IAEA-TECDOC-823

Recent developments in uranium resources and supply

Proceedings of a Technical Committee meeting held in Vienna, 24–28 May 1993

INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

The IAEA does not normally maintain stocks of reports in this series. However, microfiche copies of these reports can be obtained from

INIS Clearinghouse
International Atomic Energy Agency
Wagramerstrasse 5
P.O. Box 100
A-1400 Vienna, Austria

Orders should be accompanied by prepayment of Austrian Schillings 100,— in the form of a cheque or in the form of IAEA microfiche service coupons which may be ordered separately from the INIS Clearinghouse.

The originating Section of this publication in the IAEA was:

Nuclear Materials and Fuel Cycle Technology Section
International Atomic Energy Agency
Wagramerstrasse 5
P.O. Box 100
A-1400 Vienna, Austria

RECENT DEVELOPMENTS IN URANIUM RESOUCES AND SUPPLY
IAEA, VIENNA, 1995
IAEA-TECDOC-823
ISSN 1011-4289

Printed by the IAEA in Austria
September 1995

FOREWORD

While the IAEA's projections of the growth of nuclear power remain a modest 1.5% per year through 2010, uranium continues to be an important source of energy. In January 1993 there were 424 nuclear power plants in operation with a combined electricity generating capacity of 331 G(e). In 1992 these plants generated over 2027 TW.h electricity, equivalent to nearly 17% of the total. To achieve this, 57 200 tonnes uranium were required as nuclear fuel.

Historically, nuclear fuel activities were primarily segregated in two mutually exclusive areas consisting of WOCA (world outside centrally planned economy areas) and non-WOCA. Throughout most of the 1980s the WOCA uranium market experienced declining prices because of a very large excess uranium inventory resulting from over-production in earlier years. Since the relaxation of tensions between WOCA and non-WOCA in the late 1980s, a worldwide market in nuclear goods and services has been developing. Emergence of this world market placed additional stress on the uranium supply and demand balance as the previously unavailable non-WOCA supply entered the market. This material came from both current production and the existing inventory.

In recent years substantial uncertainties regarding uranium supply have made it very difficult for both uranium producers and users to plan for the future. In 1992 uranium production met only about 63 percent of reactor requirements. This resulted in a very unstable supply/demand balance where inventory drawdown (supplemented by minor amounts of reprocessing) filled the 20 960 tonne shortfall.

The IAEA convened this Technical Committee meeting to take advantage of the new opportunities to collect and analyse information related to the future supply and demand balance and to help reduce uncertainties regarding the relationship. The meeting was effective in bringing together experts from all regions to share, exchange and disseminate information regarding uranium related activities.

The Technical Committee Meeting on Recent Developments in Uranium Resources and Supply was held in Vienna from 24 to 26 May 1993. It was attended by 47 participants from 23 countries. Twenty-one papers were presented. Contributions from China, the Czech Republic, India, Kazakhstan, Mongolia, Romania and the Russian Federation represent new information in this field.

The IAEA is grateful to those participants who contributed papers and took part in discussions. Thanks are also extended to: F. Barthel (Germany), M. Giroux (France), M. Matolin (Czech Republic), V. Ruzicka (Canada), and S. Simov (Bulgaria), the session chairmen.

The IAEA staff member responsible for the organization and implementation of the meeting was D.H. Underhill, Division of Nuclear Fuel Cycle and Waste Management.

The papers presented by A.A. Abakumov, C. Bejenaru and D. Cioloboc, F. Bunus and I. Miu, K.K. Dwivedy, J. Hrádek, D. Kelter and F. Barthel, I.L. Loutchinin, Z. Logar et al., M. Matolin, Y.B. Mironov et al., G.R. Parslow and R. Karma, G.P. Poluarshinov and V.M. Pigulski, V. Ruzicka have been published in the Chinese language in 1994 in Beijing (Overseas Uranium and Gold Geology Editorial Committee Eds), Atomic Energy Publishing House, Volume 11, No. 1, Mar. 1994.

EDITORIAL NOTE

CONTENTS

SUMMARY OF THE MEETING

The Technical Committee Meeting on Recent Developments in Uranium Resources and Supply was held in Vienna from 24 to 26 May 1993. It was attended by 47 participants from 23 countries and two international organizations (OECD and Uranium Institute). Twenty-one technical papers covering uranium resource and supply activities in 17 countries were presented.

The meeting was followed by a two day site visit to the Rozna uranium production facilities in the Czech Republic. Rozna is the site of one of the largest conventional uranium mines operating in central Europe. The site visit of 25 participants from 14 countries, was hosted by Diamo, the state enterprise responsible for uranium production in the Czech Republic. A description of the Rozna project is given in the Appendix of this publication.

Many of the papers presented at this meeting reflect the massive reduction and realignment of all uranium related activities resulting from the development of a worldwide uranium market undergoing recovery from over-production. The 13 year decline of the Nuexco Exchange Value (NEV) or spot uranium price, reaching an all time low annual average in 1992 of $20.67/kg U ($7.95/pound U_3O_8), has had a profound impact on these activities. Current uranium prices have no relation to the cost of production. They are being set, not by transactions between traditional producers and users, but by sales of excess inventories, or by non-traditional producers in non-market economic areas, selling to uranium users.

The impact of the extremely depressed market is demonstrated by the current status of both production and exploration activities. The 1992 world production of 36 246 t U was down 40% from 1988 and met only 63% of world demand. The 1992 WOCA uranium exploration expenditure of $104 million was at the 1972 level on a constant dollar basis. In the United States of America uranium production in 1992 was about 1200 t — equivalent to only 7% of the USA reactor requirements. Low uranium prices continue to result in the closure of production facilities throughout the world. One paper discusses the status of a mine and mill closure in Slovenia.

Other reports in these proceedings describe the history, current operations and plans for the future for many uranium activities. Topics discussed include:

- National reports of geology, exploration and production
- Geological models of uranium deposits
- Geophysical exploration methods
- New exploration target areas
- Evolving exploration strategies and techniques
- Mining/milling production technology
- Mine/mill closure
- Resource estimation systems and practice
- Supply and demand projections.

Today uranium activities worldwide are being reassessed with the evolution toward a worldwide uranium market. This reassessment includes aspects of all relevant disciplines including uranium geology, uranium resources and production technology. To conduct this reassessment it is necessary to have information from all areas, including the previously inaccessible countries.

Papers presented at this meeting provide information about recently discovered resources in China and India, as well as the first comprehensive disclosures of the uranium deposit types and associated resources of the Czech Republic, Kazakhstan, Mongolia and Romania. New information was made available regarding production facilities in several countries including China, the Czech Republic, Hungary, Kazakhstan, Mongolia, Romania and Slovenia.

New discoveries rely heavily on geological models and indirect exploration techniques such as geochemical and geophysical methods. In this regard an update was presented by Matolin on the use of gamma ray and radon detection methods for exploration and environmental studies. New information on uranium deposit models and their use was also provided for Bulgaria, Kazakhstan and the Russian Federation.

As producers attempt to survive and/or become competitive under extremely depressed uranium market conditions, deposit types with the greatest potential for production costs are being selected as exploration targets and for new project development. The two important uranium deposit types that may, under appropriate circumstances, provide for low cost production are high-grade unconformity and sandstone hosted deposits producible by in situ leach (ISL) technology. In 1992 an estimated 38% of world production came from these two deposit types; about 27% from unconformity deposits and 11% from ISL mines.

As a guide to understanding and evaluating unconformity-type deposits, Ruzicka presented a paper describing geological models for Canadian deposits of this type. The worldwide recognition of ISL mining as a major production technology is relatively recent. Utilization of this technology has exhibited modest growth over the last decade in the western countries. In 1993 it represented the only production technology (other than phosphate by-product recovery) currently producing uranium in the USA.

Disclosures made at this meeting (as well as at other recent meetings) regarding uranium production in eastern Europe, central Asia, and China demonstrate the significance of ISL technology in the rest of the world. During the 1980s uranium production from sandstone ores was on the decline as the relative importance of production from other deposit types increased. Now the industry wide recognition of the potential of low cost production from properly selected sandstone hosted deposits has resulted in a resurgence of interest in this type of deposits. In addition to the previously known operations, sandstone deposits are important ore sources in Bulgaria, the Czech Republic, Kazakhstan and Uzbekistan. Sandstones hosted deposits are being considered for new projects in China, India and the Russian Federation.

Papers were presented on resource assessment and classification, a particularly important topic during this time of the integration of different resource systems used in the former WOCA and former non-WOCA areas. The challenge of resource assessment is made particularly important under the present day conditions of historically low uranium prices. Resource classifications developed under previous conditions of higher uranium prices and different economic systems may be of limited use in today's market. The paper by Blase and Derange provided a detailed analysis of the sensitivity of reserve estimates even where they are carried out using detailed sample results and sophisticated estimation methodologies.

With the long decline of the uranium market, less and less emphasis has been placed on the importance of uranium production as the primary source of reactor fuel. However, once the excess uranium inventory is exhausted reactor operators will again have to turn to producers as their primary source of supply. Giroux and Capus present a projection of world uranium production, consumption and inventories through 2010. Their analysis indicates the need for new production will lead to a uranium price increase within a few years. To meet projected demand it will be necessary to produce from uranium resources with a production cost of $78/kg U ($30/pound U_3O_8) or higher before 2010. This represents a uranium price increase of at least 4 times the average 1992 spot (NEV) price.

The emergence of a worldwide uranium market in the 1990s has resulted in an extreme reduction in all uranium related activities. One of the principal causes of this depression has been the uncertainty associated with the adjustment required to establish a worldwide supply and demand equilibrium. This uncertainty has resulted in part, from the lack of information about existing worldwide resources and production facilities. The information made available in this meeting provides some of the information required to reduce the uncertainty regarding the future uranium supply.

CONCEPTS, RECOGNITION CRITERIA AND DEPOSIT MODELLING APPLIED IN URANIUM EXPLORATION OF BULGARIA

S.D. SIMOV
Enterprise Oil Exploration Ltd., Bulgarian Branch, Sofia, Bulgaria

Abstract

The systematic uranium exploration in Bulgaria started 47 years ago. During the first 10 years it was influenced by the big uranium rush and the main tasks were radioactive anomalies discovery. Within a short period the whole Bulgarian territory was covered by airborne gamma ray survey followed by ground gamma ray study. The evaluation of the identified radioactive anomalies was mainly based on general geological considerations. If uranium minerals were discovered, the anomaly was quickly evaluated by trenching and the drilling of short bore holes. The first recognition criteria and concepts were developed on the basis of geological environment of deposits discovered. Paleozoic black shales soon become the most promising target for uranium exploration, followed by sandstone and acid volcanic environments. Geological study of different uranium type deposits helped deposit modelling and criteria for application in preliminary estimation of uranium potential of regions to be studied. Six main geological processes of importance for uranium deposit formation are considered: (1) Modification of the global uranium source and formation of local one; (2) Host rocks formation; (3) Mobilization of uranium and its transportation; (4) Fixation; (5) Regeneration of the primary uranium accumulations; (6) Deposit conservation. Eight uranium deposit models are discussed. According to the geological environment each of these models could have four modifications applicable to regions built up mainly by sedimentary, metamorphic, igneous and volcanic rocks. Indicators of the main and associated geological processes are presented.

1. CONCEPTS AND RECOGNITION CRITERIA APPLIED

Two main periods are recognized in uranium exploration of Bulgaria. The first started in 1946 when the first uranium deposit was discovered at Buhovo near the capital of Sofia. The high ore grade attracted all geological, finance and material resources and the black schists became the major exploration target.

At these years indicators for juvenile ore origin was the main exploration guide and criteria for estimation uranium potential of mineral occurrences. It was found later that some indicators for hydrothermal activity in the deposits were not connected with formation of ore bodies. Exploration to great depth showed low ore grade and limited reserves. This led to a revision of dominated hydrothermal hypothesis and development of more pragmatic model of deposits of this type.

The second period started in 1956 when sandstone type deposits was discovered near Eleshnitsa village close to Razlog town in southwest Bulgaria. This period could be subdivided as follows:

(a) 1956 - 1973 Exploration of molasses paleogenic sediments.

(b) 1973 - 1985 Miocene and Pliocene fluvial sediments were main exploration target for discovery of low grade ore for applying uranium in situ leaching.

Both periods lead to a better understanding of exploration criteria and development of deposit modelling. It was found that the two type deposits are located near the uranium local source. Based on this phenomenon and on the data for genesis of uranium deposits formed in different geological environments genetic models of uranium deposits have been developed.

2. GENETIC MODELS OF URANIUM DEPOSITS

W.I. Finch considers eight chronological stages in the process of genetic-geological building (precursor processes; host-rock formation; preparation of host-rock; uranium-source development; transport of uranium; primary uranium deposition; post-deposition modification and preservation) and submits an abbreviated example of a genetic conceptual model of the sand-stone type uranium deposits. Both papers consider mainly the application of genetic-geological modelling to evaluate uranium favourability using a computer. Five main geological processes are of essential importance for uranium deposit formation:

(I) modification of the fundamental source of uranium and formation of the local source,
(II) mobilization of uranium,
(III) its transportation,
(IV) fixation and
(V) regeneration of the primary uranium accumulation.

The development of genetic models starts with the study of the uranium migration during the geological processes,includes formulation of genetic concepts and ends in building up principal models. The diversity of the genetic models depends on the ore formation conditions and variety of geological environment. Based on the genesis of the most important known uranium deposits, seven genetic models were developed.

2.1. Lateral uranium mobilization and deposition

The source of uranium is disclosed and there is a good hydro-geological communication system between the uranium source and the host rocks. Oxygen charged ground waters mobilize

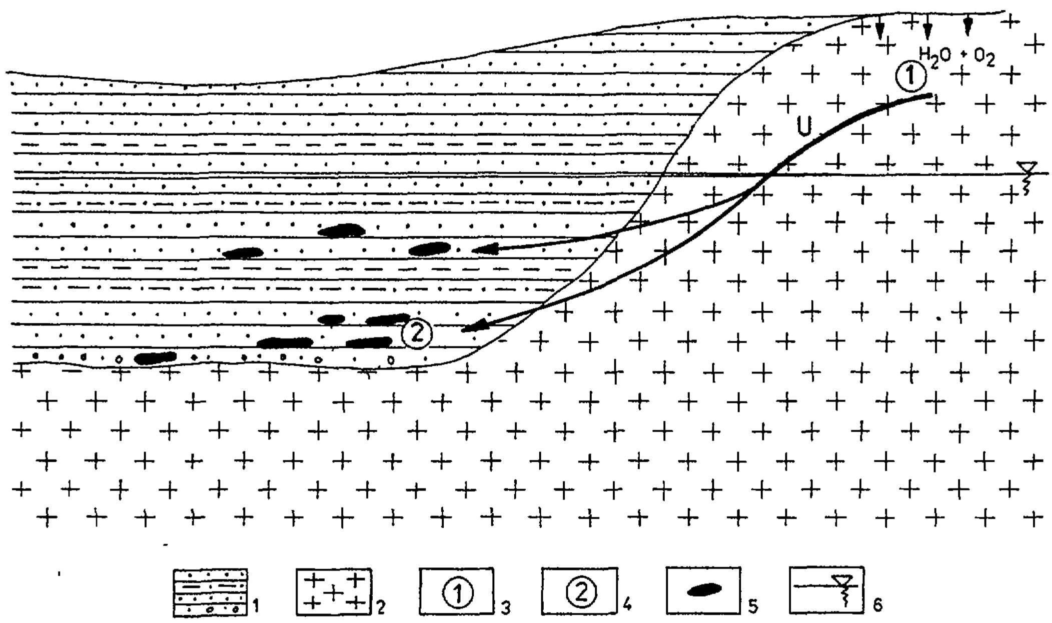


FIG. 1. Lateral uranium mobilization and deposition.

1. Water permeable sediments
2. Uranium Source Rocks
3. Uranium mobilization
4. Deposition of Uranium
5. Ore body
6. Ground water level

uranium dispersed within the source rocks and transport it to the host rocks, where uranium is fixed under favourable geochemical conditions (Fig. 1). This genetic model is applicable to roll type uranium bodies in Pliocene fluvial sediments in south Bulgaria.

2.2. Sublateral mobilization and precipitation of uranium

Modification of the above mentioned genetic model is the sublateral mobilization of uranium dispersed within sediments and uranium concentration in the same rocks.During the devitrifaction of uranium containing volcanic glass, pH and the ionization of the pore water could be raised which makes easier uranium mobilization.

The mineral recrystallization could make sediments water-tight (less permeable) and this could provoke migration of pore water to permeable sandstones where uranium is fixed (Fig. 2).

Pore water in clay sediments are alkalic in nature, therefore they can dissolve humic material. Humic acid containing solutions are good uranium dissolving agents. When these pore solutions are mixed with atmospheric waters, pH becomes lower and humic acids are dissociated from the solutions. Uranium is precipitated as complicated uranium-humic composition.

This genetic model is applicable to young sedimentary basins with constant water table. The ore forming processes are taking place below the water table. When the uranium source is surrounded by reductor containing rocks this is the most favourable trap for uranium deposition. This is the case of Buchovo deposits in Bulgaria (Fig. 3).

If the source of uranium is disclosed or is covered by thin layer of rocks, then mobilized uranium is transported by ground water below to the reductor containing host rocks. Uranyl ions carried by oxygen charged water are reduced to the uranous state forming uranite and coffinite in the reducing environment (Fig 4).

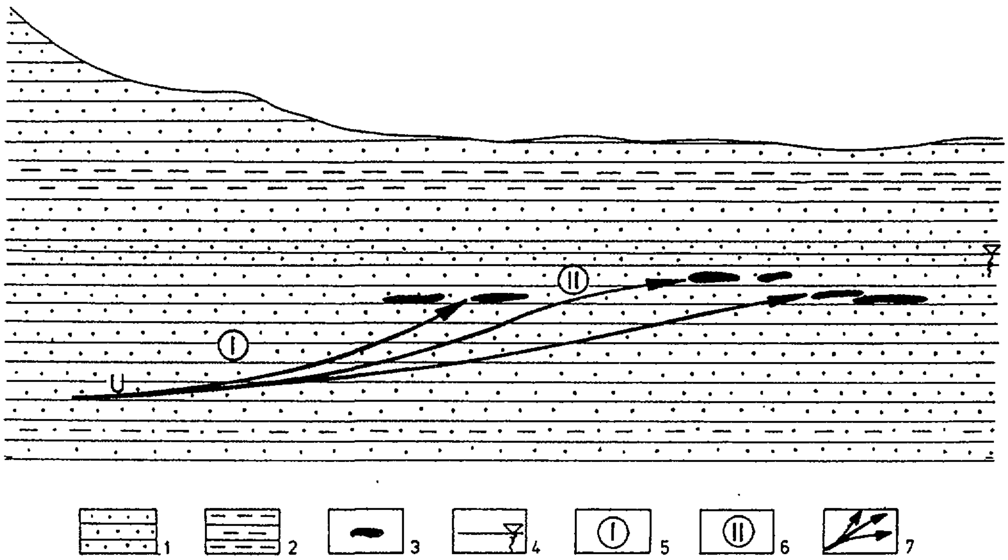


FIG. 2. Sublateral mobilization and precipitation of uranium.

1. Uranium conteining water permeable sediments
2. Water non permeable sediments
3. Ore body
4. Ground water level
5. Uranium mobilization
6. Uranium fixation and deposition
7. Direction of uranium conteining solutions movement.

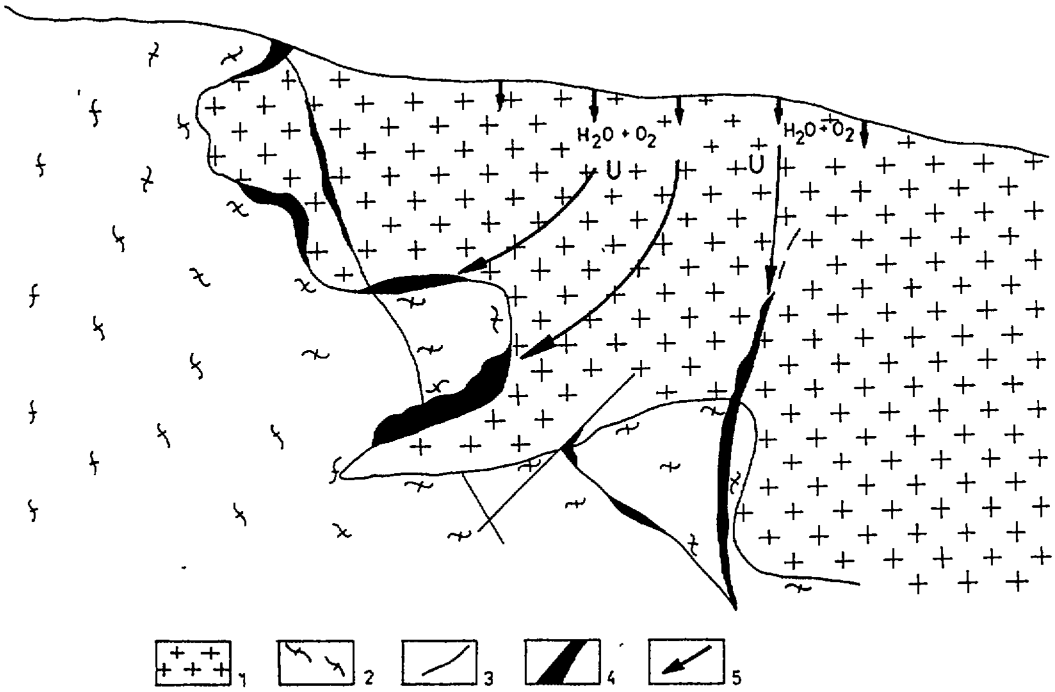


FIG. 3. Sublateral uranium mobilization and its deposition at the contact of reductor containing rocks.

1. Local Uranium source
2. Reductur containing rocks
3. Faults
4. Ore body
5. Direction of Uranium bearing solutions movement.

2.3. Mobilization of uranium by brines

The uranium containing and permeable rocks are located at depth and are saturated by brines. The high chemical aggressive energy and temperature of the brines make them most effective leachable solutions and normally they are enriched with uranium. During a compression typical for an orogeny, the brines are driven to the surface and when they cross the reductor containing rocks uranium is fixed (Fig. 5).

The genesis of the Ambrosia Lake deposit and the Woodrow deposit in the Grants mineral belt and the Hamra deposit (Tchechia) can be considered as similar to this model.

2.4. Uranium mobilization by combined action of ascending brines and descending meteoric water

The uranium source rocks are located below and above host rocks. The leached uranium is transported by descending meteoric water and ascending brines. The migration of the two types of uranium charged solutions can be simultaneous and when they mix each other uranium is precipitated (Fig. 6). This genetic model is applicable to uranium deposits in Northern Australia and the Key Lake and the Rabbit Lake deposits in Canada.

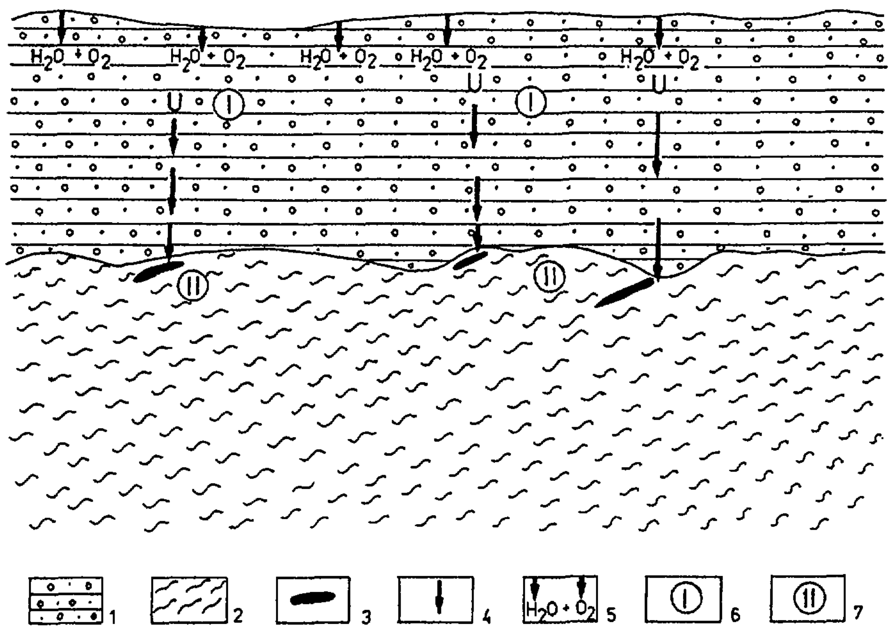


FIG. 4. Uranium mobilization by oxygen containing meteoric water and its deposition within reductor containing rocks.

1. Uranium containing rocks
2. Reductor containing rocks
3. Ore body
4. Direction of uranium containing solutions
5. Oxygen containing meteoric water
6. Uranium mobilization
7. Uranium fixation and deposition

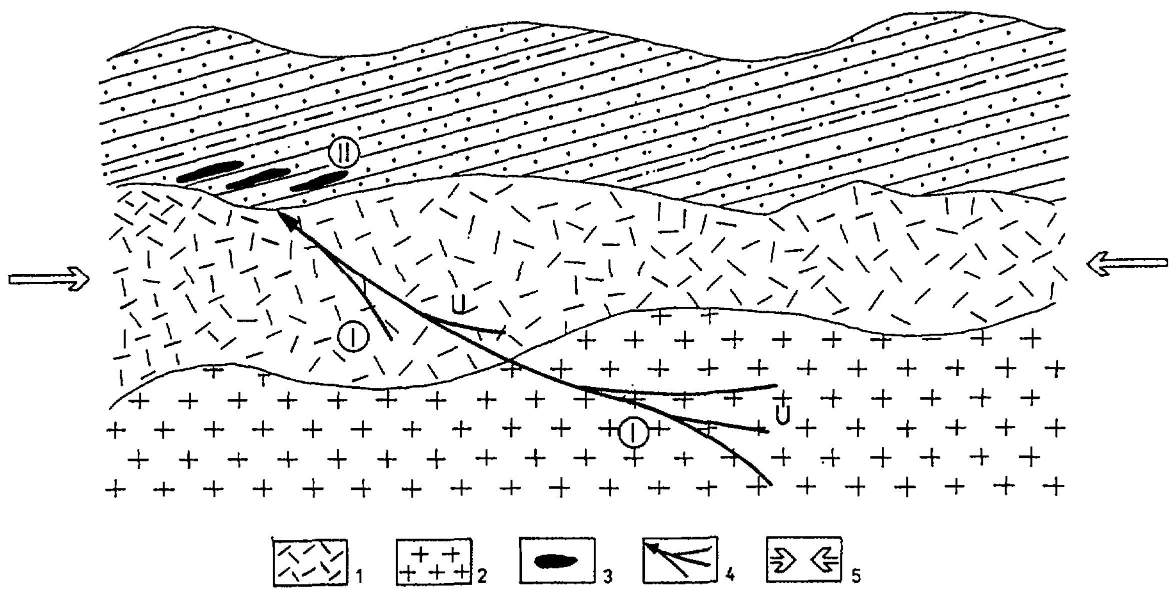


FIG. 5. Uranium mobilization by brines.

1./2. Local uranium source
3. Ore body
4. Direction of uranium bearing brines movement
5. Compression pressure

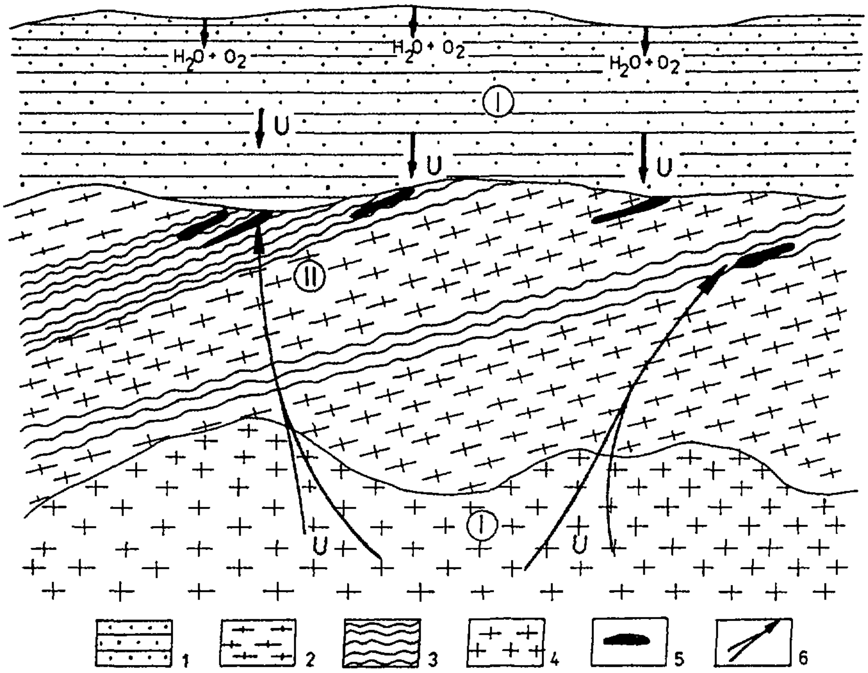


FIG. 6. Uranium deposition by combined action of ascending brines and descending meteoric water.

1. Water permeable uranium bearing rocks
2. Metamorphic rocks
3. Granite containing schists
4. Uranium source
5. Ore body
6. Direction of uranium bearing solutions movement.

2.5. Mobilization of uranium by metamorphogenetic solutions

The uranium mobilization during metamorphism is most effective at a high metamorphic grade. The solutions formed through dexydration of minerals leach uranium and transport it away from the metamorphosed rocks. Uranyl ion reduction to the uranous state and uranium accumulation is taking place when mineralized solutions cross reductor containing rocks (Fig. 7). The effectiveness of uranium accumulation could be multiplied by retrograde metamorphism.

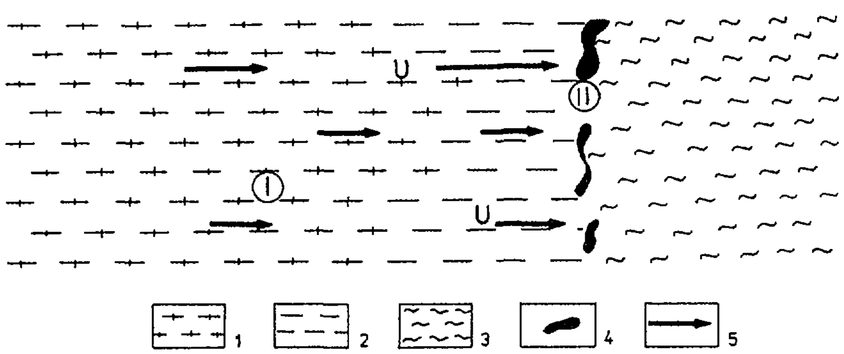


FIG. 7. Uranium mobilization by metamorphic fluids and its fixation by reductor containing rocks.

1. Metamorphic rocks with granular facies
2. Metamorphic rocks with amphibole facies
3. Metamorphic rocks with green schists facies
4. Ore body
5. Direction of uranium bearing fluids movement

2.6. Uranium mobilization and fixation in hydrogeological pressured systems

The uranium permeable source rocks build up the upper part of the ground and host rocks are located in the lower part of the terrain.

The oxygen charged atmospheric waters leached uranium from the source rocks during their descending moving and transporting it along the hydrogeological pressured system to reductor containing rocks (Fig. 8). Reduced uranyl ion is precipitated as uranite or coffinite (Fig. 4). This genetic model is applicable to uranium deposits located at the foothhills of mountains and associated with thermal springs.

2.7. Uranium mobilization during anatexix of uranium enriched rocks and its deposition from juvenile fluids

The uranium source is heterogenous with contrasting geochemical character such as alternation of sediments deposited under oxidation conditions with reductor containing sediments. The generated magma and fluids are enriched in uranium. Fluid injection in reductor containing rocks could lead to uranium precipitation. Multistage metamorphism is the most essential feature of this model.

