's "'Three Mine Policy" meant any new discoveries could not be developed; and
– secondly, the most prospective areas in the Northern Territory were located in Aboriginal land or National Park.

In the past year, however, exploration activity has increased partly because of the change in Government but also because the Aboriginal groups are once again allowing exploration on their land.

The Aboriginal Land Rights Act requires mining companies to enter agreements with the traditional Aboriginal owners prior to exploration activities. These agreements cover such aspects as environmental protection and royalty payment if mining proceeds. The granting of an exploration licence by the Minister is dependent on a current agreement between the mining company and the traditional owners.

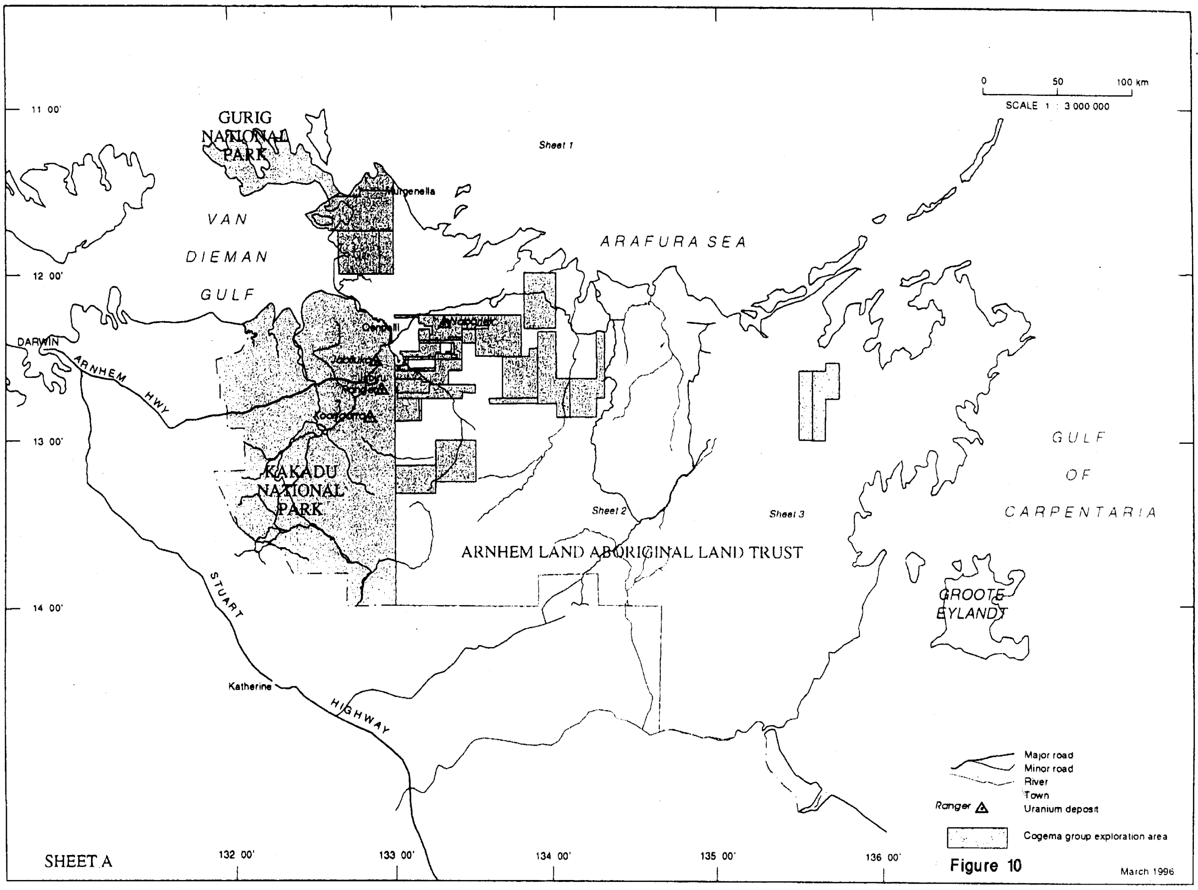

FIG. 10. COGEMA Group uranium interests in the northern territory (Australia).

The willingness of traditional owners to enter these agreements has provided sufficient encouragement for several companies to recommence exploration activity in Australia.

Cogema, in association with EDF, is actively exploring in Arnhem Land in the Northern Territory on exploration leases surrounding the Nabarlek lease as shown in Figure 10. Cogema has a portfolio of 34 tenements covering 11,000 km^2 of which:

- tenements are granted covering 1,200 km^2
- 17 tenements are under negotiation covering 7,500 km^2
- 9 are vetoed by the traditional owners

Other main player, PNC of Japan and Cameco. The PNC-Cameco joint venture have:

- 5 tenements granted covering 3,000 km^2; and
- are negotiating 6 other areas covering 2,000 km^2.

In general, the exploration for uranium is confined to Arnhem Land in the Northern Territory because of its prospectivity. A small amount of exploration is being conducted in Western Australia around Kintyre. It is estimated total exploration expenditure in 1997 will be approximately US$10 million.

ERA is planning to proceed with further exploration at Jabiluka in 1998 once underground access is available. The orebody is believed to be open to the east and at depth.

Junior exploration companies have also joined the rush to explore for uranium. One of the most promising is Uranium Australia Pty Ltd (formerly Noble Resources).

Uranium Australia has a substantial portfolio of under explored uranium based tenements located mainly in the West Alligator Uranium Province of the Northern Territory. These tenements were acquired from Uranerz Australia Pty Ltd when the German parent company pulled out of Australia in 1991 following delays and frustrations surrounding the ALP's "Three Mines Policy".

Uranium Australia has a series of farm-in joint venture agreements for these tenements, mainly with Cogema.

Uranium Australia also has an interest in the Angela Resource, 25 km south of Alice Springs in the Northern Territory. This resource is currently covered by a Ministerial Reserve (since the introduction of the Three Mines Policy) however, the company has applied for a reinstatement of the area.

7. NATIVE TITLE AND ABORIGINAL APPROVAL

In 1992 the High Court of Australia handed down a decision known as the "Mabo Decision". It recognised for the first time that indigenous people who may have been able to maintain traditional connections with their land have legal rights under Australian Law to the ownership of their country according to traditional laws and customs. The legal rights so recognised are known generally as "native title".

Following the Mabo Decision, it was generally believed that a pastoral lease would extinguish any claim to native title. In another historic decision, the High Court of Australia, on 23 December 1996, handed down its determination in the Wik Case. The Court found that the grant of pastoral leases did not necessarily extinguish native title.

Following the Wik Decision, the Federal Government has been under pressure from pastoralists and miners to introduce legislative changes which will guarantee some certainty over land tenure. The negotiation between the Government, Aboriginals, miners and pastoralists has reached some consensus but it will be some time before definitive legislation is passed.

While the application of the Native Title legislation is still uncertain, and it is possible that the Native Title Act could apply to Ranger, Jabiluka and Koongarra in the Northern Territory, notwithstanding that the land in question is already Aboriginal freehold land, ERA's view is that the courts would adopt a pragmatic approach and not allow Native Title claims over these projects. All exploration in Arnhem Land in the Northern Territory is similarly unlikely to be affected by Native Title provisions.

The Olympic Dam mine in South Australia is located on freehold land and is exempt from Native Title provisions however the service corridors for power and water are on pastoral leases. The mine does lie within the traditional Aboriginal territory of the Kokutha people. WMC has entered into a formal agreement with these people to ensure a high level of involvement in the protection of Aboriginal sites in the area.

Kintyre in Western Australia is subject to Native Title claims which will have to be resolved before mining commences. RTZ-CRA are currently negotiating with the relevant traditional owners.

In summary, although the new Native Title provisions do not apply to most of Australia's uranium mines, all companies must work with the traditional Aboriginal owners to negotiate access for exploration and mining. The Aboriginal community is a key stakeholder in the Australian uranium industry and this has been recognised by the mining industry.

The royalties and payments by uranium miners to date have provided the Aboriginal people with funds to invest in many community projects that would otherwise not have been possible. In ERA's case, the Gagudgu people now own the two large tourist hotels in Kakadu National Park providing a long term investment for their people.

As part of its commitment to the local Aboriginal Communities, ERA is currently working with the traditional owners to complete the Kakadu Regional Social Impact Study. This study has been initiated by the community to resolve concerns raised by the proposed development of Jabiluka. The study is sponsored by ERA, the Federal and Territory Governments and the Aboriginal community.

The study will investigate the impact of mining, tourism, conservation, retail and Government activity on the Aboriginal Community. The key objectives of the study will be:

– a clear statement of Aboriginal experiences, values and aspirations regarding development of the Kakadu region; and
– a proposed community development programme to enhance/mitigate impacts associated with development of the region.

The report will be released on 30 June 1997 and will provide factual information which can be used by the traditional owners to assist them in negotiations for the approval of the Jabiluka proposal.

8. SENATE SELECT COMMITTEE ON URANIUM MINING AND MILLING

On 15 May 1997, the Senate Select Committee on Uranium Mining and Milling tabled its report in Parliament. The Committee was formed to inquire into the environmental impact, health and safety and other implications and effectiveness of security agreements in relation to the mining, milling and export of Australian uranium.

The Committee concluded that the findings of the Ranger Uranium Environmental Inquiry — the Fox Report (1977) — *"that the hazards of mining and milling uranium, if those activities are properly regulated and controlled, are not such as to justify a decision not to develop Australian uranium mines"* have been vindicated by two decades' experience.

Uranium mining and milling in Australia in the last two decades has only had minimal impact on the environment and has adhered to a strict health and safety regime.

The Committee used the following quote about Ranger from the Supervising Scientist for the Alligator Rivers Region as an indicative example of the success of uranium mining operations in Australia. *"The co-existence of a uranium mine with a major national park for over 16 years, with no adverse impacts on the ecological integrity of the park, has to be considered a notable achievement".*

The findings of the Committee are a strong endorsement of the Australian uranium mining industry. The report will give the government confidence to approve new developments subject to the implementation of the stringent environmental and health and safety requirements that have proven so successful over the past 20 years.

9. CONCLUSION

Australian uranium miners are quietly optimistic about the opportunities for increased production over the next few years. The current spot market weakness is an anomaly when viewing supply/demand fundamentals. The likelihood of a return to favourable market conditions and a supportive Government have encouraged at least two Australian companies to commit to the expansion of existing operations and the development of new mines as a counter balance to the Canadian dominance.

Australia expects to increase production to 11,630 t U_3O_8 by the end of the decade, significantly in excess of 1996 production levels. Australia and Canada will be major suppliers of uranium to the world's nuclear power utilities in the 21st Century.

ACKNOWLEDGEMENTS

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URANIUM RECOVERY FROM PHOSPHATE FERTILIZER IN THE FORM OF A HIGH PURITY COMPOUND

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Abstract

Uranium recovery from phosphate fertilizer industry is based on a one cycle extraction-stripping process. The process was experimented on both sulfuric and nitric acid attack of phosphate rock when uranium is dissolved in phosphoric acid (WPA) or phosphonitric (PN) solution respectively. The WPA and PN solution must be clarified. In the first alternative by ageing and settling and in the second by settling in the presence of flocculant. The organic components must be removed on active carbon for WPA only since in the case of nitric attack calcined phosphates are used. In both alternatives uranium is extracted from aqueous acidic solutions in the same time with the rare earths (REE), by di(2-ethylhexyl) phosphate (DEPA) as basic extractants, eventually in the presence of octylphosphine oxide (TOPO) as synergic agent. The stripping process is carried out in two stages: in the first stage REE are stripped and precipitated by HF or NH_4F + H_2S0_4 and in the second stage uranium as U(VI) is stripped by the same reagents but in the presence of Fe(II) as reductant for U(VI) to U(IV) inextractible species. Tetravalent uranium is also precipitated as green cake either UF_4xH_20 or $(NH_4)_7U_6F_{31}$ as dependent on reagents HF or NH_4F + H_2S0_4. Uranium stripping is possible for PN solution only if HNO_3 partially extracted is previously washed out by a urea solution. The green cake washed and filtered is dissolved in nitric acid in presence of $Al(OH)_3$ as complexant for F. The filtered nitric solution is adjusted to 3-5 mol/L HNO_3 and extrated by 20% TBP when uranium is transferred to the organic phase which after scrubbing is stripped in the classic way with acidulated ($HN0_3$) demineralized water. Uranium is precipitated as diuranate of high purity. Rare earths left in the aqueous raffinate are extracted by pure TBP from 8-10 mol/L HNO_3 medium. The stripping process takes place with acidulated water. Rare earths are precipitated as hydroxides.

In the previous papers [1,2,3,4] a one cycle extraction - stripping process was described for uranium recovery from phosphate fertiliser industry in Romania (Fig.1).

There are 8 industrial plants in Romania processing each 330,000 t/yr phosphates, mostly of sedimentary origin, therefore a total of approx. 3 millions t/yr. The average content of uranium in sedimentary phosphates is 0.012% U or at total capacity 300 t/y recoverable uranium.

Four plants processing phosphates in Romania are based on sulphuric acid attack (dihydrate process) resulting as intermediate phosphoric acid (WPA) which contains more than 90% of uranium of the rock in the dissolved form as U (VI).

The rest of the four plants of identical capacity are processing calcined phosphates by nitric acid attack resulting a mixture of phosphoric and nitric acids so called phosphonitric (P.N.) solution containing all uranium in dissolved form from the rock.

In the first alternative WPA is filtered and separated of calcium sulphate in the second P.N. solution filtered is cooled to separate calcium nitrate leaving uranium unaffected. Both solutions still have solids which must be eliminated in a solvent extraction system. In the case of WPA the clarification process is carried out by ageing and settling but for P.N. solution a settling process is required and is possible only in the presence of flocculant of certain type efficient at low temperatures, which are characteristic for P.N. solutions.