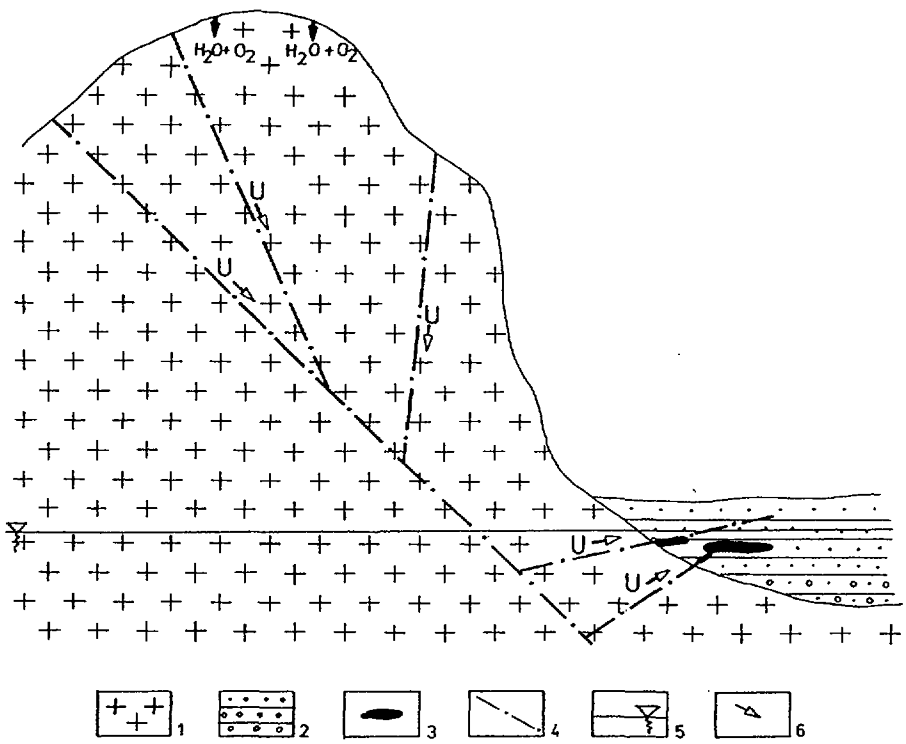


FIG. 8. Uranium mobilization and deposition in hydrogeological pressured system.

1. Uranium source rocks
2. Host rocks
3. Ore body
4. Fault
5. Water table
6. Direction of uranium bearing solutions movement

3. APPLICATION OF GENETIC MODELS IN PRELIMINARY ESTIMATION OF THE URANIUM POTENTIAL OF REGIONS TO BE STUDIED

The application of these genetic models in the preliminary evaluation of the uranium potential of regions is possible by considering the ore processes evolution in seven geo-chronological stages: modification of the fundamental uranium source; local uranium source formation (rocks with abnormal uranium content); host rocks deposition; development of the local source of uranium; mobilization of uranium; its fixation; regeneration of the first uranium accumulation and conservation of deposits. According to the geological environment, each of these genetic models could have three modifications: applicable to regions built up mainly by sedimentary, metamorphic or igneous rocks.

3.1. Preliminary evaluation of the uranium potential of region built up by igneous rocks

a. Modification of the Fundamental Uranium Source

	Geological Process	Associated Process	Indicators
a1/	Mobile belts development	regional metamorphism associated by migmatization and uranium mobilization	amphibolitic granulitic facies of the rocks
		retrograde metamorphism and additional uranium enrichment	retrograde schists with low Th/U ratio
		of rocks peripheral to migmatic zone	
a2/	Intra-mountain basins formation,volcanic depression development	remobilization of uranium dispersed within metamorphic rocks and uranium migration to sedimentary basins; uranium mobilization and transportation to the surface during volcanic activity	

b. Local Uranium Source Formation

	Geological process	Associated process	Indicators
b1/	Anatexis of sialic material in a thick earth's crust under mesozonal and catazonal conditions in a zone enriched in fluids and U	formation of alaskites and leucogranites enriched in uranium	high content of SiO_2,Na_2O,F and low Th/U ratio
b2/	Eruption or extrusion of magma	formation of subvolcanic and volcanic rocks with abnormal uranium content	high ratio of NaO + K_2O/Al_2O_3

	c. Host Rocks Development		
	Geological process	Associated process	Indicators
c1/	Dykes of basic and intermediate rocks emplacement within granitoids	favourable geochemical environment development in host rocks	high Fe^{2+} and Mg^{2+} content in dyke rocks
c2/	Fracturing of the granitoids-the source,and the host rocks of uranium	increasing rock's permeability	
c3/	Metasomatism of the granitoids	metasomatic rocks formation with higher permeability	the rock's chemical composition is different from the primary rocks
c4/	Volcanic activity, reactivation and small basins development	alternation of permeable and not permeable rocks deposition	

	d. Local Uranium Source Development		
d1/	Rejuvenation of igneous rocks by percolation of oxydated fluids	uranium remobilization and accumulation in rejuvenated granitoids	zones with higher SiO_2,NaO_2 or K_2O content,lower FeO, CaO,MgO content and Th/U ratio
d2/	Main stage of volcanic activity	uranium remobilization and formation of volcanic rocks enriched in uranium	lower Th/U ratio
d3/	Fracturing of uplifting granitic massif	uranium oxidation by descending meteoric water	development of secondary uranium minerals containing only U^{6+}

e. Mobilization and Transportation of Uranium

	Geological process	Associated process	Indicators
e1/	Penetration of residual juvenile fluids enriched in CO2, genetically connected with lamprophyre dykes introduction in granites	leaching of Uranium by acid solutions	high concentration of CO2 in mineral fluid inclusions
e2/	Convection cells development in zones with high geothermal potential,or close to cooling magmatic body or in zones with high radiogenic heat	Uranium mobilization by solutions circulating in a system of convection cells	
e3/	Downward migration of Oxygen containing solutions	mobilization and migration of Uranium in depth	
e4/	Migration to the surface along volcanic structures of hot water and fumaroles enriched in CO2	Uranium mobilization and transportation by hot solutions to the surface	aerial argillition of volcanic rocks

f. Uranium Fixation and Primary Ore Formation

f1/	Neutralization of acid uranium containing solutions at the contacts of basic dykes solutions	Uranium precipitation	pyrite grains in basic dykes
f2/	Equilibrium breaking at lower lithostatic pressure and lower temperature,or during other condition change	Uranium accumulation	pitch blende pyrite-marcasite, ankerite mineral association for weak basic solutions and hematite-pyrite mineral association for weak acid solution

g. Regeneration of Primary Ores

	Geological process	Associated process	Indicators
g1/	Penetration of descending Oxygen containing meteoric water in primary uranium ores	Uranium remobilization and accumulation as Uranium silicates	hematite,sulphides

	h. Uranium Deposits Conservation	
h1/	Covering of Uranium deposits by clay sediments	ore bodies are isolated from Oxygen containing meteoric water
h2/	Depending on the host rocks	the same as in h1
h3/	Falling of ore deposits	ore bodies are in the static ground water

BIBLIOGRAPHY

FINCH W.I., Potential uses of genetic-geological modelling to identify new Uranium provinces, Proceedings of the Symposium on Uranium Exploration Methods, Review of the NEA/IAEA R and D Programme, Paris, 1-4 June, 1982.

FINCH W.I., GRANGER, H.C., LUPE, R., Research on interactive genetic geological models to evaluate favourability for undiscovered Uranium resources, Uranium and Mining Techniques, IAEA, Vienna (1980).

SIMOV S.D., Migration of Uranium and Uranium provinces, Technica, Sofia (1984).

SIMOV S.D., Uranium deposits in the foothills of granite massif in the Southeastern Alps, Uranium deposis in Magmatic and Metamorphic rocks, Proceedings of a Technical Committee meeting,Salamanca, 29 September - 3 October 1986, Vienna (1989).

Next page(s) left blank

MODELS FOR CANADIAN UNCONFORMITY DEPOSITS: AN IMPORTANT COMPONENT IN METALLOGENIC STUDIES, EXPLORATION AND MINERAL RESOURCE APPRAISALS

V. RUZICKA
Geological Survey of Canada,Ottawa, Ontario, Canada

Abstract

Canadian unconformity uranium deposits contain the world's largest high grade concentrations of uranium ores. Two models, a regional metallogenic model and a conceptual deposit model, have been developed from studies of the Athabasca Basin metallogenic province. The regional model, which has been derived from the well documented Cigar Lake - Key Lake and Rabbit Lake - Eagle Point trends and the Carswell Structure, includes specific lithological and structural controls within the large Athabasca intracratonic basin. The deposits are spatially related to Archean granitoid domes, such as the Swanson, Collins Bay and Dominique-Peter, which are flanked by a Lower Proterozoic metasedimentary sequence that contains layers of euxinic rocks. These basement rocks are capped by a regolith. They are unconformably overlain by a sequence of undisturbed sediments of the Athabasca Group. The Athabasca Group rocks have been subjected to high-temperature prograde diagenesis, which was followed by retrograde alteration. The deposit model, which has been derived from observations on the Cigar Lake, P2 North, Key Lake, Collins Bay and Cluff Lake deposits, postulates deposition of the metals and associated gangue minerals from highly saline brines at redox fronts. Uranium was transported in hexavalent form and deposited due to reduction to tetravalent form. The mineralization processes took place predominantly at the sub-Athabasca unconformity and, to a lesser degree, a short distance from it in the basement or in the cover rocks. At present these models are used in metallogenic studies, for delineation of new exploration targets, and in mineral potential appraisals of the Athabasca Basin frontier areas.

1. INTRODUCTION

Canadian unconformity uranium deposits contain the world's largest high grade concentrations of uranium ores. At present their Reasonably Assured resources (RAR), recoverable at prices up to $US 80/kgU, represent about 90 per cent of Canada's total RAR and contribute in the same proportion to Canadian uranium production, which in 1992 amounted to 9300 tonnes of uranium metal. This proportion is increasing as a result of new discoveries and the diminishing viability of uranium resources in other types of deposits.

The known deposits of this type occur in the Middle Proterozoic intracratonic basins, namely in the Athabasca Basin domain, Saskatchewan (No. 1 in Fig. 1), and in the Thelon Basin domain, Northwest Territories (No. 2 in Fig. 1). Environments similar to these also occur in the Hornby Bay domain, Northwest Territories (No. 3 in Fig. 1), in the Otish Basin domain, Quebec (No. 4 in Fig. 1) and in the Sibley Basin, Ontario (No. 5 in Fig. 1).

The most important deposits of the Athabasca Basin metallogenic province (Fig. 2) occur in the southeastern part of the Athabasca Basin, namely along the Key Lake - Cigar Lake structural trend (the Key Lake, P2 North, Cigar Lake and Midwest deposits) and along the Rabbit Lake Eagle Point trend, particularly within the aureole of the Collins Bay Granite Dome (the Rabbit Lake deposit, the Collins Bay 'A', 'B' and 'D' Zones, the Eagle Point and the Sue 'A', 'B', 'C', 'CQ', 'D' and 'E' deposits). The deposits of these two trends represent the world's richest uranium resource quadrangle with an endowment of more than 400,000 tonnes of uranium metal in ores grading more than 2% U. Another cluster of deposits occurs in the Carswell Structure, which is located in the western part of the Athabasca Basin. This cluster includes the Cluff Lake 'D' Zone, OP, Claude, Dominique-Peter and Dominique-Janine deposits (Fig. 3). Most of these deposits are being exploited, some (e.g., Rabbit Lake and Cluff 'D') are depleted and several are under advanced exploration (e.g., Cigar Lake, Eagle Point and P2 North).

Uranium deposits in the Thelon Basin domain, associated directly or indirectly with the sub-Thelon unconformity, occur in the Kiggavik trend at the northeastern rim of the Thelon Basin, Northwest Territories. They include the Kiggavik (formerly Lone Gull), Andrew Lake and End deposit. The deposits are under exploration. The Hornby Bay Basin domain contains the Dismal Lakes deposits, which have been dormant for several years. The Otish Basin domain hosts uranium occurrences associated with the Middle Proterozoic/Archean unconformity (Fig. 1).

2. GEOLOGICAL SETTING OF THE UNCONFORMITY DEPOSITS

The unconformity deposits typically consist of uranium concentrations at the base of Middle Proterozoic sandstone, where it is in unconformable contact with Lower Proterozoic basement rocks. The mineralization is structurally controlled by faults or fracture zones.

The basement rocks, which originally were deposited in shallow intracratonic basins, now flank Archean granitic domes. They include graphitic, pyritic, non-graphitic and aluminous pelites and semipelites, calc-silicate rocks, banded iron formation, volcanic rocks and greywackes. The basement rocks are typically capped by regolith. The cover rocks (Athabasca sandstones) consist primarily of unmetamorphosed clastic sediments, but include very minor amounts of volcanic rocks.

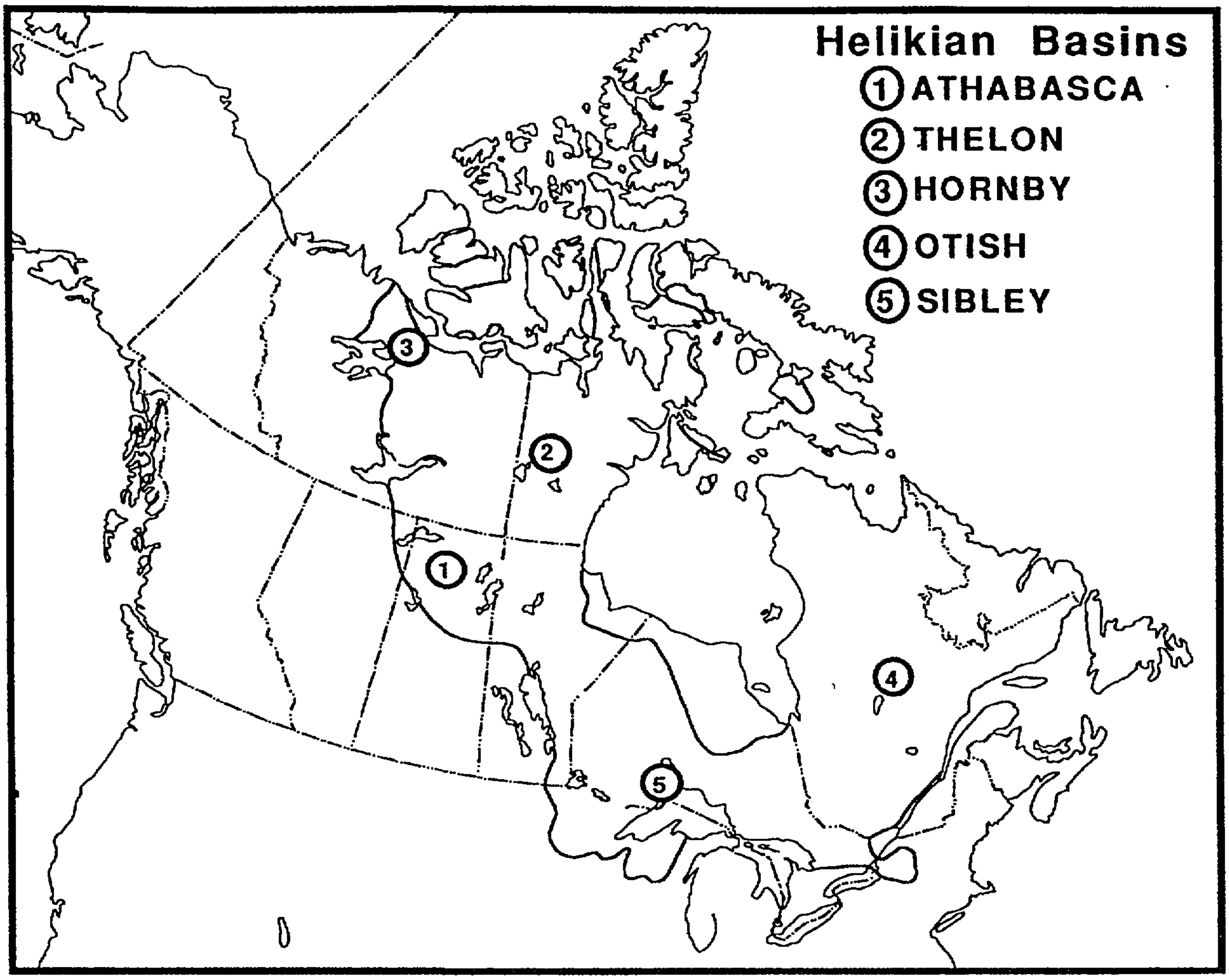


FIG. 1. Areas with unconformity uranium deposits and with environments favourable for their formation.

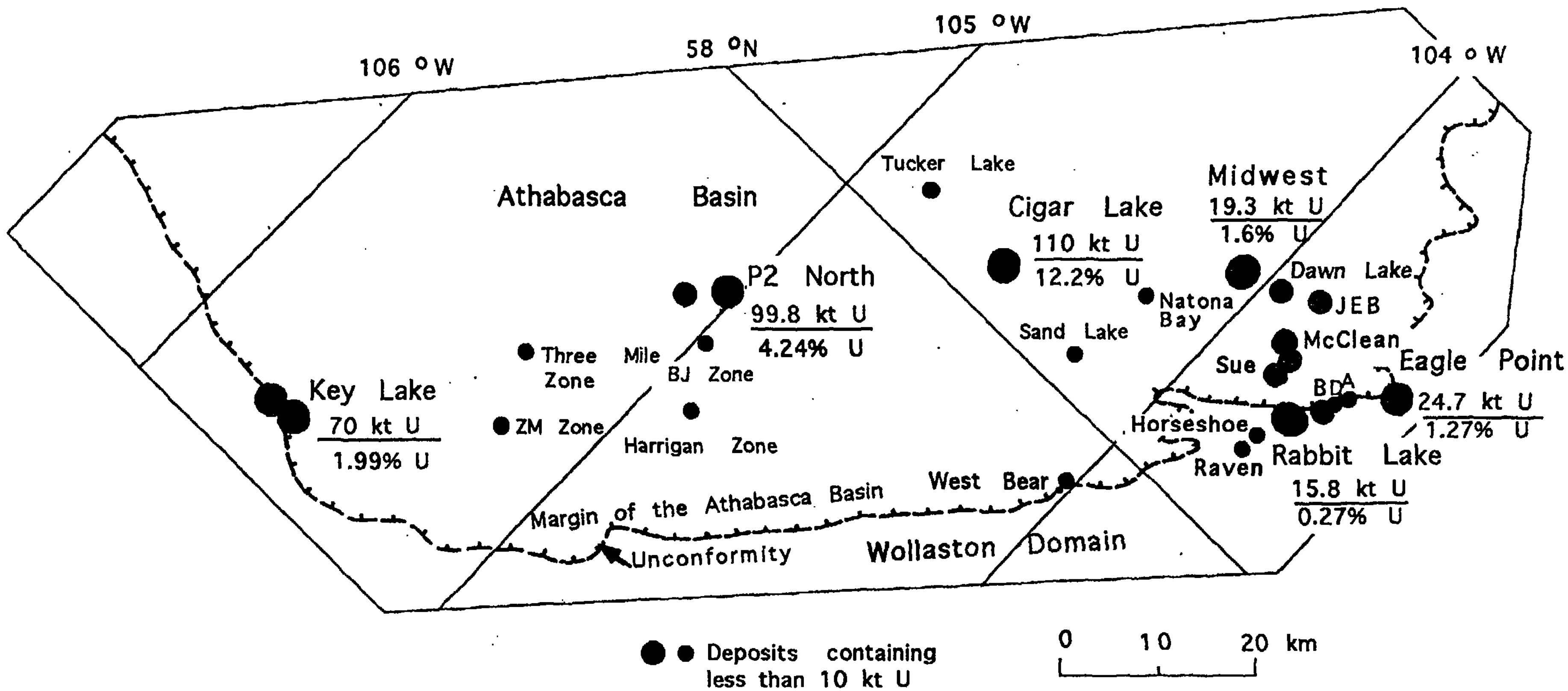


FIG. 2. Location of unconformity deposits and uranium resources in the southeastern part of the Athabasca Basin.

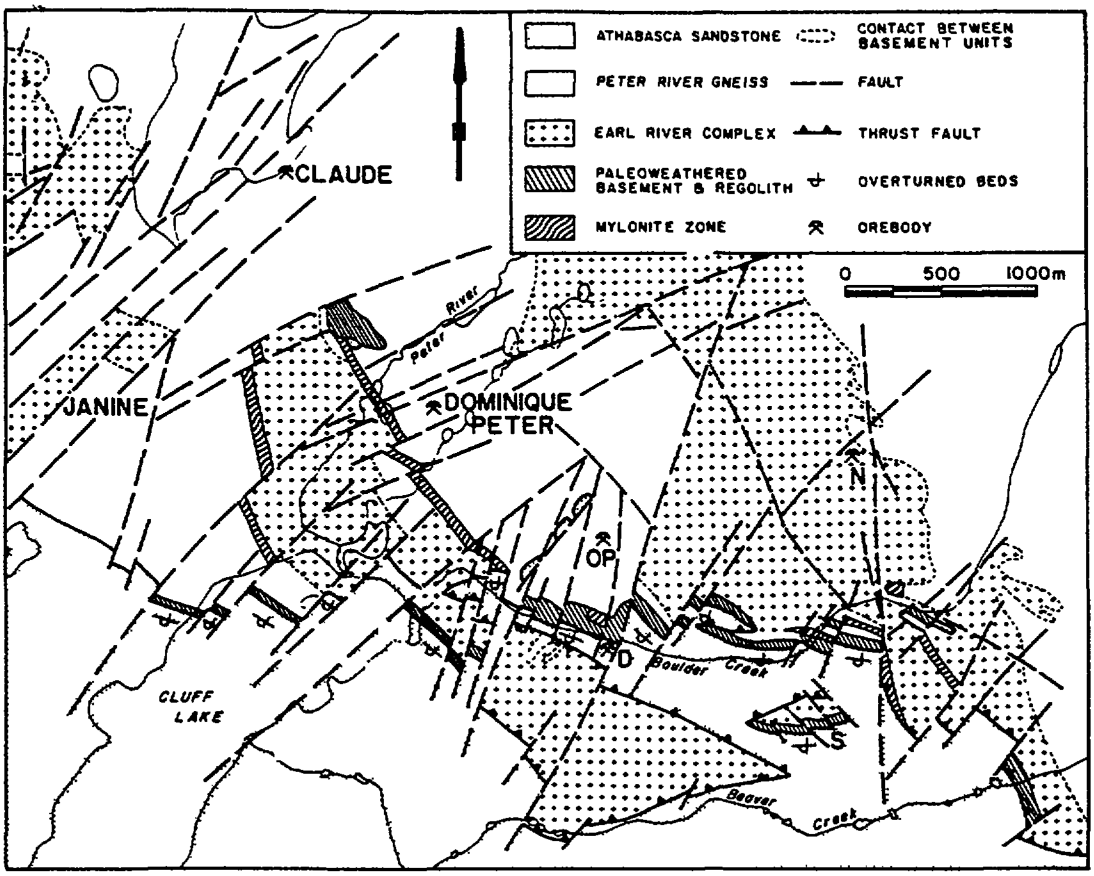


FIG. 3. Uranium deposits in the Carswell Structure, Saskatchewan.

The principal commodity is uranium, which occurs either as the predominant metallic constituent (monometallic deposits) or accompanied by other metals, particularly Ni, Co, and As (polymetallic deposits); these accompanying metals, however, do not constitute significant recoverable byproducts at present. A Metal Tonnage/Ore Grade diagram for the Canadian and Australian unconformity deposits displays differences in sizes and grades for the monometallic and polymetallic subtypes (Fig. 4).

The monometallic deposits occur typically in basement rocks and, exceptionally, in the cover rocks. For instance, the predominant host rocks of the Rabbit Lake deposit, which has been mined out, were Lower Proterozoic albite-rich gneisses, graphitic semipelites and dolomite. The Eagle Point deposit occurs in Lower Proterozoic Wollaston Group rocks, which consist of graphitic schist, gneiss and calcareous and quartz gneisses. The Dominique-Peter deposit, which is located in the Carswell Structure, occurs in fractures within a mylonite zone, which is at a contact between quartzofeldspathic and mafic gneisses and garnet-cordierite-sillimanite-quartz metapelites. The P2 North deposit occurs in the Athabasca sandstone beneath an overthrust block of basement rocks. The Fond-du-Lac deposit occurs in hematized, carbonatized and silicified sandstone of the Athabasca Group.

The polymetallic deposits typically occur directly at the unconformity. The Key Lake deposit is located between the basal Athabasca sandstone and the underlying Lower Proterozoic gneisses of the Wollaston Group. The orebodies occur at the unconformity between basement rocks, which consist of graphitic metapelites, gneiss, amphibolite, calc-silicate rocks, migmatite, and granite pegmatite, and the Athabasca sandstone, some conglomerate, siltstone and shale. The Cigar Lake deposit occurs predominantly in clay-altered Athabasca sandstone and to a lesser degree in altered basement rocks just beneath the unconformity. The mineralization of the Collins Bay 'A' and 'B' zones occur mainly in clay-altered Athabasca sandstone and a small amount in altered basement rocks.

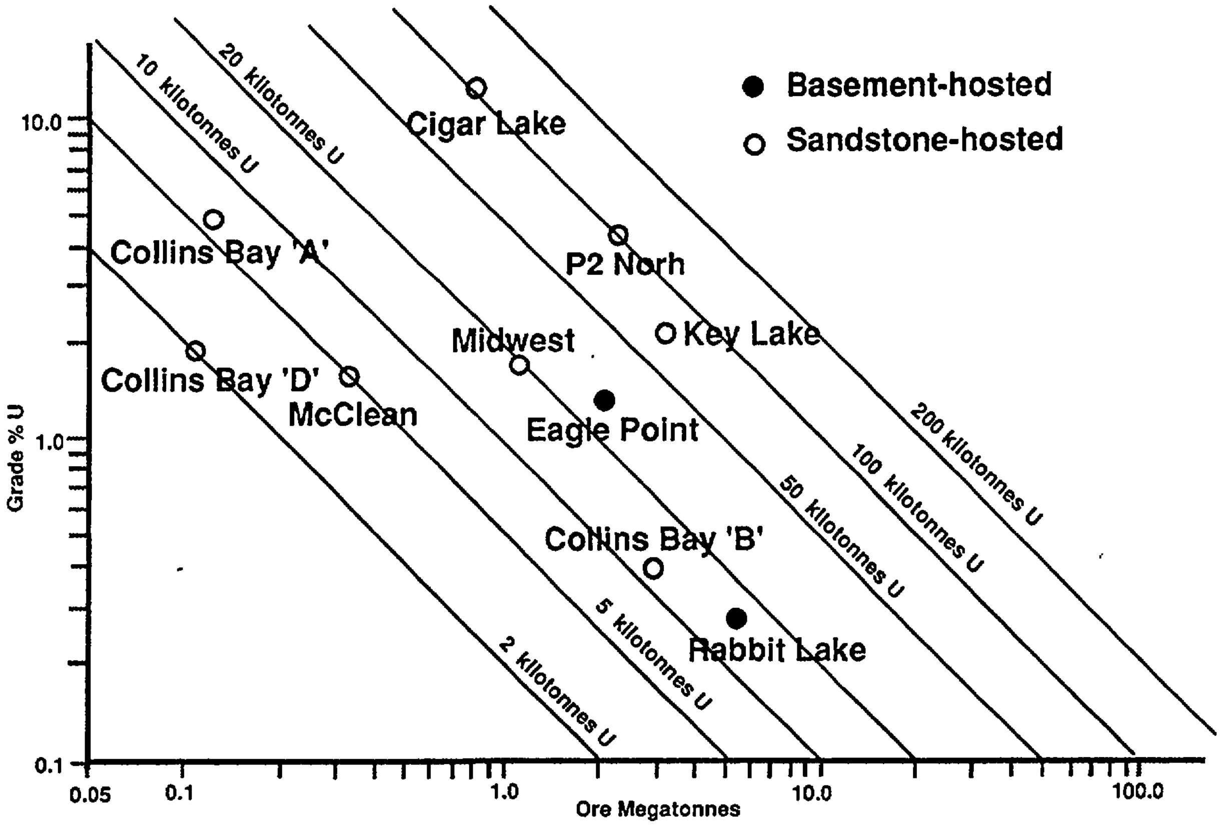


FIG. 4. Tonnages and grades of unconformity deposits in the SE part of the Athabasca Basin.

The sub-Athabasca unconformity and intersecting faults and fracture zones, which displace the unconformity, are the principal structural controls on regional and local scales. The fault and fracture systems commonly follow and are along the projection of the graphitic pelitic layers in the basement rocks. The faults strike northeasterly (e.g. the Key Lake Fault, the P2 Zone, the Rabbit Lake Fault, the Collins Bay Fault, the Eagle Point Fault), or easterly (e.g. the Cigar Lake structural zone). Locally these structures are offset by northwesterly striking faults (e.g. at the West Bear and McClean deposits).

3. MODELS FOR THE UNCONFORMITY DEPOSITS

Several conceptual models have been proposed for genesis of Canadian unconformity deposits: (i) a near-surface supergene origin, which involves extraction of uranium and other ore constituents from basement rocks by supergene processes, their transport by surface and ground waters and their deposition in reducing host rocks; (ii) a magmatic or metamorphic hydrothermal origin, whereby it is postulated that uranium was derived from deep-seated sources, and transported in and deposited from ascending solutions; and (iii) a diagenetic-hydrothermal origin, according to which uranium mineralization is related to diagenetic processes active under burial temperatures in Athabasca Group sediments and the of uranium was precipitated from diagenetic fluids under reducing conditions.

For practical application in metallogenic studies, exploration and mineral resource appraisals it is convenient to develop two models: (i) a regional metallogenic model for application in studies on a broad scale, such as favourability studies, field reconnaissance and preliminary potential appraisals; and (ii) a conceptual deposit model, for detailed studies, such as detailed mapping, evaluation of exploration drilling and resource assessment. Such models, based on observations on the Athabasca Basin metallogenic province and the known unconformity deposits, are presented here.

3.1. Regional model

The regional model relates uranium mineralization periods to selected geological events, which took place in the northern Saskatchewan part of the Churchill structural province (Fig. 5).

(a) The regional geochemical cycle of uranium apparently started with granitoid magmatism at least 2.2 Ga ago, as suggested by Koeppel [1] for the Beaverlodge area, which is in the proximity of the Athabasca Basin. His suggestion is supported by Krogh and Clark [2], who reported an age as great as about 2.6 Ga for uranium-rich zircons from an unfoliated, nonmagnetic, white granitic body at Colquhoun Lake (near Key Lake).

(b) Koeppel [1] also summarized the results of a number of U-Pb and Rb-Sr age studies of uraninite, uranothorite, thorite, betafite, allanite and zircon from other uranium occurrences in pegmatites and mafic portions of the metasedimentary rocks within the Tazin Group in the Beaverlodge region and concluded that these occurrences belong to a younger period of syngenetic mineralization in the area. His conclusion is consistent with dating of the Viking Lake deposit, Saskatchewan, by Robinson [3], who found that the mineralization, which consists of pyrochlore and other minerals in a pegmatite dyke, is about 1930 Ma old.

(c) Major mobilization of uranium, associated with the waning stage of the Hudsonian Orogeny, led to formation of epigenetic uranium deposits in the Beaverlodge area. Ward [4] concluded that the earliest ages for the deposits are on the order of 1800 to 1700 Ma and that additional episodic reworking occurred at least twice later.

(d) Weathering of the Archean and Lower Proterozoic metamorphic basement rocks led to formation of regolith, which persists under the Athabasca sandstone throughout the basin and

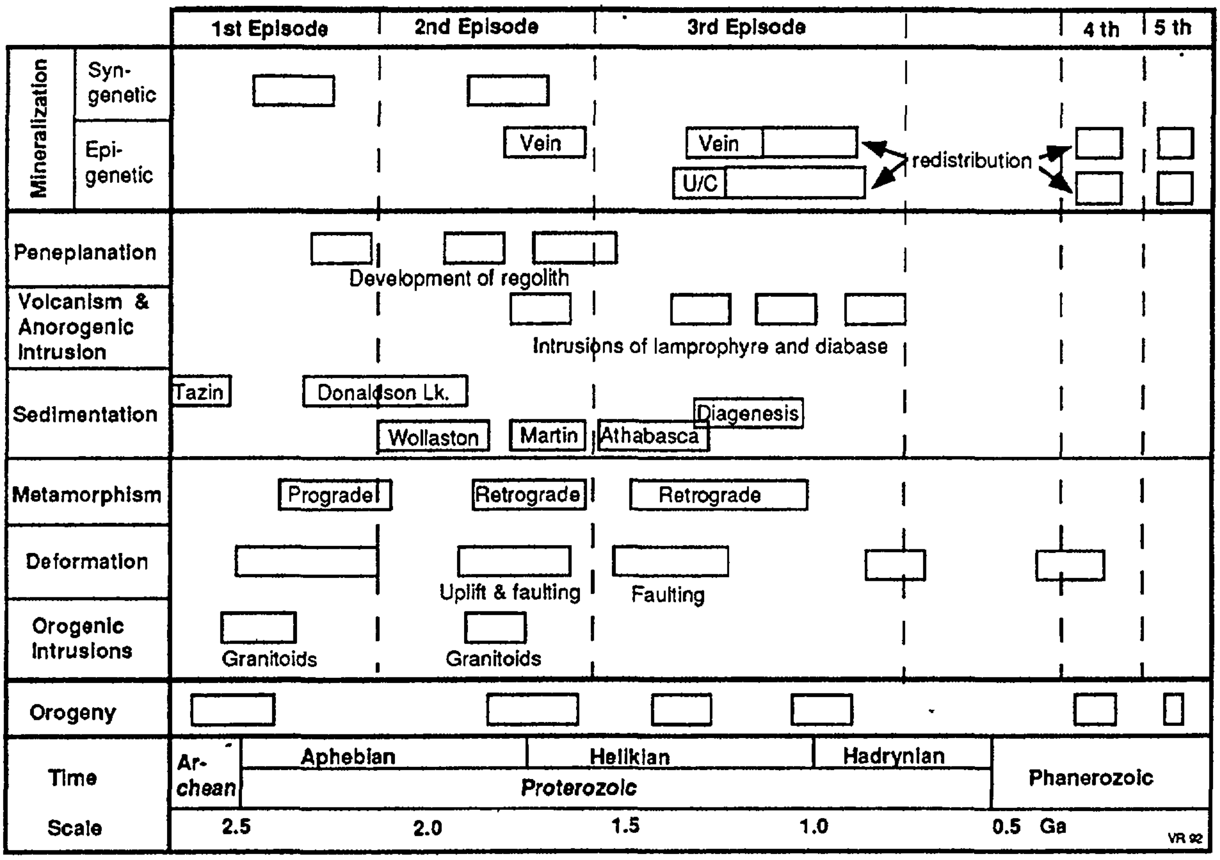


FIG. 5. Regional metallogenic model for uranium in northern Saskatchewan.

shows many features compatible with present-day lateritic soil profiles formed in subtropical to tropical climates. Development of the regolith lead to liberation of minerals containing uranium and trace elements, such as V, Mo, Ni, Co, and As. This mineral assemblage survived weathering in chemically resistant oxide and heavy mineral phases and became available as detritus for subsequent sedimentary accumulation in the Middle Proterozoic intracratonic basins, where they were subjected to dissolution and their elements became part of the oxidized basinal fluids. During high-temperature, prograde diagenesis of the sandstone these basinal metalliferous fluids evolved into highly saline hot brines.

(e) The deposits are commonly spatially related to elongated Archean granitoid domes that are flanked by metasedimentary Lower Proterozoic rocks. The metasedimentary sequence includes graphitic, pyritic, non-graphitic, and aluminous metapelites, calc-silicate rocks, banded iron formation, volcanic rocks, and greywackes. The crystalline Archean and Lower Proterozoic rocks were then unconformably overlain by the Athabasca Group fluviatile and marine sequence of undisturbed sediments; the entire sequence was intruded by late Proterozoic diabase dykes. Localization of the deposits was structurally controlled by the unconformity itself (as a barrier for the basinal fluids) and by faults and fracture zones that intersect this surface (as conduits for ascending basement fluids).

(f) Diagenetic and epigenetic processes affected the Athabasca Group and the basement rocks, caused their alteration and brought about their metallic mineralization.

(g) The mineralization was remobilized and redeposited during at least two later periods.

3.2. Conceptual deposit model

The following model for the deposits associated with the sub-Athabasca unconformity results from an integration of the geological observations and interpretations of the ore-forming processes and their lithological, structural and geochemical controls (Fig. 6).

(a) The Archean and Lower Proterozoic basement rocks, which include granitoid domes surrounded by metamorphosed Lower Proterozoic sedimentary rocks that contain layers of euxinic rocks controlled the mineralization process lithologically by reduction of the basinal fluids.

(b) The sub-Athabasca unconformity, and faults or fracture zones that displace the unconformity, along with porosity and permeability of the sediments, controlled the mineralization processes structurally.

(c) The Athabasca sediments have been subjected to high-temperature prograde diagenesis involving basinal fluids at temperatures of 120° to 240°C and salinities of 10 to 36 wt.% NaCl equivalent. This diagenesis was followed by retrograde alteration involving low temperature fluids derived from meteoric waters.

(4) Tectonic and thermal events caused convective flow of fluids and mobilization of the metals from the reservoirs. Because of their specific gravity the oxidized metalliferous basinal fluids moved downwards. At the unconformity they continued flowing laterally, but some of the fluids also entered fault and fracture zones in the basement rocks and became a part of the basement fluids. The proportion of reduced basinal fluids in the ore-forming fluids and whether or not the basement fluids also contained water from deep-seated sources, are not known. Due to the geothermal gradient the reducing basement fluids entered the sedimentary rocks in ascending flows along faults and fracture zones, where they mingled with the laterally moving oxidized metalliferous basinal waters at the unconformity.

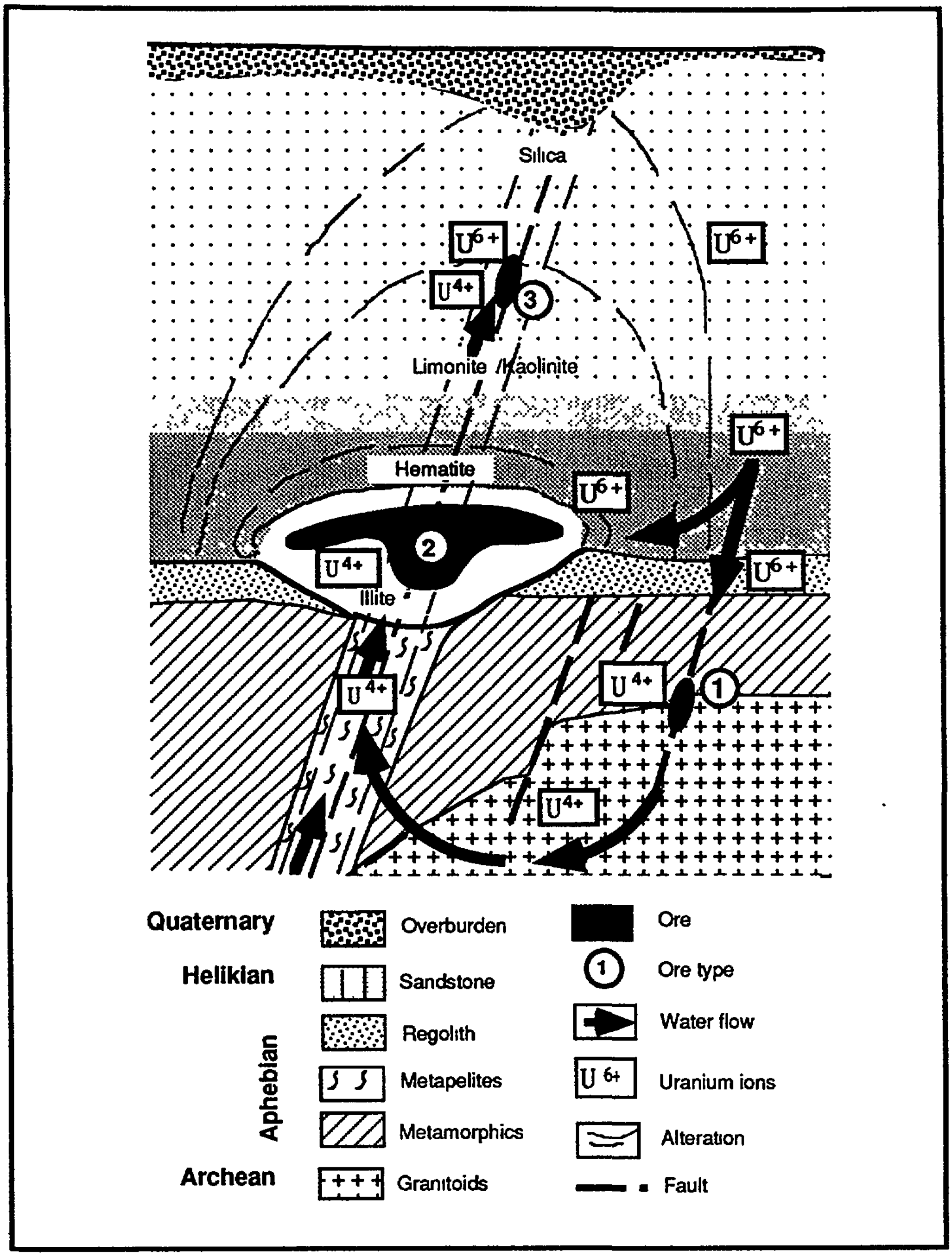


FIG. 6. Conceptual genetic model for unconformity deposits in the Athabasca Basin, Canada.

(d) Deposition of the metals and associated gangue minerals took place at the interface between the oxidizing and reducing fluids, i.e. at the redox front, during the diagenesis of the sedimentary cover rocks. Depending upon the location of the redox front, the mineralization took place (i) directly at the unconformity (location 1/circled/ in Fig. 6). (ii) in fractures and faults in the basement rocks below the unconformity (location 2 /circled/ in Fig. 6) and (iii) to a lesser extent also within the sedimentary sequence at some distance above the unconformity (location 3 /circled/ in Fig. 6).

(e) The host rocks were affected by alteration at various stages of the ore-forming processes:

(i) Chloritization and hematitic alteration of ferromagnesian minerals, sericitization, illitization or kaolinization of K-feldspars and saussuritization of plagioclase at the paleosurface due to weathering led to formation of regolith.

(ii) The mineralizing fluids caused argillization (illitization, kaolinization), chloritization, bleaching, hematization, tourmalinization (particularly development of dravite) and magnesian metasomatism of the host rocks. The ascending fluids caused dissolution of quartz in the area of mineralization, and its redeposition in a distant aureole around the orebodies, and partial destruction of graphite and carbon in the metapelitic rocks. The orebodies are commonly surrounded by clay envelopes.

(iii) Oxygen and hydrogen isotopic analyses of illite, kaolinite and chlorite, associated with uranium mineralization, have indicated that (i) the basement fluids have produced clinochlore that has $\delta 180$ and δD values +2 to +4 and -15 to -45‰, respectively and sudoite that has $\delta 180$ and δD values -25 to -60 and 7 to 9‰ respectively; (ii) the basinal fluids produced illite and kaolinite that have $\delta 180 = +4 \pm 2$ and $\delta D = -60 \pm 20‰$; whereas (iii) "retrograde" fluids, i.e., meteoric waters that circulated along fault zones, produced a late-stage kaolinite with $\delta 180 = -16$ and $\delta D = -130 \pm 10‰$ [5, 6].

(iv) The ore-forming and alteration processes produced changes in the volume of the rocks, which caused their brecciation and the development of collapse structures.

(v) Renewed tectonic movements in the basin at about 300 Ma caused low temperature meteoric waters to percolate into reactivated faults and fracture zones, and this resulted in formation of new alteration minerals, particularly chlorite, smectite and mixed-layer clays, and kaolinization of illite and quartz. This alteration reduced the permeability of the host rocks, and thus protected the orebodies from destruction by groundwater and transient basinal fluids.

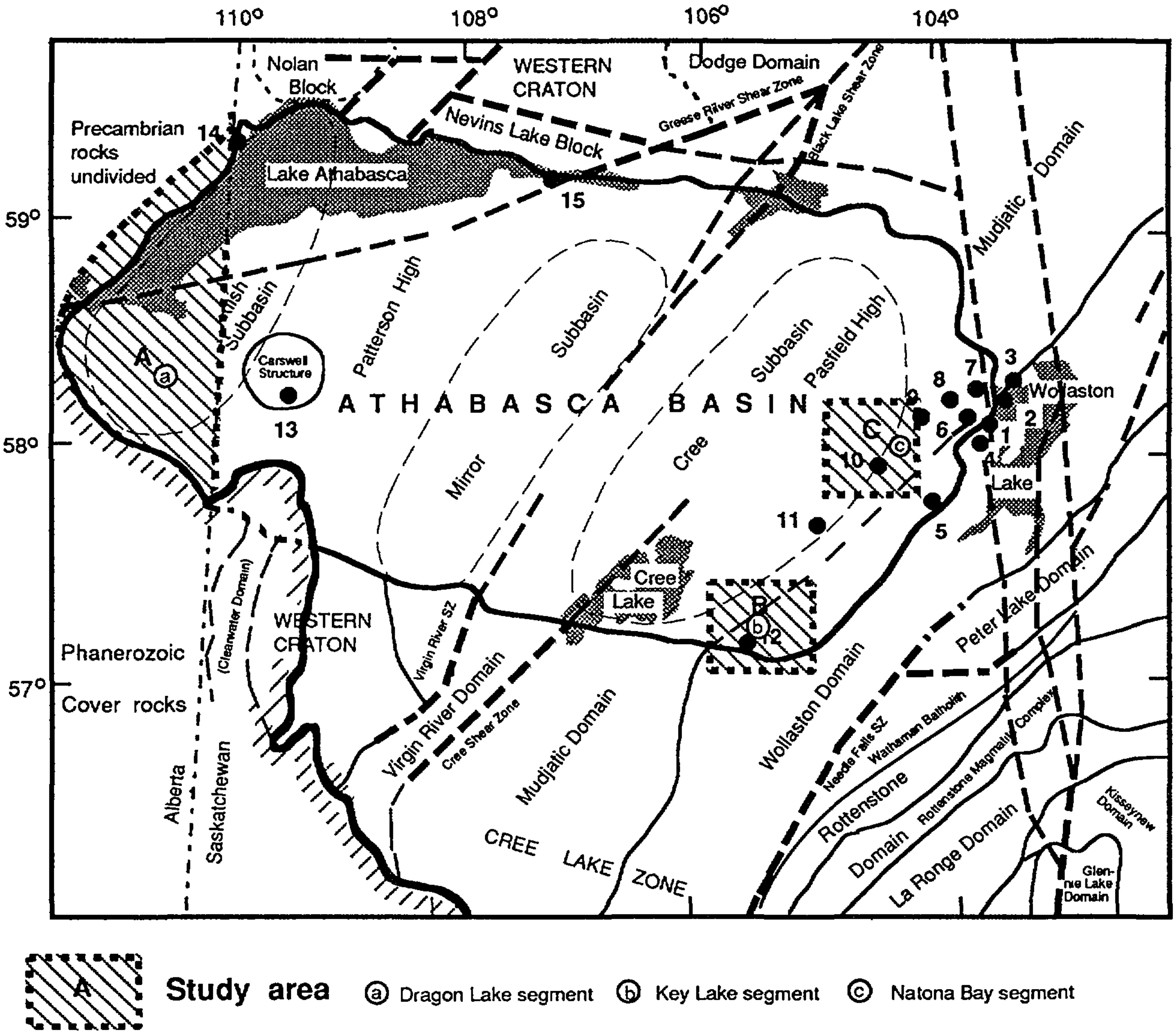
4. APPLICATION OF THE MODELS IN METALLOGENIC STUDIES

Recently, metallogenic studies have been conducted for a selected part of northeastern Alberta by comparison with selected areas of the Saskatchewan part of the Athabasca basin [7], (Fig. 7).

The Saskatchewan part of the basin, which in 1992 participated significantly in Canada's uranium production, contributed, along with exploration for this deposit type, almost a billion dollars to Canadian economy. The Alberta part of the basin, however, remained for several years as a less attractive target for such exploration and mining activities. In order to assess the mineral potential of this area, comparative metallogenic studies of the Alberta and Saskatchewan parts of the basin have been introduced.

The main aim of the studies is to investigate whether or not the metallogenic observations for the Alberta part of the Athabasca Basin are compatible with the models established for the Saskatchewan part of the basin. The studies involve areas 'A' in Alberta and areas 'B' and 'C' in Saskatchewan .

Geochemical analyses of samples from area 'A' have been compared with analyses from the combined areas 'B' and 'C' by statistical analysis of variance (ANOVA model). This statistical treatment determines the significance of the effects in a model by calculating the variability in relationship between contents of the selected constituents in comparable lithostratigraphic units from



Deposits (m = monometallic, p = polymetallic):

1 = Rabbit Lake (m), 2 = Collins Bay cluster (p), 3 = Eagle Point (m), 4 = Horseshoe and Raven (m), 5 = West Bear (p), 6 = McClean-Sue cluster (p), 7 = JEB (m), 8 = Dawn Lake (p), 9 = Midwest (p), 10 = Cigar Lake (p), 11 = P2 North (m), 12 = Key Lake (p), 13 = Cluff 'D' (p), Dominique-Peter (m), Dominique Janine (m), Claude (m), 14 = Maurice Bay (p), 15 = Fond-du-Lac (m).

FIG. 7. Index map showing the location of study areas and unconformity type deposits in the Athabasca Basin.

the areas in question. The area 'A' consists of a crystalline basement unit and the Fair Point, Manitou Falls and Lazenby Lake formations of the Athabasca Group, whereas investigation of areas 'B' and 'C' encompassed the crystalline basement and Manitou Falls Formation of the Athabasca Group.

The comparison (Fig. 8) indicates that the basement rocks in Alberta contain less uranium than those in areas 'B' and 'C'. However, the graph also indicates that there is a distinct enrichment of the basal formations of the Athabasca Group (i.e. of the Fair Point Formation in Alberta and of the Manitou Falls Formation in Saskatchewan) with uranium. This enrichment indicates that the epigenetic uranium concentration processes in area 'A' were controlled by the unconformity and fits perfectly to the pertinent conceptual deposit model.

ANOVA Table for U ppm

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Formation	1	8.903	8.903	.155	.6943
Area	0	0.000	•	•	•
Formation * Area	1	32.393	32.393	.565	.4539
Residual	107	6134.837	57.335		

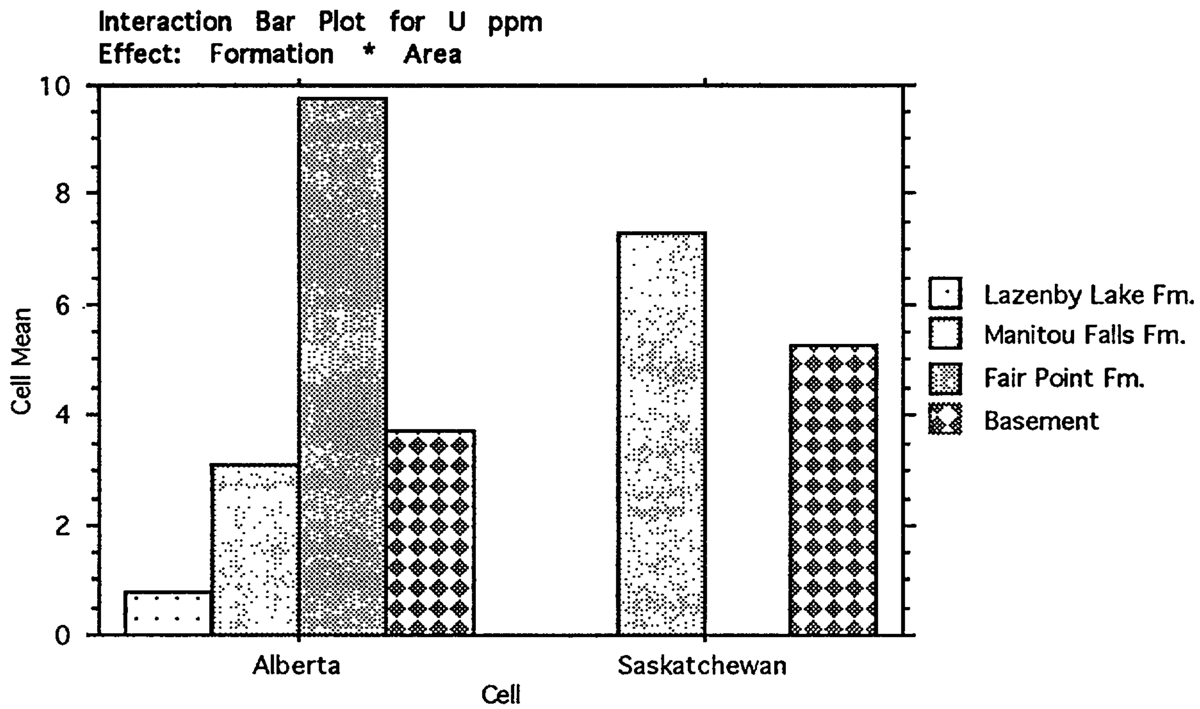


FIG. 8. ANOVA Table and Graph for URANIUM contents in geological formations of the Alberta and Saskatchewan parts of the Athabasca Basin (from selected drillholes).

On the other hand chromium exhibits a very specific distribution pattern (Fig. 9). In area 'A' it is distinctly enriched in the upper part of the sequence (Lazenby Lake Formation), in which it exceeds the values from the Saskatchewan areas. Chromium is distributed inversely to uranium, as demonstrated by vertical logs of selected drillholes from areas 'A' (Fig. 10) and 'C' (Fig. 11). Distribution of chromium and uranium supports, according to these logs, a model for deposition of chromium by sedimentary syngenetic processes, whereas deposition of uranium is epigenetic and takes place from metalliferous brines at redox fronts.

The source for chromium was, apparently, deeper parts of the basement, composed of mafic to ultramafic rocks. Chromiferous detritus, derived from these rocks by erosion, was transported to the basin and deposited in a large fan of the Lazenby Lake Formation.

The ANOVA models are supported by the results of factor analyses of selected samples. An unrotated factor plot for selected constituents in samples from area 'A' indicates that uranium has a geochemical affinity to arsenic, molybdenum, boron and nickel, whereas chromium exhibits an entirely different geochemical behavior (Fig. 12). An unrotated factor plot for constituents in samples from areas 'B' and 'C' shows also that chromium occupies a specific position, separated from the uranium and titanium groups of elements (Fig. 13).

ANOVA Table for Cr ppm

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Formation	1	91011.782	91011.782	5.086	.0261
Area	0	-1.137E-13	•	•	•
Formation * Area	1	13.917	13.917	.001	.9778
Residual	107	1914541.932	17892.915		

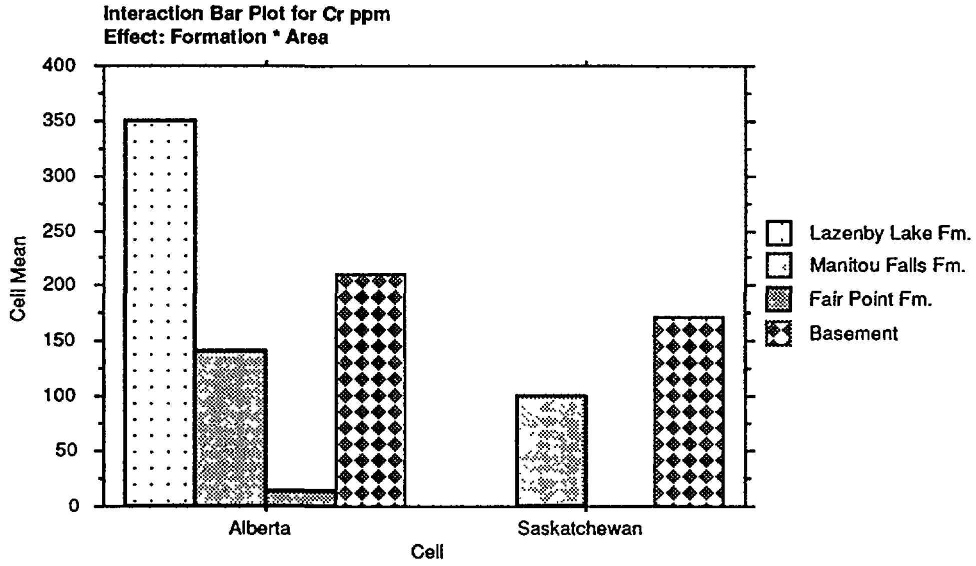


FIG. 9. ANOVA Table and Graph for CHROMIUM contents in geological formations of the Alberta and Saskatchewan parts of the Athabasca Basin (from selected drillholes).

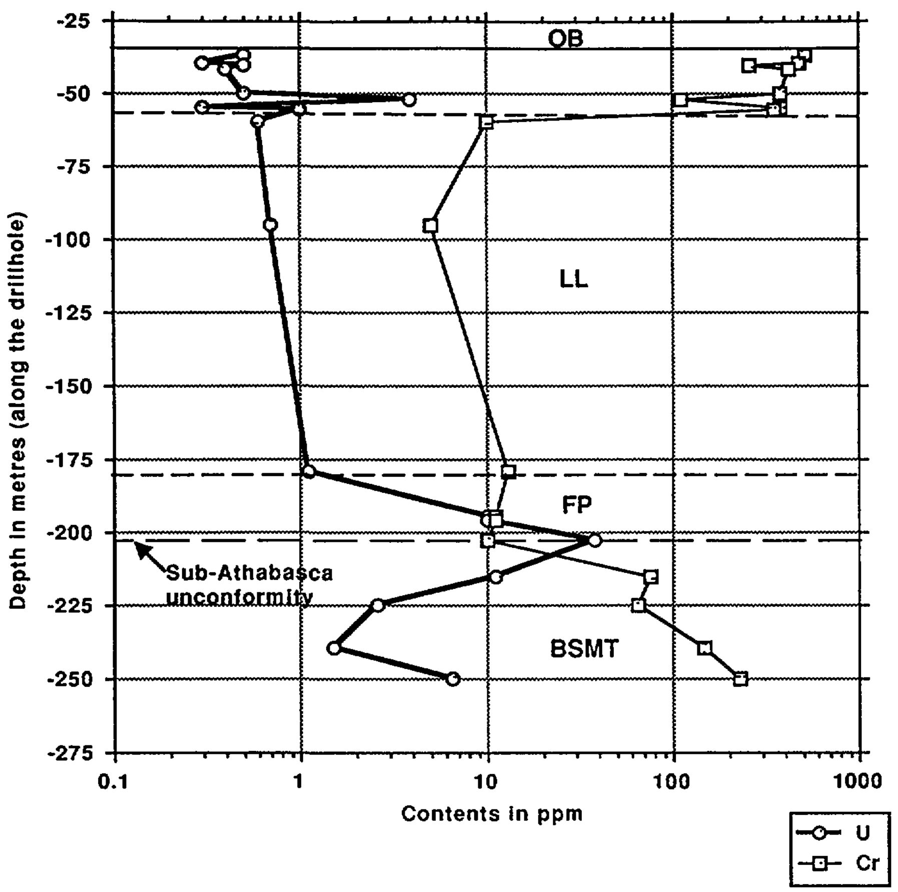


FIG. 10. Vertical distribution of U and Cr in samples from a drillhole in the Alberta part of the Athabasca Basin.

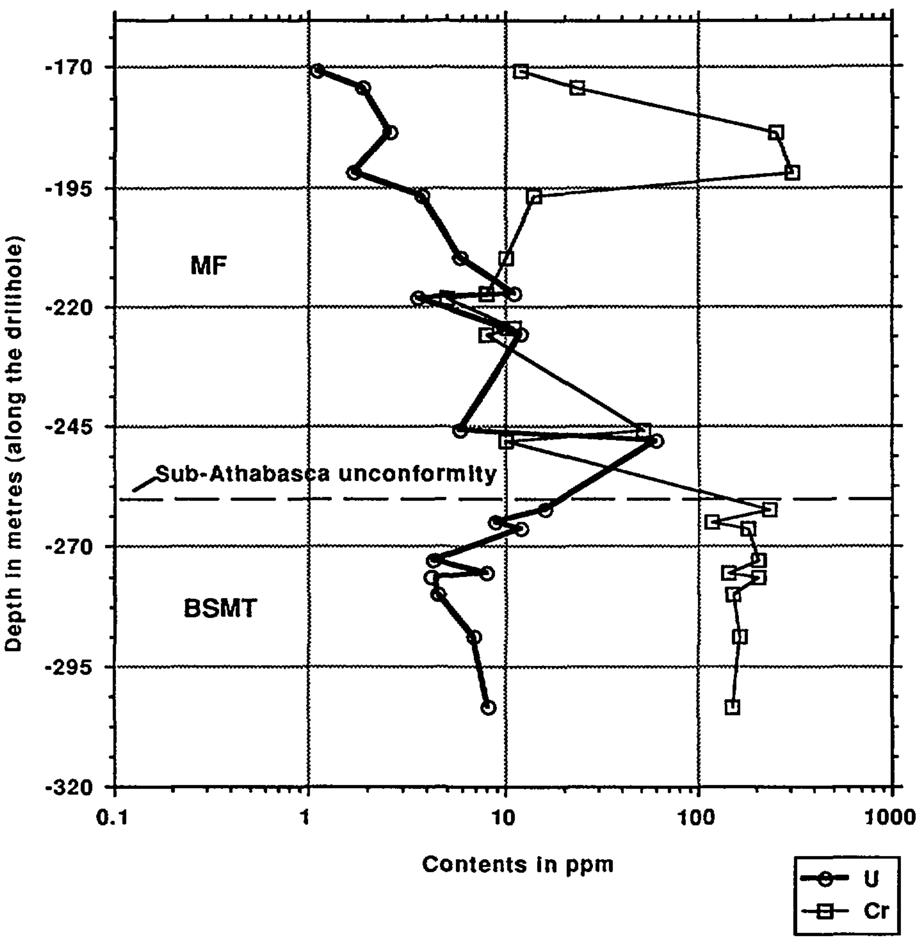


FIG. 11. Vertical distribution of U and Cr in samples from a drillhole in the Saskatchewan part of the Athabasca Basin.

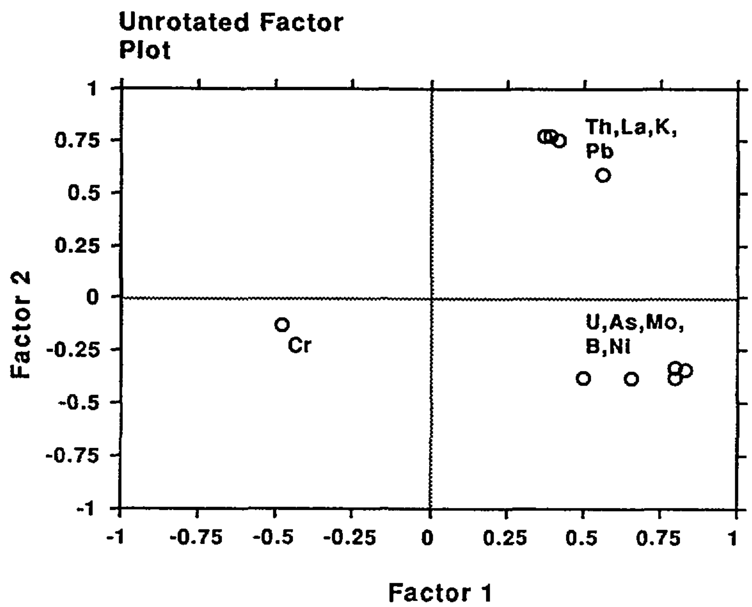


FIG. 12. Unrotated factor plot for selected constituents in samples from area 'A'.

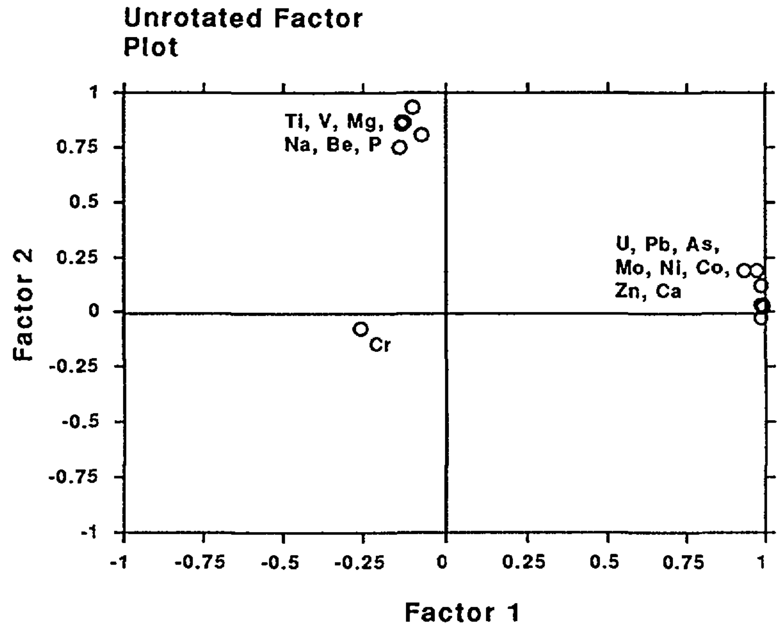


FIG. 13. Unrotated factor plot for selected constituents in samples from areas 'B' and 'C'.