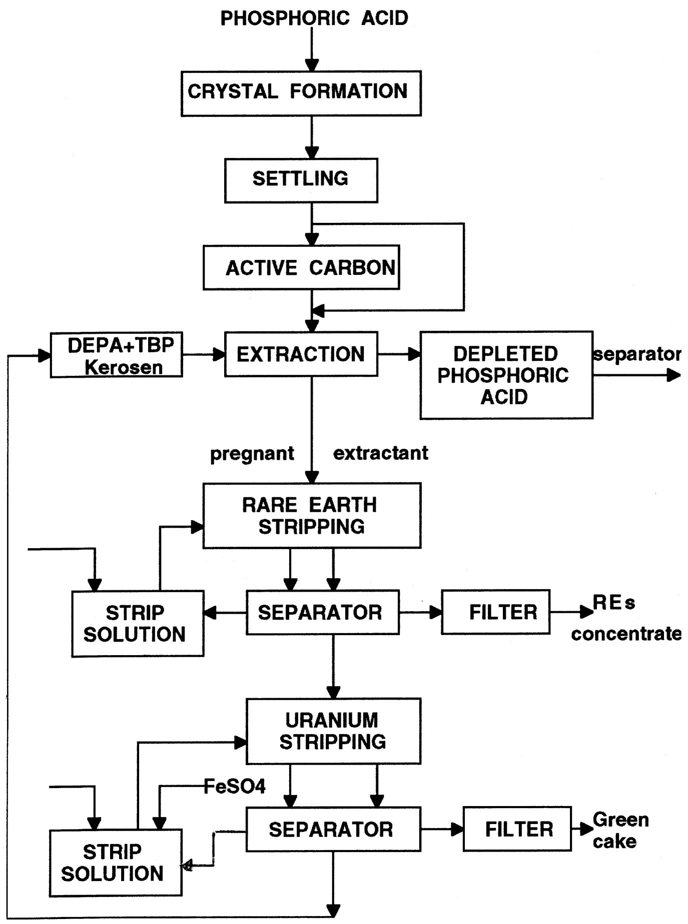

FIG. 1. One cycle extraction stripping flowsheet sulfuric attack

The clarified WPA acid usually has organic components content. In the case of green acid the organic components contents is low and need no extra treatment but for yellow or brown acid the high content of organics require a further treatment to eliminate these components, a process which in this paper was carried out on active carbon. A suitable regeneration and treatment of column led to a high efficiency and long life span of carbon. Uranium retention on active carbon may attain several percent for high content of organics.

Extraction process takes place in a multistage mixer-settler extractor using as basic extractant di (2-ethylhexyl) phosphate (DEPA) used at 1.2 mol/L concentration in kerosene. It may also be used in presence of 0.2 mol/L tri-n-butyl phosphate (TBP) or tri-n-octyl phosphine oxide. In the last case the best synergic mixture is 0.6 mol/L DEPA+0.1 mol/L TOPO [5,6] (See Fig.2).

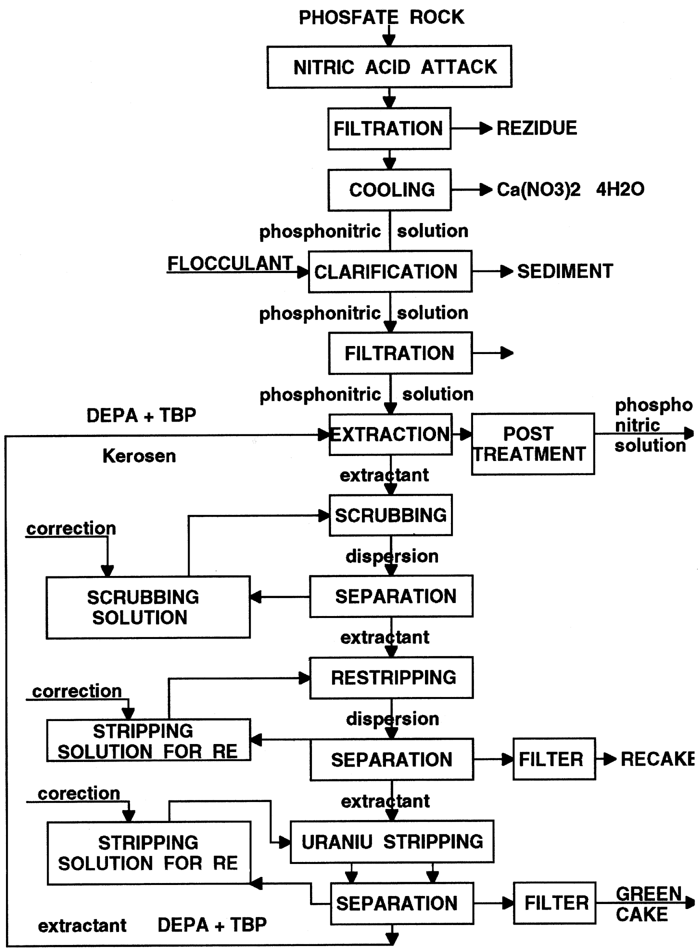

FIG.2. Uranium and rare earth recovery from phosphonitric solution

The synergic mixture with TOPO for U (VI) led to an important enhancement with much higher distribution coefficients permitting the use of extractant / aqueous ratio 1:2 with all favourable consequences resulted.

During the extraction process uranium extracted as U (VI) is attended by rare earth elements (REE). The REE are precipitated as hydroxides of high purity (See Fig.3).

The extractant mentioned was stable therefore no change in distribution coefficients, IR. spectra, potentiometric titration was noticed.

The pregnant extractant leaving the extractor is sent to the stripping stages. The depleted raffinate (WPA or P.N. solution) is sent to a separator in order to achieve an advanced recovery of extractant entrained. This process is important in the alternative of P.N. solution where a final treatment on active carbon might be required to avoid an eventual fire hazard resulted in the end fertiliser product due to the presence of organic extractant.

The first stripping stage consisted of a mixer where the extractant and stripping reagents are introduced. The chemical reagent is either 15% HF or 15% F as NH_4F + 2 mol/L H_2SO_4.

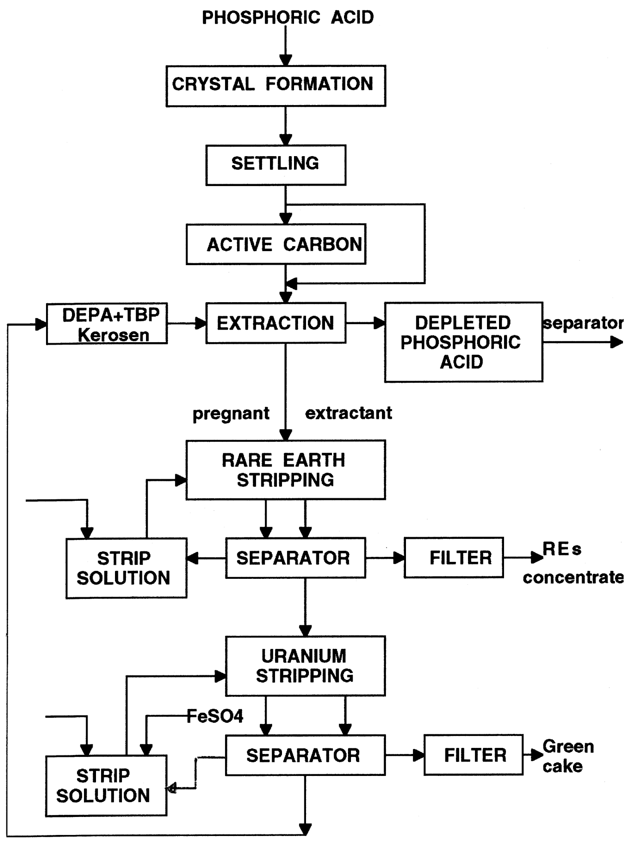

FIG.3. Uranium and RE separate extraction and stripping process

At this stage REE and some impurities are stripped and precipitated. The fine dispersion of the mixer is continuously discharged in a separator where the three existent phases are separated. The solid product from the bottom is unloaded on the filter. The aqueous reagent via hydraulic tubes is sent to a storage tank and is recirculated.

The extractant with U(VI) unaffected via overflow is discharged to uranium stripping stage of similar construction with previous equipment met at REE stripping.

In the mixer the same time with pregnant extractant, the stripping reagent is also introduced. The stripping reagent consisted of: 15% HF + 2-4 g/L Fe (II) or 15% F^- as NH_4F + 2 mol/L H_2SO_4 + 2-4 g/l Fe (II). The stripping reagents have a strong reduction capacity for U (VI) which will be transformed to U(IV) inextractible species. The redox potential involved is even lower than in the phosphoric medium [7].

The U (IV) in presence of F^- is precipitated as dependent on reagents used: UF_4xH_20, $(NH_4)_7U_6F_{31}$.

The fine dispersion from the mixer is discharged to the separator where the solid product is separated at the bottom and is unloaded on the filter, obtaining so called "green cake".

The aqueous reagent eventually corrected in the recirculation tank is reintroduced at stripping stage of uranium. The separated depleted extractant is recirculated at extraction stage without any further treatment.

This flowsheet is valid in the case of WPA. In the case of P.N. solutions during the extraction process some HNO_3 (HNO_2) is also extracted. The presence of HNO_3 (HNO_2) seriously interferes in the stripping stage of uranium. The divalent iron is oxidised to Fe(III) leading to an increase of redox potential of the system, uranium as U(VI) being left unaffected and thus cancelling the stripping effect. In order to avoid this behaviour, the extractant is previously scubbed with urea solution when HNO_3 is eliminated as urea nitrate. For this process a similar mixer-separator unit is used.

The whole system is based and regulated by gravity flow reducing at minimum the power requirements.

The data obtained in the pilot plant processing 5-7 m^3/h WPA have permitted to estimate the operation costs at $ 30/Kg U.

This cost is difficult to be attained by any other process and the green cake resulted in our process, calcined at 400°C in nitrogen media led to anhydrous UF_4. This was fluorinated to obtain UF_6 of high purity because no other existent impurity produced volatile fluorides.

Starting with this process three uranium recovery plants were built in Romania adjacent to three fertiliser plants processing phosphate rock by sulphuric attack (dihydrate).

Since our nuclear power plants are based on CANDU reactors a further study was required in order to obtain in a wet process an uranium compound of high purity.

For this purpose the green cake of 30-50% U has been used to feed a purification plant.

The process studied in this paper started with dissolution of green cake which is not a simple process. The dissolution in nitric acid is only feasible in the presence of a complexing agent for F^-. Any kind of aluminium salt, even in solid form is suitable for this process. The most convenient to use is aluminium hydroxide. The dissolution process is fast in 33% HNO_3 and in the presence of aluminium hydroxide.

The nitric solution is filtered and adjusted at 3-5 mol/L HNO_3.

A similar behaviour is envisaged for REE which were not completely removed at the stripping stage and some are present in the green cake. There is also the possibility to strip both uranium and REE in the same product.

Uranium is extracted from nitric solution with 15-25% TBP in kerosene using a 5-7 step mixer settler extractor. The REE and the rest of impurities are left in the aqueous raffinate. For this purpose it is required to saturate as much as possible the TBP in uranium.

The stripping process of pregnant extractant is also carried out in 7 step mixer settler (extractor) using as stripping reagent 0.1 mol/L HNO_3 aqueous solution.

Uranium is precipitated as a diuranate or with perhidrol as peroxide when the product is of nuclear purity.

The aqueous nitric raffinate is adjusted to 8-10 mol/L HNO_3 and the REE are extracted in pure TBP. At high nitric acid concentration and in pure TBP the distribution coefficients for REE are high. Several extraction steps are required as in case of stripping process carried out with 0.1 mol/L HNO_3.

The REE are precipitated as hydroxides of high purity.

The total operation costs of a product of nuclear purity starting from the green cake is estimated at $ 17/Kg U and from the WPA $ 47/ Kg U.

The one cycle extraction stripping process described in this paper is different of ORNL two cycle extraction-stripping process [8] since uranium is obtained as a green cake and REE are also recovered especially from WPA where yttrium is predominant, more than 90%. There is also the advantage of obtaining UF_6 directly from the green cake.

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RELIABILITY AND DEVIATIONS OF RADIOMETRIC DATA

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Abstract

Reliability of radiometric data has been studied by field instruments tests and by analyses and control measurements for available radiometric maps. Terrestrial gamma radiation is measured by total count instruments and by gamma ray spectrometers. Repeated measurements by total count rate meters showed the deviations of gamma dose rate in the range 2–15 $nGy.h^{-1}$, in dependence on exposure time. Airborne and ground gamma ray spectrometry shows the data deviations in the range 0.1–0.2% K, 0.3–0.8 ppm eU and 0.3–1.2 ppm eTh in dependence on the geological setting. Ground verification of regional radiometric maps indicated standard deviation 13 $nGy.h^{-1}$. Radiometric manifestation of U mineralized bodies is compared with indicated values of data reliability.

1. PHYSICAL PROPERTIES OF URANIUM

Direct indication of uranium by geophysical methods is due to its physical properties based on the measurement of radioactivity. Metal uranium exhibits low electrical conductivity, belongs to paramagnetic elements, and in spite of its extremely high density, its mineral accumulations form bodies hardly detectable by gravimetric methods. Uranium and its decay products, forming U disintegration series, are the source of nuclear radiation. In U exploration, gamma rays are mostly detected due to their relatively high penetration through the matter.

2. RADIOMETRIC DATA

Separate radiometric data, radiometric profiles or radiometric contour maps are the output of airborne and ground uranium exploration. Total count measurements of terrestrial radiation are mostly expressed in gamma dose rate ($nGy.h^{-1}$), gamma ray spectrometry gives concentrations of K, U and Th in rocks. Detection of K is direct and the concentration is expressed in % K, determination of U and Th is indirect, by means of daughter products, and their concentrations are expressed in equivalents, ppm eU and ppm eTh. Reported numerical values of natural radionuclides concentrations, or of the terrestrial radiation, are the results of a sequence of complex operations, starting with detection of gamma rays and including data processing. Summation of the physical nature and characteristics of individual steps and their inaccuracy is reflected by deviations of output data, that should be considered in data interpretation.

3. CAUSES OF RADIOMETRIC DATA DEVIATIONS

Techniques of measurement, data processing and compilation of radiometric maps contribute to resultant deviations. Substantial influence on results may have the statistical nature of radioactive decay and fluctuations of nuclear radiation, technical parameters of used instruments, calibration facilities and methods of instrument calibration, geometry, density and the mode of field radiometric measurement, data processing, data levelling and their graphical presentation. If maps and data are used for the assessment of the natural radiation environment or for the interpretation of registered radiometric anomalies, reliability of reported radiation quantities should be acceptable and should be checked. Analysis of sources of possible errors in data processing quotes also natural variation in radiometric field, data entry or output faults, class interval definition in data interpolation and data positional inaccuracy [1].

Consistency of radiometric data, recorded with different instruments, is affected by their technical parameters. The use of total count instruments, based on integral detection of gamma rays of a broad interval of energies, reflects type of detectors, energy threshold of instruments and the way of their calibration. Gamma ray spectrometry analyses of K, U and Th in rocks has been substantially improved by introducing the IAEA laboratory reference materials for geological analyses and by research, development, establishment and inter-comparison of world net of calibration facilities for field radiometric equipment [2, 3].

4. PRECISION OF IN SITU RADIOMETRIC MEASUREMENTS

Deviations of radiometric data have been studied. Gamma dose rate deviations of a single very short (t = 10 s) measurement, with portable count rate meter with small NaI(Tl) 20 × 30 mm scintillation detector and low discrimination energy threshold (50 keV), are due to counting statistics in the range 7–15 $nGy.h^{-1}$, while longer (t = 100 s) exposures showed deviations 2–4 $nGy.h^{-1}$. Repeated measurements with portable gamma ray spectrometer fitted up with a NaI(Tl) 76 × 76 mm scintillation detector, exposure time t = 4 min. in low–medium radioactive rocks showed standard deviations in determination of natural radionuclides in the range 0.05–0.1% K, 0.3–0.7 ppm eU and 0.3–0.8 ppm eTh, while in highly radioactive rocks (4% K, 6 ppm U, 30 ppm Th) standard deviations are 0.15–0.2 % K, 0.7–0.8 ppm eU and 1.2 ppm eTh. In situ gamma ray spectrometry analyses, with longer exposure time exhibit lower standard deviations. Airborne measurements give similar values.