The chromium-bearing Athabasca sandstone might be comparable, to a certain degree, to some chromiferous deposits, which occur in the eastern Ugui Graben, in the Olekma-Vitim province of the Russian Republic [8]. The chromium occurs in sandstone of the Precambrian Pravdinskaya Formation, which is 100 metres thick, either as coastalmarine placers or as concentrations of chromian glauconite and clastic chromite grains associated with a redbed-greybed transition zone within the sandstone.

In the light of these and other comparisons, Ruzicka [7] concluded that the specific metallogenic features of the Alberta rocks are compatible with a conceptual model for unconformity deposits derived from observations on the polymetallic and monometallic deposits in Saskatchewan, and therefore suggest a good potential for discovery of unconformity-type deposits in northeastern Alberta.

5. APPLICATION OF THE MODELS IN EXPLORATION

The conceptual deposit model for unconformity deposits includes, in addition to presence of the unconformity, three very important components: (a) association of the deposits with Lower and Middle Proterozoic rocks flanking reactivated Archean granitic domes; (b) presence of a Lower Proterozoic metasedimentary sequence that contains graphitic-pyritic layers of euxinic rocks; (c) presence of regolith at the top of the basement and of effects of high-temperature prograde diagenesis, which was followed by retrograde alteration.

This model has been very successfully applied to revision of strategy for exploration of the area around the Collins Bay Granite Dome [9]. The application consisted of (i) a careful reinterpretation of the magnetic surveys, which led in turn to more precise delineation of the granitic domal structure; (ii) meticulous interpretation of repeated VLF, resistivity and other geophysical surveys that led to pinpointing of graphitic-pyritic metapelite layers in the basement rocks; (iii) establishment of alteration trends from geochemical sampling, reconnaissance mapping and drilling. This complex revision led to discoveries of several deposits, namely the Sue 'A', 'B', 'C', 'CQ' etc., in an area which had been designated by previous explorers as a less prospective target. This successful case history was presented at the International Atomic Energy Agency Technical Committee Meeting on New Developments in Uranium Exploration, Resources, Production and Demand in Vienna in 1991 [9].

6. APPLICATION OF THE MODELS IN MINERAL RESOURCE APPRAISALS

Both the regional and conceptual deposit models have been successfully applied to uranium resource appraisal of an exploration target are in the southeastern part of the Athabasca Basin before the inception of the exploration project [10].

The following input from the existing data base was used in the study:

(a) Distribution of granitic domal structures in the basement rocks from interpretation of electromagnetic surveys (Fig. 14).

(b) Distribution of conductive graphitic-pyritic horizons in the basement rocks from interpretation of resistivity and other geophysical surveys (Fig. 15).

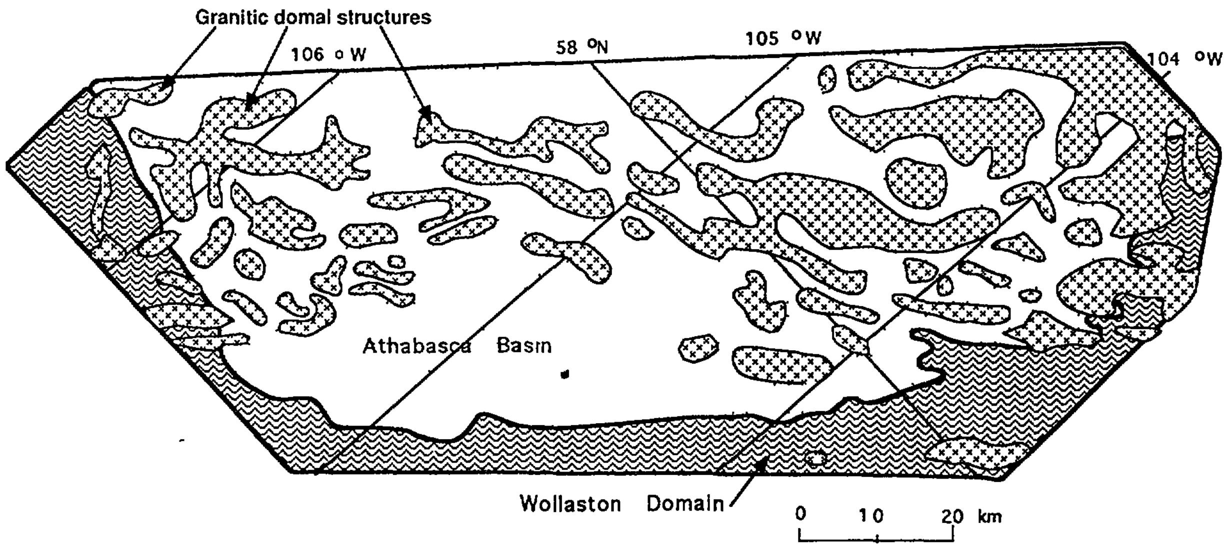


FIG. 14 Distribution of granitic domal structures in the basement rocks.

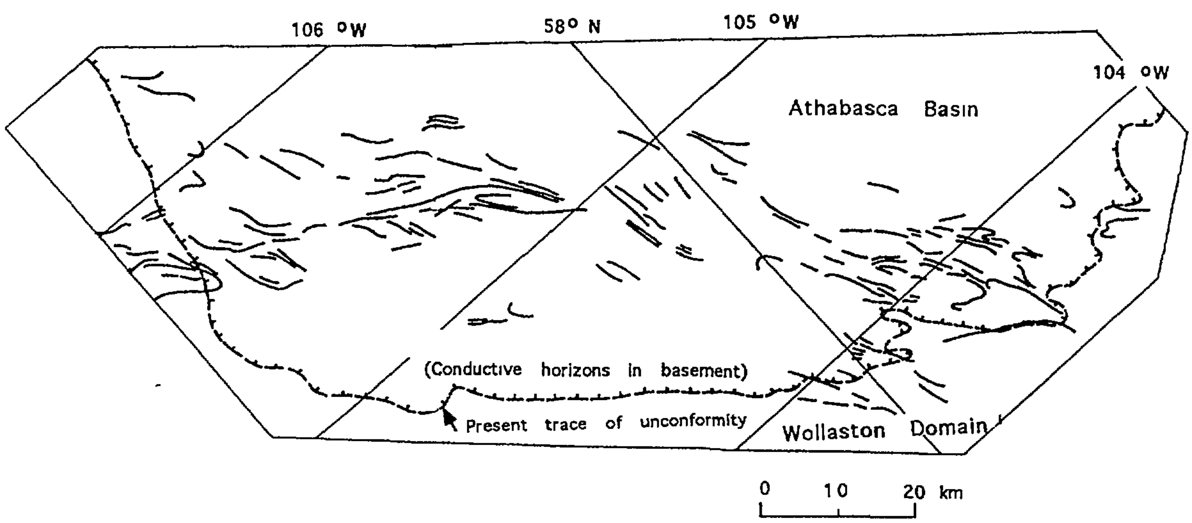


FIG. 15. Graphitic-pyritic metapelite layers in the basement rocks.

(c) Distribution of quantities of uranium metal (Fig. 16) and uranium ore grades (Fig. 17) in the known deposits in the Athabasca Basin.

(d) Information on areal extent and on quantitative attributes of identified uranium deposits and occurrences, uranium production and resources of metal and ore grades within a selected control area.

(e) Information on the areal extent and favourability degree for the area to be evaluated, by comparison of selected variables from the models with those known in the area to be assessed, using favourability scores.

The quantification of the potential resources has been made using the TENDOWG model as described in the IAEA Technical Reports Series No. 344 "Methods for the Estimation and Economic Evaluation of Undiscovered Uranium Endowment and Resources" [11]. The output of the study indicated quantities of uranium resources for various degrees of probability (Fig. 18).

During the subsequent five years of successful exploration in the appraised area, several deposits have been discovered; the identified resources amount to more than half of the quantities predicted at the 95% confidence limit during the assessment. The area is still under active exploration.

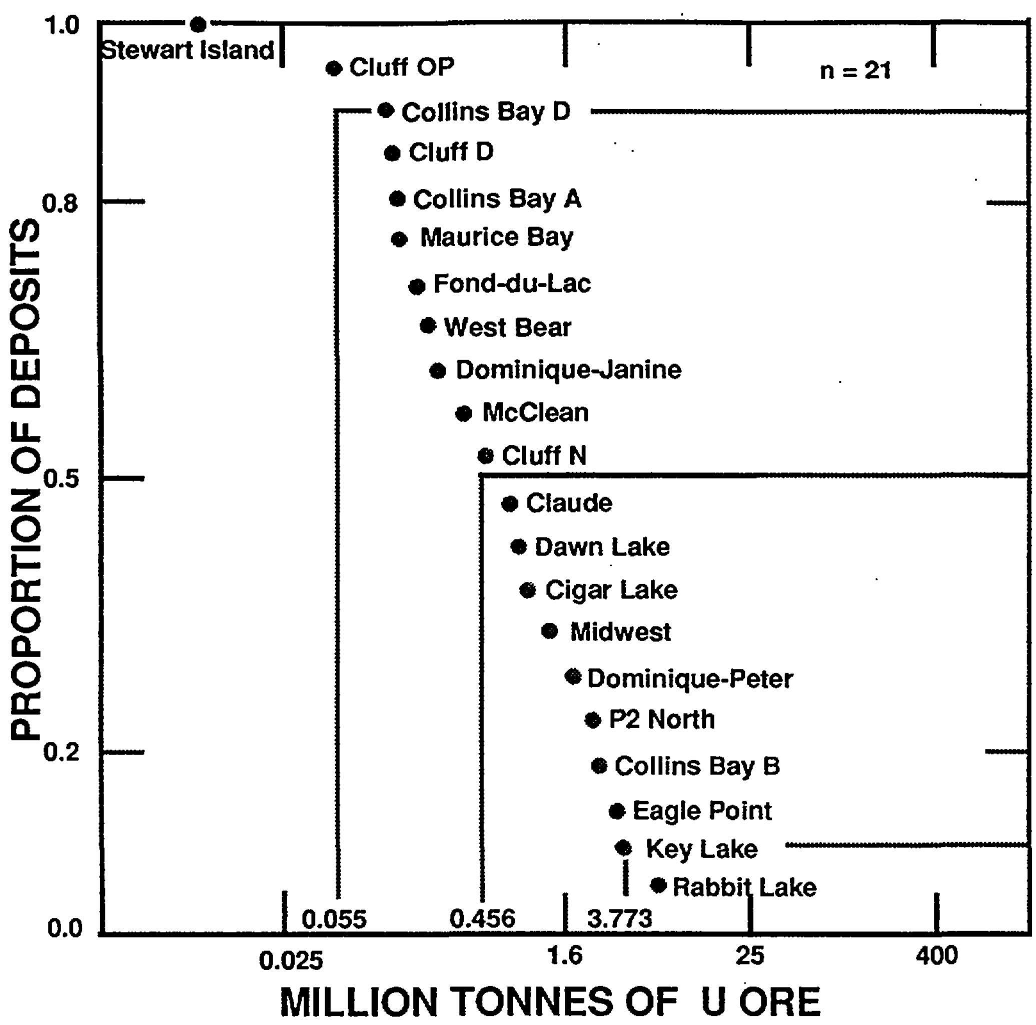


FIG. 16. Distribution of U ore tonnages in the known deposits in the Athabasca Basin.

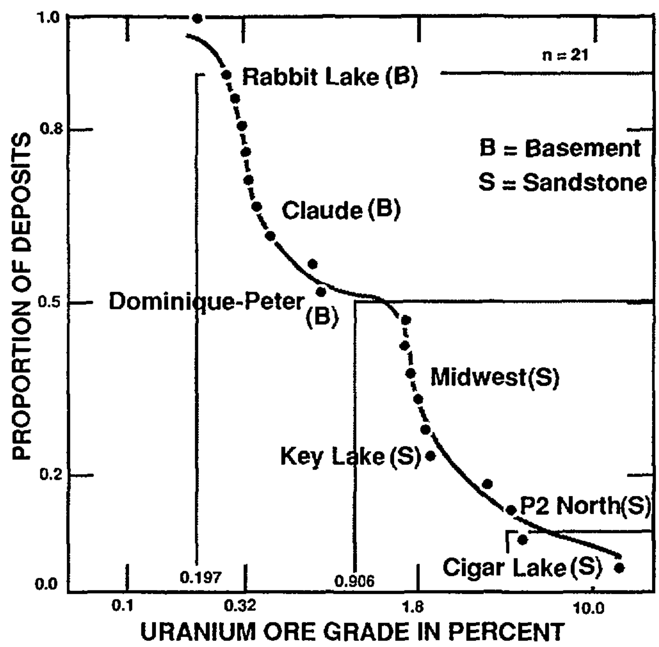


FIG. 17. Distribution of ore grades in the known deposits in the Athabasca Basin.

--------------------UNCONDITIONAL ENDOWMENT: E(PO) = 1.0000-----------------

: 4.31047E+04 CO.VAR'N: 1.09890E+00 SKEWNESS: 2.86125E+00

KURTOSIS: 1.58981E+01

------------------------------SUMMARY OF INPUT FACTORS----------------------------

	AREA	FRACTION	TONNAGE	GRADE
LOWER %:	5.0	5.0	5.0	5.0
LOWER X:	3.1250E+02	2.0000E -02	3.2596E+06	3.0000E -03
MODE:	3.1250E+02	3.2000E -02	2.3429E+07	7.0000E -03
UPPER %:	95.0	95.0	95.0	95.0
UPPER X:	3.1250E+02	4.0000E -02	4.5764E+07	5.0000E -02
MEAN:	3.1250E+02	3.0657E -02	2.5307E+07	1.7778E -02
CO.VAR'N:	0.0000E+00	1.9686E -01	4.8938E -01	8.4533E -01
SKEWNESS:	0.0000E+00	- 4.7766E -01	2.8393E -01	1.9470E+00
KURTOSIS:	0.0000E+00	3.2686E+00	2.6229E+00	7.8732E+00

--------------------PEARSON PERCENTILES FOR ENDOWMENT---------------------

TONS U_3O_8	PROBABILITY UNCOND.	TONS U_3O_8	PROBABILITY UNCOND.
.89859E+04	0.0500	.20986E+05	0.5500
.96436E+04	0.1000	.23292E+05	0.6000
.10301E+05	0.1500	.25834E+05	0.6500
.10959E+05	0.2000	.28682E+05	0.7000
.11617E+05	0.2500	.31901E+05	0.7500
.12833E+05	0.3000	.35554E+05	0.8000
.14091E+05	0.3500	.39705E+05	0.8500
.15467E+05	0.4000	.44424E+05	0.9000
.17142E+05	0.4500	.49919E+05	0.9500
.18929E+05	0.5000		

FIG. 18. The output of a uranium resource appraisal study for various degrees of probability using the US Geological Survey TENDOWG computer program described in the IAEA Technical Reports Series No. 344.

7. CONCLUSION

The regional and conceptual deposit models for Canadian unconformity deposits are important tools for application in metallogenic studies, in generation of mineral exploration strategies and in mineral resource appraisals. If similar models are established for other deposit types and/or other commodities, they may serve analogous purposes. Thus proper application of correct modeling may improve efficiency in research, exploration and evaluation of mineral resources.

ACKNOWLEDGMENTS

The study was carried out as part of the appraisal of Canadian uranium resources at the Geological Survey of Canada. Critical reading of the paper by Dr. R.I. Thorpe of the Geological Survey of Canada is sincerely acknowledged.

REFERENCES

[1] KOEPPEL, V., Age and history of the uranium mineralization of the Beaverlodge area, Saskatchewan, Geological Survey of Canada, Paper 67-31, Ottawa (1968) 111 pp.

[2] KROGH, T.E., CLARK, L.A., Zircon dating of sub-Athabasca granitoid rocks, Saskatchewan, Program with Abstracts, Geological Association of Canada / Mineralogical Association of Canada, Annual Meeting, Saskatoon, 12 (1987) 64.

[3] ROBINSON, S.C., Mineralogy of uranium deposits, Goldfields, Saskatchewan, Geological Survey of Canada, Bulletin 31, 128 p.

[4] WARD, D. M., Uranium geology, Beaverlodge Area, Proterozoic Unconformity and Stratabound Uranium Deposits (Ferguson, J., ed.), IAEA-TECDOC-315, IAEA, Vienna (1984) 269-284.

[5] KYSER, T.K., KOTZER, T.G., WILSON, M.R., Isotopic constraints on the genesis of unconformity-type uranium deposits, Program with Abstracts, Geological Association of Canada / Mineralogical Association of Canada, Annual Meeting, Montreal, 14 (1989) A 120.

[6] KOTZER, T.G., KYSER, T.K., Isotopic, mineralogic and chemical evidence for multiple episodes of fluid movement during prograde and retrograde diagenesis in a Proterozoic basin, Water-Rock Interaction, (Kharaka, Y., Maest, N., eds.), Balkema, Rotterdam (1992) 1177-1181.

[7] RUZICKA, V., Comparative metallogenic studies of the Alberta and Saskatchewan parts of the Athabasca basin, Current Research, Part E, Geological Survey of Canada, 93-1E, Ottawa (in press).

[8] BOGDANOV, YU. V., BERLYAND-KOZHEVNIKOV, P.V., Cupriferous and chromiferous Precambrian deposits in Olekma-Vitim Province, U.S.S.R., Program with Abstracts (8th IAGOD Symposium, Ottawa, Canada, 1990), Ottawa (1990) A223.

[9] EY, F., PIQUARD, J.P., and ZIMMERMAN, J., The Sue uranium deposits (Saskatchewan, Canada), New Developments in Uranium Exploration, Resources, Production and Demand, IAEA TCM on New developments in U exploration, Resources, Production and demand, IAEA, Vienna, (1992) 68 pp.

[10] RUZICKA, V., Conceptual models as a part of resource evaluation of nuclear energy minerals at the Geological Survey of Canada, Program with Abstracts, Current Activities Forum 1992, Geological Survey of Canada, Ottawa (1992) 23.

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, Methods for the Estimation and Economic Evaluation of Undiscovered Uranium Endowment and Resources, IAEA Technical Reports Series No. 344, IAEA, Vienna (1992) 145 pp.

ECONOMIC POTENTIAL OF BLACK SHALE: THE BAKKEN FORMATION IN SASKATCHEWAN

G.R. PARSLOW, R. KARMA
Dept. of Geology, University of Regina, Regina, Saskatchewan, Canada

Abstract

The Bakken Formation in Saskatchewan comprises a lower and upper radioactive black shale separated by a sandstone. On the basis of its gamma ray response in petroleum well logs, the sequence constitutes a premier marker horizon in Williston Basin stratigraphy. Fifty-one drill cores that penetrate the Bakken Formation were logged and 569 samples taken for geochemical study. The five hundred plus samples were analysed "in-house" for major elements and a selected suite of trace elements (Ba, Cr, Nb, Ni, Pb, Rb, Sr, Th, U, V, Y, Zn, Zr). In addition, a limited number of samples (44 lower shale, 36 middle sandstone, 39 upper shale) were analysed commercially by NAA for 34 elements (Au, Ag, As, Ba, Br, Ca, Co, Cr, Cs, Fe, Hf, Hg, Ir, Mo, Na, Ni, Rb, Sb, Sc, Se, Sr, Ta, Th, U, W, Zn, La, Ce, Nd, Sm, Eu, Tb, Yb, Lu). The results confirm the general observation that black shales are enriched in many elements; in the particular case of the Bakken Formation the zinc values are exceedingly anomalous (as high as 5.5%). Given that the elements are loosely bonded (i.e. show strong correlations with clay minerals and organic material), the extraction of multiple commodities from the Bakken Formation using a simple metallurgical process is a reality. However, the fact that the Bakken Formation in Saskatchewan only subcrops (at depths between about 500 and 2000 metres below present surface) presents a problem for accessing the "ore". On the other hand, existing mine shafts for potash mines (which exploit the evaporites underlying the Bakken Formation and thus penetrate the Bakken Formation) could be used as low-cost conduits to the black shales. In addition, outside of Saskatchewan, the Bakken equivalent is actually exposed on surface (e.g. Exshaw Formation, Alberta).

1. INTRODUCTION

Many characteristics of late Devonian-early Mississippian black shales set them apart from other shale units; among these are their unusual widespread distribution and homogeneity, high organic carbon content, high radioactivity, paucity of benthic fossils and, in addition, their importance as source rocks for hydrocarbons (oil and gas). They also contain high concentrations of trace metals. Numerous investigators (Russell, 1945; Beers, 1945; Swanson, 1961; Bell, 1978; Leventhal, 1981; Ettensohn and Barron, 1981; Olson, 1982; Otten and Zielinski, 1985) agree that these high concentrations of metals are related to the rich organic carbon content, but they argue about the role of the organic material. Some consider the organic matter to have had an active role in fixing the metals either by adsorption or complexation; others conclude that the conditions favorable for organic matter accumulation are similar to those necessary for metal concentration, therefore by coincidence they occur together. A third group suggest that the organic matter provided nutrients for bacteria which generate the H_2S needed for metals reduction.

Devonian-Mississippian black shales in North America were first recognized in the Appalachian Basin; subsequently their stratigraphic equivalents were found in intracratonic basins and cordilleran miogeoclinal regions such as: the Michigan Basin, the Illinois Basin, the Williston Basin, and the Great Basin.

The origin of these shales is still uncertain. Many workers (Conant, 1956; Christopher, 1961; Conant and Swanson, 1961; Gutschick et al., and Bell, 1978) suggested restricted shallow-water origin; others (Rich, 1951; Adams and Weaver, 1958; Pelzer, 1966; Cluff, 1980; Ettensohn and Barron, 1981; Hayes, 1985; and Lineback et al., 1987) debated the shallow water origin and concluded that these shales were formed in deep water, starved basins, under anaerobic conditions. The objectives of this study were:

1) to review the geological and sedimentological aspects of the Bakken formation in the Saskatchewan portion of the Williston Basin;

2) to assemble and evaluate the geochemical data that directly or indirectly pertain to the origin and the nature of the Bakken trace element and uranium enrichment.

The latter is significant since few data exist on the uranium and trace element contents in the Bakken, particularly as they relate to depositional environments.

Sample locations in boreholes are illustrated in Fig. 1.

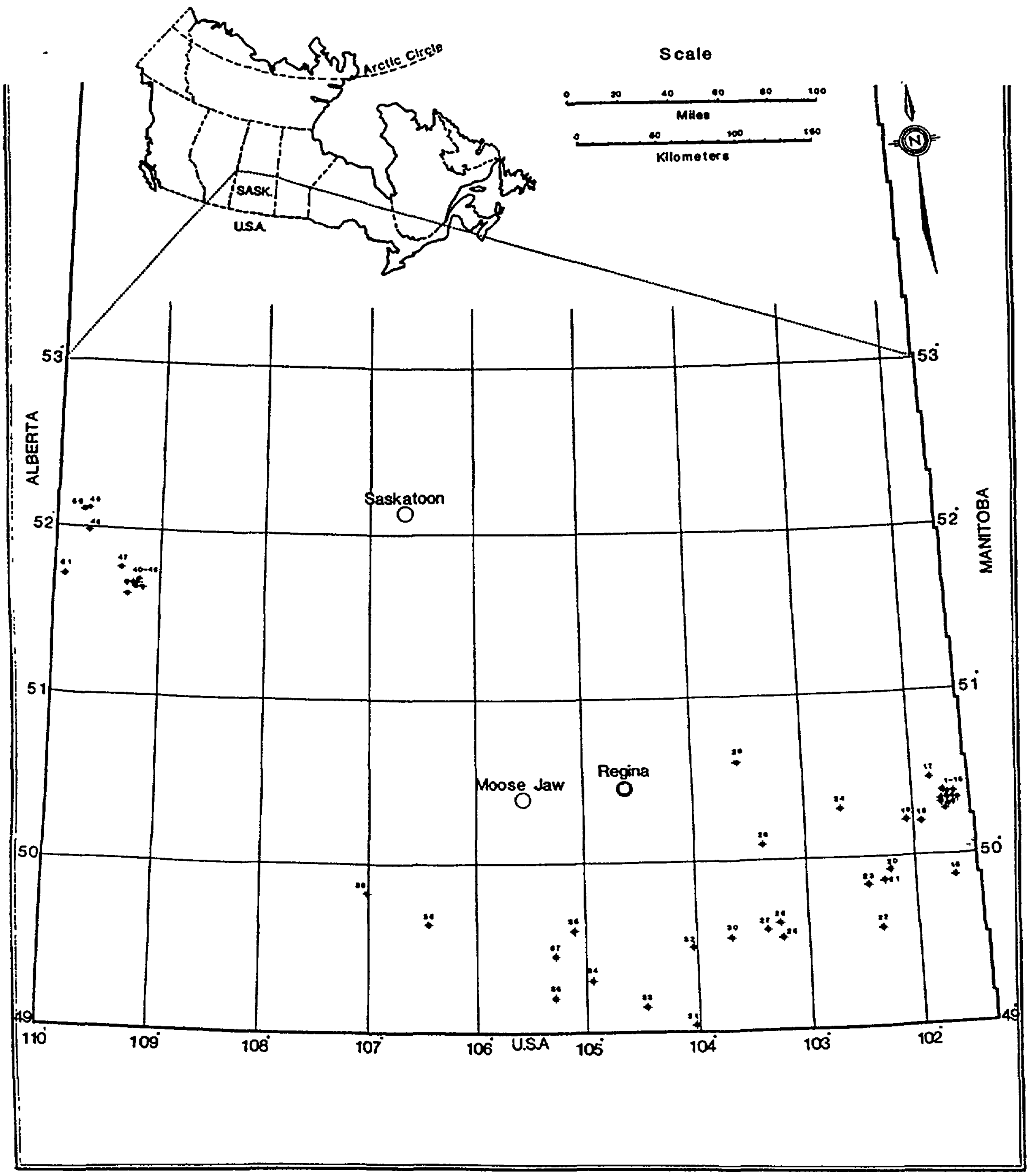


FIG. 1. Borehole and sample location map.

2. GEOLOGY OF THE BAKKEN FORMATION

2.1. General geology of the late Devonian/early Mississippian Bakken black shale in the Williston Basin

The name Bakken formation, proposed by the Williston Basin stratigraphic nomenclature committee in 1953 (Nordquist, 1953) refers to the tripartite sequence, black shale-siltstone and sandstone-black shale, as it occurs in the Amerada Petroleum Corporation H.O. Bakken No. 1 well (NDGS Well No. 32) in Williams County, North Dakota.

The Bakken Formation occurs everywhere in the Williston Basin throughout southern Saskatchewan, southwestern Manitoba, North Dakota, Montana, and eastern Alberta, as a subsurface unit unconformable with underlying and overlying rocks. Its thickness is up to 45 m and it consists of a lower organic carbon-rich, non-calcareous, radioactive, black shale, a middle calcareous, gray siltstone-sandstone, and an upper carbonaceous, radioactive, black shale.

The Bakken formation in the Williston Basin and its Devonian-Mississippian counterparts elsewhere (Chattanooga, New Albany, Ohio, Exshaw etc; see Fig. 2) have been recognized as part of a vast depositional complex of closely related units stretching across the North American continental interior. The characteristics of this complex include:

(1) lithogenetically related clastic units;

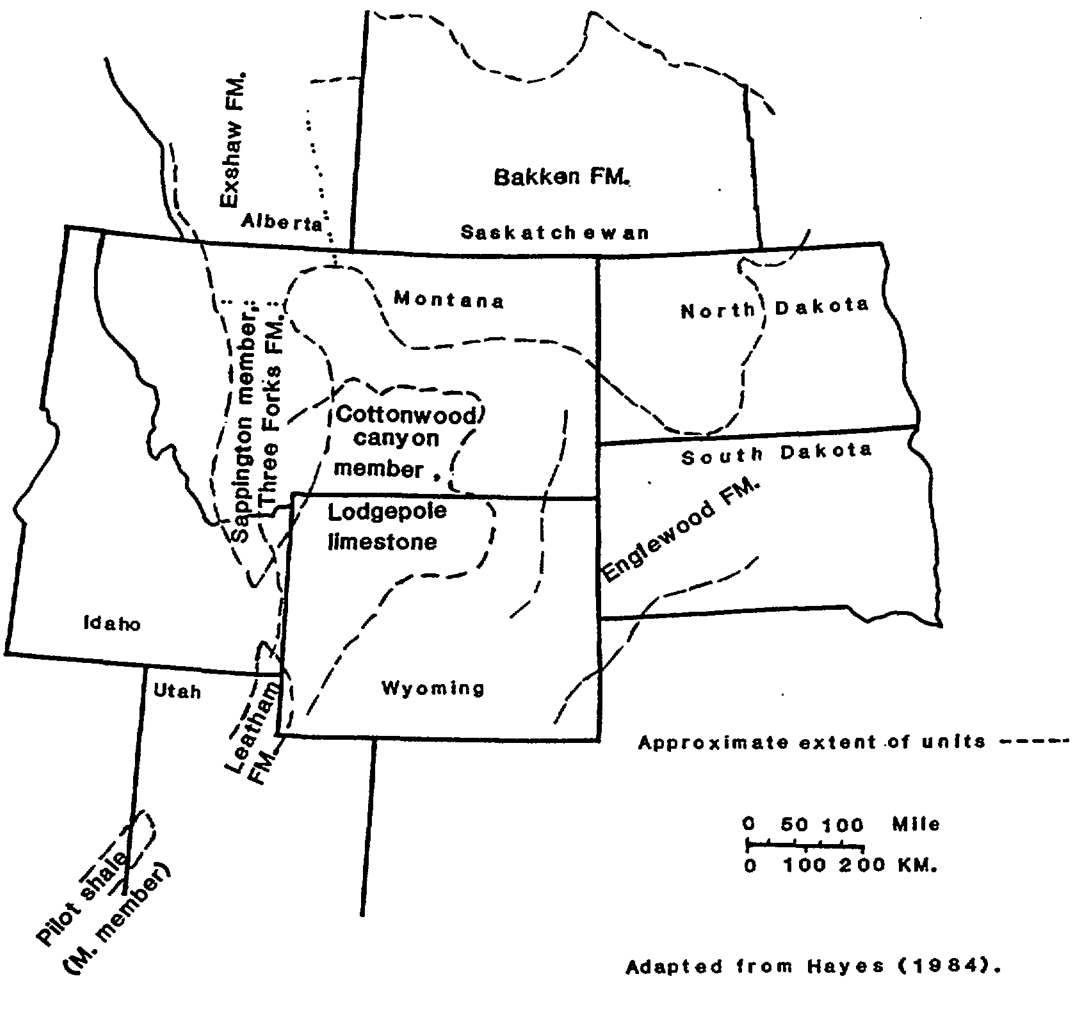


FIG. 2. Approximate areal extent of the Bakken Formation and rocks of equivalent age in the western interior region of North America.

(2) predominantly black, organic-rich, radioactive shale and gray, calcareous siltstone-sandstone units;

(3) comparable fauna;

(4) the sequence straddles the Devonian-Mississippian boundary.

Sloss (1963) reported that the Late Devonian time was characterized by tectonic instability which culminated, near the Devonian-Mississippian boundary in the deposition of the Bakken Formation. Ettensohn and Barron (1981) speculated that the black shales owe their origin to an interplay of tectonic and paleoclimatic factors unique to the Laurasian continental mass from the middle Devonian through to the earliest Mississippian.

The Bakken has been interpreted by some workers as being deposited in a deep-water sediment-starved basin, developed when subsidence exceeds sediment supply. The depositional model for these black shales is based on oxygen stratification under starved basin conditions (Cluff et al., 1980; Lineback, et al., 1987) which developed during middle-late Devonian and continued into the middle Mississippian in the Williston Basin. Three depositional environments are recognized in a starvation system: Anaerobic (oxygen depleted), Dysaerobic (low oxygen) and Aerobic (normal oxygen). Subsidence in the Williston Basin may be related to one or more of the following causes: left-lateral shear along the Colorado-Wyoming and Fromberg zones, suggested by Gerhard et al. (1982); thermal contraction related to a hot body emplaced deep in the lithosphere during the early Paleozoic which cooled and contracted and thus depressed the crust and upper lithosphere, reported by Ahern and Mrkvicka (1984); or by thermal subsidence as result of the steady transformation of a mafic subcrustal body to eclogite since the Hudsonian event, suggested by Fowler and Nisbet (1984). The two Bakken shales (upper and lower) were deposited under anaerobic conditions during episodes of marine transgression, while the sandstone bed was deposited under dysaerobic conditions during rapid regression accompanying a period of tectonic quiescence and decreased subsidence.

Parrish (1982) suggested that the Bakken may have been deposited during an inter-regional upwelling event related to worldwide marine circulation patterns during the Paleozoic.

While the age of the Bakken has significance in interpreting the geologic history of the Williston Basin, the formation is also important economically because of its potential as a hydrocarbon source rock and reservoir (Dembicki and Pirkle, 1985; Dow, 1974; Hayes, 1985; Leenheer and Zumberge, 1987; Murray, 1968; Spencer, 1987; Thode, 1981; Webster, 1987; Williams, 1974, 1987).

2.2. The late Devonian/early Mississippian Bakken formation in Saskatchewan

2.2.1. Geographic and Geological Setting

The area studied extends westward from the Manitoba-Saskatchewan border to Range 28 West of the Third Meridian, and northward from the border with U.S.A. to Township 36 (Fig. 1).

The area lies in the northern portion of the Williston Basin, which is considered as one of the three intracratonic basins in North America that has subsided episodically over spans of 10-100 million years (Sloss, 1987).

The Bakken Formation described herein is late Devonian-early Mississippian in age and lies wholly within the subsurface. In the region of study the depth to the top of the upper Bakken shale fluctuates from 1600 m below the present sea level in the southeast part of the province to 70 m above present sea level in the east and northwest (Fig. 3), or in terms of subsurface depths, from 2340 m to 527 m, respectively. The thickness of the Bakken ranges between 6 m and 40 m.

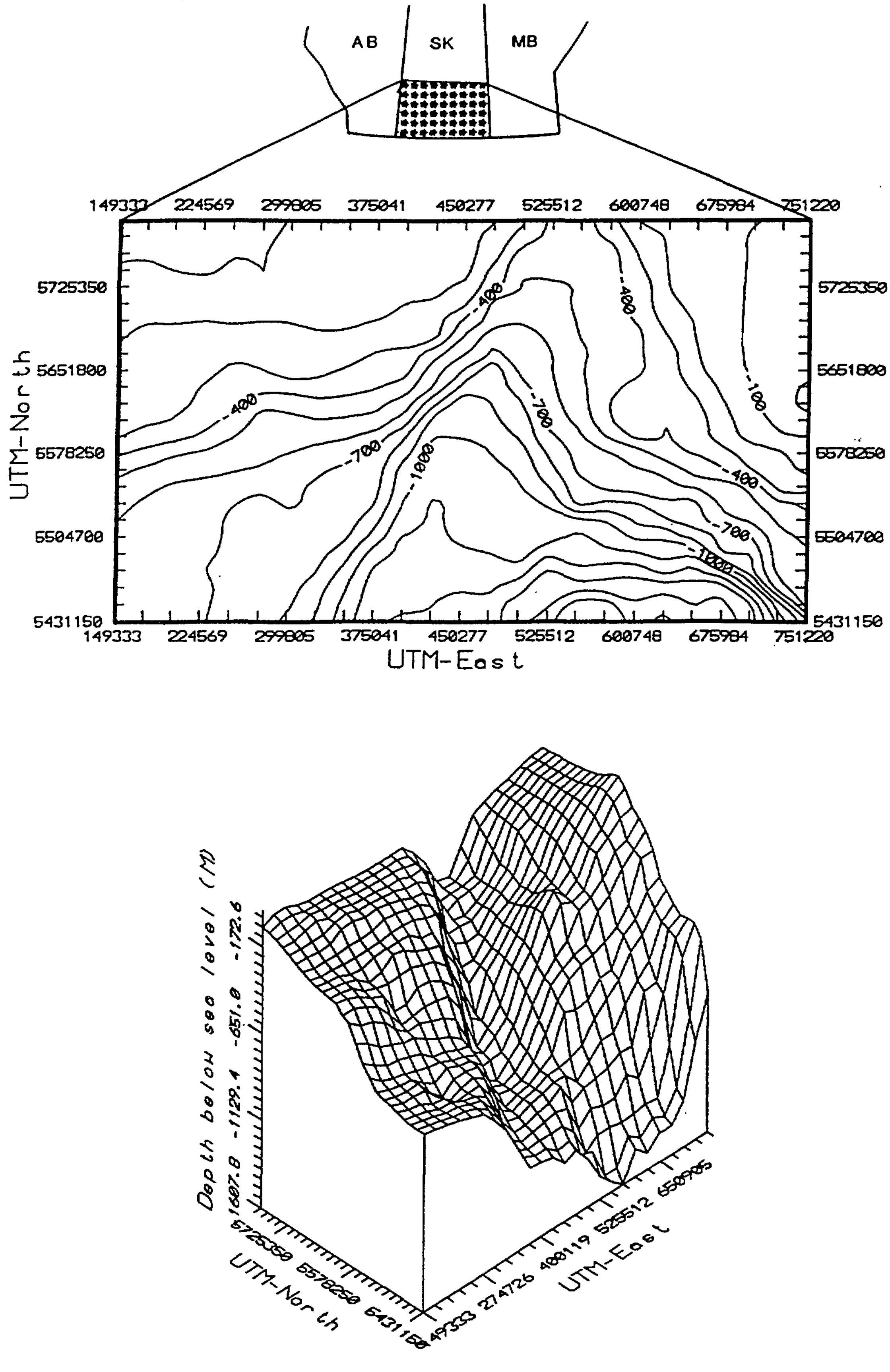


FIG. 3. Upper: Isopach map of depth to top of upper Bakken shale. Lower: Perspective surface of same.

The Bakken beds rest on more than 1500 m of sedimentary rocks of Devonian, Silurian, Ordovician, and Cambrian age. In turn, they are overlain by more than 3200 m of Mississippian to Tertiary strata.

2.2.2. *Stratigraphy and Sedimentology*

In the Williston Basin the Bakken is widely used as a subsurface stratigraphic marker for geophysical correlation because of its high gamma ray response (greater than 200 API units). This formation and its equivalents straddle the Devonian-Mississippian boundary in southern Saskatchewan and are adjacent to the carbonates of the Madison Group. Kent (1984, 1987a, 1987b) considers the Bakken to represent a transitional interval resulting from a change in structural configuration of the Williston Basin from Upper Devonian to Mississippian time.

On the basis of macrofossil evidence, principally brachiopods, in southeastern Saskatchewan Brindle (1960) considered the Bakken entirely Mississippian in age. Christopher (1961) disagreed and pointed out that the **earliest** Kinderhookian brachiopods were reported by Brindle from the middle Bakken member, and he stated (p. 19) "Thus until faunal evidence is introduced to prove the Kinderhookian age of the Bakken Lower shale member, the Devonian-Mississippian boundary is more appropriately placed at the base of the middle sandstone". In North Dakota, Hayes (1985), Thrasher (1987), Holland et al. (1987) reported a Devonian-Mississippian age for the Bakken on the basis of conodonts and macrofossils and they placed the boundary at or close to the top of the middle sandstone member.

The following observations are made on the basis of the study of core at the Saskatchewan Energy and Mines Subsurface Laboratory. The Bakken in Saskatchewan is a relatively thin unit, with a maximum thickness of 40 m in the northwest to minimum of 9 m in the northeast part of the study area. The Bakken is readily divided into three members consisting of an upper and lower radioactive, organic-rich, black shale separated by a calcareous, gray siltstone-sandstone middle member. The two shales were apparently deposited in an offshore marine anoxic environment developed during stratification of the water column resulting from restricted circulation. Organic matter is assumed to have been derived mostly from the planktonic algae that inhabit surface waters almost everywhere.

Regional studies (Sandberg and Mapel, 1967; Sandberg and Klapper, 1967; Macqueen and Sandberg, 1970) have indicated that the upper shale of the Bakken has a stratigraphic position similar to the upper tongue of the Cottonwood member of the Lodgepole Formation and to the base of the Banff Formation. The Exshaw formation, the Sappington member of Three Forks, the Leatham formation and middle member of the Pilot shale consist of a black shale overlain by a siltstone and thus correlate with lower and middle Bakken members.

In Saskatchewan the limits of the three members of the Bakken display an onlapping relationship with each successively younger member. Christopher (1961) reported erosional features at the contact between the lower shale and middle sandstone members. Hayes (1984) speculated that the contact between the middle sandstone and upper shale members is abrupt but appears conformable.

The Bakken is everywhere overlain by Lodgepole limestone, and oversteps the Big Valley in the west (extending from Range 9 West of the Second Meridian to Range 28 West of the Third Meridian) to become unconformable with the Torquay member of the Three Forks to the east before terminating at the erosional edge. The basal contact with the Three Forks formation is, in some areas, characterized by a lag-concentrate bed indicating a period of non-deposition, or by a conglomerate bed indicating a disconformity which can be interpreted to represent a period of uplifting followed by erosion and peneplanation. Webster (1987) reported that, truncation of the upper member of the Three Forks occurs beneath the Bakken and thus an angular unconformity is inferred for the northern part of the basin; additionally, he stated that the basal contact of the Bakken appears conformable in the deeper portions of the basin and unconformable on the basin flanks.

The upper contact of the Bakken with the Lodgepole limestone varies from unconformable in the west to conformable in most of the study area. Webster (1987) concluded that the limit of the upper Bakken shale must be a depositional limit because of its generally conformable contact with the overlying Lodgepole formation. This does not agree with the observations of Kent (1974).

2.2.3. *Lower Bakken Shale Member*

In Saskatchewan, the lower Bakken shale is found everywhere except in the southeastern portion of the study area (which extends from Range 30 West of the First Meridian to the Manitoba border) where it is truncated at the erosional edge. The basal contact is marked in places by a lag concentrate bed, a basal conglomerate or an erosion surface. The thickness of this member ranges from 11.5 m in the northwest to zero in the southeast.

The lower shale is composed of homogeneous, non-calcareous, carbonaceous to bituminous, fissile, and massive shale but in some areas displays parallel very closely spaced thin laminations, waxy, hard, pyritic, radioactive, dark brown to black units. The black color of the shale is believed to be related to the rich organic content (average of 12% organic carbon) (Williams, 1987; Leenheer, 1984) and to the abundance of pyrite that commonly concentrates in thin, wispy laminae, or as macro-framboids, or as disseminated grains.

Fractures and fissures subparallel to subvertical to bedding are filled by white calcite and disseminated pyrite (Fig. 13). Christopher (1961) interpreted these fissures as compressed mudcracks. At the base, the lag-concentrate bed contains pyritized clasts, fossil fragments, quartz sand and silt, and phosphatic particles.

Although locally macrofossils were rare or absent, Thrasher (1987) reported that fossils in both of the Bakken shales are preserved as flattened molds of the interior or as carbonaceous impressions, and those found in the lower shale consist of lingulids, cephalopoids, disarticulated fish fragments and plant stems.

2.2.4. *Middle Bakken Sandstone Member*

A regional unconformity separating the middle Bakken sandstone from the underlying lower Bakken shale is recognized either by the presence of a basal conglomerate in the middle member, or a weathering pavement. Elsewhere it is evident due to overstepping of the lower shale by the middle member and truncation of the Torquay. The middle Bakken sandstone ranges between 2.4 m and 33.8 m in thickness. It consists mainly of interbedded siltstone and sandstone with lesser amounts of shale and limestone. The color is mostly light grey to medium dark grey but in some areas it is obscured due to heavy oil saturation (as in 5-4-16-31W1; 6-33-14-1W2; 9-29-31-23W3; and 3-30-36-26W3). Shale in the middle member is commonly silty, greenish gray, and the limestone is represented by lenses of calcarenite (90% oolitic). Fossils are common, and principally consist of brachiopods with lesser amounts of trace fossils. Christopher (1961) divided this member into two lithological units: A and B. Thrasher (1987) using the macrofossils, proposed three subdivisions: units I, II and III. During core examination using both lithology and macrofossils, three units were recognized.

Unit I. The lowermost bed of the middle member, ranging in thickness from 0 to 7 m, consists of a well sorted, fine to medium grained, very calcareous, fossiliferous (spirifer sp., Rhipidomella missouriensis; Eumetria cf. osagensis, Lingula sp.), unstratified, gray to dark brown sandstone unit. The brachiopods of this unit are randomly oriented and mostly disarticulated, indicating rapid sedimentation; also corroborated by the lack of an epifauna on the shells (Thrasher, 1987).

The unit locally grades into an oolitic limestone or calcarenite bed (as in 9-29-31-23W3; 8-20-31-23W3; 5-30-31-23W3).

Unit II. Unit II makes up the middle part and ranges between 1.5 m and 9 m in thickness. Typically it is composed of alternate dark grey to greenish grey, shaly siltstone sandstone beds that display numerous primary bedding features. It consists of two interfingering sub-units:

(1) a pyritic, slightly calcareous, gray sandstone alternating laterally with thin, dark grey to black clay beds or shale laminae with predominant sedimentary structures such as current bedding, ripple marks, cross bedding, channel fill, scour surfaces and stylolite features;

(2) a discontinuous bedding unit of silty sandstone to muddy siltstone, where the sandstone layers are spherically rolled into ellipsoids and broken into pebble size fragments along bedding surfaces forming pod- and stringer-like features.

Framboids, lenses and disseminated grains of pyrite are common in this unit (II) of the middle Bakken, whereas it lacks fossils.

Unit III. The topmost unit of the middle Bakken sandstone member ranges between 0.6 and 2.8 m in thickness, and consists of olive gray, non-calcareous, bioturbated, pyritic, massive, silty shale and contains the brachiopod Choneetes gregarious and abundant impressions of blade-like "leaves". Webster (1982) identified these plant remains from rocks in an area near the depocenter of the basin. Conkin and Conkin (1973) used these leaves to mark the base of the Mississippian; thus, their presence in this unit suggests an earliest Mississippian age for this unit of the middle Bakken sandstone member.

2.2.5. Upper Bakken Shale Member

The upper Bakken shale conformably overlies the middle Bakken sandstone and underlies the Lodgepole limestone, respectively. Webster (1987) speculated that the limit of this member must be depositional because of its conformable contact with the underlying Middle Bakken member. The upper Bakken shale ranges from close to zero in the northwest to 7.9 m in the south-west center.

The lithology of the upper shale member is similar to that of the lower shale member and represents a repetition of depositional conditions.

2.3. Geological history of the Bakken formation

The Williston Basin in which the Bakken Formation is found, is considered as one of a unique group of basins that can be identified as "intracratonic" or "cratonic interior" type. These are a category of sedimentary basins developed on ancient continental crust that have undergone episodes of subsidence over spans of hundreds of millions of years and form subcircular or ovate sediment sinks (Sloss, 1987). The Williston Basin is the model for this subset of cratonic basins that are characterized by being totally encircled by regions of continental crust and have as their dominant mechanism of subsidence flexure as opposed to fault-control.

Toward the end of Devonian time, southern Saskatchewan was part of a broad and long established sea. Moderate uplift, or sea level change, caused the sea to become shallow during deposition of the Three Forks Formation. With subsequent subsidence, the basin became deeper. There was little or no indigenous carbonate production, and also a lack of significant clastic sources, creating sediment-starved conditions (Lieback, 1969; Lineback and Davidson, 1982, Lineback et al., 1987) in Late Devonian throughout Early Mississippian.

These conditions were accompanied by a widespread sea transgressive period (Sloss, 1963; Sandberg et al., 1982) and oxygen stratification expanded from the oceans across the continental shelves, into cratonic basins. In the Williston Basin, during Late Devonian-Early Mississippian, the lower part of the water column became oxygen depleted (anaerobic), the middle part oxygen reduced (dysaerobic), while the top surface retained a normal oxygen content (aerobic) (Cluff, 1980; Cluff et al., 1981). Anaerobic conditions occurred in the basin center and black, organic-rich shales were accumulated. Carbonate production ceased except in extreme shoreward areas (aerobic conditions). The middle Bakken sandstone-siltstone sequence, interbedded with shale and limestone, represents different oxygenation conditions and can be attributed to the vertical movements of anaerobic/dysaerobic/aerobic boundaries throughout the water column sweeping across the basin. Occasionally, the anaerobic/dysaerobic boundary was severely depressed and dysaerobic conditions prevailed even in the deepest water areas (the absence of the lower Bakken shale in some areas can be attributed to this process).

Ettensohn and Barron (1981), in their model for deposition of the Devonian-Mississippian black shale in North America, reported that these shales reflected a low rate of clastic sediment influx, high organic productivity, and development of anaerobic conditions, the result of interactions of tectonism and climatic factors unique to the Laurussian continental mass in Middle Devonian to Early Mississippian times. Parrish (1982) interpreted these black shales of North America as upwelling marine deposits, and excluded a shallow-water origin.

Rich (1951) discussed the features indicating a fondo-environment and suggested the Devonian-Mississippian black shales were deposited as fondo beds when the enclosed basins were presumably deep and the bottom was unaerated, charged with hydrogen sulfide and deficient in oxygen, so that a high organic material content was preserved over a long period of time. Sandberg et al. (1982) speculated that two major transgressive-regressive marine cycles, dominated the Middle Devonian to Late Mississippian time period, separated by a period of continental stability at Devonian-Mississippian boundary. The regional regressive part extends to the end of Devonian and was interrupted by two brief transgressions. The second such was within the upper polygnathus styriacus conodont zone, when the upper Famennian rocks (including lower Bakken shale) were all deep-water deposits. This transgressive pulse ended 1.5 m.y. before the end of the Devonian, and the major regression continued to Late Devonian times at the top of siphonodella praesulcata zone (time of middle Bakken sandstone deposition). They consider (Sandberg et al., 1982) that the Mississippian began with a major transgression represented by the siphonodella sulcata zone (upper Bakken shale).

Webster (1987) reported that the thin, planar laminations of the Bakken shales, the conodonts and fish remains suggest offshore marine, very low energy water. High organic content and pyrite indicate chemically reducing and anoxic environments. These environments must have been very uniform over a large area to account for the widespread lithologic similarity.

3. GEOCHEMISTRY OF THE BAKKEN FORMATION (EXCLUDING REE)

3.1. Introduction

Geochemistry of black shales has received extensive study during the last two decades, mainly because of their economic potential. Studies on the inorganic geochemistry of shales have mostly been of trace elements, which when combined with mineralogy and petrology have proved to be a useful tool for interpreting the history of a sedimentary basin.

Because of their high radioactivity, gamma-ray logs (estimators of uranium and thorium contents are considered as good indicators for the sedimentary process and geochemical facies. Adams and Weaver (1958) used Th/U ratios for interpreting the sedimentary processes and depositional environments of various black shales from North America. Russell (1985) and Schmoker and Hester (1983) used the gamma-ray logs as a tool to calculate the total organic carbon in the Devonian Kettle Point black shale of Ontario and the Devonian-Mississippian Bakken formation of North Dakota, respectively.

Associated trace metals such as Pb, V, Zn, Zr, Cu, Co, Cr Mo, Ni, Rb, Sr, Cs, Hf, W and REE also have been used with somewhat less success to serve that purpose. Bjorlykke (1974) used Ni and Cr in a lithostratigraphic analysis of lower Paleozoic shales of the Oslo region in Norway. Pelzer (1966) suggested that Rb/K ratios are an effective water depth indicator, and that Sr tends to increase with increasing ages of the rocks.

Rare earth elements are believed to have significance in sedimentary rocks; shales in particular, because their distribution patterns are good indicators for determining the sediment provenance (Taylor and McLennan, 1985). In this research project, the inorganic geochemical analyses, on the Bakken formation, were carried out in attempt to:

(1) establish the nature of the Bakken black shales gamma-ray response;

(2) identify any regional trends in the radioactivity;

(3) determine general major and trace element concentrations; and

(4) identify possible factors controlling elemental concentrations.

3.2. Definition of uraniferous black shale

The first recognition of uranium-bearing organic-rich shale was in the Cambrian Alum shale in Sweden by Nordenskiold (1893). Since then, uraniferous black shales have been reported throughout the world in rocks of Precambrian to Recent age.

Swanson (1961) used the name black shale to describe a rock type composed primarily of mineral grains of clay and silt size containing sufficient disseminated organic matter amounting to more than 2% organic carbon, and iron sulfide or manganese oxide to give the rock an overall dark gray to black color. Any black shale containing more than 20 ppm uranium he called uraniferous. All known uraniferous black shales are marine in origin and were deposited in epi-continental seas on stable cratonic areas. Most uraniferous black shales are Paleozoic in age. These shales are rarely more than a few tens of meters thick and consistently are found to contain recoverable economic hydrocarbons.

Potter et al. (1980) applied the term black shale to fine grained terrigenous rocks where more than 60% of the grains are less than 0.062 mm in diameter and that owe their dark color to organic-rich matter, and formed in marine environments.

Young (1984) suggested that for black shales to be classified as uraniferous, they must contain more than 50 ppm uranium.

The Chattanooga shale (U.S.A.) and the Alum shale (Sweden) are the two best known examples of uraniferous black shales.

3.3. Sample preparation and analytical methods

In the area studied (Fig. 1) 569 samples were collected from 51 subsurface cores which penetrated the Bakken formation in southern Saskatchewan. One quarter of each sample was crushed and ground in tungsten carbide vessels to approximately -200 mesh.

All samples were analysed for SiO_2, TiO_2, Al_2O_3, total Fe_2O_3, MnO, MgO, CaO, Pz_2O_5 by ICP; N_2O and K_2O by AAS; H_2O^- and LOI (at 650 and 950°C) by gravimetry; and trace elements Ba, Cr, Cu, Nb, Ni, Pb, Rb, Sr, Th, U, Y, Y, Zn, Zr were determined by XRF. All samples were analysed for U and Th by NAA. Since some samples contained significant pyrite, 23 samples of the lower shale, 30 samples of the middle sandstone, and 28 samples of the upper shale were analysed for S by XRF. A limited number of samples (44 lower shale, 36 middle sandstone, 39 upper shale) were analysed by NAA for 34 elements: Au, Ag, As, Br, Ca, Co, Cr, Cs, Fe, Hf, Hg, Ir, Mo, Na, Ni, Rb, Sb, Sc, Se, Sr, Ta, Th, U, W, Zn, and REE (La, Ce, Nd, Sm, Eu, Tb, Yb, Lu). Finally seven samples of shale were subjected to inorganic solvent extraction (tetrahydrofluran +0.025% butylated hydroxytoluene) and rock residues and oil extracts were analysed for 34 elements by NAA.

Summary statistics of the analytical results are shown in Tables I through VII. The average black shale (ABS) values listed in the right hand column are calculated from data for Exshaw black shale (EBS, Duke,1983), the average shale (AS) of Cambel and Khum (1983), the average black shale (ABS) of Vine and Tourtelot (1970), and the average Ohio black shale (AOBS) values of Maynard (1983).

3.4. Major elements in the Bakken formation

The major components of black shales are mainly made up of three groups: silica and clay minerals, organic matter and sulfides, and carbonates.

Because of their similarity, the lower and upper Bakken shales geochemistry will be discussed together. The sandstone is mainly composed of quartz with variable amounts of clay minerals, carbonates, and minor iron oxides.

TABLE I : SUMMARY STATISTICS FOR BAKKEN LOWER SHALE
(analyses by ICP and XRF)
where n=193, DL=detection limit, ABS=average black shale
(ABS based on average of EBS, AS, ABS, AOBS composites –see refs. in text)
** indicates >20% enrichment in Bakken relative to average value

%	MEAN	SD	MIN	MAX	DL	ABS
SiO_2	53.85	10.20	2.94	86.22	0.01	–
TiO_2	0.59	0.17	0.03	1.20	0.01	–
Al_2O_3	12.98	3.70	0.56	20.65	0.01	–
Fe_2O_3	0.32	0.21	0.01	2.73	0.01	–
MnO	0.04	0.11	0.01	1.42	0.01	–
FeO	2.57	1.69	0.10	22.15	0.01	–
MgO	2.08	0.86	0.46	7.64	0.01	–
CaO	3.08	5.27	0.06	54.93	0.01	–
Na_2O	0.59	0.29	0.05	1.95	0.01	–
K_2O	5.02	1.43	0.13	7.51	0.01	–
P_2O_5	0.33	0.40	0.08	3.78	0.01	–
LOI 110	0.60	0.61	0.01	3.65	0.01	–
LOI 650	14.22	7.80	1.75	30.22	0.01	–
LOI 950	3.52	3.64	0.41	39.13	0.01	–
ppm						
Ba	306	526	1	6689	1	419
**Cr	102	26	1	160	1	81
Cu	71	92	1	1094	1	66
Nb	11	3	1	23	1	20
**Ni	285	216	1	1098	1	85
Pb	29	25	1	193	1	25
Rb	150	48	1	247	1	127
Sr	206	1008	1	13917	1	189
Th	8	3	1	26	1	11
**U	62	117	3	1500	1	23
**V	934	759	1	3182	1	187
**Y	35	28	1	289	1	28
**Zn	854	3706	1	44377	1	141
Zr	142	52	1	498	1	127

TABLE II : SUMMARY STATISTICS FOR BAKKEN LOWER SHALE
(analyses by NAA)
where n=44, DL=detection limit, ABS=average black shale
(ABS based on average of EBS, AS, ABS, AOBS composites —see refs. in text)
** indicates >20% enrichment in Bakken relative to average value
all values ppm except where noted [(b)=ppb]

	MEAN	SD	MIN	MAX	DL	ABS
**Au(b)	7.6	6.5	2.0	29.0	2.0	4
Ag	2.5	0.1	2.0	2.5	2.0	2
**As	42	45	1	270	1	15
Ba	304	160	50	710	50	419
Br	2.3	2.5	0.4	10.0	0.4	–
Ca(%)	1.5	2.0	0.4	9.0	0.4	–
**Co	23	19	5	100	5	15
Cr	94	25	41	150	10	81
Cs	8	3	1	14	1	–
Fe(%)	3.15	1.53	0.48	8.45	0.02	–
Hf	4	2	2	15	1	–
Hg	0.6	0.2	0.4	1.0	0.4	0.5
Ir(b)	1.0	0.2	0.5	2.0	0.5	–
**Mo	97.6	140.1	0.5	740.0	0.5	10
Na	3806	1829	1160	10300	500	–
**Ni	147	115	25	450	25	85
**Rb	154	56	43	260	30	127
**Sb	12.9	12.7	0.5	60.0	0.2	1
Sc	12.6	3.6	4.8	20.0	0.1	–
**Se	23.6	22.1	2.0	130.0	2	0.6
**Sr(%)	0.062	0.235	0.025	1.600	0.025	0.019
Ta	0.5	0.1	0.4	1.0	0.4	2
Th	9.4	3.8	5.3	26.0	0.5	11
**U	77.8	89.6	2.7	460.0	0.5	23
**W	21	26	2	130	2	2
**Zn	1943	8156	25	55000	25	141

TABLE III : SUMMARY STATISTICS FOR BAKKEN MIDDLE SANDSTONE
(analyses by ICP and XRF)
where n=196, DL=detection limit, ABS=average black shale
(ABS based on average of EBS, AS, ABS, AOBS composites —see refs. in text)
**indicates >20% enrichment in Bakken relative to average value

%	MEAN	SD	MIN	MAX	DL	ABS
SiO_2	56.22	13.42	19.26	94.26	0.01	–
TiO_2	0.38	0.14	0.04	0.85	0.01	–
Al_2O_3	6.31	2.69	0.59	16.14	0.01	–
Fe_2O_3	0.17	0.10	0.02	0.96	0.01	–
MnO	0.06	0.03	0.01	0.13	0.01	–
FeO	1.38	0.83	0.19	7.76	0.01	–
MgO	4.87	2.42	0.37	9.84	0.01	–
CaO	11.74	6.21	0.03	44.90	0.01	–
Na_2O	0.53	0.35	0.01	1.90	0.01	–
K_2O	2.86	1.21	0.05	6.67	0.01	–
P_2O_5	0.21	0.08	0.11	0.85	0.01	–
LOI 110	0.27	0.40	0.01	3.96	0.01	–
LOI 650	7.43	4.27	0.85	21.19	0.01	–
LOI 950	7.66	5.97	0.08	32.21	0.01	–
ppm						
Ba	253	518	10	6265	1	419
Cr	65	24	1	237	1	81
Cu	11	8	1	86	1	66
Nb	7	3	1	18	1	20
Ni	33	28	1	250	1	85
Pb	14	17	1	143	1	25
Rb	71	27	13	186	1	127
Sr	124	236	18	2546	1	189
Th	6	2	1	22	1	11
U	5	5	1	49	1	23
V	109	205	1	1906	1	187
Y	23	8	10	99	1	28
Zn	59	154	5	1908	1	141
**Zr	248	89	52	632	1	127

TABLE IV : SUMMARY STATISTICS FOR BAKKEN MIDDLE SANDSTONE
(analyses by NAA)
where n=36, DL=detection limit, ABS=average black shale
(ABS based on average of EBS, AS, ABS, AOBS composites –see refs. in text)
** indicates >20% enrichment in Bakken relative to average value
all values ppm except where noted [(b)=ppb]

	MEAN	SD	MIN	MAX	DL	ABS
Au(b)	2.6	0.6	2.5	6.0	2.0	4
Ag	2.5	0.0	2.4	2.5	2.0	2
As	18	38	1	230	1	15
Ba	244	150	50	1000	50	419
Br	2.3	2.2	0.4	9.0	0.4	–
Ca(%)	7.1	5.2	0.5	29.0	0.4	–
Co	14	6	5	37	5	15
Cr	48	21	5	140	5	81
Cs	2	1	1	7	1	–
Fe(%)	1.72	1.93	0.28	11.00	0.02	–
Hf	7.4	3.4	0.5	16.0	0.5	–
Hg	0.5	0.0	0.5	0.5	0.4	0.5
Ir(b)	1	0	1	1	0.5	–
**Mo	13.4	43.1	2.0	260.0	0.5	10
Na	2809	1966	240	7250	240	–
Ni	32	30	24	200	24	85
Rb	50	25	15	140	15	127
**Sb	1.6	2.5	0.1	11.0	0.1	1
Sc	4.9	2.4	1.0	13.0	0.1	–
**Se	3.3	4.9	2.3	32.0	2	0.6
Sr(%)	0.025	0.000	0.025	0.025	0.025	0.019
Ta	0.5	0.0	0.5	0.5	0.4	2
Th	6.0	1.8	1.2	12.0	0.5	11
U	14.1	52.0	1.5	320.0	0.5	23
**W	102	95	8	400	2	2
**Zn	256	776	24	4000	24	141

TABLE V : SUMMARY STATISTICS FOR BAKKEN UPPER SHALE
(analyses by ICP and XRF)
where n=178, DL=detection limit, ABS=average black shale
(ABS based on average of EBS, AS, ABS, AOBS composites –see refs. in text)
** indicates >20% enrichment in Bakken relative to average value

%	MEAN	SD	MIN	MAX	DL	ABS
SiO_2	46.46	10.55	19.34	88.84	0.01	–
TiO_2	0.50	0.12	0.13	0.92	0.01	–
Al_2O_3	10.94	3.16	2.86	26.41	0.01	–
Fe_2O_3	0.30	0.13	0.05	0.86	0.01	–
MnO	0.03	0.02	0.01	0.11	0.01	–
FeO	2.40	1.03	0.41	6.93	0.01	–
MgO	2.70	1.71	0.43	8.70	0.01	–
CaO	5.52	6.27	0.04	38.81	0.01	–
Na_2O	0.49	0.22	0.10	1.32	0.01	–
K_2O	4.75	1.34	0.12	7.69	0.01	–
P_2O_5	0.29	0.15	0.15	1.33	0.01	–
LOI 110	0.74	0.73	0.01	3.78	0.01	–
LOI 650	20.06	10.83	0.98	44.03	0.01	–
LOI 950	4.69	3.75	0.15	20.25	0.01	–
ppm						
Ba	496	1428	10	10556	1	419
**Cr	109	33	1	217	1	81
**Cu	99	125	5	1642	1	66
Nb	10	3	3	24	1	20
**Ni	344	209	8	1257	1	85
**Pb	43	46	5	304	1	25
Rb	118	37	13	196	1	127
Sr	120	265	23	3452	1	189
Th	8	3	1	21	1	11
**U	42	41	1	262	1	23
**V	1107	726	1	3904	1	187
**Y	36	15	12	119	1	28
**Zn	1223	3135	11	24342	1	141
Zr	137	45	56	381	1	127