Portable gamma ray spectrometers with a Cs-137 reference source spectrum stabilization are capable to determine highly radioactive mineralization up to limits of 500 ppm U or 1000–2000 ppm Th with acceptable accuracy. Gamma radiation of U mineralization of higher grade with 609 keV energy line of Bi-214 interferes with the peak 662 keV of Cs-137 reference source and the energy spectrum stabilization of the instrument is disabled. Improvement in spectrum stabilization under these conditions can be reached by using Ba-133 reference source with its 356 keV energy peak.

5. VERIFICATION OF REGIONAL RADIOMETRIC MAPS

Radiometric map of the Czech Republic 1:500000, published in 1995 [4], expressed in gamma dose rate, is based on regional (1957–1959) and detailed (1960–1971) airborne total count measurement, airborne gamma ray spectrometry (from 1976 onward), and has been completed by ground radiometric survey. Original airborne maps of contours, on the scale 1:200000, has been converted to vector form by digitizing and expressed by 871652 data in a regular grid 300 × 300 m over the territory. Back calibration was applied in 1994 to convert the data into dose rate and to level the map. Map of contours, with the step of 10 $nGy.h^{-1}$, was compiled by computer processing using the method of kriging. Regional terrestrial radiation in the Czech Republic, formed by magmatic, sedimentary and metamorphic rocks, is in the range 15–200 (6–245) $nGy.h^{-1}$, with the mean 65.6 +/- 19.0 $nGy.h^{-1}$.

A series of factors affect resultant data. Verification of the Radiometric map of the Czech Republic 1:500000 has been carried out in 1995 and 1996 by comparison with ground gamma ray spectrometry measurements.

In 1995, 81 regional traverses 1–5 km long, situated in rocks of high, medium and low radioactivity, in the whole area of the Czech Republic, has been measured with calibrated portable gamma ray spectrometer GS-256, totally at 761 segments of the length of 200 m, with exposure time 2 min. per segment, in dynamic mode. Results of ground measurement were expressed in dose rate, averaged in each traverse, and compared with gamma dose rate values of the radiometric map 1:500000. The average difference of compared data sets 2.1 $nGy.h^{-1}$ shows good map regional dose rate data levelling, while the mean deviation +/- 13.8 $nGy.h^{-1}$ illustrates expected differences at individual sites. Coefficient of correlation of compared data sets (N = 81) is 0.942.

In 1996, ground gamma ray spectrometry measurement of the area 6 × 6 km at 49 stations in regular grid 1 × 1 km, in static mode, with exposure time 4 min., has been carried out at Lovosice, northern Bohemia, in an area formed by Cretaceous sediments. The mean of determined gamma dose rate was 50.7 $nGy.h^{-1}$ and the median 53 $nGy.h^{-1}$, what is comparable with the interval 50–60 $nGy.h^{-1}$ indicated by the radiometric map 1:500000.

In 1996, 50 traverses, each 1 km long, situated in the area of the Czech Republic along the Czech-German (Saxony) border, in the geographical traverse Vojtanov–Hrádek and Nisou of the length 200 km, has been measured with portable gamma ray spectrometer GS-256, in dynamic mode, at 255 segments of the length of 200 m, with exposure time 2 min. per segment. Results were averaged for each traverse and compared with the radiometric map 1:500000. Average difference of compared data sets is 1.7 $nGy.h^{-1}$ with the mean deviation +/-12.9 $nGy.h^{-1}$.

6. ANALYSES OF RADIOMETRIC DATA DEVIATIONS

Differences in comparisons of radiometric data were observed. The test measurement with various radiometric instruments at common sites in various geological setting showed a limited distribution of resulting gamma data. Significant differences in maps of adjoining regions may be caused due to the different data field grids, data processing and maps interpolation. Different detection range of airborne measurement, averaging the data, and ground local measurement, instrument calibration inconsistency and instrument gamma energy response contribute to deviations. Radiometric maps describe well general radioactivity features of an area, while local data reliability can be affected by various phenomena. Indicated radiometric deviations by their magnitude form a fraction of the range of natural terrestrial radiation.

7. MANIFESTATION OF GAMMA RADIATION OF URANIUM MINERALIZATION

Outcropping uranium mineralization is the source of increased radiation easily detectable by radiometric equipment. Corresponding ground radiometric anomalies of magnitude X00–X0000 $nGy.h^{-1}$ and X00–X0000 ppm U of local sources limited prevailingly by their extension, become weaker at ground and airborne survey traverses distant from the centre of the anomaly. Though attenuation of gamma radiation of local sources with the distance is very progressive, at the distance of 100 m of the order 10^{-2} up to 10^{-4}, in dependence on the dimension of mineralized body, airborne and carborne survey, with instruments of high sensitivity, can be effective in their location.

Attenuation of gamma rays in rocks limits direct detection of natural radiation subsurface sources situated deeper than 0.5 m from the earth surface. However, mineralized U bodies form in their surroundings radioactive mechanical, chemical and gaseous halos, that manifest themselves by anomalies attaining values X0–X00 $nGy.h^{-1}$ and X–X0 ppm U. Due to usual larger surface dimensions of these targets of U exploration, their radiometric manifestation can be detected at larger distance from the proper mineralized objects.

ACKNOWLEDGEMENTS

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CONTRIBUTION TO CHARACTERISTICS OF URANIUM OXIDES

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Abstract

Uranium oxides from pegmatitic, metamorphic and metasomatic uranium occurrences were investigated with the objective to check for differences in their physico-chemical properties and, whether such properties are sufficiently distinct to be applied as an exploration tool. Research methods included microscopy, electron microprobe and X-ray diffractometry amended by determinations of reflectance, Vickers hardness, unit-cell dimension and oxidation grade. Tentative research results are as follows:

(a) U-oxides (uraninites) of pegmatites always contain significant amounts of Th (1,5–10 wt.% ThO2).
(b) U-oxides from metasomatic environments have high, but variable contents of Fe, Ca, Ti, Si and Th (around 10 wt.%), Th being low.
(c) U-oxides crystallised during metamorphism contain minor impurities of the above listed elements (total of oxides < 2 wt.%).
(d) Redistributed U-oxides have elevated amounts of these elements.
(e) Unit-cell dimensions of U-oxides tend to reflect a complex function of formation temperature, oxidation grade and the influence of incorporated elements caused by their radius and electro-negativity.
(f) A global negative correlation of unit-cell dimension and oxidation grade of uranium oxides is indicated but based on widely varying ratios of the two parameters.
(g) Colloform U-oxide (pitchblende) is characterised by elevated Ca-contents (1–5 wt.% CaO) and an almost complete lack of Th (< 1 wt.% ThO2).
(h) Idiomorphic U-oxide (uraninite) is commonly low in Ca (< 1.5 wt.% CaO) but contains relatively high Th values.
(i) The reflectance of U-oxides generally correlates positively with Vickers hardness and unit-cell dimension, but the incorporation of other elements in the lattice of U-oxides may cause strong interference.

1. INTRODUCTION

The research programme was primed (a) to define uranium oxides by means of physico-chemical parameters which (b) may help to decipher, together with other criteria, the behavior of uranium in geological environments. Beside microscopy and auto-radiographic methods the following investigations were performed:

(a) Reflectance (RV) was measured between 436 and 644 mm with a Leitz photometer using SiC and a glasprisma as standard (analytical error: 0,5% RV).
(b) Vickers hardness (VH) was determined with a Leitz micro-hardness tester and a weight of 100 p.
(c) Electron microprobe analyses were carried out with a measurement time of 20 and 60 seconds, operating voltage of 25 kV, and a sample current of 10 namps. Standards were Al, Ca, Ti, Si and Fe bound to minerals, synthetic PbS, metallic Th, Ce and U.
(d) X-ray diffractometry: Gandolfi and powder method.
(e) The unit-cell was found on material separated directly from the polished section by drilling to obtain homogeneous mineral fractions and examined with a Guinier-Jagodzinski Camera using sodalite as internal standard (see JCPDS 41–1422).
(f) The oxidation grade respectively U(VI) and U(total) were analysed polarographically and determined by the standard addition method [1, 2].

2. GEOLOGY, MINERALOGY AND ORE PARAGENESIS OF INVESTIGATED OCCURRENCES

A summary of physico-chemical data of the investigated U-oxides and the corresponding occurrences is provided in Table I.

2.1. Pegmatite

Madawaska, formerly Faraday mine, Bancroft district, Ontario, Canada. Uranium ore bodies occur in late tectonic pegmatitic and granitic dikes located in a metagabbro-amphibolite belt [12]. The origin of the pegmatites is considered of partial melting during the Grenvillian Orogeny [13]. Principal ore minerals are Th-rich uraninite and uranothorite dated 1100 to 800 m.y. old [5]. Other uraniferous minerals are sphene, cryolithe, zircon, uranophane and REE-minerals. Uraninite is euhedral to subhedral, weakly corroded and broken due to growth of isotropic zircon. The autobrecciation shattered the host rocks, intense hematitization overprinted the rocks.

Hagendorf, NE — Bavaria, Germany. Granites and pegmatites of late Hercynian age form intrusions within Proterozoic rocks. The Hagendorf pegmatite is considered a derivation of the Flossenbürger Granite [4, 14]. The pegmatite contains a number of irregularly distributed ore minerals including uraninite, columbite, hematite, sulfides and rare minerals [3, 15, 16]. Two varieties of uranium oxides are noticed: up to 0,2 mm large uraninite octahedrons and cubes occur peripheral within and upon columbite (uraninite 1). The other variety consists of irregular shaped aggregates which commonly occur suspended along the long axis of columbite (uraninite 2). The latter were interpreted as exsolutions [17]. The chemical composition of both is similar. Host rock alteration is restricted to hematite along cracks, hematite halos around uraninite hosting columbite, and corrosion of columbite.

Way Lake, Wollaston Domain, Saskatchewan, Canada. Uraniferous pegmatite cutting Aphebian quarz-feldspar gneiss is overprinted by albitization caused by Na-metasomatism [6]. Mineralization occurs as massive uranium lenses emplaced in a shear zone which is cut off at both ends by faults. Two U-oxides are distinguished:

(a) Massive Pb-rich U-oxide with high reflectance. A minimum age of 1735 to 1765 [6] corresponds to the Hudsonian Orogeny (Pitchblende 1).
(b) Ca-rich U-oxide strongly pitted, cracked, corroded and patchy oxidized. Where fresh, RV is relatively high (Pitchblende 2). Partly euhedral looking U-oxides within the pitchblende are interpreted as relics of pegmatitic uraninite.

2.2. Metamorphite

Orient, Kettle Falls Gneiss Dome, NE Washington State, USA. The occurrence is situated in a belt of Proterozoic metasediments of upper amphibolite facies (Boulder Creek Formation) intruded by a variety of plutons. Country rocks are quartzite and quartz-feldspar-biotite gneiss. Mineralization is hosted by a schlieren augengneiss with bands of biotite accumulations. Principal uranium mineral is finely disseminated broken and corroded euhedral U-oxide (uraninite) arranged in bands and lenses together with magnetite and pyrite. The uraninite contains about 1 wt.% ThO_2, PbO and SiO_2 each. The Vickers hardness is high. Alteration is very minor consisting of chloritization and bleaching of biotite.

TABLE I: SUMMARY OF OUR CHEMICAL AND PHYSICAL DATA OF U-OXIDES FROM PEGMATITE, METAMORPHITE AND METASOMATITE ENVIRONMENTS

Occurrence U-oxide	Average microprobe analyses of uranium oxides																	Age m.y.	
	n	UO_2	ThO_2	PbO	CaO	Ce_2O_3	FeO	TiO_2	SiO_2	Al_2O_3	Total	UO_2/ThO_2	CaO/ThO_2	UO_{2+x} x =	VH 100 p	$RV_{546\,nm}$ (%)	a_o (Å)	Rock	U-oxide
Pegmatite																			
Hagendorf																			
Uraninite 1	23	94,29	2,22	3,55	0,04	0,01	0,09	0,01	0,08	---	100,29	42	<0,1		981	18,0	5,50 [3]	293 [4]	
Uraninite 2	3	94,30	1,57	3,32	0,07	---	0,16	---	0,13	0,03	99,58	60	<0,1			18,3			
Madawaska																			
Uraninite	24	72,38	6,40	10,77	1,16	1,38	0,02	0,04	0,18	---	92,33	11	0,2	0,12	898	16,4	5,460		800-
Uranothorite	5	13,76	43,34	1,04	3,48	0,75	0,37	0,02	20,38	---	83,44	<1	0,1		266	5,8			1100 [5]
Way Lake																			
Pitchblende p1	8	67,48	2,59	17,79	1,43	2,15	---	---	0,16	---	91,60	26	0,6	0,42		16,4	5,494		1765 and
Pitchblende p2	9	67,99	1,02	15,18	2,96	1.10	0,02	---	0,75	0,02	89,04	67	2,9	0,41	619	16,7	5,463		1735 [6]
Metamorphite																			
contact-met:																			
Alm Bos																		Intrusion	
Uraninite	29	98,20	0,25	0,54	0,45	0,13	0,02	0,01	0,15	0,01	99,76	393	1,8	0,06	1394	17,4	5,467	52-19 [7]	
med.grade:																			
Orient																			
Uraninite	33	94,68	1,11	1,08	0,15	0,11	0,01	0,01	0,08	0,02	97,25	85	0,1		1333	17,8			
Höhenstein																			
Uraninite	23	90,59	0,10	2,73	0,60	0,22	0,12	0,36	0,51	0,02	95,25	906	6,0		980	16,5			
Pitchblende p1	23	86,81	0,20	1,65	2,49	0,52	0,17	0,20	0,44	0,01	92,79	434	12,5	0,23	1155	16,0	5,436		295 [8]
Pitchblende p2	7	79,69	0,37	2,19	0,94	0,57	0,61	0,45	0,73	0,12	85,67	215	2,5		564	13,8			
Pbl.-schlieren (s)	6	81,83	0,42	2,89	1,89	0,85	2,18	0,51	1,15	0,02	91,74	195	4,5		524	15,7			
Wäldel																		Granite	
Uraninite	22	92,91	0,24	2,91	0,54	0,09	0,07	0,21	0,26	0,04	97,27	387	2,3		927	16,5		303 [9]	
low-grade:																			
Niamtougou																			
Pitchblende	5	90,77	0,18	7,12	0,73	0,01	0,08	---	0,29	0,05	99,23	504	4,1						
Forstau																			
Pitchblende	7	87,57	0,22	2,49	0,38	0,17	0,09	0,10	0,36	0,08	91,46	397	1,7						
Metasomatite																			
Mosquite Gulch																			
Uraninite (u)*)	12	63,91	0,15	10,94	2,77	0,08	7,28	0,34	4,69	1,50	91,66	426	18						
Pbl veinlets (v)	15	73,07	0,07	18,37	2,66	0,28	0,03	0,06	0,42	0,03	94,99	1045	38			16,8			2200 [10]
Pbl on grains (g)	9	85,55	0,21	4,18	2,33	0,11	0,02	0,02	3,82	0,09	96,33	407	20						
Kitongo																			
Uraninite (I)*)	29	74,44	0,13	2,78	3,11	0,17	2,98	0,30	6,19	0,43	90,53	572	24		351	11,2		590 [11]	
U-Ti-oxide (II)	5	57,84	0,19	1,27	2,53	0,15	1,17	17,77	3,40	---	84,32	351	21			10,2			

*) Corroded/stained Pbl: Pitchblende pl: massive Pitchblende p2; Spherulitic/oxidized Pitchblende ( ): see Fig. 1+2

Höhenstein/Poppenreuth and *Wäldel*/Mähring, NE-Bavaria, Germany. Moldanubian biotite-sillimanite-mica schist and gneiss of upper amphibolite facies contain granitoid bands and lenses parallel to the schistosity [18].