TABLE VI : SUMMARY STATISTICS FOR BAKKEN UPPER SHALE
(analyses by NAA)
where n=44, DL=detection limit, ABS=average black shale
(ABS based on average of EBS, AS, ABS, AOBS composites –see refs. in text)
** indicates >20% enrichment in Bakken relative to average value
all values ppm except where noted [(b)=ppb]

	MEAN	SD	MIN	MAX	DL	ABS
**Au(b)	7.1	5.8	2.5	24.0	2.0	4
**Ag	3.1	3.0	2.4	21.0	2.0	2
**As	75	132	2	820	1	15
Ba	417	979	50	6400	50	419
Br	2.7	2.6	0.4	10.0	0.4	–
Ca(%)	3.1	4.3	0.5	21.0	0.4	–
**Co	30	20	6	100	5	15
Cr	89	29	45	150	10	81
Cs	5	2	2	11	1	–
Fe(%)	3.53	2.61	0.83	15.60	0.02	–
Hf	3	2	1	8	1	–
Hg	0.5	0.1	0.5	1.0	0.4	0.5
Ir(b)	0.9	0.2	0.5	1.0	0.5	–
**Mo	207.3	416.6	2.5	2490.0	0.5	10
Na	2786	1272	789	6780	500	–
**Ni	180	105	25	540	25	85
Rb	104	37	52	190	30	127
**Sb	17.5	13.6	0.7	55.0	0.2	1
Sc	9.9	2.9	4.9	17.0	0.1	–
**Se	15.0	15.9	2.5	91.0	2	0.6
Sr(%)	0.025	0.000	0.025	0.025	0.025	0.019
Ta	0.5	0.0	0.5	0.5	0.4	2
Th	7.5	1.8	3.5	13.0	0.5	11
**U	53.7	47.8	2.5	260.0	0.5	23
**W	25	45	2	280	2	2
**Zn	2014	4123	25	22000	25	141

TABLE VII: SUMMARY STATISTICS FOR SELECTED REE IN THE BAKKEN
(analyses by NAA)
DL=detection limit, AS=average shale
(AS based on average of NASC, PAAS, ES composites –see refs. in text)
** indicates >20%enrichment in Bakken relative to average value

	MEAN	SD	MIN	MAX	DL	AS
LOWER SHALE (n=44)						
**La	62	84	21	580	1	37
**Ce	102	111	35	770	3	78
**Nd	57	59	18	380	5	35
**Sm	11.5	10.3	2.6	58.0	0.1	6.2
**Eu	1.7	1.5	0.6	8.2	0.2	1.3
Tb	1.0	1.1	0.4	6.0	0.5	0.9
Yb	2.6	0.9	1.6	6.8	0.1	3.1
Lu	0.41	0.16	0.16	1.06	0.05	0.50
MIDDLE SANDSTONE (n=36)						
La	27	9	9	49	1	37
Ce	58	22	18	120	3	78
Nd	24	9	7	50	5	35
Sm	4.8	1.8	1.5	9.6	0.1	6.2
Eu	1.1	0.4	0.3	2.1	0.2	1.3
Tb	0.5	0.1	0.3	1.0	0.5	0.9
Yb	1.9	0.5	0.9	3.1	0.1	3.1
Lu	0.27	0.11	0.08	0.58	0.05	0.50
UPPER SHALE (n=39)						
La	32	8	16	54	1	37
Ce	70	21	41	150	3	78
Nd	39	12	21	75	5	35
**Sm	8.5	3.3	3.8	20.0	0.1	6.2
Eu	1.4	0.5	0.1	2.9	0.2	1.3
Tb	0.7	0.4	0.4	2.0	0.5	0.9
Yb	2.2	0.7	0.9	3.9	0.1	3.1
Lu	0.36	0.17	0.10	0.75	0.05	0.50

3.4.1. *Lower And Upper Bakken Black Shales*

3.4.1.1. Silica and Clay Minerals

SiO_2 is the most abundant oxide in the Bakken shales, and quartz is probably the common form of free silica. Armands (1972) reported that SiO_2/Al_2O_3 ratios >6 suggest a highly alkaline depositional environment and that half of the silica is free quartz. Values around 5 reflect a low alkalinity and hence less free silica. A value of 3 corresponds to silicate-bound silica in muscovite, and excess silica is free quartz (20-25%). In the Bakken shales the value of this ratio ranges between 3.3-7.59 with an average of 4.2 indicating low alkalinity during deposition of these shales, and hence less free quartz. The interaction of free quartz and clay minerals (i.e. as represented by silica, alumina and potash) is clearly seen in Fig. 4. where the linear trend with a sharp cut off towards the upper left defines an illitic trend and the spread of values towards the lower right suggests "contamination" of the authigenic trend with clastic(?) silica. The good correlation of TiO_2 with SiO_2 suggests that the original authigenic clay mineral may have been glauconite with the TiO_2 replacing iron, which in turn replaced A_2O_3 to an extent. The upper shale has more obvious linear trends than the lower shale, indicative of a more chemical than clastic control of sedimentation. The majority of the "spread" forming the linear trend can be attributed to varying LOI content (i.e. higher LOI values bringing the absolute values down, proportionally). Armands (1972) reported that an Al_2O_3/K_2O + Na_2O molecular ratio of 1.5-2 is due to the presence of glauconite and above 2.5 represents illite. In the Bakken shales the ratio varies between 1.65 and 3.87 and indicates the presence of initial glauconite, now illite, where Fe^{+3} substituted for Al^{+3} during slow sedimentation under anaerobic marine conditions. This is confirmed by Al_2O_3/SiO_2 ratios that range between 0.10-0.31 which are identical to Al_2O_3/SiO_2 ratios of illite and glauconite. However, during core examination some parts of the Bakken shale appear to contain a higher content of swelling clay minerals. Thus, it is possible that vermiculite may be common (but at present unsubstantiated) in sections where Mg is high, and was possibly derived from volcanic ash.

The conclusion achieved herein is coincident with the observation that most of Paleozoic black shales are dominated by authigenic illite-glauconite, swelling clays, and minor mixed layer clays.

3.4.1.2. Organic Matter and Sulfide

Organic geochemistry has not been carried out in this project, and only a few samples from the lower and upper Bakken shales were analysed for sulfur content. However, the loss of ignition (LOI) measurement is here used as an approximation of inorganic carbon plus organic carbon plus inorganic sulfur plus organic sulfur plus any bonded water. Although an imperfect unit, the LOI does indicate that for most lower shale samples there is no change in the major components with increasing LOI, when major elements are normalized to 0% LOI. This suggests that almost all the LOI is due to organic carbon.

Organic carbon geochemistry by Webster (1987) indicates that the Bakken shales in North Dakota have organic carbon values ranging from 5 to 20% with an average of 11.33% and dominated by amorphous kerogen of algal origin (70-95%) and small amounts of woody kerogen, herbaceous kerogen, coaly kerogen, and tasmanite spores; Leenheer (1984) also reported total organic carbon in the Bakken shales from Saskatchewan within the range 6.45% to 24.73%. Such values could be used to account for much of the observed range in LOI in the present study and therefore suggest that LOI does approximate the organic carbon content of the Bakken shales.

As stated earlier, visible pyrite is not uncommon in certain sections of core. This was reflected in certain major element analyses that failed to total 100% $\pm 2\%$; they generally fell in the range 90-96% and suggest that the LOI procedure failed to breakdown and volatilize S in the sulfide form. In order to verify this, the "lowtotal" samples were analyzed for inorganic S. In all cases it was found that there was enough sulfide material to account for the discrepancies in totals; in many cases

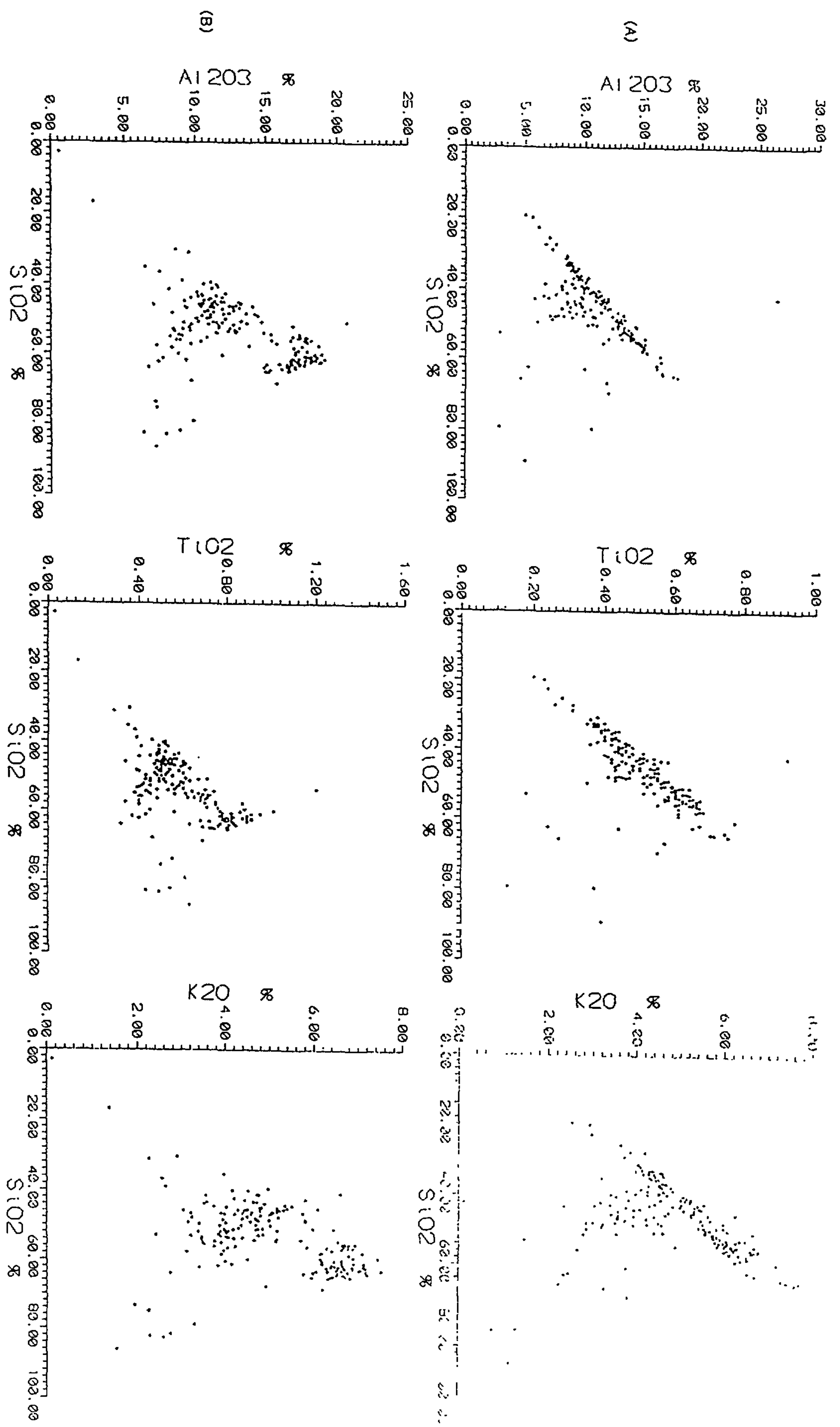


FIG. 4. Plots of Al_2O_3, TiO_3, and K_2O vs SiO_2 for the upper shale.

the S content was more than adequate, illustrating that the LOI procedure may in some cases partially breakdown the sulphide. Clearly, a more rigorous treatment of S is preferable to the LOI method.

3.4.1.3. Carbonates

The patchy cement (vein fillings and concretions of calcite, and occasionally dolomite) average about 10% (i.e. about 6% CaO + MgO) in most of the shales. This carbonate is considered to have been produced as a result of bottom conditions with a pH of >7.8 (i.e. over the limestone "fence").

3.4.2. Middle Bakken Sandstone

Values of the SiO_2/Al_2O_3 ratio range from 6 to 20, suggesting a very highly alkaline depositional environment where more than two thirds of the total silica is present as free quartz. Bjorlykke (1965 & 1974) reported that the geochemical maturity index [m = $(Al_2O_3 + K_2O)/(MgO + Na_2O)$] is mainly controlled by the chlorite/illite ratio. In the Bakken sandstone m varies between 1 and 12, indicating more chlorite than illite.

The second major constituent of the middle sandstone is carbonate; negative correlations for SiO_2 vs CaO, SiO_2 vs MgO, and a strong positive correlation for CaO vs MgO exist, suggesting significant amounts of calcite and minor dolomite as the dominant carbonate minerals.

Sulfur analyses were carried out for only a few "low total" samples and represent pyrite (the only visible sulfide) that appears to be secondary and replacing some fossil fragments, infilling cavities, or as disseminated fine grains. In general, there appears to be more S (i.e. pyrite) in the sandstone compared to the shale.

In contrast to the shales, the loss on ignition analyses of the sandstone are considered to represent mainly inorganic carbon because of the positive correlation between LOI and CaO, and from the small amounts of organic carbon (0.22-0.84%) reported by Leenheer (1984).

3.4.3. Discussion

Comparison of major elements contents of the Bakken Formation with other shales in North America reveals that the major elements are generally conformable except that perhaps the Bakken is depleted slightly in iron oxides (Fe_2O_3 + FeO) and enriched slightly in CaO, MgO, K_2O. Depletion of iron may be due to the oxidation of organic matter and/or the reduction of Fe_2O_3.

Rateev et al. (1969) stated that regions with rapid erosion and slow weathering will produce significant quantities of chlorite, while tropical and subtropical regions will yield illite and little or no chlorite. Armands (1972) explained the absence of chlorite as being due to successive transgressions of detritus from the nearby sources and warmer climates. So, the apparent absence of chlorite from the lower and upper Bakken shales and the enrichment of it in the middle sandstone may indicate changes in the provenance conditions (climate, weathering, transportation) and changes in the depositional environment patterns for each of the Bakken members.

3.5. Trace elements (except REE) in the Bakken formation

Studies of trace element geochemistry in black shales are important since they may play a decisive role in the stratigraphic correlations, geochemical assessment of source, and characterization of depositional environments. It has been convincingly argued that the trace elements in the black shales can be attributed directly to the conditions that prevailed during sedimentation (Adams & Weaver, 1958; Armands, 1972; Berry, et al., 1986; Cambel & Khum, 1983; Coveney & Martin, 1983).

Only the distribution and relationship of the elements U, Mo, V, Cu, Ni, Zn, Ba, Rb, Sr and Th within the Bakken Formation are discussed in this paper. These elements were chosen because 1) initial screening of the data revealed major variation across the area of study, 2) some tend to concentrate in black shales, and 3) some define the radioactive nature of the Bakken Formation. The remaining elements (Co, Pb, Y, Nb, Au, Br, Cs, Ir, W, Ag, Sb, Ta, As, Hf, Sc, Hg and Se) were not studied in detail because their more subtle variations cannot be adequately explained without better information on organic and inorganic S and C.

3.5.1. Uranium

Many marine, organic-rich black shales contain 0.01 o 0.1% uranium while a few contain as much as 0.5% (Alum shale). In the Bakken black shales the uranium content ranges from 0.001 to 0.16% and its higher concentrations occur in the eastern part of the study area.

Many workers (Adams and Weaver, 1958; Armands, 1972; Breger and Brown, 1962; Cambel and Khum, 1983; Delian, 1983; Olson, 1982; Swanson, 1961; Vine and Tourtelot, 1970;) provide evidence for uranium fixation by the detrital fraction, authigenic K-feldspar and phosphate, clay minerals, and by organic matter and sulfides; controlled by absorption, adsorption, ion exchange, and reduction processes. They also conclude that the mineralization is syngenetic.

Stasiuk et al. (in press) using incident light microscopy of polished section of the Bakken shales from Saskatchewan provided evidence for uranium incorporated within unicellular marine algae and phosphatic particles.

Plots of uranium versus various major and trace elements in the shales give generally poor correlations; some examples of the correlations are shown in Fig. 5. The lack of correlation between uranium and CaO and Al_2O_3 indicates that neither carbonate nor clay minerals played a significant role in the accumulations of uranium. The weak positive uranium-LOI correlation and the observation by Stasiuk et al. (in press) suggest that organic matter was the predominant precipitant, or reductant, for the uranium. Positive correlations of U with Ni and Cu also suggest the latter two elements were precipitated by the same process.

In the middle sandstone the uranium shows no positive correlations with other elements and the observed values may represent "detrital" uranium bound up in heavy minerals or uranium precipitated from reducing groundwaters sandwiched between the lower and upper shale.

3.5.2. Molybdenum and Vanadium

In most shales, Mo and V are found to exhibit positive correlations with U and organic carbon (Trady, 1975). Disnar (1981) found that the Mo content of recent sedimentary organic matter (of algal origin) is inversely pH dependent and becomes negligible when the pH exceeds 7.

Values for Mo (83 samples from both Bakken shales and 36 samples from the middle sandstone) range from 0.5 to 790 ppm in the shales and from 2.5 to 65 ppm for the sandstone. As in the case of uranium the highest values of molybdenum occur in the eastern part of the study area. Based on Disnar's (1981) work this suggests that the eastern area had a lower pH than the western area. In the shales, positive correlations of Mo with LOI, U, Cu, Ni, Pb and Y are observed whereas in the middle sandstone only Ni shows a positive correlation. On the other hand, the middle sandstone exhibits negative correlations of Mo with LOI, Cu, Pb, Co and Y.

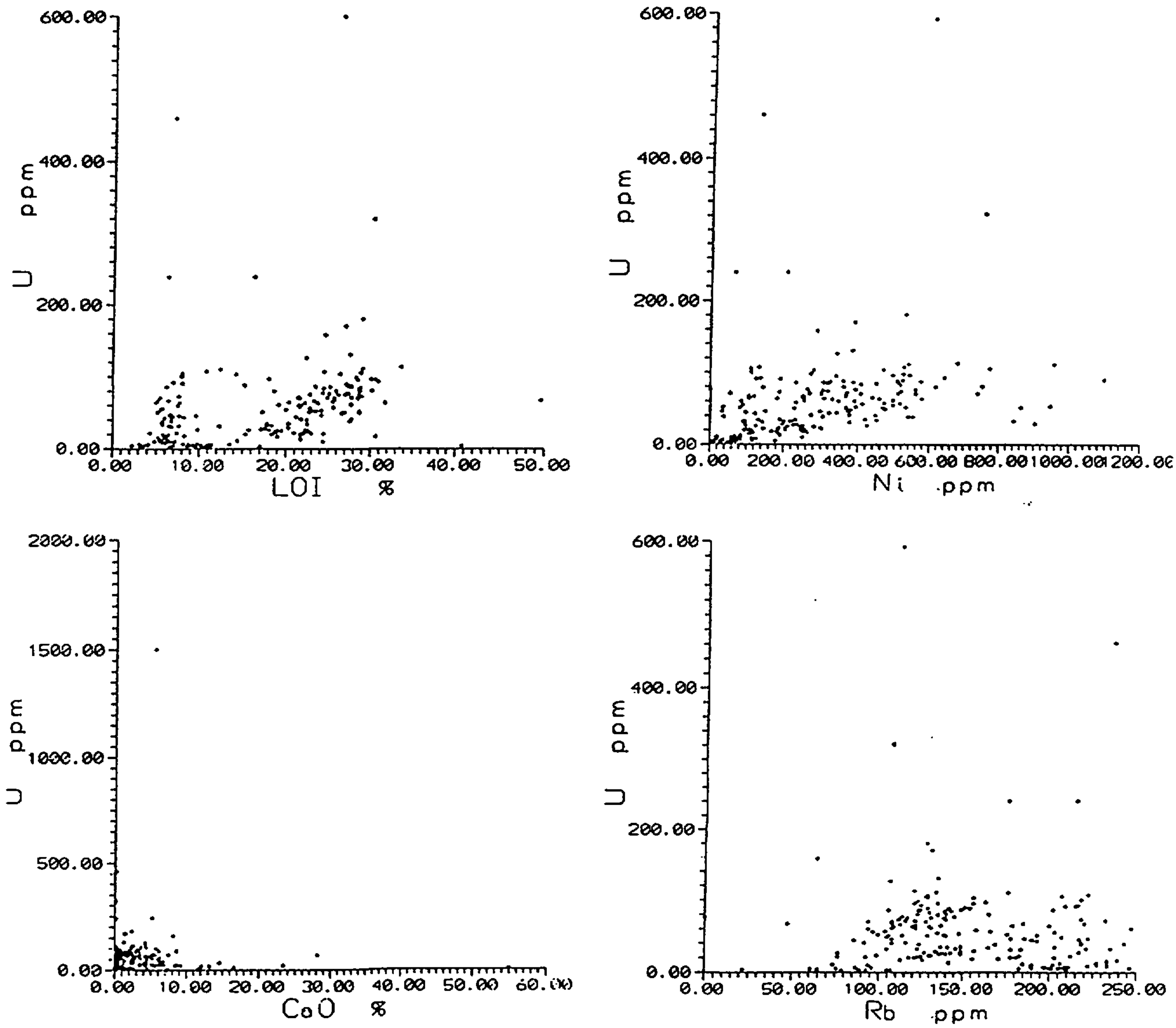


FIG. 5. Plots of uranium vs LOI, CaO, Ni, and Rb for the lower shale.

Because of its biophile character, vanadium tends to concentrate in most organic rich black shales that were formed in a reducing environment. The vanadium content in the Bakken shales is no exception, it varies from 55 ppm up to 0.39%; in the sandstone it ranges from 1 ppm to 0.19%. Again, the shales contain more vanadium in the eastern part of the study area. In contrast to the U and Mo, the V in the middle sandstone tends to be highest in the northwest. Vanadium in the shales exhibits positive correlations with LOI, Cr and Ni while in the sandstone it has negative correlations with LOI, Ba, Cr, Co and Ni.

3.5.3. Copper, Nickel and Zinc

In the Bakken shales the Cu content ranges between 5 and 1640 ppm, Ni between 8 and 1260 ppm, and Zn from 11 to 44 400 ppm; values in the sandstone are 1 to 86, 1 to 250, and 5 to 1910 ppm, respectively.

Although these elements exhibit strong enrichments they do not exhibit any clear correlations either with each other or with other major and trace components.

The Zn values are often very but not unusual for black shales; Brumsack (1980 & 1986) states that Zn often exhibits greater enrichments than the other metals in black shales and usually occurs in a discrete mineral form (i.e. sphalerite).

According to Cambel and Khum (1983) Cu and Ni are commonly enriched in sedimentary environments by their incorporation in pyrite. Since no analyses of pyrite in the Bakken Formation were carried out it is not possible to say whether the observed enrichments are "sulphide" or "organic matter" controlled.

3.5.4. Barium, Rubidium, Strontium and Thorium

Distributions of these elements are similar in all three members of the Bakken Formation and seem consistent with an essentially detrital origin.

Barium in the shales varies between 10 and 10 550 ppm, and in the sandstone between 10 and 6300 ppm. Its positive correlations with K_2O and Al_2O_3 and negative correlation with LOI indicate a clay mineral association.

Similarly Rb, which varies between 20 and 250 ppm in the shales and 13 and 190 ppm in the sandstone, gives "clay mineral type" correlations. Although Sr exhibits fairly large ranges (50-3600 ppm for shales and 50-900 ppm for sandstone) it shows no demonstrable correlations, either negative or positive, with any other components.

Thorium has a very limited range within the entire Bakken Formation (1 to 26 ppm). The data indicate convincingly that the anomalous gamma ray responses, typical of the Bakken Formation in Saskatchewan, are effectively a function of the U content of the rocks.

BIBLIOGRAPHY

ADAMS, J.A.S., WEAVER, C.E., Thorium-uranium ratios as indicators of sedimentary processes: example of concept of geochemical facies, American Association of Petroleum Geologists Bulletin, 42 (1958) 387-430.

AHEM, J.I., MRKVICKA, S.R., A mechanical and thermal model for the evolution of the Williston Basin. Tectonics, 3 (1984) 79-102.

ANDERSON, R.F., Redox behaviour of uranium in an axoxic marine basin. ln: concentration mechanisms of uranium in geological environments, program and extended abstracts, SFMC-CREGU, Nancy-France (1985) 77-82.

ARMANDS, G., Geochemical studies of uranium molybdenum and vanadium in the Swedish Alum shale. Stockholm Contributions in Geology, 27 (1972) 1-148.

ASHIKHMIN, A.A., KUZNETSOV, S.V. and SCHMARIOVICH, E.M., Preservation and concentration of uranium ore mineralization in zones of weathering. Lithology and Mineralogy Resources (USSR), 18 (1983) 364-370.

BARRON, L.S., ROBL, T.L., KUNG, J. and OBLEG, J., Devonian-Mississippian oil shale resources of Kentucky: Summary, Proceedings 1984 Eastern Oil Shale Symposium. IMMR 84/124 (1984) 347-363.

BARWISE, A.J.G., WHITEHEAD, E.V., Fossil fuel metals. In: S.S. Augustithis (ed.) The significance of trace elements in solving petrogenetic problems and controversies, Greece (1983) 599-643.

BASU, A., BLANCHARD, D.P. and BRANNON, J.C., REE in the sedimentary cycle: a pilot study of the first Leg. Sedimentology, 29 (1982) 737-742.

BATS, T.F., STRAHL, R.O., Mineralogy, petrography and radioactivity of representative samples of Chattanooga shale. Geological Society of America Bulletin, 68 (1957) 1305-1314.

BEERS, R.F., GOODMAN, C., Distribution of radioactivity in ancient sediments. Geological Society of America Bulletin, 55 (1944) 1229-1254.

BEERS, R.F., Radioactivity and organic content of some paleozoic shales, American Association of Petroleum Geologists Bulletin, 29 (1945) 1-22.

BELL, H. (III), GARLAND, B.G., POST E.V. and SCHNABEL, R.W., Lithologic and structural control of uranium deposition in the southern Black Hills, South Dakota. U.S. Geological Survey Professional Paper 300 (1956) 345-349.

BELL, R.T., Uranium in black shales, a review. In: Short course in uranium deposits: Their mineralogy and origin (Kimberley, M.M., ed) (1978) 307-329.

BERNER, R.A., Early diagenesis: A theoretical approach, Princenton (1980) 241 p.

BERRY, W.B.N., WILDE, P., QUINBY-HUNT M.S. and ORTH, C.J., Trace element signatures in Dictyonema shales and their geochemical and stratigraphic significance. Norsk Geologisk Tidsskrift, 66 (1986) 45-51.

BJORLYKKE, K., The Middle Ordovician of the Oslo Region, Norway, 20. The geochemistry and mineralogy of some shales from the Oslo Region. Norsk geol. Tidsskr., 45 (1965) 435-456.

BJORLYKKE, K., Geochemical and mineralogical influence of Ordovician island arcs on epicontinental clastic sedimentation. A study of lower paleozoic sedimentation in the Oslo region, Norway, Sedimentology, 21 (1974) 251-272.

BREGER, I.A., BROWN, A., Kerogen in the Chattanooga shale. Science, 137 (3525) (1962) 221-222.

BREGER, I.A., SCHOPE, J.M., Germanium and uranium in coalified wood from upper Devonian black shale. Geochimica et Cosmochimica, 7 (1955) 287-293.

BRINDLE, J.E., Mississippian megafaunas in southeastern Saskatchewan. Department of Mineral Resources, Report No. 45 (1960) 107 p.

BROWN, A., Uranium in the Chattanooga shale of eastern Tennessee. U.S. Geological Survey, Professional Paper 300 (1956) 457-462.

BRUMSACK, H.J., Geochemistry of Cretaceous black shales from the Atlantic Ocean (DSDP Legs 11, 14, 36 and 41). Chemical Geology, 31 (1980) 1-25.

BRUMSACK, H.J., The inorganic geochemistry of cretaceous black shale (DSDP Leg 41) in comparison to modern upwelling sediments from the Gulf of California. Geological Society of London Special Publication 21 (1986) 447-462.

CAMBEL, B., KHUM, M., Geochemical characteristics of black shales from the ore-bearing complex of strata of the Male Karpaty Mts. Geologicky Zbornik, 34 (1983) 259-382.

CAMPELL, G., New Albay Shale, Geological Society of America Bulletin, 57 (1946) 829-908.

CARSERUD, L., Soviet research on black shales and ore formation. Geologiska Foereningenistockholm Foerhandlinger, 104 (1982) 19-94.

CHAMBERLAIN, J.A., On the uranium possibilities of the southern interior plains of Canada. Geological Survey of Canada Paper 59-16 (1960) 12 p.

CHAUDHURI, S., CULLERS, R.L., The distribution of REE in deeply buried Gulf Coast sediments. Chemical Geology, 24 (1979) 327-338.

CHRISTOPHER, J.E., Transitional Devonian-Mississippian formations of southern Saskatchewan. Saskatchewan Department of Mineral Resources, Report No. 66 (1961) 103 p.

CLUFF, R.M., Paleo-environment of the New Albany shale group (Devonian-Mississippian) of Illinois. Journal of Sedimentary Petrology, 50 (1980) 767-780.

CLUFF, R.M., REINBOLD M.L. and LINEBACK, J.A., The New Albany shale group of Illinois: Illinois State Geological Survey Circular 518 (1981) 83 p.

CONANT, L.C., SWASON, V.E., Chattanooga shale and related rocks of central Tennessee and nearby areas. U.S. Geological Survey Professional Paper 357 (1961).

CONANT, L.C., Environment of accumulation of the Chattanooga shale. U.S. Geological Survey Professional Paper 300 (1956) 463-467.

CONKIN, J.E., CONKIN, B.M., The paracontinuity and the determination of the Devonian-Mississippian boundary in the type Lower Mississippian area of North America. University of Louisville studies in paleontology and stratigraphy, No. 1 (1973) 34 p.

COVENEY, R.M., MARTIN, S.P., Molybdenum and other heavy metals of the Mecca Quarry and Logan Quarry shales. Economic Geology, 78 (1983) 132-149.

CULLERS, P.L., CHAUDHUR, S., ARNOLD, B., LEE, M. and WOLF Jr. C.W. , Rare earth distribution in clay minerals and in the clay-sized fraction of the lower permian Havensville and Eskridge shales of Kansas and Oklahoma, Geochimica et Cosmochimica Acta., 39 (1975) 1691-1703.

CULLERS, R.L., CHAUDHUN, S., KILBANE, N. and KOCH, R., REE in size fractions and sedimentary rocks of Pennsylvanian Permian age from the mid-continent of the U.S.A. Geochimica et Cosmochimica Acta., 43 (1979) 1285-1301.

DELIAN, F., Polyelements in the lower Cambrian black shale series in southern China. In: S.S. Augustithis (ed.) The significane of trace elements in solving petrogenetic problems and controversies, Greece (1983) 447-474.

DELIAN, F., The lower Cambrian black shale series and the Iridium anomaly in south China. Contribution to 27th International Geological Congress, 21 (1984) 215-224.

DEMBICKI, H. Jr., PIRKLE, F.L., Regional source rock mapping using a source potential rating index, American Association of Petroleum Geologists Bulletin, 69 (1985) 567-581.

DILL, H., Metallogenesis of early paleozoic graptolite shales, from the Graefenthal Horst (North Bavaria - F.R.G.). Economic Geology, 81 (1986) 889-903.

DILL, H., Genesis and timing of secondary uranium mineralization in northern Bavaria (F.R. of Germany) with special reference to geomorphology. Uranium, 2 (1985) 1-16.

DISNAR, J.R., Etude experimentale de la fixation de metanx par un matériel sedimentaire actuel d'origine algaire II. Fixation in vitro de VO_2, Cu, Ni, Zn, Pb, Co, Mn, ainsi que de VO_2, MoO_4 et GeO_3. Geochimica et Cosmochimica Acta, 45 (1981) 363-379.

DOW, W.G., Application of oil-correlation and source-rock data to exploration in Williston Pasin. American Association of Petroleum Geologists Bulletin, 58 (1974) 1253-1262.

DREVER, J.I., Early diagenesis of clay minerals, Rio Ameca Basin, Mexico, Journal of Sedimentary Petrology, 41 (1971) 982-994.

DUKE, M.J.M., Geochemistry of the Exshaw shale of Alberta - an application of neutron activation analysis and related techniques, Unpublished M.Sc. thesis, University of Alberta, Edmonton (1983) 186 p.