At *Höhenstein* uranium occurs in a variety of minerals disseminated in schists and granitoids [8, 19, 20, 21]. Our studies yielded the following results:

(a) U-oxide with high reflectance (uraninite) predating pyrite,
(b) U-oxide with low reflectance (tetragonal U_3O7, [20]),
(c) U-oxide massive or colloform (pitchblende) present in several generations and oxidation grades with partly high reflectance,
(d) Mostly concentrically zoned globules of U-oxide and U-oxides coating quartz grains (pitchblende),
(e) Coffinite as individual grains or coating quartz and brannerite.

The reflectance decreases from the euhedral uraninite to the pitchblende globules with higher CaO and FeO content. Uraninite supposedly formed by metamorphism from sedimentary uranium. Subsequent U redistribution resulted in uraninite accumulation in veinlets. Repeated cataclasis remobilized and redistributed this material again.

At *Wäldel* U-oxides are associated with quartz-filled structures [9]. Three U-minerals are distinguished:

(a) Euhedral crystals often dissolved from the core outwards (uraninite),
(b) Globular, concentric U-oxide with very low reflectance values (pitchblende),
(c) Coffinite coating quartz grains, filling voids and concentrated in aggregates paralleling the schistosity.

Niamtougou, Lama Kara, northern Togo. Country rock is quartz-mica-amphibol gneiss and calcite-quartz-mica gneiss of greenschist facies. The Pb-rich U-oxide forms 5 to 10 μ large globules irregularly shaped and partly colloform aggregates (pitchblende) disseminated on schistosity planes as well as in minifractures. Locally the aggregates indicate euhedral habits. Biotite and hornblende are chloritized adjacent to the U-oxides. Other ore minerals are mainly ilmenite, magnetite and pyrite.

Forstau, Land Salzburg, Austria. Spotty U showings occur in the Permo-Triassic phyllite series originated from lacustrine sediments by greenschist facies grade metamorphism during the Alpine Orogeny. Host rock is a banded ankerite-sericite-quartz schist [22] stratigraphically underlain by graphitic horizons [23, 24]. Host rock alteration is very minor consisting of hematitisation, limonitization and chloritization. U-oxides are present as pitchblende and minor uraninite. The U-oxides occur parallel to the schistosity in dark quartz laminae, in sericitic parts or in fold saddles of microfolds, and along irregular joints which trend more or less perpendicular to the schistosity. U-oxides also occur at the interface between carbonate lenses and quartz-muscovite layers. These U-oxides are interpreted as replacements of algae or other organic substances. Pyrite is present in fine grained anhedral partly, framboidal aggregates associated with U-oxides and in euhedral crystals which do not show any relationship with the uranium mineralization.

Alm Bos, Adamello Massif, northern Italy. Intrusions of igneous rocks, 52 to 19 m.y. old [7] have contact-metamorphosed uraniferous arkoses and sandstones of Permian age to quartz-feldspar hornfels and quartzite. In sediments unaffected by metamorphism the Uranium is present as pitchblende and amorphous material commonly associated with organic substances. With approach to the Adamello intrusion, the U-oxides are gradationally recrystallized, ultimately to euhedral uraninites in the inner contact-metamorphosed aureole [25]. Well crystallized uraninite is distinctly anisotrop, partly porous and intergrown with silicates. The uraninite is very pure. It has a high uranium content and very low contents of the other compounds [26]. Principal associated sulfides are pyrite, pyrrhotite and chalcopyrite. The Alm Bos mineralization illustrates the spaciously transitional impact along a thermal gradient on a sedimentary, sandstone-type uranium mineralization.

2.3. Metasomatite

Mosquito Gulch, Nonacho Basin, NWT, Canada. Na-metasomatism along a cataclastic zone at the contact of the granitic basement and the overlying late Aphebian Nonacho Formation transformed the granite into albitite. Where mineralized, the albitite is massive and pink coloured due to hematitization. In strongly albitized rocks [10] U-oxides are present in several varieties/generations.

(a) Finely disseminated strongly corroded U-oxides in chloritic intervals within breccias (uraninite).
(b) Anhedral U-oxides along grain boundaries (pitchblende).
(c) Anhedral U-oxides in fractures and as veinlets (pitchblende).

Compared with (a) the varieties (b) and (c) have a relatively high reflectance and significant lower Fe content. Type (c) has a relatively high Ca content. All varieties are low in Ti.

Kitongo, Poli area, Cameroon. Metasediments of the Upper Precambrian Série de Poli (greenschist to amphibolite facies [27]) are intruded by Panafrican plutons including the Kitongo granite [11]. The U occurrence is situated at the northwestern cataclastically overprinted intrusive contact of the Kitongo granite with schists and gneisses. Intense Na-metasomatism affected the biotite-hornblende granite. U-oxides are hosted by an albitization zone in which the granite is partly transformed to Na amphibole albitite or aegerine albitite. Si and K are removed and Na is added [28, 29]. Additional alteration includes hematitization and limonitization. The U-oxides are more or less decomposed and "oxidized". The style of "oxidation" is caused by increasing incorporation of Ti. Reflectance is decreasing with increasing Ti and Si content. Paragenetic minerals are magnetite and subordinate pyrite, galena, chalcopyrite and alteration products thereof.

3. CHEMICAL AND PHYSICAL PROPERTIES OF U-OXIDES

The TiO_2-SiO_2-CaO triangles presentation (Fig. 1) illustrate the wide range of these compounds in U-oxides. Most samples group in the CaO sector. But samples of metamorphites contain higher amounts of Ti and Si compared to those of pegmatites (Fig. 1a). U-oxides of metasomatites are relatively enriched in Si and Ti (Fig. 1b). The SiO_2 -CaO correlation diagram (Fig. 2) shows that the U-oxides of metasomatites plot above about 1 wt.% SiO_2 whereas those of pegmatites and metamorphites are below this level. In the latter field two distribution groupings are obvious: all uraninites analysed contain less than 1,5 wt.% CaO whereas the CaO content of pitchblende ranges from 0,5 to 4 wt.%.

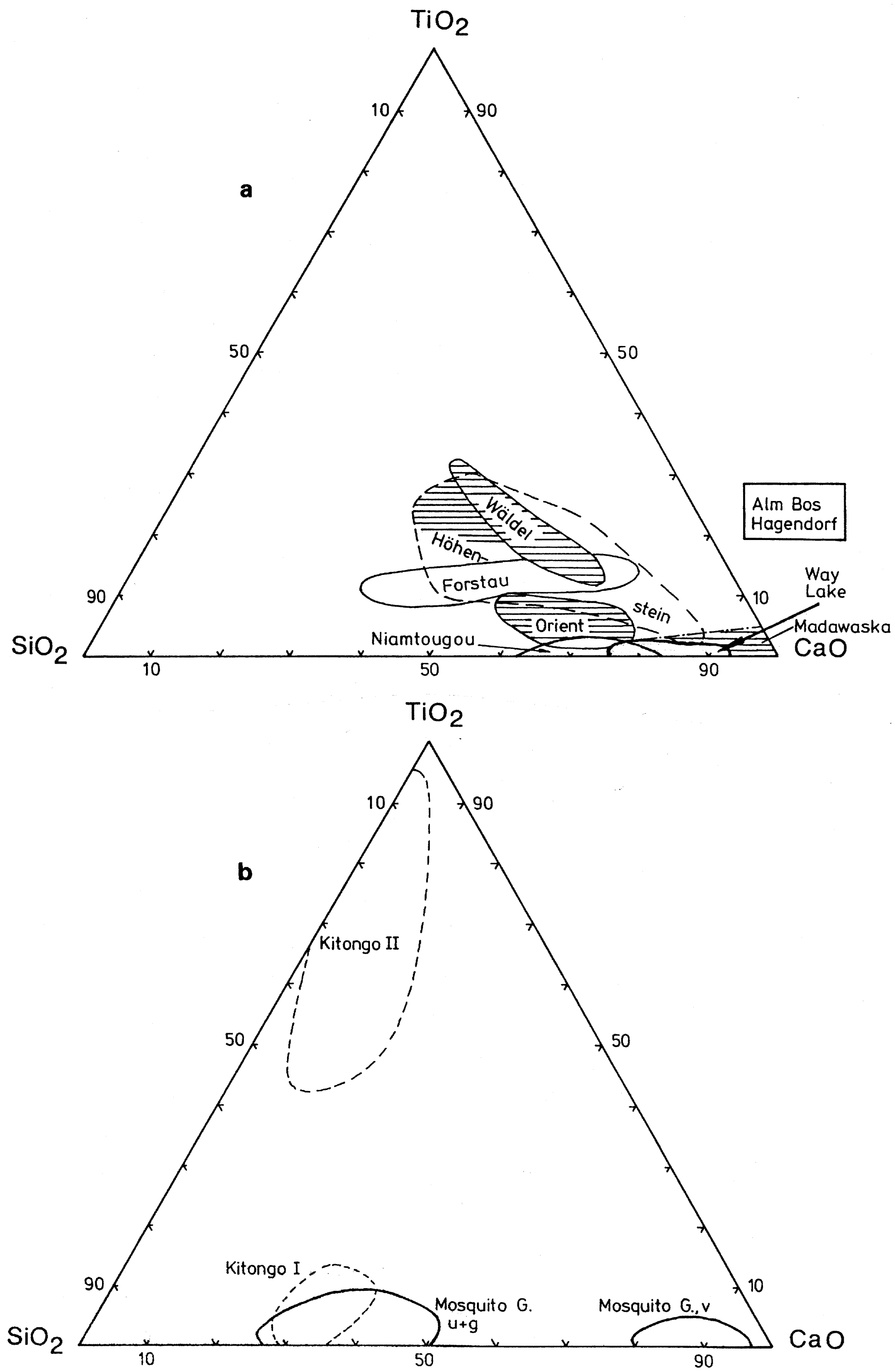

FIG. 1. Triangle diagrams for U-oxides of the investigated occurrences.
(1a) Pegmatites and Metamorphites.
Hatched sections: uraninite, white sections: pitchblende
(1b) Metasomatites. u = uraninite, v = U-oxide in veins, g = U-oxide on grains, Kitongo I = uraninite, Kitongo II = "oxidized" uraninite.
Solid line: Mosquito Gulch, dotted line: Kitongo
Alm Bos and Hagendorf do not plot in this type of diagram.

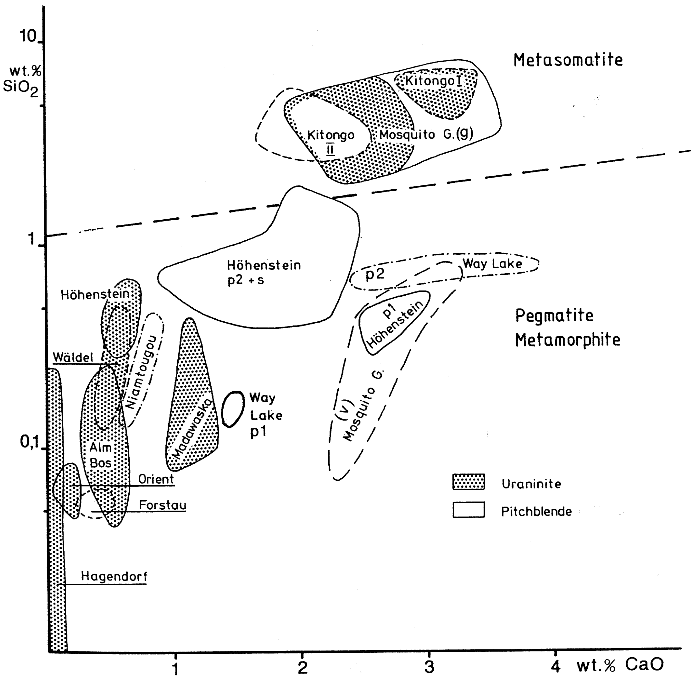

FIG. 2. Correlation diagram for U-oxides of the investigated occurrences.

p1: massive pitchblende; p2: spherulitic or oxidized pitchblende; s: pitchblende schlieren, v: U-oxide in veins.

Plotting our analytical data and literature data in a TiO_2-SiO_2-CaO triangle diagram (Fig. 3) permits in a general way the distribution of four segments. In Fig. 3a, segment 1 represents the relatively pure U-oxides (uraninite) but partly also U-oxides with high CaO content (pitchblende) of metamorphic, pegmatitic and contact-metamorphic origin. Segment 2 contains U-oxides with higher Si values (1 to 10 wt.% SiO_2) relative to Ti (< 1 wt.% TiO_2) and Ca (1–3 wt.% CaO). These are minerals from metasomatic deposits and redistributed U-oxides from metamorphites. Segment 3 and 4 includes Si-rich U-oxides (> 10 wt.% SiO_2) or coffinite, and Ti-rich U-Oxides and brannerites formed in various environments. Transferring data of segment 1 from Fig. 3a into a CaO-ThO_2-UO_2 diagram (Fig. 3b) two segments can be established representing Ca-rich U-oxides (pitchblende) and Ca-poor, partly Th-rich U-oxides (uraninite). The high Th uraninite tends to be typical for pegmatites and the low to zero Th uraninite for contact-metamorphite and metamorphite environments.

Figure 4 displays the interrelationship of lattice constants (ao), oxidation grade, reflectance (RV), and hardness (VH) for U-oxides. Diagram 4a shows no correlation of the two parameters ao and VH. Diagram 4b displays a positive correlation of ao and RV. Higher amounts of elements incorporated in U-oxides and/or U^{6+} are associated with a decrease in RV. Diagram 4c indicates a negative correlation of ao and oxidation grade except for the Way Lake samples (WL). The open dots and the extrapolated line are taken from Brooker & Nuffield [43]. The differing ao values of the Way Lake samples correspond to elevated Th contents. This illustrates that not only a change in oxidation grade provokes a variation in the unit-cell dimension. The same effect results also from the incorporation of other elements. The data imply that incorporation of certain elements in U-oxides causes unit-cell shrinking. The reason lies in the smaller ionic radius of the introduced element (Si, Ti etc.) compared to that of U^{4+} (1,01 Å in coordination 8). On the other hand, a Th^{4+} (1,06 Å) content in U-oxides causes a greater lattice constant. Replacing U^{6+} (0,80 Å) by Ca^{2+} (1.03 Å) would mean an increase of ao but when Ca^{2+} replaces U^{4+} the lattice remains more or less constant.