DUNOYER De SEGONZAC, G., The transformation of clay minerals during diagenesis and low-grade metamorphism, A Review, Sedimentology, 15 (1970) 281-346.

DYPVIK, H., BRUNFELT, A.O., Rare-earth elements in Lower Paleozoic epicontinental and eugeosynclinal sediments from the Oslo and Trondheim regions. Sedimentology, 23 (1976) 363-378.

DYPVIK, H., BRUNFELT, A.O., Distribution of REE in some North Atlantic Kimmeridgian black shales. Nature, 278 (1979) 339-341.

DYPVIK, H., BUE, B., The U, Th and K distribution in black shales of the Janusfjellet formation, Svalbard, Norway. Chemical Geology, 42 (1984) 287-296.

EPSTEIN, A.G., EPSTEIN, J.B. and HARRIS, L.D., Conodont color alteration - an index to organic metamorphism, U.S. Geological Survey Professional Paper, 995 (1977) 27.

ETTENSOHN, F.R., BARRON, L.S., Depositional model for the Devonian-Mississippian black shales of North America: A paleoclimatic-paleogeographic approach. In Roberts, T.G. (ed.) Geological Society of America, Cincinnati 81, Field trip Guidebooks, v. 2: Economic Geology, structure, American Geological Institute, Washington, D.C. (1981) 344-361.

EVENSEN, M.N., HAMILTON, P.J. and OLNIOS, R.K., Rare earth abundances in chondritic meteorites. Geochimica et Cosmochimica Acta., 42 (1978) 1199-1212.

FOWLER, C.M.R., NISBET, E.G., The subsidence of the Williston Basin, Canadian Journal of Earth Sciences, 22 (1984) 408-414.

GERHARD, L.C., ANDERSON, S.B., LEFEUER, J.A. and CARLSON, C.G., Geological development, origin and energy mineral resources of Williston Basin, North Dakota. American Association of Petroleum Geologists Bulletin, 66 (1982) 989-1020.

GORZHEVSKIY, D.I., On the role of organic matter in ore formation. International Geology Review, 29 (1987)207-217.

GUTSCHICK, R.C., SUTTNER, L.J. and SWITEK, M.J., Biostratigraphy of transitional Devonian-Mississippian Sappington Formation of southwest Montana. In Hanson, A.R. and J.H. MeKeever (eds.) The Devonian System of Montana and Adjacent Areas. Billings Geological Society 13th Annual Field Conference Guidebook (1962) 79-90.

HARRIS, A.G., Color alteration - an index to organic metamorphism in conodont elements. In Robinson, R.A. (ed.) Treatise on invertebrate paleontology, part W, Miscellanea Supplement 2, Boulder, Colorado and Lawrence, Kansas. Geological Society of America and University of Kansas (1981) W56-W60.

HASKIN, L.A., WILDEMAN, T.R., FARY, F.A., COLLINS, K.A., KEEDY, C.R. and HASKIN, M.A., Rare earths in sediments. Journal of Geophysical Research, 71 (1966) 6091-6105.

HASKIN, L.A. et al., An accurate procedure for the determination of rare earths by neutron activation. Journal of Radioanalytical Chemistry, 1 (1968) 337-348.

HASKIN, M.A., HASKIN, L.A., Rare earths in European shales: a re-determination. Science, 154 (1966) 507-09.

HAYES, J.D., PITMAN III, W.C., Lithospheric plate motion, sea level changes, and climate and geological consequences: Nature, 246 (1973) 18-21.

HAYES, M.D., Conodonts of the Bakken Formation (Devonian-Mississippian), Williston Basin, North Dakota, unpublished M.Sc. Thesis, University of North Dakota (1984) 178 p.

HAYES, M.D., Conodonts of the Bakken Formation Devonian and Mississippian, Williston Basin, North Dakota. The Mountain Geologist, 22 (1985) 64-77.

HESTER, T.C., SCHMOKER, J.W., Preliminary log-derived maps of the Bakken Formation, North Dakota and Montana portions of Williston Basin, U.S. Geological Survey Open File Report 83-717 (1983) 25 p.

HOLLAND, F.D., HAYES, M.D., THRASHER, L.C. and HUBER, T.B., Summary of biostratigraphy of the Bakken formation (Devonian-Mississippian) in the Williston Basin, North Dakota. 5th International Williston Basin Symposium, Special Publication No. 9 (1987) 68-76.

HOLLAND, H.D., Metals in black shales, a re-assessment. Economic Geology, 74 (1979) 1676-1680.

JIANFEG, W., Natural organic matter and its implications in uranium mineralization. Geochemistry, 3 (1984) 260-271.

KENT, D.M., Depositional setting of Mississippian strata in southern Saskatchewan: a conceptual model for hydrocarbon accumulation. In: J.A. Lorsong and M.A. Wilson (eds.) Oil and Gas in Saskatchewan, Saskatchewan Geological Society Special Publication 7 (1984) 19-30.

KENT, D.M., Paleotectonic controls on sedimentation in the northern Williston Basin, Saskatchewan. Rocky Mountain Association of Geologists Symposium 1987 (1987a) 45-56.

KENT, D.M.,Mississippian facies, depositional history and oil occurrences in Williston Basin, Manitoba and Saskatchewan. Rocky Mountain Association of Geologists Symposium 1987 (1987b) 157-170.

KENTS, P., Three Forks and Bakken stratigraphy in west central Saskatchewan. Saskatchewan Department of Mineral Resources Report 37 (1959) 107 p.

KHABAROV, V.V., NELEPCHENKO, O.M., VOLKOV, Y.N. and BARTASHEVICH, O.V., U, Th and K in bituminous rocks of the Bazhenov formation of west Siberia, Petroleum Geology, 17 (1981) 383-390.

KRUMBEIN, W.C., SLACK, H.A., Statistical analysis of low level radioactivity of Pennsylvanian black shale of Illinois, Geological Society of America Bulletin, 67 (1956) 739-762.
KUCTTA, H., Platinum-group metals in the Zechstein copper deposits, Poland. Economic Geology, 77 (1982) 1578-1591.

LEENHEER, M.J., Mississippian Bakken and equivalent formations as source rocks in the western Canadian basin. Organic Geochemistry, 6 (1984) 521-532.

LEENHEER, M.J., ZUMBERGE, J.E., Correlation and thermal maturity of Williston Basin crude oils and Bakken source rocks using terpane biomarkers, Rocky Mountain Association of Geologists, Williston Basin Symposium 1987 (1987) 287-298.

LEPKA, F., PODRACKY, P., Uranium and thorium distribution in the upper proterozoic and lower paleozoic marine shales of the Barrandian area (Central Bohemia). In: Concentration mechanism of uranium in geological environments, program and extended abstracts, SFMC-CREGU, Nancy, France (1985) 83-86.

LEVENTHAL, J.S., Pyrolysis gas chromatography-mass spectrometry to characterize organic matter and its relationship to uranium content of Appalachian Devonian black shales. Geochimica et Cosmochimica Acta, 45 (1981) 883-889.

LEVENTHAL, J.S., CROCK, J.G. and MALCOLM, M.J., Geochemistry of trace elements and uranium in Devonian shales of Appalachian Basin. U.S. Geological Survey Open File Report 81-0778 (1981) 80 p.

LINEBACK, J.A., Illinois Basin - sediment starved during Mississippian. American Association of Petroleum Geologists Bulletin, 53 (1969) 112-126.

LINEBACK, J.A., DAVIDSON, M.L., The Williston Basin sediment starved during the early Mississippian. 4th International Williston Basin Symposium. Saskatchewan Geological Society Special Publication No. 6 (1982) 125-130.

LINEBACK, J.A., ROTH, M. and DAVIDSON, M.L., Sediment starvation in the Williston and Illinois Basins during the Devonian and Mississippian. Rocky Mountain Association of Geologists Symposium 1987 (1987) 147-155.

MACQUEEN, R.W., SANDBERG, C.A., Petrography age and interregional correlation of the Exshaw formation, Alberta Rocky Mountains, Bulletin of Canadian Petroleum Geology, 18 (1970) 32-66.

MANN, H., FYFE, W.S., An experimental study of algal uptake of U, Bo, V, Co and Ni from dilute solutions. Chemical Geology, 44 (1984) 385-398.

MAPEL, W.J., Uraniferous black shale in the northern rocky mountains and great plains regions, U.S. Geological Survey Professional Paper 300 (1956) 469-476.

McLENNAN, S.M., NANCE, W.B. and Taylor, S.R., REE - Thorium correlations in sedimentary rocks and the composition of the continental crust. Geochimica et Cosmochimica Acta., 44 (1980) 1833-1839.

McLENNAN, S.M., Taylor, S.R., Th and U in sedimentary rocks: crustal evolution and sedimentary recycling, Nature, 285 (1980) 621-624.

MURRAY, G.H. Jr., Quantitative fracture study - sanish pool, McKenzie county, North Dakota, American Association of Petroleum Geologists Bulletin, 52 (1968) 57-65.

NAKASHIMA, S., DISNAR, J.R, PERRUCHOT, A. and TRICHET, J., Experimental study of mechanisms of fixation and reduction of uranium by sedimentary organic matter under diagenetic or hydrothermal conditions. Geochimica et Cosmochimica Acta, 48 (1984) 2321-2329.

NANCE, W.B., TAYLOR, S.R., REE patterns and crustal evolution. I. Australian post-Archean sedimentary rocks. Geochimica et Cosmochimica Acta, 40 (1976) 1539-1551.

NORDENSKIOLD, A.E., Remarques sur le fer natif d'Ovifak et sur le bitume des roches cristallines de Suède (Remarks on the native iron of Ovifak and on the bitumen in the crystalline rocks of Sweden). Extrait d'une lettre de M. Nordenskiold à M. Daubree, Acadamic Science of Paris Comptes Rendus, 116 (1893) 677-678.

NORDQUIST, J.E., Mississippian stratigraphy in northern Montana. Billings Geological Society, 4th Annual Field Conference, Guidebook (1953) 68-82.

OLSON, R.K., Factors controlling uranium distribution in upper Devonian-lower Mississippian black shales of 0klahoma and Arkansas. Unpublished Ph.D. Thesis, The University of Tulsa (1982), 210 p.

OTTEN, J.K., ZIELINSKI, R.A., Movement and concentration of uranium in young, organic-rich sediments, Stevens County, Washington. In: concentration mechanisms of uranium in geological environments, program and extended abstracts, SFMC-CREGU, Nancy, France (1985) 49-52.

PANDALAI, H.S., MAJUMDER, T. and CHANDRA, D., Geochemistry of pyrite and black shale of Amjhore, Rohtas District, Bihar, India. Economic Geology, 78 (1983) 1505-1513.

PARRISH, J.T., Upwelling and petroleum source beds with reference to Paleozoic. American Association of Petroleum Geologists Bulletin, 66 (1982) 750-774.

PELZER, E.E., Mineralogy, geochemistry and stratigraphy of the Besa River shale, British Columbia. Bulletin of Canadian Petroleum Geology, 14 (1966) 273-321.

PETERMAN, Z.E., Dating of Archean basement in northeastern Wyoming and southern Montana. Geological Society of America Pulletin, 92 (1981) 139-146.

PETERSON, J.A., Subsurface stratigraphy and depositional history of the Madison Group (Mississippian) U.S. portion of the Williston Basin and adjacent areas. Rocky Mountain Association of Geologists Symposium 1987 (1987) 171-193.

PLILER, R., ADAMS, J.A.S., The distribution of thorium-uranium and potassium in the Mancos shale. Geochimica et Cosmochimica Acta, 26 (1962) 1115-1135.

POOLE, F.G., DESBOROUGH, G.A., Metal concentrations in marine black shales. U.S. Geological Survey Circular 0949, Program and Abstracts, 1985 (1985) 43-44.

POTTER, P.E., MAYNARD J.B. and PRYOR, W.A., Sedimentology of shale, Study guide and reference source, Springer-Verlag, New York (1980).

RAISWELL, R., PLANT, J., The incorporation of trace elements into pyrite during diagenesis of black shales, Yorkshire, England, Economic Geology, 75 (1980) 684-699.

RASMY, M., BASILY, A.B., Spectrographic study of trace elements in some Egyptian black shales associated with phosphate deposits. Chemical Geology, 39 (1983) 115-123.

RATEEV, M.A., GORBUNOVA, Z.N., LISITZYN, A.P. and NOSOV, G.L., The distribution of clay minerals in the oceans. Sedimentology, 13 (1969) 21-43.

RICH, J.L., Probable fondo origin of Marcellus-Ohio-New-Albany-Chattanooga bituminous shales. American Association of Petroleum Geologists Bulletin, 35 (1951) 2017-2040.

RICH, J.L., Three critical environments of deposition and criteria for recognition of rocks deposited in each of them. Geological Society of America Bulletin, 62 (1951) 1-20.

RONOV, A.B., BALASHOV, Yu. A. and MIGDSOV, A.A., Geochemistry of rare earths in the sedimentary cycle. Geochemistry International, 4 (1968) 1-17.

RONOV, A.B., BALASHOV, Yu.A., GIRIN, Yu.P., BRATISHKA R.K.H. and KAZAKOV, G.A. Regularities of rare earth element distribution in the sedimentary shell and in the crust of the earth. Sedimentology, 21 (1974) 171-192.

RUSSEL, W.L., Relation of radioactivity, organic content, and sedimentation. American Association of Petroleum Geologists Bulletin, 29 (1945) 1470-1494.

RUSSEL, D.J., Depositional analysis of a black shale by using gamma-ray stratigraphy: the upper Devonian kettle point formation of Ontario. Bulletin of Canadian Petroleum Geology, 33 (1985) 236-253.

SANDBERG, C.P., Devonian and lower Mississippian conodont zonation of the Great Basin and Rocky Mountain. In Sandberg, C.A. and D.L. Clark (eds.) Conodont Biostratigraphy of the Great Basin and Rocky Mountains, Brigham Young University Geology studies, 26 (1979) 87-105.

SANDBERG, C.A., and KLAPPER, G., Stratigraphy, age, and paleotectonic significance of the Cottonwood Canyon member of the Madison limestone in Wyoming and Montana: U.S. Geological Survey Bulletin 1251-B (1967) 70 p.

SANDBERG, C.A., W.J. MAPEL, Devonian of the northern Rocky Mountains and plains. In Oswald, D.H. (eds) International Symposium on the Devonian system, Calgary, Alberta, Society of Petroleum Geologists, 1 (1967) 843-877.

SANDBERG, C.A., GUTSCHICK, R.C., JOHNSON, J.G., POOLE, F.G. and SANDO, W.J., Middle Devonian to Late Mississippian geological history of the over thrust Belt region, Western U.S. Rocky Mountain Association of Geologists, Geologic Studies of the Cordilleran Thrust Belt, 2 (1982) 691-719.

SAUPE, F., VEGAS, G., Chemical and mineralogical compositions of black shales Middle paleozoic of the central Pyrenees, Haute-Garonne, France). Mineralogical Magazine, 51 (1987) 357-369.
SCHMOKER, J.W., HESTER, T.C., Organic carbon in Bakken formation, U.S. portion of Williston Basin. American Association of Petroleum Geologists Bulletin, 67 (1983) 2165-2174.

SHAFFER, N.R., LEININGER, R.K. and GILSTRAP, M.S., Composition of the uppermost beds of the New Albany shale in southern Indiana. 1983 Eastern oil shale symposium, Lexington, Ky, U.S. (1983) 195-200.

SHAW, D.B., WEAVER, C.E., The mineralogical composition of shales. Journal of Sedimentary Petrology, 35 (1965) 213-222.

SHEPPARD, C.W., Radioactivity and petroleum genesis. American Association of Petroleum Geologists Bulletin, 28 (1944) 924-952.

SLEEP, N.H., Thermal contraction beneath Atlantic margin. In P.A. Scrutton (ed.) Dynamics of passive margins: Geodynamics series, American Geophysical Union and Geological Society of America, 7 (1982) 154-158.

SLOSS, L.L., Sequence in the cratonic interior of North America. Geological Society of America Bulletin, 74 (1963) 93-114.

SLOSS, L.L., Williston in the family of cratonic basins. Rocky Mountain Association of Geologists. Williston Basin Symposium 1987 (1987) 1-8.

SPEARS, D.A., AMIN, M.P., Geochemistry and mineralogy of marine and non-marine Namurian black shales from the Tansley borehole, Derbyshire. Sedimentology, 28 (1981) 407-417.

SPENCER, C.W., Hydrocarbon generation as a mechanism for overpressuring in Rocky Mountain region. American Association of Petroleum Geologists Bulletin, 71 (1987) 368-388.

STASIUK, L.D., OSADETZ, K.G. and POTTER, J., Fluorescence spectral analysis and hydrocarbon exploration: Examples from paleozoic potential source rocks, Saskatchewan. Saskatchewan Geological Society Special Publication No. 10 (in press, 1990).

STRELYANOV, N.P., Types of ore-controlling zonation in uranium deposits in sedimentary rocks. International Geology Review 25 (1983) 165-172.

SWANSON, V.E., Geology and Geochemistry of uranium in marine black shales - a review. U.S. Geological Survey Professional Paper 356-C (1961) 67-111.

TARDY, Y., Element partition ratios in some sedimentary environments. II - studies on North America black shales. Sciences Geology Bulletin, 28 (1975) 75-95.

TAYLOR, S.R., McLELLAN, S.M., The composition and evolution of the continental crust: rare earth element evidence from sedimentary rocks. Philosophical Transactions of the Royal Society A301 (1981) 381-387.

TAYLOR, S.R., McLELLAN, S.M., The continental crust: its composition and evolution. An examination of the geochemistry record preserved in sedimentary rocks. Blackwell Scientific publications, Geoscience Texts (1985) 9-56.

THODE, H.G., Sulfur isotope ratios in petroleum research and exploration, Williston Basin. American Association of Petroleum Geologists Bulletin, 65 (1981) 1527-1535.

THRASHER, L.C., Macrofossils and stratigraphic subdivisions of the Bakken formation (Devonian-Mississippian) Williston Basin, North Dakota. Fifth International Williston Basin Symposium, Special Publication No. 9 (1987) 53-67.

TILSLEY, J.E., Ore deposit models - 3, Genetic considerations relating to some uranium ore deposits; Part II: models for uranium ores in sandstones and in carbonaceous pelites, Geoscience Canada, 8 (1981) 3-7.

TOURTELOT, H.A., Minor element composition and organic carbon content of marine and non-marine shales of late Cretaceous age in the western interior of U.S. Geochimica et Cosmochimica Acta, 28 (1964) 1579-1604.

UYENO, T.T., Report on 13 conodont samples from the lower and upper shale member of the Bakken formation from 11 wells in southern Saskatchewan, GSC, Calgary, Report 08-TTU-89 (1989).

VINE, J.D., History of investigations of geochemistry of black shales. In: Proceedings of the 27th International Geological Congress, 21 (1984) 85-98.

VINE, J.D., SWANSON, V.E. and BELL, K.G., The role of humic acids in the geochemistry of uranium. Second international conference on peaceful uses of Atomic Energy process, Geneva, 2 (1958) 187-191.

VINE, J.D., TOURTELOT, E.B., Geochemistry of black shales deposits - A summary report. Economic Geology, 65 (1970) 253-272.

WAVRA, C.S., ISAACSON, P.E. and HALL, W.A., Studies of the Idaho black shale belt stratigraphy, depositional environment and economic geology of the Permian Dollarhid formation. Geological Society of America Bulletin, 97 (1986) 1504-1511.

WEBSTER, R.L., Analysis of petroleum source rocks of the Bakken Formation (Devonian-Mississippian) in North Dakota, Unpublished M.Sc. Thesis, University of North Dakota, Grand Forks (1982) 150 p.

WEBSTER, R.L., Petroleum source rock and stratigraphy of the Bakken Formation in North Dakota. Rocky Mountain Association of Geologists, Williston Basin Symposium 1987 (1987) 269-286.

WILDEMAN, T.R., HASKIN, L.A., Rare earth elements in ocean sediments. Journal of Geophysical Research, 70 (1965) 2905-2910.

WILLIAMS, J.A., Characterization of oil types in the Williston Basin. American Association of Petroleum Geologists Bulletin, 58 (1974) 1242-1252.

WILLIAMS, J.A., Characterization of oil types in Williston Basin. Rocky Mountain Association of Geologists, Williston Basin Symposium 1987 (1987) 259-268.

YOUNG, R.G., Uranium deposits of the world, excluding Europe. In: De Vivo, B., F. Ippolito, G. Capaldi and P.R. Simpson (eds.) Uranium, geochemistry, mineralogy, geology, exploration and resources. The Institution of Mining and Metallurgy (1984) 117-139.

ZIEGLER, W., SANDBERG, C.A., Palmatolepis based revision of upper part of standard Late Devonian conodont zonation. In Clark, D.L. (ed.) Conodont biofacies and provincialism. Geological Society of America Special Paper 196 (1984) 179-194.

SOME NEW URANIUM EXPLORATION AREAS IN CHINA

F. SHEN
Bureau of Geology, China National Nuclear Corporation,
Beijing, China

Abstract

This paper describes how, during the 1980s, China changed the area of emphasis of its uranium prospecting and exploration from South China to North China. The changes were made as a result of the recognition of increased need for uranium resources under the national nuclear development plan. The change in geographic area was accompanied by the de-emphasis of exploration for conventional deposit types known in the south: volcanic, granitic, sandstone and carbonaceous-siliceous-pelitic types to in situ leachable sandstone type and high grade Precambrian hosted deposits. The new programmes resulted in the discovery of sandstone-type uranium deposits in the large continental sedimentary Erlian and Yili basins in North China, as well as a granitic pegmatite hosted deposit in Shaanx Province. This paper describes the geology and uranium mineralization of the recently discovered deposits.

A significant turn in uranium prospecting and exploration in China has occurred since 1980's. As a result, the major prospecting districts are being transferred from South China to North China. Meanwhile, the main prospecting and exploration targets are also being changed from four conventional types i.e. volcanic type, granite type, sandstone type and carbonaceous-siliceous-pelitic type to in situ leachable sandstone type predominantly, and high grade deposits which could occur in Precambrian strata. The main reason for it is that more uranium resources are required according to China is national nuclear power development plan. Several large scale sandstone type uranium deposits which are favourable for in situ leaching have been discovered in large continental basins in North China. This paper reports the up-to-date achievements on uranium prospecting and exploration in Erlian Basin, Inner Mongolian Autonomous Region, and Yili Basin, Xinjiang Uygur Autonomous Region, and Danfeng area, Shaanxi Province (Fig. 1). These areas are still the major districts for prospecting and exploration now, and new exploration achievements are to be expected.

1. SANDSTONE TYPE URANIUM DEPOSITS IN ERLIAN MESO-CENOZOIC BASIN

Erlian Basin lies in the central part of Inner Mongolian Autonomous Region. It is a Meso-Cenozoic basin composed of four sub-downwarpped basins and a central uplifted area (Fig. 2). In geotectonic position, it is located at the southern margin of Late-Hetcynian Inner Mongolian folded belt. This basin is northeast trending, 1 000 km long, 50-200 km wide, and the total area is about 130 000 square kilometers.

The uranium exploration work in Erlian basin was started in 1980, and several prospecting targets were preliminarily selected based on the systematic analysing of a series of basic geological information such as regional stratigraphic correlation columns, lithofacies-paleogeographical maps as well as contour maps of airborne gamma survey. In 1984, one of the prospecting targets was explored by grid drilling of 100 × 100 m, and a small uranium deposit, namely No. 110, was discovered. This deposit occurs in redox interface of Tertiary mudstone and argillaceous sandstone of shore lake and delta lithofacies. The host rocks are rich in organic matter and pyrite, and the ore bodies are in disequilibrium, with higher content of uranium.

The No. 110 deposit is classified as syn-sedimentary and reworked type uranium deposit. According to the metallogenic model of No. 110 deposit, the second prospecting target, namely 861 area was selected. The 861 area is located northeast to No. 110 deposit. This area is also characterized by shore lake-delta facies, and the sandstone is also rich in organic matter and pyrite.

Moreover, seven polonium anomalies and some uranium -radon water anomalies were detected in addition to a number of radioactivity gamma anomalies. In 1986, four widely spaced drilling profiles, 4-8 km in exploration-line spacing, 800-1 600 m in drill-hole spacing, were designed and a new uranium deposit, Subeng deposit, was discovered. Subeng deposit was only a mid-sized one when all the exploration work within 861 area was completed in 1989. The deposit is different from No. 110 deposit in that the Subeng uranium deposit is hosted by Cretaceous sandstone. The ore bodies are mainly stratoid and flat-lying and confined in argillaceous sandstones rich in organic matter and pyrite, and occur at or near the redox front. The thickness of ore bodies ranges from 0.29 m to 2.17 m, and 0.63 m in average. The grade ranges from 0.03% U to 0. 756% U, and 0.133% U in average. The buried depth of ore bodies is from 5.23 m to 36.71 m. The explored reserve of No. 1 orebody occupies 87.5% of the total of Subeng deposit. From 1990 to 1992, the preliminary in-situ leaching test was carried out in some selected areas in Subeng deposit. It has been proved that this kind of sandstone type uranium deposit can be operated by in-situ leaching in the future. In 1990, another new and large uranium deposit, Nuheting uranium deposit, was discovered by drilling in 15 km away, southeast to Subeng uranium deposit. The geological and metallogenic setting and the mineralization characteristics in Nuheting deposit are generally similar to those in Suben deposit. The prospect reserves of Nuheting deposit are expected to be more than 10,000 t U, and now the deposit is still under exploration.

FIG. 1. Locality map of uranium exploration areas in China.

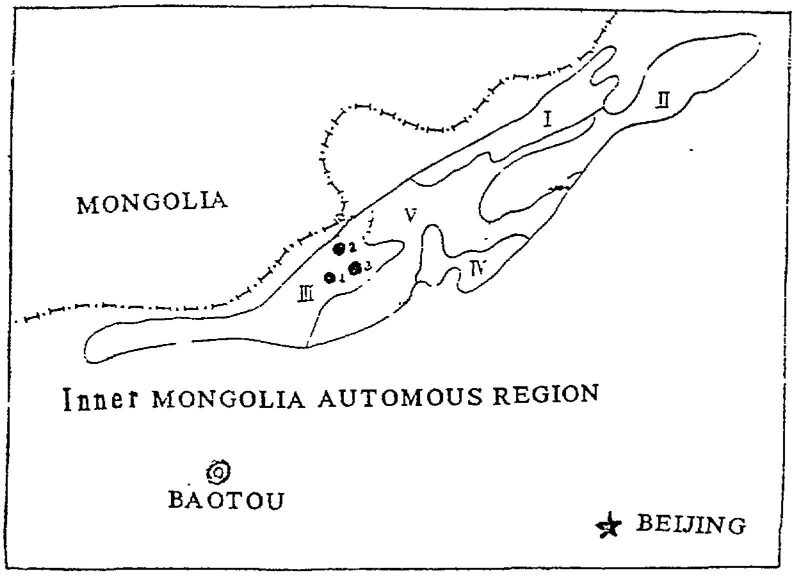


FIG. 2. Locality map of uranium deposits in Erlian Basin.

I, II, III, IV: Sub-downwarpped basins
V: Central uplifted
1: No. 110 deposit
2: Subeng deposit
3: Nuheting deposit

2. SANDSTONE TYPE URANIUM DEPOSITS IN YILI MESO-CENOZOIC BASIN

Yili Basin is located in the western part of Xinjiang Uygur Autonomous Region, and its total area (in China territory) is about 20 000 km^2. The basement of the basin is composed of Paleozoic intermediate-acidic tuffaceous rocks, and the cover consists of Triassic-Jurassic and Cretaceous-Tertiary sequences.

The Triassic-Jurassic cover rocks in the basin are divided into three groups, namely:

(1) The coal-underlying group consisting of Middle-Upper Triassic mottled classic series characterized by upward grain size fining sedimentary sequence.

(2) The coal bearing group composed of Lower-Middle Jurassic interbedding of sandstone and mudstone with intercalations of coal beds, 13 sedimentary sequences can be observed in the basin, and a coal bed appears at the top of each sequence.

(3) Coal-overlying group, represented by Middle-Upper Jurassic mottled conglomerate, coarse-grained sandstone with intercalcations of sandstone lens. Uranium mineralizations mainly occur in Lower-Middle Jurassic coal-bearing group. The Triassic-Jurassic are unconformably covered by Cretaceous-Tertiary red beds.

The earliest uranium exploration work in Yili Basin was begun in 1955. Three sandstone type uranium deposits, namely No. 510, No. 511 and No. 512 were discovered during 1950's (Fig. 3).

All the above mentioned deposits occur within Jurassic coal-bearing group. Uranium ore bodies are predominantly hosted in the 11th and the 12th coal beds, as well as in the 5th and the 7th

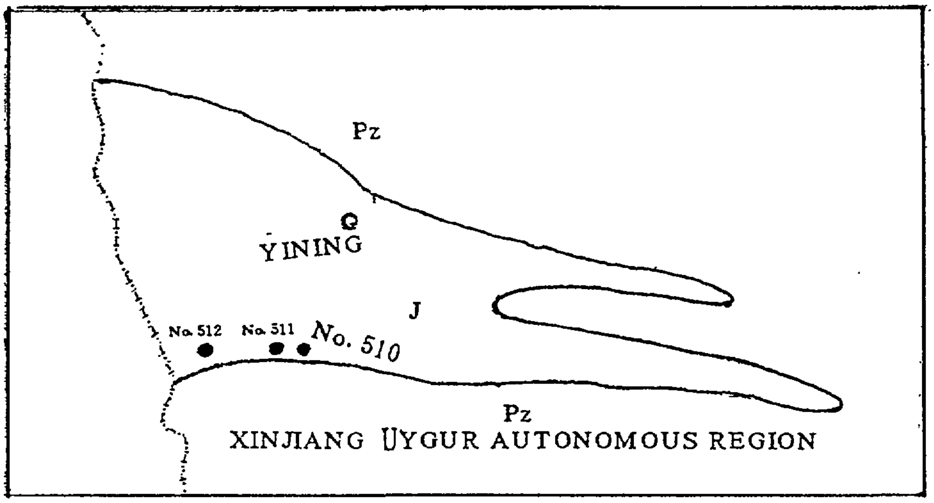


FIG. 3. Locality map of uranium deposit in Yili Basin.

coal beds. In other words, they are concentrated in the upper and middle parts of the coal-bearing group. Ore bodies are controlled by braided channel shore delta-lake bog facies at the frontier of fan-delta. Mineralization is closely associated with interlayer redox process and the coal-overlying mottled beds show some spatial and genetic relationship with uranium mineralization. These deposits were described as of diagnetic-epigenetic concentration origin. Since the dimension of these deposits was not large and the cost would be too high if exploited by underground mine, all the exploration on uranium in Yili Basin ended in late 1960's. Then the exploration activity was rejuvenated gradually within Yili Basin since middle 1980's, as the regional geological survey and research work evidenced that uranium deposits in coal-bearing group, Yili Basin can be economically mined by in situ leaching. Moreover, the wide area surrounding the early discovered deposit shows great potential. In 1991, several uranium ore bodies around the No. 512 deposit were discovered and their metallogenic characteristics are quite similar to those of the early discovered ones. At present, the basin is still under exploration.

3. PEGMATITIC GRANITE TYPE URANIUM DEPOSITS IN DANFENG AREA

The discovery of pegmatitic granite type uranium deposits in Danfeng area, Shaanxi Province, is considered as one of the most important achievements of uranium exploration in the southern border of North-China Platform during 1980's.

Dangfeng area lies in the eastern part of Qinling orogenic belt, and major rocks are Early Proterozoic marble, gneiss and migmatite of Qinling Group. The abundance of uranium and thorium in Qinling Group is 2.7 ppm and 17.4 ppm respectively and the group is regarded as the main U-source bed. Caledonian gneissic biotite granite and medium- coarse grained granite intruded the metamorphic rocks of Qinling Group and a series of pegmatitic granite dykes were formed within metamorphic rocks and at exocontact areas of granite massifs (Fig. 4). All discovered uranium ore bodies occur in these pegmatitic granite dykes, which are distributed in Dangfeng area in the form of dyke-swarm. The length of individual pegmatitic dyke ranges from 500 m to 1,000 m in general, and the maximum reaches 3 400 m. The thickness usually varies from 2 m to 5 m and the maximum can be 90 m.