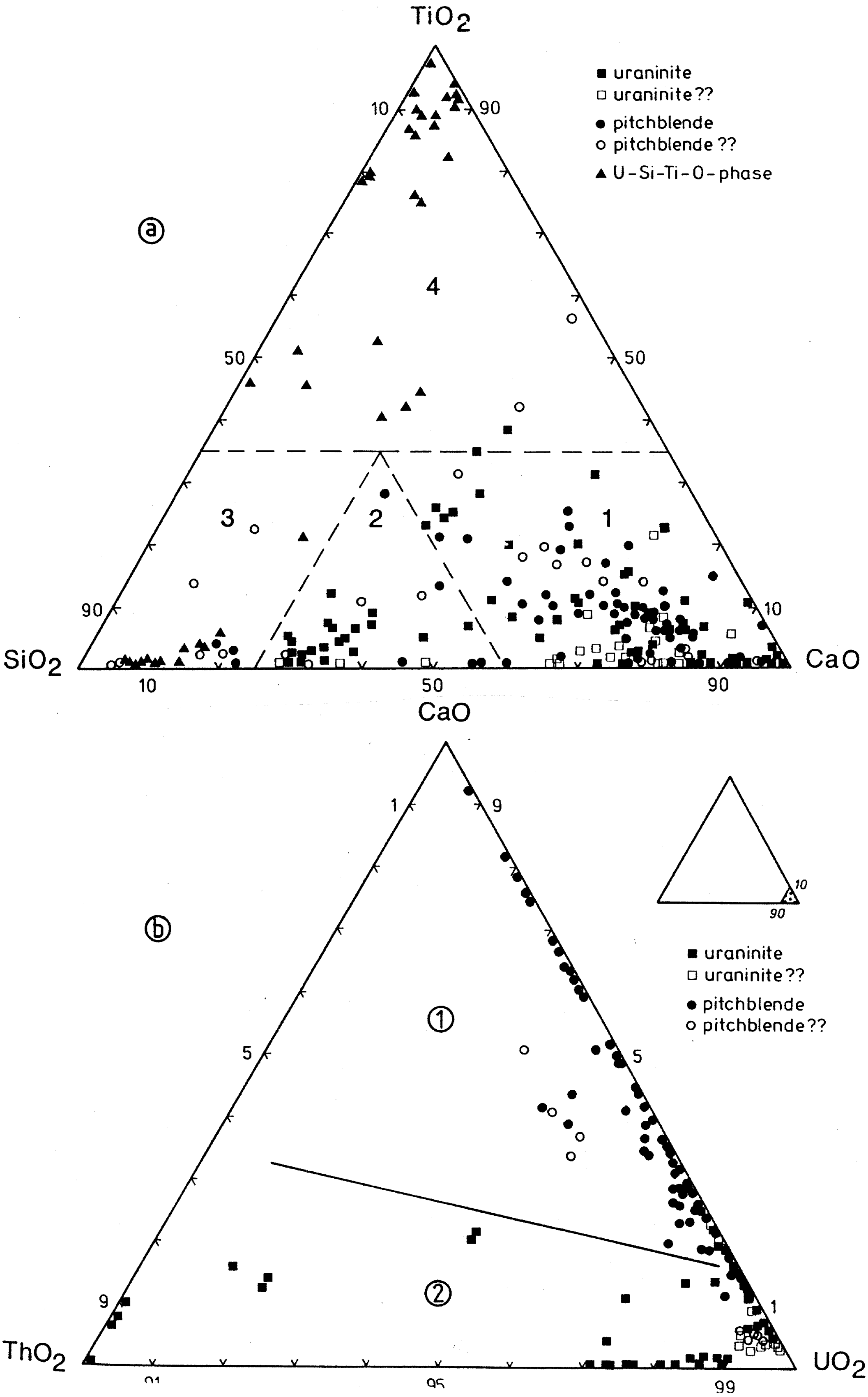

FIG. 3. Triangles for uranium mineral phases. (own data amended by data from [30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42]. Fig. (a) data of all samples (number analyses: 205). Fig. (b) data of samples from segment 1 of Fig. (a). Field 1 in Fig. (b) reflects the composition of pitchblende, field 2 that of uraninite.

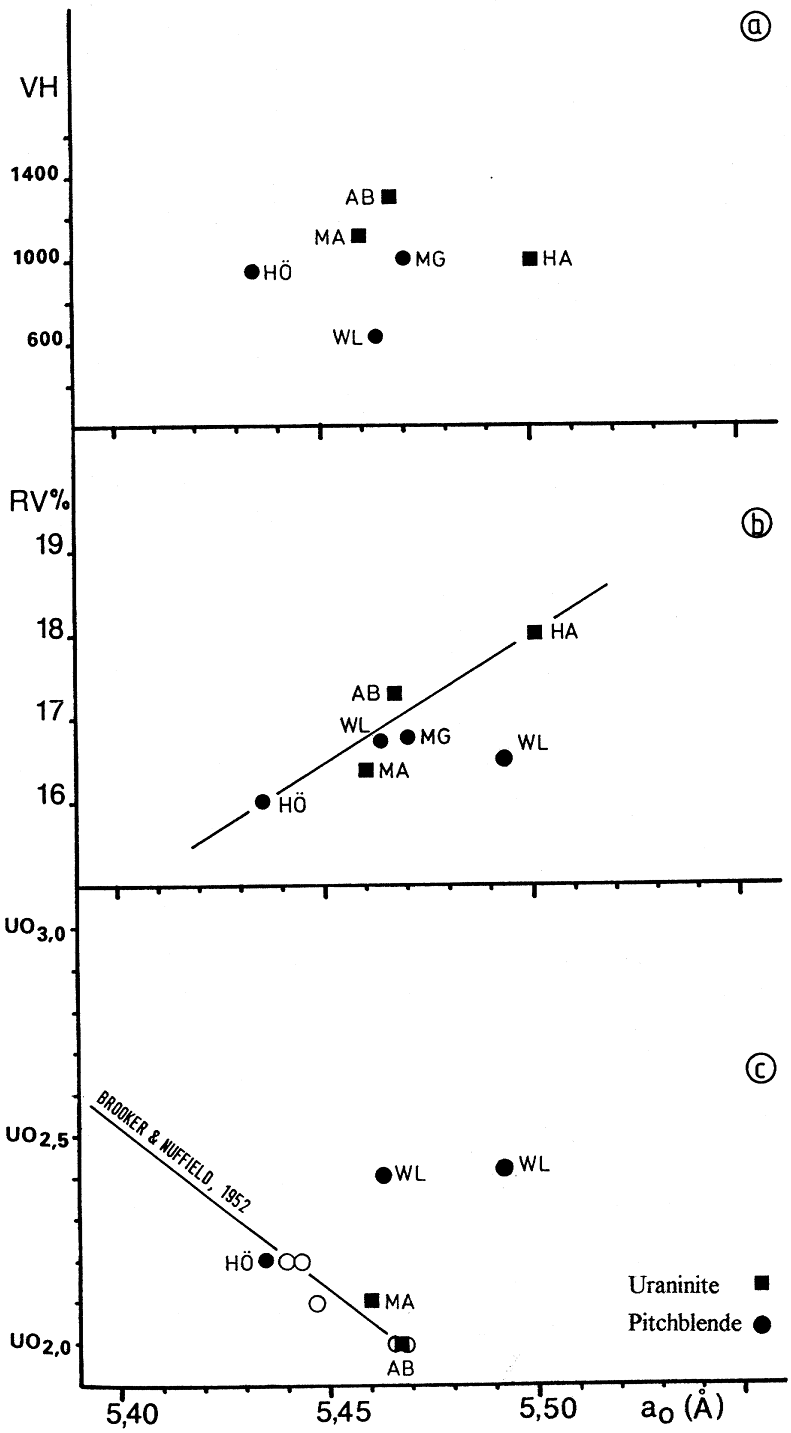

FIG. 4. Correlation diagram of unit-cell dimensionn versus Vickers hardness (VH), reflectance values (RV) and oxidation grade of pitchblende and uraninites. Open dots: [43]
AB: Alm Bos HA: Hagendorf HÖ: Höhenstein
MA: Madawaska MG: Mosquito Gulch WL: Way Lake
open dots:

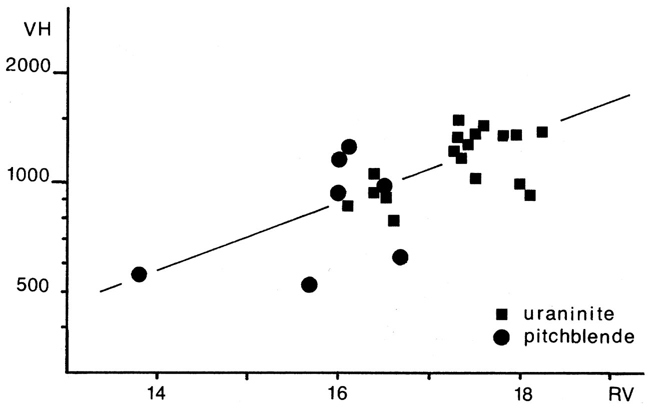

FIG. 5. Correlation diagram of reflectance (RV) versus Vickers hardness (VH) of U-oxides.

Figure 5 illustrates a positive correlation of reflectance and hardness of U-oxides. The uraninites tend to have higher values. Up to a certain amount (ThO_2 ca. 2 wt.%, PbO ca. 4 wt.%, SiO_2 ca. 0,5 wt.%, CaO ca. 1 wt.%) substitutes do not influence the reflectance of the U-oxides.

4. COMPARISON WITH LITERATURE DATA AND DISCUSSION

Physico-chemical characteristics of U-oxides and related crystallographic variations and genetic implications have been researched by a number of geoscientists. Results from some of these authors be summarized as follows: Brooker & Nuffield [43] and other authors established a negative correlation between lattice constant and oxidation grade of U-oxides. Wasserstein [44] views a reduction of lattice constants with increasing age and explains this as a result of replacement of U^{4+} by Pb^{4+}. Morton & Sassano [36] demonstrate a positive relationship of Pb contents with hardness and reflectance but with some exceptions. The data also display a positive correlation of lattice constant and Pb tenor. Xu et al. [45] figured out that U-oxides with high Pb content have larger lattice constants than those with lower Pb tenors. They constitute further a positive correlation between lattice size and formation temperature as mentioned by other authors as well. Cathelineau et al. [32] document a correlation between radiogenic Pb loss and lattice reduction but without a change in the oxidation grade. These authors also noticed that old U-oxides (Proterozoic: ao > 5,44 Å) have larger lattice sizes than younger ones (Hercynian: ao 5,44–5,38 Å, Tertiary: ao < 5,38 Å). Therefore they consider the size of U-oxide lattice being also a function of age. Nakhla [46] shows that both radius and electro-negativity of a cation influence the reflectance of a mineral. Increasing radius of a cation impose higher reflectance. That means, consigned to U-oxides, reflectance is positive correlated with the lattice size.

The above listed features would infer the following conclusions under the assumption that only almost pure U-oxides are involved.

(1) Temperature — oxidation grade-unit-cell: The unit-cell dimension appears to be a function of formational temperature i.e. the higher the temperature the larger the ao and the lower the oxidation grade.

(2) Unit-cell dimension-Pb content: The postulated positive correlation of ao and Pb content can be only valid if elementary Pb (ionic radius = 1,75 Å) is involved. Pb^{4+} has a radius of 0,84 Å hence it is smaller than U^{4+} (1.01 Å) and almost equals U^{6+} (0,8 Å) and can therefore not cause expansion of the U-oxide lattice. Due to this a lattice reduction is postulated if Pb^{4+} replaces U^{4+} with increasing age [44].

(3) Unit-cell dimension — age: Larger unit-cells related to older U-oxides [32] would imply that the often cited autooxidation of U-oxides plays only an insignificant role. On the other hand, a positive correlation of ao and temperature exists. This would theoretically permit the deduction of a positive correlation of age and temperature what does not appear feasible. For these reasons the correlation of ao and age can be only fictitious, or of secondary nature respectively.

This is supported by the Alm Bos occurrence of Tertiary age. Here temperature conditions from sandstone-type to contact-metamorphic U-oxides can be studied in the aureole of the Adamello intrusion. Sedimentary U-oxides have a composition of $UO_{2,61}$ whereas U-oxides formed closest to the intrusive contact have a composition of $UO_{2,06}$ and a unit-cell dimension of 5,467 Å [26] which compares with data of synthetic material and old samples e.g. from Mosquito Gulch (Table I). Lead content in the contact-metamorphic Alm Bos U-oxide is very low.

Relevant information published by other authors have been compiled cumulatively with our values in a diagram showing lattice constants versus U oxidation grades (Fig. 6). There is globally a negative correlation of unit-cell dimension and oxidation grade but with wide deviations. Genetically founded distribution segments could be established. Particularly the segment of hydrothermal formed U-oxides is widespread and overlaps the fields of U-oxides in sediments and matasediments.

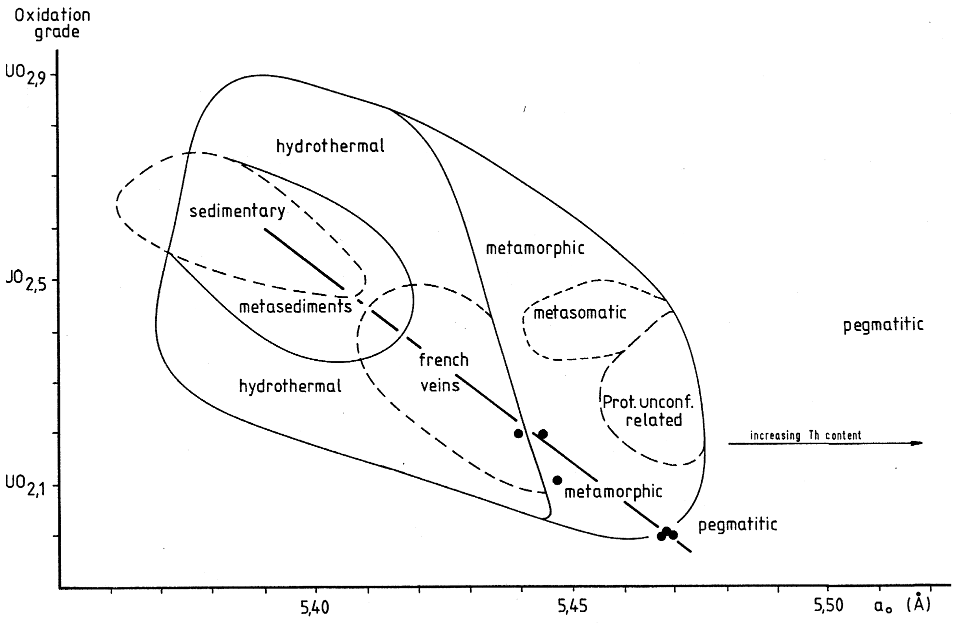

FIG. 6. Oxidation grade versus unit-cell dimension for uranium oxides, and their attribution to genetic fields (number of samples: 120) hydrothermal = vein type, french veins = granite related vein-type mineralization Own data and from [43] (dots and extrapolated line), [32, 26, 47, 45, 39].
The terms e.g. metasediments or metomorphic are taken from the used literature.

5. CONCLUSIONS AND RESULTS

The above discussed features and relationships illustrate the complex influence of the various ingredients involved in the formation of U-oxides and their crystallographic properties. The following relationships for our samples can be outlined.

(a) The chemical composition of U-oxides is different in each occurrence or group of occurrences respectively .
(b) The content of Ti, Si, Ca, and Fe in U-oxides is variable.
(c) The UO_2/ThO_2 and CaO/ThO_2 ratios of U-oxides permit the attribution of these oxides to formational environments (Table I).

(d) It is possible to distinguish in a general way between euhedral U-oxide (uraninite) and colloform U-oxide (pitchblende) by means of their physico-chemical parameters as follows:

	Uraninite	***Pitchblende***
Habit	euhedral	colloform
Unit-cell dimension	> 5.46 Å	<5.46 Å
Oxidation grade	< $UO_{2.2}$	>$UO_{2.2}$
CaO content	< 1.5 wt.%	1–5 wt.%
ThO_2 content	up to several %	< 1 wt.%

(e) U-oxides of pegmatites always contain significant amounts of Th (1,5 to 10 wt.%).
(f) U-oxides of metamorphic and contact-metamorphic origin are relatively pure in composition containing only minor amounts of other elements (Fe, Ca, Ti, Si, Th less than 1,5 wt.% each, and < 2 wt.% combined). U-oxides of these environments tend to be chemically the purer the higher the grade of metamorphism.
(g) Redistributed U-oxides derived from metamorphic and pegmatitic parent minerals are characterized by substitution of U by other elements.
(h) U-oxides of metasomatic environments have high but variable contents of Si, Ti, Ca, Fe up to 10 wt.% each and ranging from 10 to 15wt.% combined. Thorium is low (< 0,3 wt.%).
(i) The unit-cell dimensions of U-oxides is a function of formational temperature, oxidation grade, substitution of U by other elements and their radius and electro-negativity. U substituted by Th (and REE) results in enlargement of the lattice. Most other elements such as Si, Ti and Fe correlate with reduced lattice. Due to different ionic radius of U^{4+} and U^{6+} the replacement by Ca has different effects on the lattice size: the lattice remains more or less constant if Ca^{2+} replaces U^{4+} but by replacing U^{6+} the lattice would increase.
(j) Reflectance and lattice constant of U-oxides correlate positively but incorporation of U substituting elements strongly interfere. Almost all elements except Th and Ca reduce RV.

Distinct U substituting elements and their ratios, and physico-chemical parameters of U-oxides seen as a whole may provide significant hints on the possible formation temperature and/or the formational environment.

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REGULARITIES OF MINERAL AND COMMERCIAL ORE TYPES: LOCATION IN URANIUM DEPOSITS OF STRELTSOVSKY DISTRICT (RUSSIA)

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Abstract

Hydrothermal uranium deposits of Streltsovsky district are represented by pure uranium, molybdenum and complex uranium and molybdenum ores. The specific character of Mo–U deposits consist of a combination of different age of uranium mineral paragenesises with molybdenum mineralization, forming independent uranium and molybdenum as well as complex U–Mo deposits. The composition of the ores of the new commercial type of molybdenum hydrothermal deposits found within the uranium–ore field is described. The mineral and element composition of the ore assemblage are cited as well as the structure and paragenesises of molybdenum sulfides. The composition and structure of dispersed molybdenum sulfides are noted based on data obtained from electron microscopy and other techniques of investigation. Based on the mineral composition, structures as well as the properties of the main ore minerals, the pure molybdenum mineralization can be considered as a new independent molybdenum ores. The main types of ore mineral assemblages are: pitchblende–coffinite, pitchblende–molybdenite–coffinite, coffinite, quartz–fluorite–molybdenite. Brannerite–pitchblende ore is smaller on deeper horizons, at the flanks of the ore bodies, in granites and dacite. The prevalent commercial ore types are silicate and carbonate. Carbonate ores are typical for Argunsky deposit.

1. CLASSIFICATION AND LOCATION REGULARITIES OF INDUSTRIAL AND MINERAL ORES TYPES ON DEPOSITS OF THE STRELTSOVSKOYE ORE DISTRICT

At present there are 16 known uranium deposits in the Streltsovsky region (Fig. 1).

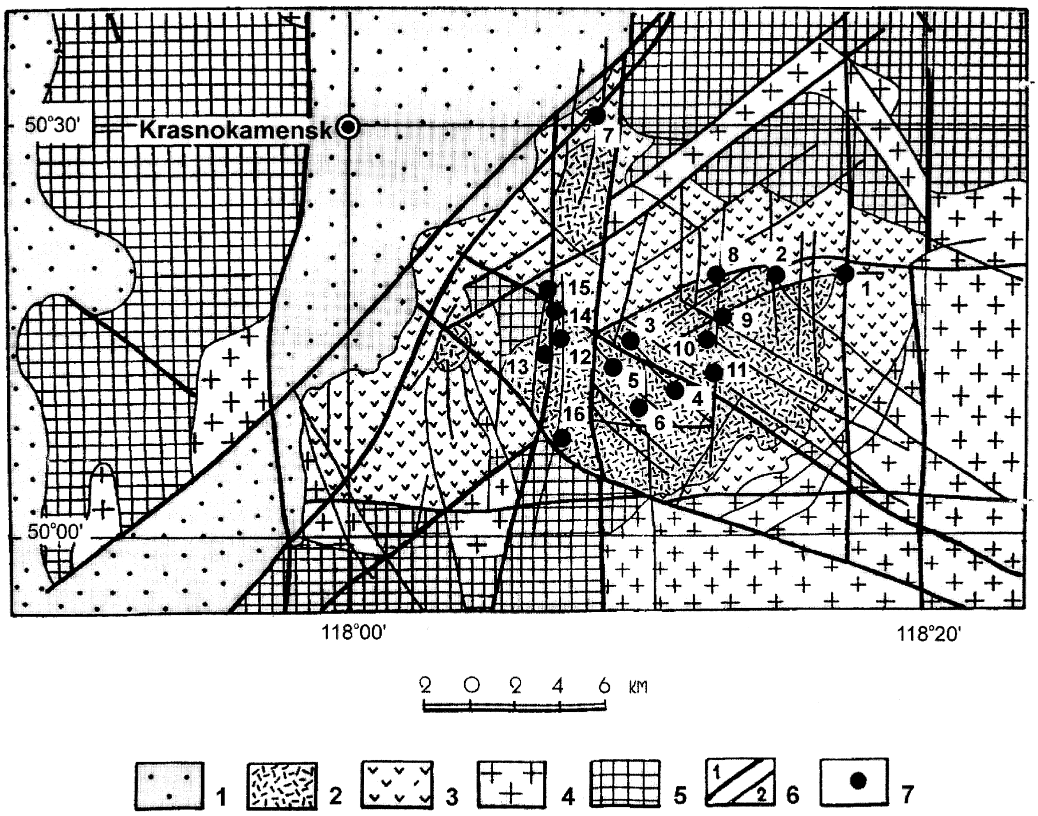

FIG. 1. Geological map of the Streltsovsky uranium-ore region.

The major features of the geological structure of Streltsovskoye ore field and deposits, as well as the mineral composition of ores have been described in numerous reports and articles by L.P. Ishchukova [1, 2], the pioneer of this ore district, and other works [3, 4]. At the same time too little attention is given to mineralogical-and-technological classification of ores and regularities of major mineral and industrial types.

Long experience of research at the Institute of Chemical Technology studying the structural localization of ore bodies, the zonality of deposits and particularly mineralogical-and-technological mapping of almost all ore field deposits made it possible to carry out the classification of ores and to reveal major regularities concerning variability of their composition and technological properties. Mineralogical-and-technological mapping was carried out on different stages of exploration and exploitation of deposits and it solved different tasks from preliminary appraisal of the ores technological properties and their dependence of mineral composition to geometrization of different mineral and technological types of ores with the purpose of making forecasts and managing the quality of raw material. The major problems of mapping methodology and ores classification for the Streltsovskoye ore field were reported by us earlier [5]. So they are only briefly considered in this report, and most attention is concentrated on regularities of location and sequence of the uranium and molibdenium-uranium mineralization formation. Proper understanding of these regularities makes it possible to solve numerous tasks of different mineralization predicting both in the Streltsovskoye ore field and in regions similar in geological structure.

Mineralogical-and-technological mapping included trench sampling in underground workings on main prospecting horizons and in operational blocks. In deep horizons and flanks of the deposits sampling was performed along drill cores. The sampling grid size was defined by mining and technical conditions of exploration and operation works and generally measured 50 x 60 m. Technological tests of samples and analysis of their mineral composition made it possible not only to distinguish technological types and grades of ores and to reveal the ores technological properties dependence of their mineral and material composition, but to study regularities of their location as well. Mineral composition and technological properties of hundreds samples of ores on the deposits of the Streltsovskoye ore field varying in the mining mass composition and major paragenesis have been studied. The practice of mineralogical-and technological mapping has revealed that the main characteristics to be used in distinguishing the technological types and grades of ores are the following:

a) mining mass composition;
b) set of major useful components;
c) quantitative ratio of main ore minerals.

The analysis of the mineralogical-and-technological mapping results made it possible to classify ores from the deposits of the Streltsovskoye ore field (Fig. 2).

The Streltsovskoye ore field is unique because of the variety of geological and structural deposits and ore bodies localisation conditions, as well as the variety of the enclosing rocks composition. The variety of geological and structural localisation environments for uranium deposits and ore bodies, their location in interbedding sedimentary, igneous and volcanic rocks causes the variety of morphology, mineral and chemical composition, ores quality and consequently mineral, natural and technological types. And differences in these parameters are clearly defined not only in the ore field, but on individual deposits. On deposits of the Streltsovskoye ore field ores of almost all types listed in the table are found though in different amounts.

<table>
<tr><td colspan="13">Commercial types</td></tr>
<tr><td colspan="7">Silicate</td><td colspan="6">Carbonate</td></tr>
<tr><td colspan="13">Natural types ores</td></tr>
<tr><td colspan="3">Uranium</td><td colspan="2">Molybdenum</td><td colspan="2">Uranium-molybdenum</td><td colspan="2">Uranium</td><td colspan="2">Molybdenum</td><td colspan="2">Uranium-molybdenum</td></tr>
<tr><td colspan="13">Mineral types ores</td></tr>
<tr><td>Quartz - uraninite - brannerite</td><td>Quartz-pitchblende</td><td>Quartz - pitchblende - coffinite</td><td>Quartz-molibdenite</td><td>Fluorite-femolite</td><td>Pitchblende-femolite</td><td>Pitchblende-femolite-brannerite</td><td>Quartz-carbonate-pitchblende</td><td>Pitchblende-coffinite</td><td>Quartz-molibdenite</td><td>Fluorite-femolite</td><td>Quartz-pitchblende-femolite</td><td>Fluorite-pitchblende-femolite</td></tr>
</table>

FIG. 2. Classification commercial and natural types ores uranium deposits Streltsovsky ore field.

The enclosing rocks of deposits of the Streltsovskoye ore field are different in composition and are represented by granites, limestones, dacites, basalts, felsites, conglomerates and sandstones. The variety of enclosing rocks cause deviations in mining mass composition both on different deposits and in ore bodies within the same deposits. It is the difference in the composition of enclosing rocks (mainly the carbonates content) that is decisive in determining technological methods of mineral raw material processing. This is the key characteristic in ore classification. According to this characteristic two technological ore types have been distinguished for deposits of the Streltsovskoye ore field: silicate (less than 6% of carbonates) and carbonate (more than 6% of carbonates). These two types require basically different technological flow sheet for their processing. The ores of the first type are processed in the process of sulfuric acid leaching, and those with high degree of carbonates (more than 12%) — in the process of autoclave sodium leaching. Among carbonate type are primarily ores which are localized in dolomites (the Argunskoye deposit). The total amount of carbonates reaches up to 87% and is seldom less than 40–45% in the areas of their intensive silisification. Ores with small (6–12%) and medium (12–25%) amount of carbonates are registered in granites (the Argunskoye deposit), basalts, dacites (the Streltsovskoye deposit), conglomerates (the Martovskoye and Lutchistoye deposits). Their carbonate character is caused by intensive carbonate sedimentation during hydrothermal process of ores formation. Processing of ores with small and medium carbonate content is possible with sulphuric acid leaching using their batching with silicate ores.

In some cases the enclosing rock composition influences such ore characteristics as texture, structure, grade according to major components content, quantitative ratio of uranium minerals, as well as ore bodies morphology. Thus, for example, contrast lode pitchblende ores in conglomerates alternate with brannerite ores in dacites in the lower parts of the Oktyabrskoye deposit.

Other important characteristics for classification are the useful components composition of ores and their major mineral forms. They depend on the ore bodies quantitative ratios in ore mineral paragenesis.

The ore bodies on the Streltsovskoye ore field were formed in the result of long hydrothermal process and are characterized with telescoping of various mineral associations within repeatedly renovated discontinuity. The major ore paragenesises are brannerite–uraninite, pitchblende–coffinite, pitchblende femolite and quarz–fluorite femolite. Note that earlier proper uranium paragenesises are proceeded by more or less intensive process of enclosing rocks albitization, and Mo and U-Mo mineralization — by argillization in combination with locally but intensively manifested silisification and carbonatization.

Both in silicate and in carbonate types one can distinguish simple uranium and molybdenum types according to the prevalence of major ore components, as well as complex molybdenum-uranium subtype. The molybdenum-uranium subtype is prevailing. It is present on all deposits of the ore field. Simple ores are found only locally. Thus the uranium type is found primarily on the Antey deposit and in a number of lode ore bodies on the Martovskoye, Lutchistoye and Oktjabrskoye deposits. Proper molibdic ore bodies occur on the Argunskoye deposit. Distinguishing between these subtypes is specially important for silicate ores, because for proper recovery of molybdenum processed in sulfuric acid leaching tough conditions are required (acid and pyrolusite consumption).

According to the prevailing ore paragenesises and major ore minerals several mineral varieties are distinguished. The mineral varieties have generally identical composition of major ore paragenesises but differ in details of texture, structure, quantitative lode and ore mineral ratio, major ore components content.

The most characteristic paragenesises of proper uranium ore bodies are quartz–pitchblende and brannerite–uraninite. Presence of coffinite and brannerite in ores, often in substantial amounts, makes it possible to distinguish such varieties as pitchblende-coffinite and pitchblende-brannerite.

Of prime importance is distinguishing and mapping of pitchblende-brannerite variety, for when the amount of brannerite is more than 10% of the total amount of uranium minerals, the ore resistance and reagent consumption during their processing are increased significantly. Ores with high degree of brannerite are characteristic primarily for ore bodies localized in granites (the Antey deposit), basalts (the Streltsovskoye deposit) and sometimes in dacites (the Oktyabrskoye deposit). Uraninite is commonly present in the upper parts of ore bodies of the Antey deposit just on the border with dacites, and lower it is quickly replaced by pitchblende.

Molybdenum-uranium ore bodies are generally presented by pitchblende-femolite mineral variety, which is the most widespread in the Streltsovskoye ore field.

Simple molibdic ores differ as a rule by its quartz-fluorite ratio and are subdivided into quartz-femolite (the Antey, Argunskoye, etc. deposits) and fluorite-femolite (the Argunskoye and Tulukui deposits) varieties.

Besides the already mentioned mineral varieties strongly acetified ores with uranophane, uranospinite etc. have been registered on the upper horizons of some deposits (Lutchistoye, Tulukui, Shirondukkui).

Uranium-molybdic mineralization relations in space and time on the deposits of the Streltsovskoye ore field seem interesting and important because understanding of them enables to update prediction methods for new deposits and quality of ores on known deposits. Traditionally deposits of the Streltsovskoye ore field are classified as molybdenum–uranium formations. It is believed that formation of uranium and molybdic mineralization took place synchronous in time and space. Meanwhile the mapping data obtained by the authors concerning deposits of the Streltsovskoye ore district suggest an idea of some discreetness of uranium and molybdic mineralization both in time and in space. According to this feature, as well as to characteristics of mineral composition and geological-and-structural conditions of localization the molybdic mineralization of the Streltsovskey district can be classified as a new type of molybdic deposits of volcano–tectonic activization regions [4, 5].

What characteristics of the location and sequence of uranium and molybdic ores formation allow such a conclusion? Deposits of the Streltsovskoye ore field feature polystage formation, different mineral associations telescoping within repeatedly renewing interruptions. The formation of different types of ore bodies and deposits is defined by the realization of two stages of ore process — uranium and molybdic (Fig. 3). The first stage is characterized by more or less intensive process of the enclosing rocks albitisation and by subsequent uranium (brannerite–coffinite–uraninite) paragenesis formation. The second ore stage is often isolated in space and is characterized by the appearance of potassium hydromicas, chlorite, quartz and carbonates with iron, copper, zinc and molybdenum sulfides. On a number of uranium deposits the molybdenum minerals association with quartz, carbonate and fluorite overlaps directly the albitization rocks and minerals of proper uranium, brannerite-uraninite paragenesis. Uranium and molybdic mineralization ratios in space and time can be illustrated by the Argunskoye and Antey deposits (Figs. 4, 5, 6). For these deposits telescoped uranium and subsequent molybdic mineralization in common ore zones often with some isolation of molybdic mineralization is typical. This is evident on the horizon plan +374 M and the geological section of the Argunskoe deposit. Complex Mo-U mineralization is usually developed locally in broader contours of the uranium mineralization distribution. Note that molybdic mineralization is drawn to upper and central parts of complex ore bodies and localizes in large renewed interruptions like, for example on the Antey deposit (Fig. 6). It is characterized by lode and metasomatic vein form in deeply altered rocks and earlier uranium ores (Fig.7). Uranium lenses intersected by lode zones of the quartz–fluorite pyrite–molibdenite composition were registered. Uranium-bearing are molybdic zones near their intersection with uranium ore bodies. Sometimes molybdic mineralization stretches beyond limits of uranium basins and form separate molybdic ore bodies (Fig. 4). Such mineralization progresses also beyond Mo-U deposits and form separate Mo deposits at some distance. The main minerals for complex molybdenum–uranium and molybdenum ores are quartz, hydromicas, montmorillonite, kaolinite, fluorite, galena.

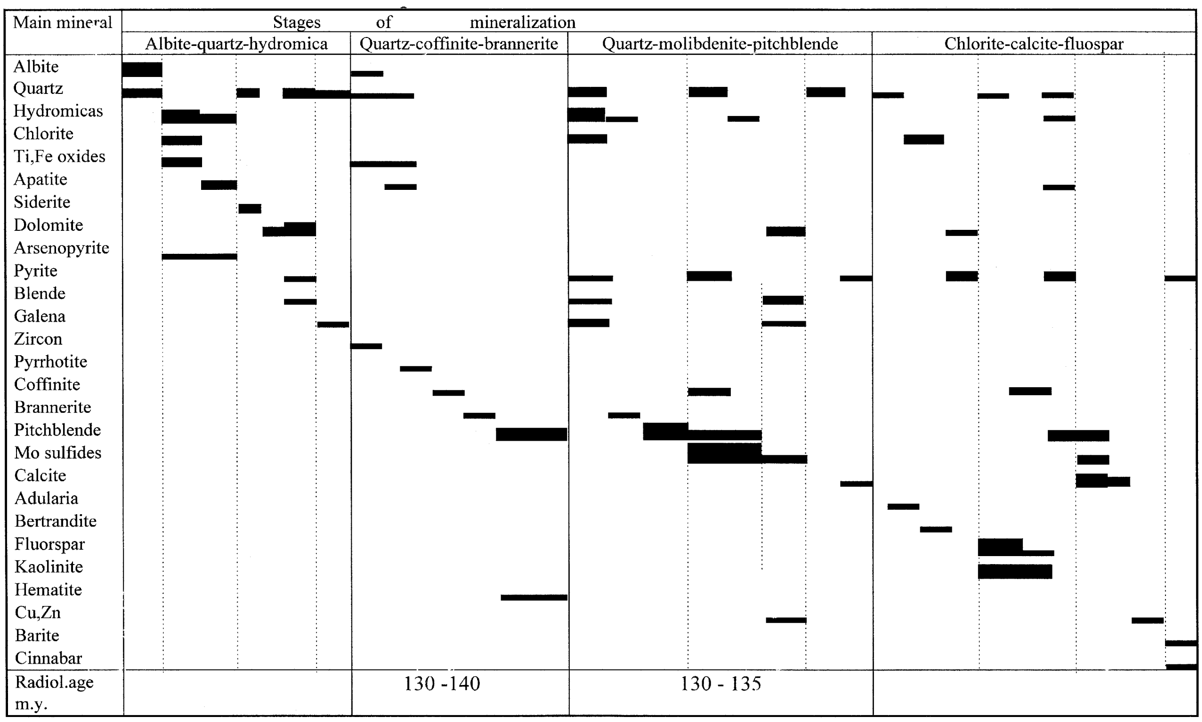

FIG. 3. Generalized sequence of chief mineral association formation.

Complex molybdenum-uranium ores with fluorite build up areas within early uranium mineralization. In the breccia zones fragments are presented with brannerite-uraninite (pitchblende) impregnated or vein ores. In cement the molybdenite-pitchblende mineralization with fluorite and carbonates is present. Femolite-pitchblende and fluorite-marcasite-coffinite are associations that distinguish complex ores from uranium ores. The uranium silicate forms pseudomorph along different generations of pitchblende in the areas of quartzfluorite and carbonate vein.

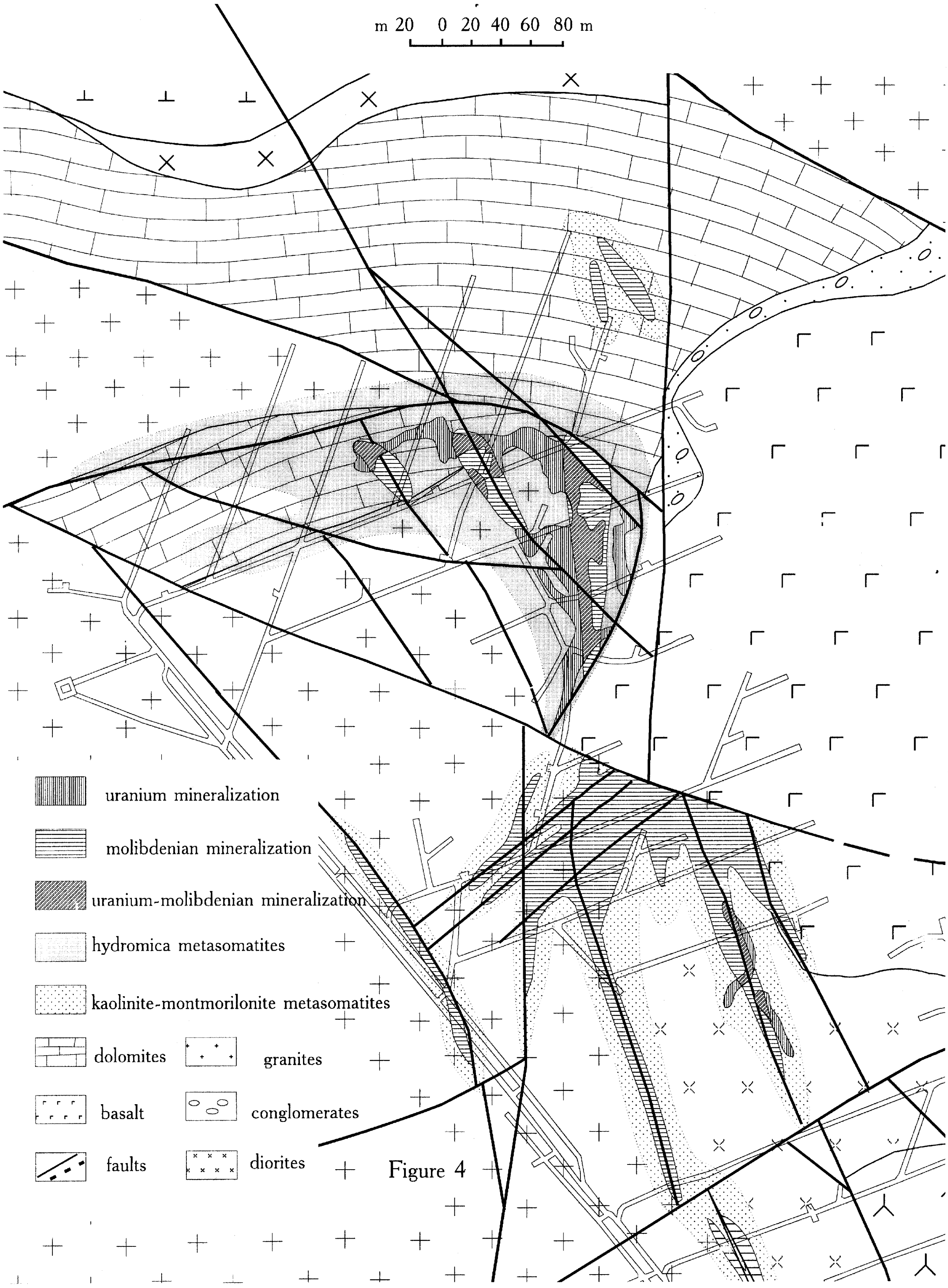

FIG. 4. Argunskoye deposit, schematic plan horizon +374 m.

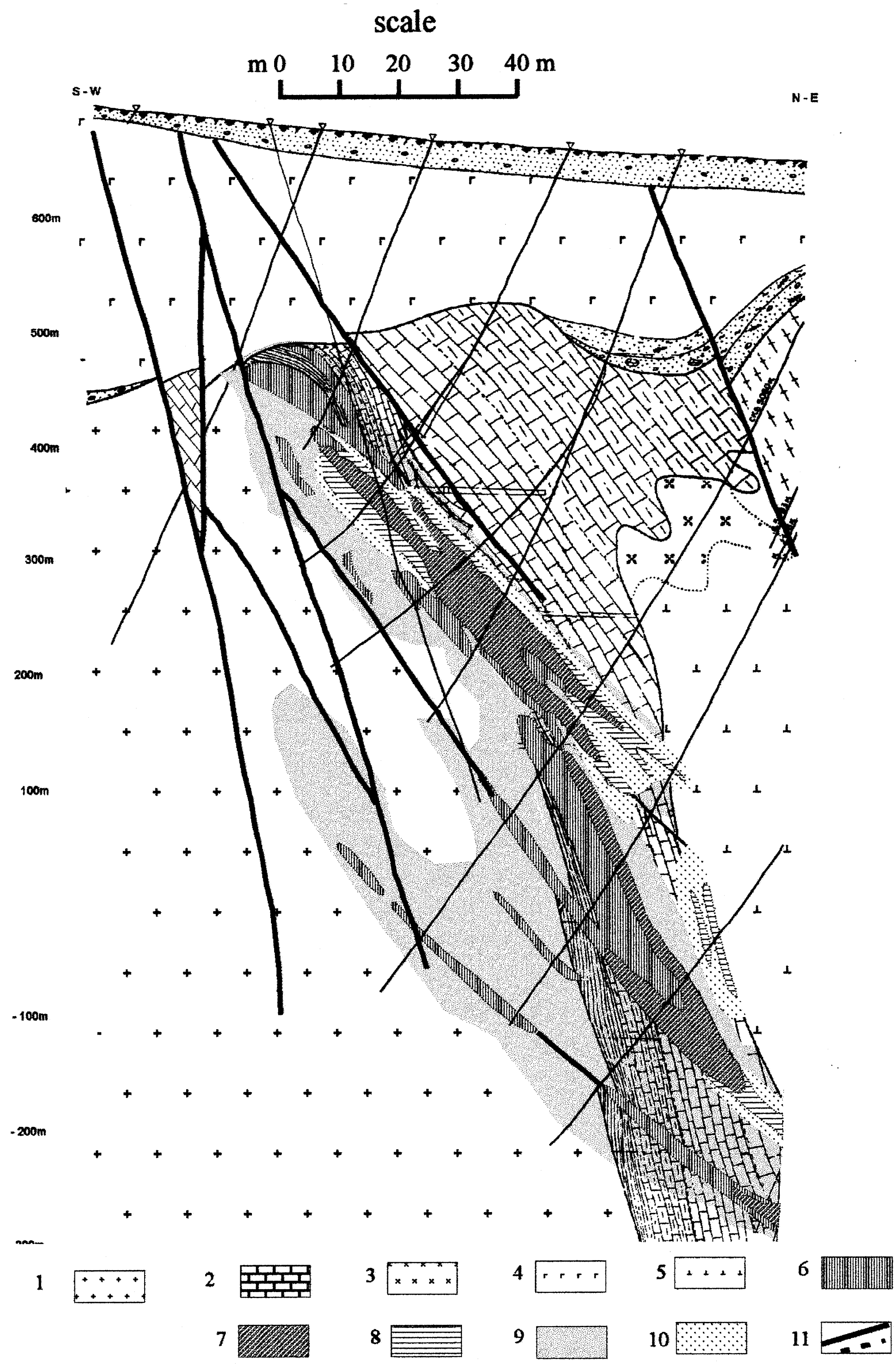

FIG. 5. Argunskoye deposit, geological profile.
1. granites; 2. carbonates; 3. diorites; 4. basalt; 5. diabazes; 6. uranium mineralization;
7. uranium-molibdenian mineralization; 8. molibdenian mineralization;
9. hydromica metasomatites; 10. kaolinite-montmorilonite metasomatites; 11. faults.

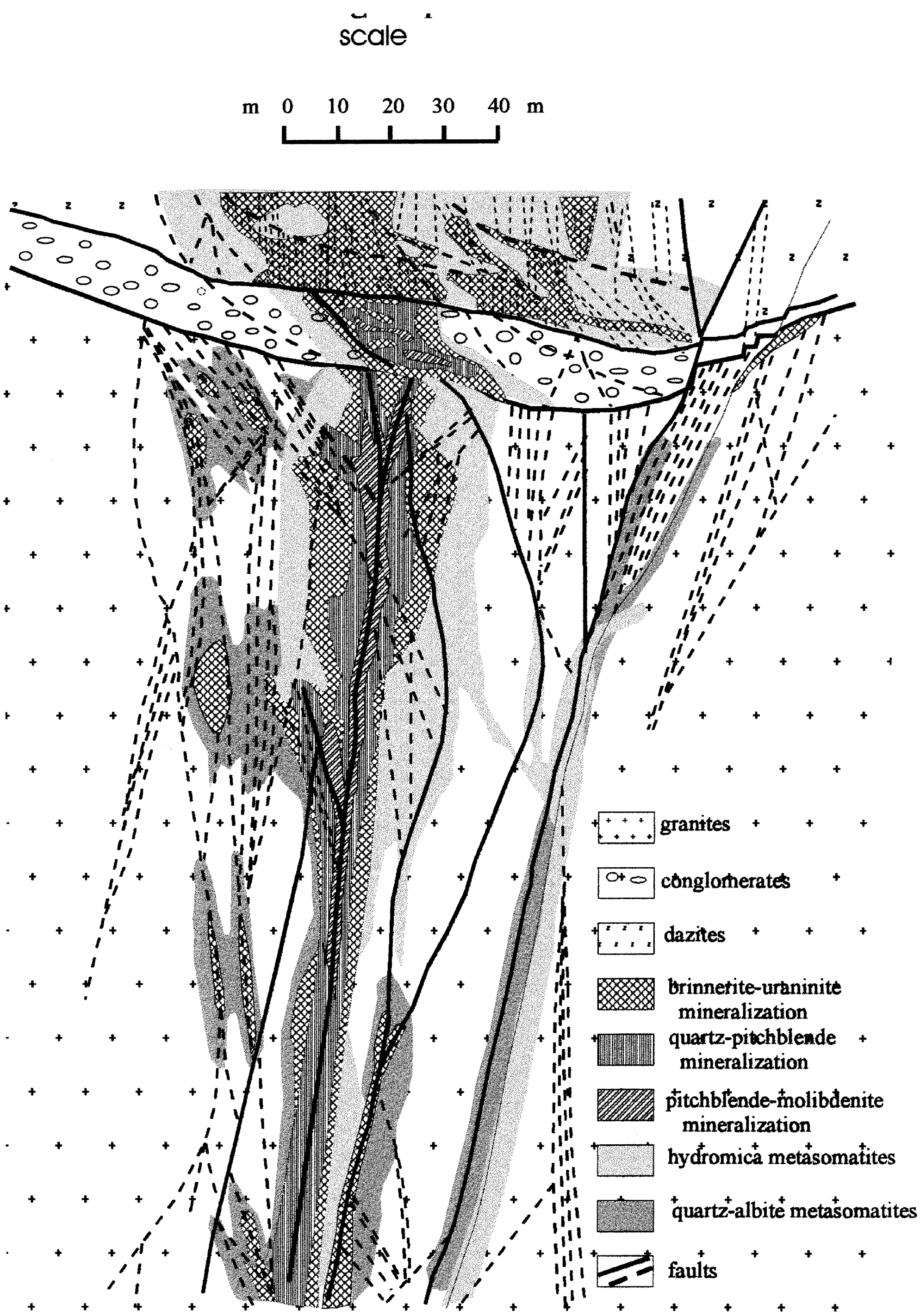

FIG. 6. Antei deposit, geological profile scale.

The molybdenum sulfides corrode brannerite and uraninite. Molybdenite replaces spherulites pitchblende along the zones of growth and radiating cracks, cements the fragments of such spherulites. In the areas of pitchblende replacement in the molibdenum sulfide zonal crusts frame spherulites of regenerated oxide of uranium are present. Such formations are characterised with features of simultaneous common growth of spherulites femolite and pitchblende (Fig. 9).

In molybdic ore bodies beyond uranium basins sulfides of molybdenum are localized in silicification rocks in the form of impregnation, nests, metasomatic vein. They are often associated with veins of fluorite.

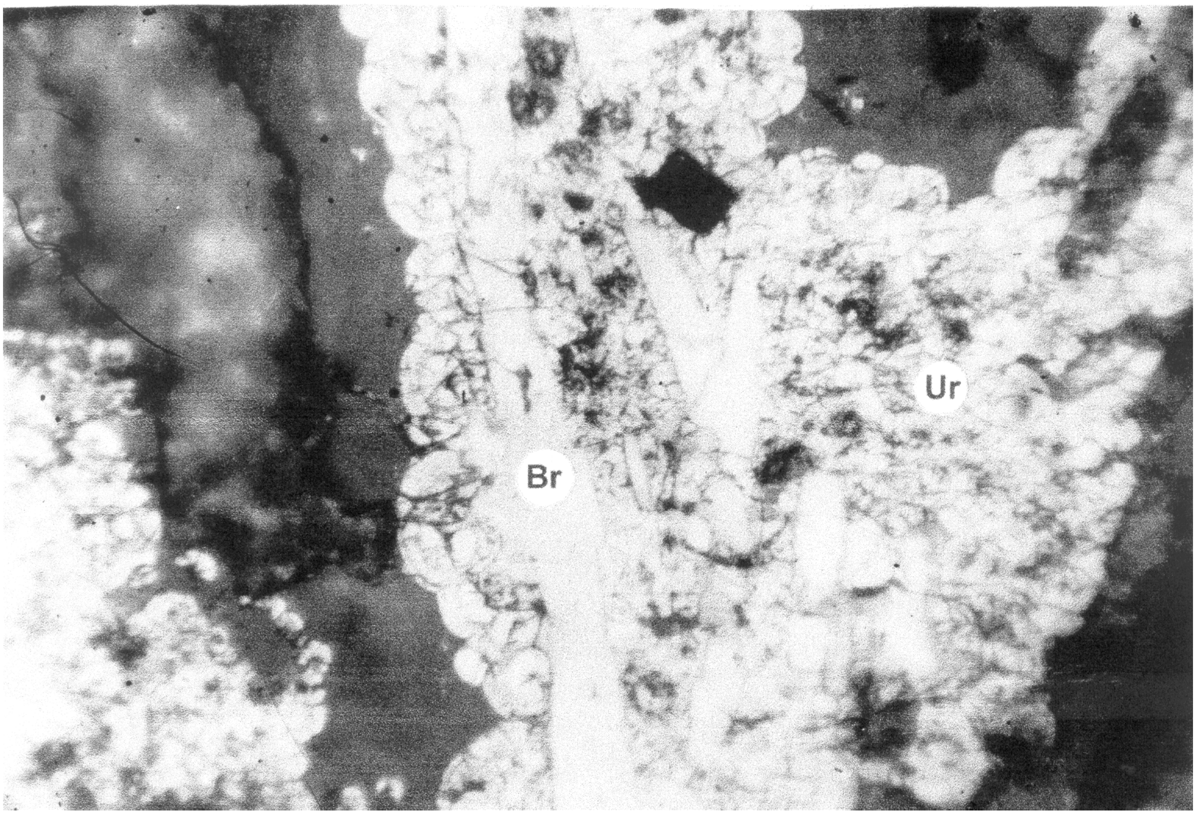

FIG. 7. Uranium mineralization in albitite, Streltovsky deposit. (Agregates of uraninite (Ur) and brannerite (Br) after diagnostics solution. Reflected light. Magnification 400).

Mentioned data concerning age relationship's uranium and subsequent molybdic mineralization are evident of an interval in their formation. The aggregations of molybdenite and pitchblende with the structures of simultaneous growth are reaction and originate in the molybdic and uranium mineralizations combination areas. Space-time correlations of molybdic and uranium mineralization make it possible to conclude that uranium from molybdenum-uranium ores could be mobilized by sulfide-bearing solutions from early uranium ores or from abyssal the parts of zones albitite with uranium mineralization.

The sulfide of molybdenum is very unusual. It is presented by badly decrystallized varieties which belong relate to femolite and iordizite (Fig. 8). Typical are spherilitic zonal individuals of mineral formed as a result of coprecipitation of molybdenum sulfides, iron, lead, copper at the very limited possibilities of their isomorphism, and subsequent colloidal-dispersive systems crystallisation and their weak metamorphism. It comprises iron (6–10%), lead (1.5–11%), uranium (0.3–5.0%), antimony (0.5–6.0%) and copper (0.1–1.5%). Lead and uranium impurities are characteristic only for minerals from molybdenum-uranium ore bodies. The distribution of impurities is rather irregular, that suggests the presence of inclusions in the sulfides of molybdenum aggregation [6].

Thus on the deposits of the Streltsovskoye ore field two industrial types of ores are distinguished: one of them can be processed by acidic process, and the other by carbonate process. Each of these types includes uranium, molybdic and molybdenum-uranium subtypes. The latter in turn consist of several mineral varieties, the major of which are quartz–uraninite–brannerite, quartz pitchblende, pitchblende–femolite–coffinite, quartz–femolite and fluorite–-femolite. Ores with brannerite, as well as silicate uranium–molybdic and molybdic require tougher modes of processing compared with other mineral varieties.

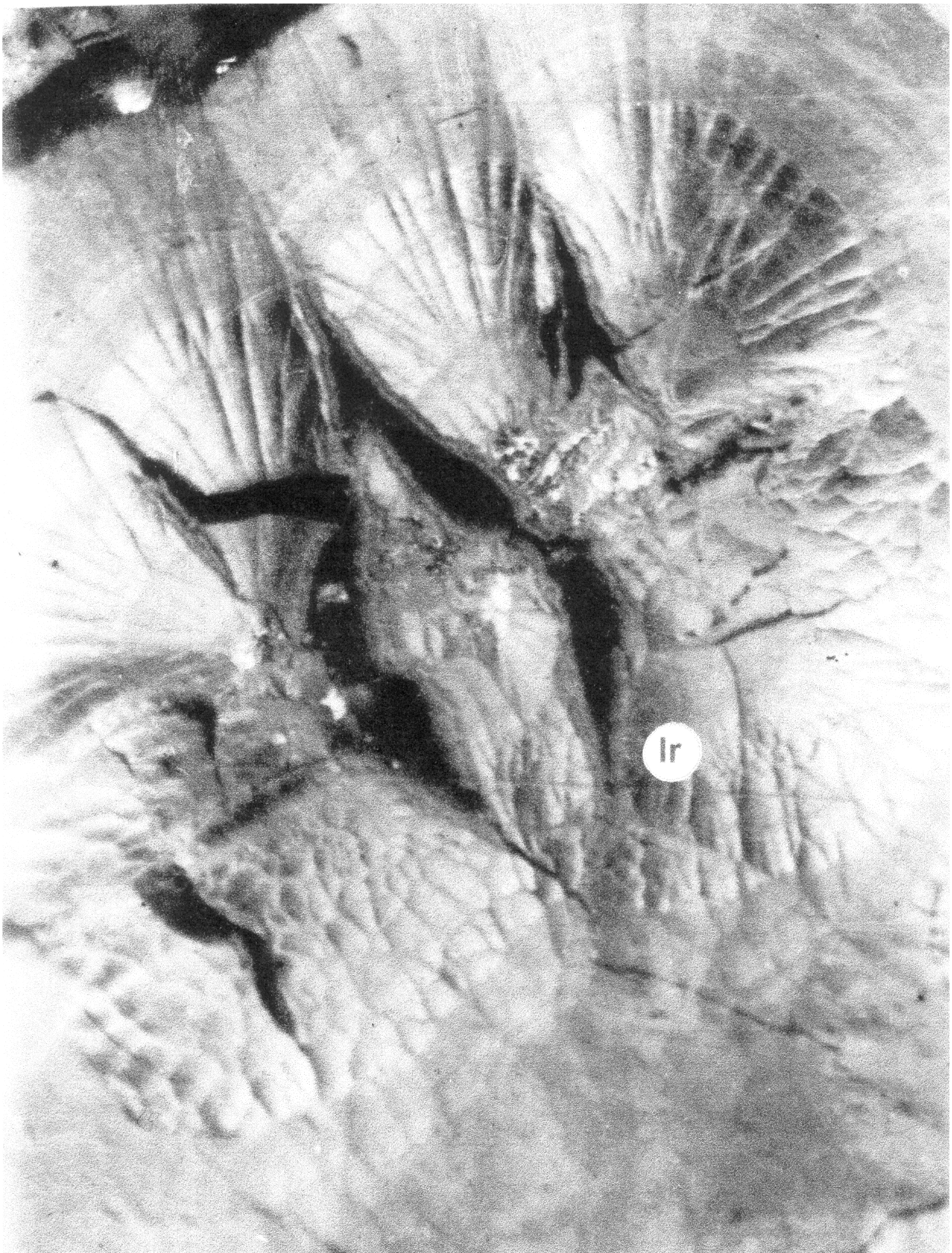

FIG. 8. Mo Mineralization in Kaolinite-montmorilonite metasomatates, Argunskoe deposit (Radiate-fibrous aggregates of iordisite (Ir). Reflected light. Magnification 800).

FIG. 9. U–Mo mineralization in hydromica metasomatites Argunskoe deposit (Spherolitic crusts of iordisite (Ir) with pitchblende (Pb) inclusions. Reflected light. Magnification 500).

Molybdic mineralization is an independent mineralogical type of hydrothermal formations of the continental volcanism regions. It is characterised by geological conditions of localization common to uranium deposits. Molybdic mineralization on complex molybdenum–uranium deposits is the product of the second ore stage of mineral formation. It is similar to ores of the low-temperature deposits of molybdenum by main paragenesises structure and sequences of their formation. On uranium deposits its structure is complicated due to reactive minerals such as oxide of uranium, galena, etc. For low-temperature deposits of molybdenum fine-dispersed accentuation of the sulfides of molybdenum (iordizite–femolite) are typical. As for mineral composition, specific structure, crystallochemical nature of admixtures and the conditions of their genesis, ores from the low-temperature deposits of molybdenum differ essentially from common copper-molybdic sulfide deposits. This should be undoubtedly taken in consideration while identifying the criteria for their exploration, appraisal, as well as for the development of ores processing methods. Particularly important is to take into account the specific nature of such formations in case of processing of ores with complex structure and genesis found on the telescoped molybdenum deposits.

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