The uranium exploration activity began in 1963, and a number of surface mineralization occurrences and gamma anomalies were discovered in that year. In 1966, a preliminary evaluation of these occurrences and anomalies was done and no uranium deposit was found, so the exploration

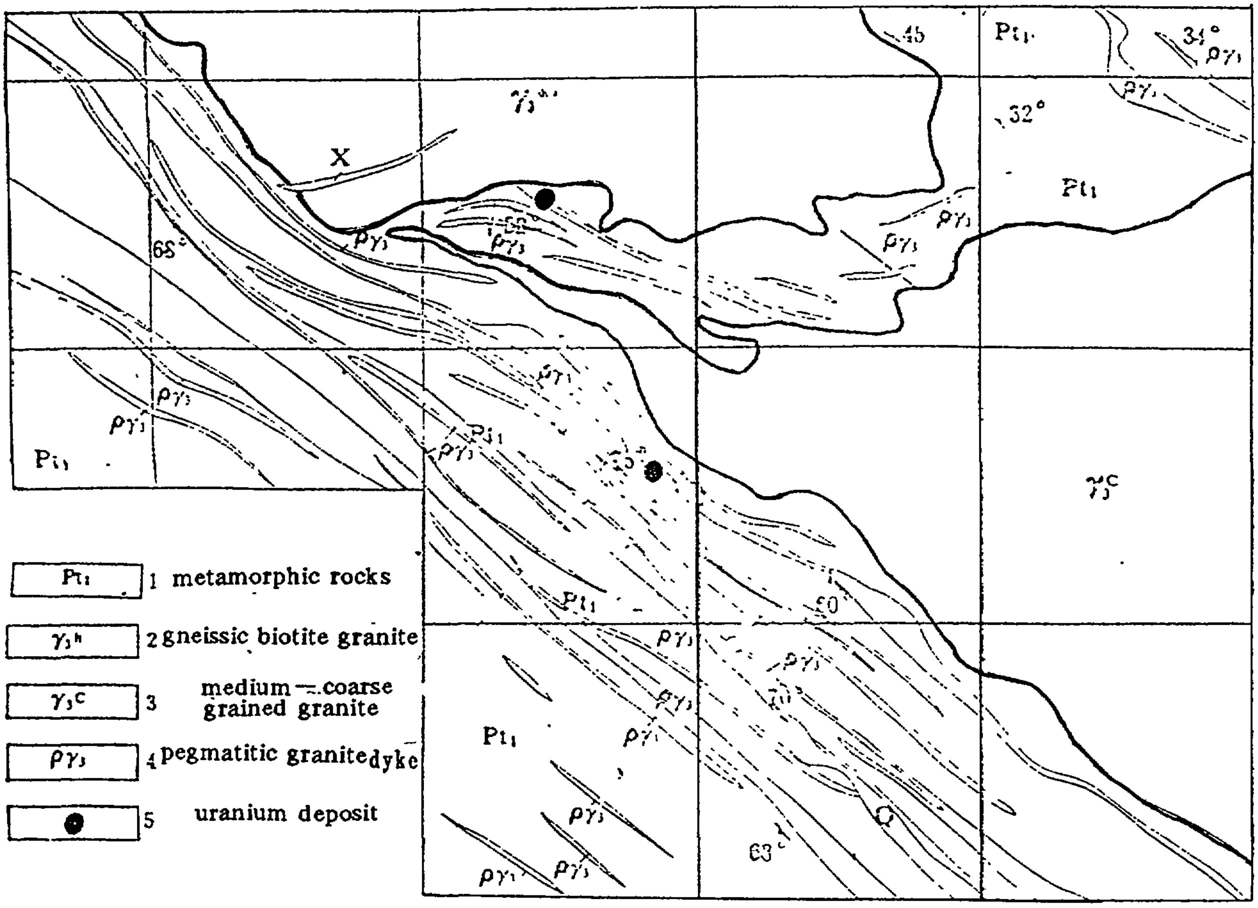


FIG. 4. Locality map of uranium deposits in Danfeng Area.

activity was stopped. In 1985, according to some new knowledge gained from the research work on ore-forming condition about pegmatitic granite dykes, the uranium exploration work in Danfeng area was resumed. A lot of new anomaly zones in uranium-bearing pegmatitic granite were found through activated charcoal survey and geological mapping. A systematic drilling and tunneling in this area on pegmatitic granite dykes were done from 1986 to 1989, and two small-sized uranium deposits were discovered. Uraninite is the main uranium mineral in pegmatitic granite. Although the size of pegmatitic granite type uranium deposits is not large at present, it is a kind of new type uranium deposit discovered in China in recent years. In addition, large amounts of unexplored pegmatitic granite dykes exist within Danfeng area, therefore, the potentiality of development in this area in the future is very good.

DEVELOPMENT OF URANIUM HEAP LEACHING IN CHINA

R. ZHANG
Bureau of Mining and Metallurgy, China National Nuclear Corporation,
Beijing, China

Abstract

After more than 20 years efforts,the uranium heap leaching technology in China has reached the application stage. Recently the heap leaching experiments have been conducted in most of the uranium mines, two of them have adopted heap leaching technology for production on full scale. In 1992 nearly 16 percent of uranium was produced by heap leaching technology and it is expected that this proportion will reach 25 percent in 1995. Therefore the heap leaching as a uranium extractive technology has become very competitive in uranium production. Extensive research work has been done in China on uranium heap leaching for different conditions and requirements. The problems encountered in heap leaching production and the technique developed for solving them are described. The economic comparison between the heap leaching and the conventional processing is also given in this paper.

1. INTRODUCTION

In China, experimentation with uranium heap leaching started in the early 1960s led to application in production in late 1980s. At present the heap leaching tests have been conducted in most of the uranium mines and two of them are operating by heap leaching on production scale. The amount of uranium produced by heap leaching in 1991 accounted for 12.5 percent of total production and in 1992 accounted for 15.7 percent. It is estimated that this proportion will be about 25 percent in 1995. Therefore the heap leaching as a uranium extractive technology plays more and more significant role in China's uranium production.

2. DEVELOPMENT OF RESEARCH ON URANIUM HEAP LEACHING IN CHINA

In China the development of research on uranium heap leaching covers three aspects: underground heap leaching test, condition test of surface heap leaching and test on industrial scale.

2.1. Underground heap leaching test

On the basis of the laboratory column tests and the underground test in raise, the underground heap leaching test of 3000 tonnes was carried out during 1969-71. The recovery of U was 82%. This was the first attempt of underground uranium heap leaching in China.

2.2. Condition test of surface heap leaching

The condition tests were conducted in laboratory column mainly for low grade uranium ore. The feasibility study on heap leaching was made for 3 types of uranium ores. For the granite type uranium ore characterized by lower calcium and magnesium and higher silicate content, the recovery of uranium was more than 90% and the acid consumption was lower than 3% and the leaching cycle was about one month due to simple composition and less acid consumption matter in the ore. This type of ore is most suitable for heap leaching. The second type of ore belongs to the primary sedimentary and subsequent superposed eluvial deposits. The ore contains also higher silicates, but the content of CaO, MgO and Fe_2O_3 is higher than that of the first one. In addition, it has clay content and a small amount of organic substance. The leaching recovery could reach 80% and over, with 3-5% acid consumption and 2 months leaching cycle due to its slightly poorer leachability. This type of uranium ore can also be treated by heap leaching according to the technico-economic analysis. The third one is molybdenum containing carbonate type uranium ore which contains some clayey matter and organic substance. It is unsuitable for acid leaching and treated by carbonate solution and the uranium recovery is only 50-60% and the molybdenum recovery 70-80%. According to economic estimation, this type of uranium ore is not suitable for heap leaching.

The asphalt felt, polyethylene film and compacted clay were tested as the pad materials for the heap bottom. The results indicated that all the three pad materials could attain the goal of acid resistance and imperviousness and could meet the requirements of environmental protection.

The tests on the ways of distributing leaching solution, influence of ore grade, heap height and other factors were conducted. These tests have provided a great deal of data and information for the industrial scale heap leaching.

2.3. Industrial tests

In 1984, the tests on heap leaching entered the commercial stage. The Chongyi Uranium Mine in Jiangxi province was first engaged in heap leaching of 5000 tons. The Lantian Uranium Mine carried out two heap leaching tests of 2000 tons. The tests showed that for these two mines the heap leaching is feasible and profitable. The success of Chongyi and Lantian mines in heap leaching has provided a reliable basis for other mines to use heap leaching technology. Even Saerbulake gold mine used this experience and completed heap leaching of 100 000 tonnes ore with satisfied result in 1991.

3. PRACTICAL CASES

3.1. Surface heap leaching of Chongyi Mine

Chongyi Mine was put into production with a conventional mill. The first years operation indicated a low level of economic result. After a series of experimental works, in 1989, the whole uranium production of this mine had transferred from conventional technology to heap leaching. In 1990 the leaching operation had heap capacity of 120,000 tons of ore with average U grade 0.086%. The production cost was reduced by 35%. The production practice of this mine marked that China's uranium heap leaching has entered into industrial application.

3.2. Surface heap leaching of Lantian Mine

The deposits belong to the low-temperature hydrothermal type. The cracks and fissures are developed in the ore bodies. The uranium in the ore mainly occurs in clay with hematite, chlorite, pyrite and fluorite in dispersed form. The heap leaching-ion exchange-precipitation process was adopted. Sulfuric acid was used for leaching. The barren solution was recycled after H_2SO_4 is added to adjust its acid concentration. The concentration of H_2SO_4 during leaching ranged from 3% in initial period to 0.5-1% in the later period. The pH of leaching solution was controlled at 1.5-2.0. The results of heap leaching tests for two heaps of 2000 tonnes each in Lantian Mine are shown in Table I.

According to the original design, the Lantian ore would be transported to the mill located far away. Compared with the original process, the treatment of all ores by heap leaching made the mine increase its economic benefit. The comparison between the two processes are shown in Table II.

TABLE I. RESULT OF HEAP LEACHING TESTS IN LANTIAN MINE

Item	Heap I	Heap II
Heap capacity, t	1843	2211
Heap height, m	2.2 - 2.4	2.95
Ore particle size, mm	-100	-200
Leaching cycle, day	96	70
Ore grade, %U	0.369	0.113
Acid consumption, %	2.36	2.91
Percolation rate, Lm^2/h	10 - 22	10 - 100
L:S	2.5	1.6
Residue grade, %U	0.013	0.0096
Recovery rate, %	96.5	91.5

TABLE II. COMPARISON OF ECONOMIC BENEFITS BETWEEN TWO PROCESSES FOR LANTIAN URANIUM MINE

Item	Conventional Process	Heap Leaching
1. Capital construction		
Total investment, rel %	100	100
Ore production capacity, t/year	40 000	40 000
Cost per tonne of U in yellow cake, rel.%	100	78.3
2. Operation		
Total output value, rel.%	100	215.8
Annual profit, rel.%	100	326

The uranium level in residue is similar both for heap leaching and for conventional process. Lower raw material and energy consumption for heap leaching is the evident advantage. For example, the sulphuric acid consumption is only 40% of that of conventional process, the lime is 37%, the resin is 30%, the energy is 44%, the water is 16%. And the manpower needed for heap leaching is decreased by ¼. The operation cost of heap leaching is only about 80% of that of conventional process.

3.3. Underground heap leaching in Lantian Mine

The deposit lies in the cataclastic granoblastic rock,and the ore bodies are fragmentary, small and scattered. It would be very difficult to mine the ore with conventional technology and the production cost would be higher and most low grade ores would be unusable. However, the deposit has the following features favourable for heap leaching: developed cracks in the ore bodies, better blastability of the ore, even ore particle size after blasting, stable, less permeable host rocks above and below the ore. Therefore it was decided to carry out the test of underground heap leaching of blasted ore at the end of 1992. The test is still in progress and the uranium recovery rate has reached 81%. It is estimated that the operation cost can be reduced by 30%. In addition, there are other advantages, such as less land requirement, less surface disturbance and pollution and lower grade ore can be treated and recoverable reserves of uranium are therefore increased.

3.4. Uranium recovery from mined area in Chenzhou Mine

The Chenzhou Mine has been operated for over 30 years. For 80% of the ore bodies the cut-and-fill mining method is employed successfully. The filling materials contain 0.018% of uranium in average and the residual uranium in them amounts to at least several hundred tons. Because of FeS_2 and thiobacillus ferro-oxidant present in the ore, usually it is unnecessary to add acid to the leaching solution. The water supplied underground is used successfully. The leaching cycle is about 10 months and the recovery rate is about 40% with highest of 60%. The direct production cost is only 30% of that from conventional process. The service life of the mine will be extended for 10 years.

4. MAIN PROBLEMS IN RECENT PRODUCTION PRACTICE OF HEAP LEACHING

In general, the surface heap leaching technology of uranium in China has come up to application in production. However,some uranium mines used to suffer from long leaching cycles and agglomeration of ore during heap leaching, which have negatively affected its further application. Therefore great attention has been paid to solving these problems.

4.1. Reduction of heap leaching cycle

The cycle of heap leaching for uranium is usually in the range of 3-6 months. However, for some mines, the cycle of heap leaching can be as long as 1-1.5 years which resulted in increasing operating cost and land occupation. The leaching cycle can be reduced to less than 6 months by proper selection of heap capacity or set of dimensions, especially heap height, ways of distributing lixiviant,ore particle size and technical conditions, etc. For example,the test on concentrated acid curing-ferric sulphate leaching process conducted in Quxian Mine showed that leaching cycle can be reduced from more than 200 days to 44 days. The ore grading 0.080% of U was crushed to -6 mm, then mixed with 60% concentrated sulphuric acid and the ratio of L/S was less than 0.06. The mixed material was kept at ambient temperature for 3 days,then it was cured for 2 hours at 95°C. The ferric sulphate was used for percolation leaching at the rate of 30 L/m^2/h. The uranium recovery was in the range of 86.5-89.5%. Compared with the conventional heap leaching the capital and operating costs are lower. The other distinguishing feature of this process is that it has much less waste water.

4.2. Prevention of ore agglomeration

There are many factors resulting in ore agglomeration in heap leaching. The main reason is excessive amount of fine materials and clayey matter in the ore. This type of ore is not suitable for heap leaching directly. Leaching rates can be improved only with pretreatment of ore. For example, heap leaching after granulation is an effective way for solving the problem.

In 1990, the heap leaching experiment with ore granulation for a uranium mine in Yunnan province had attained good result. The ore has high clay content and -200 mesh particles are more than 20%. Conventional percolation or agitating leaching technology resulted in low metal recovery and high production cost. The ore was granulated by adding high molecule granulator after grinding into -10 mm. Heap leaching lasted 15 days, using sulfuric acid solution at a spraying speed of 34 L/m^2/h. The uranium leaching efficiency reached over 90%.

5. FUTURE OUTLOOK FOR CHINA'S URANIUM HEAP LEACHING

In China, most of uranium deposits belong to granite type, suitable for heap leaching. In addition, most mines are located in southern China where the climate is warmer, which is favourable for heap leaching. It can be expected that the heap leaching in China will make a new progress either in production or in research work. The surface heap leaching technology will be further improved and the economic benefit will be increased. The underground heap leaching will be speeded up in testing and application, the recovery of uranium from the mined area will be strengthened by heap leaching technology. The proportion of heap leaching in uranium production in China will be increased continuously.

Next page(s) left blank

URANIUM DEPOSITS OF THE CZECH REPUBLIC[1]

J. HRÁDEK
DIAMO s.p., Stráž pod Ralskem, Czech Republic

Abstract

The existing uranium production in the Czech Republic has a long tradition for about 100 years The unimportant production of uranium ores used in the glass and ceramic industries and medicine was replaced after World War II by an intense evolution of uranium ore exploration, mining and processing activities. This whole period is characterized by a steadily increasing level, of exploration work and of linked research activities in a few stages. A substantial reduction in the volume of geological exploratory works aimed at the detection and development of new deposits occurred as a result of the contraction programme of the uranium industry, pronounced in 1989. There are only two regions with prospective uranium deposits at present time. The first one is in northern Bohemia with the Hamr and the Straz deposits in production. These deposits are connected with basal Cretaceous sediments (sandstones). The other one is in western Moravia (Moldanubian) with the Rozna and the Brzkov deposits. These deposits are connected with metamorphosed rocks of the Moldanubian. All the exploration, extraction and processing activities were operated by the state for approximately 50 years. Nowadays the only uranium producer in the Czech Republic is the DIAMO state enterprise, based in Straz pod Ralskem. The continuation of extraction is planned at the Rozna and the Hamr deposits in the near future. The ISL-production of uranium is planned at the Straz deposit during the restoration activities.

1. HISTORICAL REVIEW

The prevailing part of the Czech Republic is formed by the Czech massif which belongs to the important uraniferous provinces of Europe. Its mining history reaches far into medieval times. The term "Pechblend" — pitchy looking ore from the silver mines of Jachymov - appeared in the books by Georgius Agricola (1494-1555) for the first time. Pierre and Mary Curie succeeded in preparing radium and later also polonium from the same pitchblende in 1898.

The unimportant production of uranium ores used in the glass and ceramic industries and for the production of radioactive preparations was replaced after 1945 by an intense evolution of uranium ore exploration, mining and processing activities. It continued until 1989. The contraction programme for the Czech uranium industry started at that time for the first time. Other important deposits, namely Horni Slavkov (1946), Pribram (1947), Zadni Chodov (1952), Rozna and Olsi (1956), Vitkov II (1961), Okrouhla Radoun (1962), Dylen (1964), Hamr and other deposits of the north Bohemian Cretaceous (1963-1968) were discovered during this period. The localization of the important deposits containing extracted or recoverable amounts of uranium greater than 100 t are shown in Fig. 1.

2. METHODOLOGY OF EXPLORATION AND RESEARCH WORKS

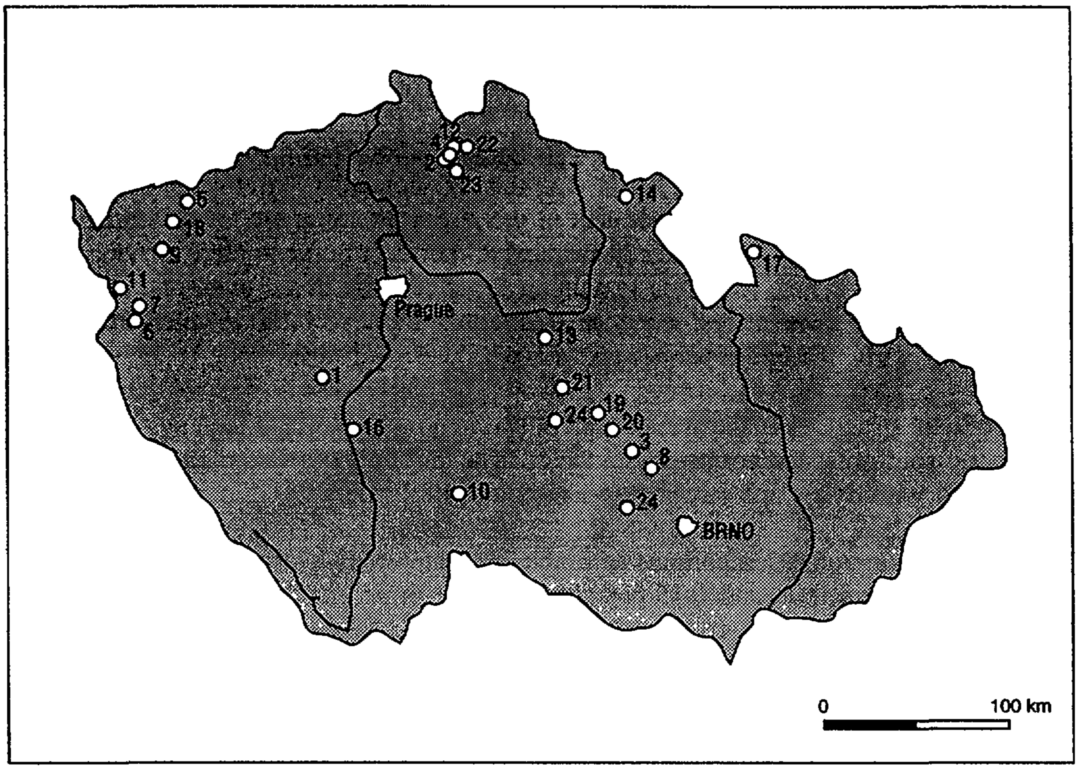
The whole period 1946 - 1992, aimed exclusively at the exploration and extraction of uranium in the Czech Republic, is characterized by a steadily increasing level of exploration work and of linked research activities. Gradually the whole Czech Republic was covered by a complex survey made by geological, geophysical and geochemical methods in the course of several stages. Promising areas were explored in detail by drillings and underground mining works. Exploratory underground work and drilling efforts were made in the flanks and the deeper parts of the exploited deposits under

[1] Translated by P. Kühn and J. Slezák

operation, too. The exploration activities may be divided into several stages characterized mainly by the evolution of exploration and research methods:

1. Stage (1946-1960)

Checking and revision work, radiometry, emanation surveys, drill logging with Geiger-Muller counters, geological mapping, laboratory evaluations



No.	Deposit	Size	Status	Type	No.	Deposit	Size	Status	Type
1.	Pribram	B	V	H	13.	Licomerice–Brezinka	S	V	H
2.	Straz •	B	T	S	14.	Vnitrosudetska panev	S	V	S
3.	Rozna •	B	T	Z	15.	Jasenice	S	V	Z
4.	Hamr	B	T	S	16.	Predborice	S	V	H
5.	Jachymov	M	V	H	17.	Javornik–Zalesi	S	V	H
6.	Vitkov	M	V	M	18.	Hajek	S	V	S
7.	Zadni Chodov	M	V	Z	19.	Skrdlovice	S	V	H
8.	Olsi	M	V	Z	20.	Slavkovice–Petrovice	S	V	H
9.	Slavkov	M	V	H	21.	Chotebor	S	V	H
10.	Okrouhla Radoun	M	V	Z	22.	Osecna–Kotel	B	P	S
11.	Dylen	M	V	Z	23.	Hvezdov	M	P	S
12.	Brevniste	M	V	S	24.	Brzkov	M	P	H

Legend

Type : B > 10 000 tonnes U
M > 1 000 and < 10 000
S > 100 and < 1 000

Status : V = mined out
T = being exploited
P = planned, prospective

Type : H = vein deposits ("classic" veins)
Z = vein deposits ("zone" deposits)
M = vein deposits (metasomatic deposits)
S = stratiform, sandstone – type

• Milling plant

FIG. 1. Uranium deposits in Czech Republic.

The uranium deposits of Horni Slavkov (1946), Pribram (1947), Zadni Chodov (1952), Rozna, Olsi (1956) and some other smaller deposits were discovered. Besides this there was a substantial enlargement of the Jachymov deposit area.

2. Stage (1961-1970)

Use of scintillation radiometers, methods of deep radiometric prospecting (10-15 m), construction of maps with the conditions for the carrying out of radiometric surveys, enhancement of the level of drill logging, computer-based evaluation of gamma-logging (elementary layer method), increasing volume of exploratory drilling in sedimentary rocks, construction of our own laboratory base, evolution of the hydrogeological services, basic prognostic evaluation of the uranium potential of Czechoslovakia.

The evolution of new exploration methods led to the discovery of types of deposits not known until that time in Czechoslovakia. E.g. in the granitoid rocks of the Bor massif (Vitkov, 1961), in the sedimentary rocks of the Hroznetin basin (Oder, Hroznetin, Hajek, 1963), in the sedimentary rocks of the north Bohemian Cretaceous basin (Hamr, Straz, Brevniste, 1963-1968) and the Okrouhla Radoun (1962) and Dylen (1964) deposits.

3. Stage (1971-1980)

First complex prognostic evaluation of the whole Czechoslovak Republic for uranium, utilization of the 2nd and 3rd generation of computer technology in the evaluation of all the geological, geophysical and geochemical information, foundation of deposit databases, introduction of pedestrian and car-borne gamma-spectrometry, the method of alpha-tracks, neutron logging, electron scanning microscopy, electron microanalyses.

The new deposits of Osecna-Kotel and Hvezdov were discovered by the concentration of exploration activities in the north Bohemian Cretaceous basin. Moreover the Brzkov deposit in crystalline rocks and the Nahosin deposit in granitoid rocks were discovered.

4. Stage (1981-1992)

The second prognostic evaluation for uranium in the Czechoslovak Republic, the complex solution of the mathematical and geological models of the deposits according to morphological types, the mathematical three-dimensional hydro-geological modelling, technical-economical evaluation of the deposits, technological research, development and modelling, final evaluation of the uranium deposits of the Czech Republic in connection with the contraction programme of the uranium industry, the construction of the databases for the preservation of final stage information.

Detailed evaluatory works were carried out at the north Bohemian deposits and the prognostic value of the Brzkov and Rozna deposits were confirmed during this stage.

The expenses necessary for the exploration of the uranium deposits and for the corresponding volumes of main exploration works (drillings, horizontal mining works) during 1971-1992 are illustrated in Table 1 and Fig. 2. The conversion to US$ in Table I was made by means of the rate of the "internal difference of price counterbalance" with regard to the inconvertibility of the Czechoslovak currency for the years 1971-1990 and by means of the "internal convertibility" rate of the Czechoslovak currency for the years 1991-1992.

A substantial reduction in the volume of geological exploratory works aimed at the detection and development of new deposits occurred as a result of the contraction programme of the uranium industry, pronounced in 1989. A small volume of work was done to finish the exploration in the western part of the Hamr deposit. New exploration activities were aimed at the initiation of the

TABLE I. VOLUME OF EXPLORATION WORKS AND TOTAL EXPLORATION EXPENDITURES

PERIOD	EXPLORATION DRILLING 1000 m	EXPLORATION UNDERGR.WOR 1000 m	EXPENDITURES mil.Kcs	EXPENDITURES mil.US$
71-80	1215.54	264.14	2475.30	138.95
81	·112.75	17.60	290.80	21.54
82	105.93	18.30	288.80	20.70
83	90.53	16.06	269.00	18.82
84	92.45	17.45	264.70	15.80
85	93.56	17.90	263.40	15.49
86	92.48	16.95	265.00	17.81
87	85.78	16.59	262.40	19.08
88	73.17	14.19	238.40	16.20
89	58.20	10.64	282.30	18.60
90	18.35	3.60	119.90	7.37
91	6.18	0.48	47.60	1.54
92	1.24	0.00	18.20	0.66
TOTAL	2046.14	413.89	5085.80	312.57

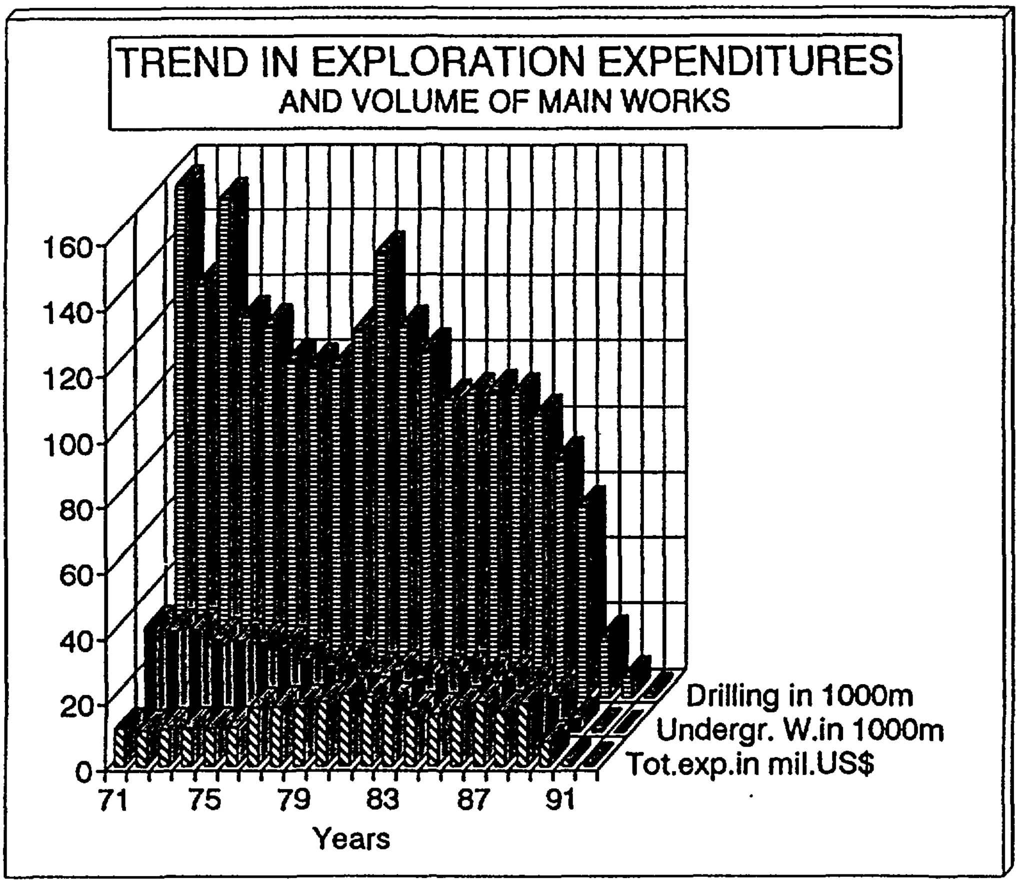


FIG. 2. Trend in exploration expenditures and volume of main works.

restoration activities in the Straz deposit, to the elaboration of the final reports and to the creation of a complex uranium deposits database for the Czech Republic. All these exploratory activities are carried out solely by the DIAMO state enterprise, based in Straz pod Ralskem.

The drilling of four technological wells in the Hvezdov deposit area and the continuation of work connected with the restoration of the Straz deposit (forefield exploration) are planned for 1993. The final evaluation of the results of this exploratory and extraction work will be continued parallel to these activities.

3. CHARACTERIZATION OF THE PRESENT CONVENTIONAL RESOURCES

3.1. Known conventional resources (RAR & EAR-I)

A substantial decrease of the conventional uranium resources in the Czech Republic occurred after a significant contraction in the extraction and processing of uranium ores, started in 1989. Since 1 January 1993 there are only two regions with prospective uranium deposits. Two exploited deposits are in northern Bohemia - the Hamr and Straz deposits. The Brevniste (mining interrupted in 1989 - mothballed) and Osecna-Kotel deposits are not exploited. All of these deposits are connected with basal Cretaceous sediments (sandstones). The other region is in western Moravia (Moldanubian) with the Rozna (operating) and Brzkov deposits (explored by underground mining works).

The Rozna deposit lies in a complex body of metamorphosed sedimentary and effusive rocks of Precambrian age. It belongs to the eastern branch of the Moldanubian. The host rocks mainly belong to the variegated series of the Moldanubian, consisting of plagioclase-biotitic to amphibolitic gneisses of different stages of migmatization and of amphibolites. Small bodies of marbles, erlanes, serpentinites and pyroxenites have also been found.

The uranium mineralization of hydrothermal character is associated with fault structures. Longitudinal faults striking 340-355° and dipping 45-70°W can be genetically divided into tectonic zones and plumose structures - veins. The zones up to 10-15 km long are mostly a few meters thick, only occasionally reaching up to 25-30 m. The zone filling consists mainly of crushed host rocks with small contents of gangue minerals (calcite, graphite, pyrite). The uranium concentrations in these zones occur in large bodies and consist mainly of a finely dispersed mineralization. The thickness of the ore bodies is up to 10 m. The main ore minerals are uraninite and coffinite of Varisan age (about 250 Ma). The average grade of uranium in the exploited ore is 0.130%.

The deposit is mined by underground mining works prevailingly by the benching up and fill method. The present depth of ore breaking is about 1000 m.

The Brzkov uranium deposit is developed in the region of the Strazek crystalline area (western Moravia). Its host rocks are biotite paragneisses, amphibolites, skarns, crystalline limestones, erlans and pegmatites of Proterozic age. The uranium mineralization is bound in a series of NW-SE striking parallel faults dipping 60-70° NE. The ore bodies are between 0.1 and 10 m thick and they contain mainly uraninite and coffinite. The deposit was technically and economically evaluated by detailed underground exploration mining works down to a depth of 280 m. The results are shown in Table II.

The Hamr deposit is developed in the basal Cenomanian sediments of the North Bohemian Cretaceous basin. These sediments lie on an Upper Proterozoic variegated complex of phyllitic rocks containing small bodies of cataclazed granitoids. The Cretaceous rock sequence begins with a 0-30 m thick sedimentary series of freshwater Cenomanian conglomerates, gravels, breccias, sandstones, siltstones and mudstones. These rocks are overlain by 0-10 m of the so-called "washout" horizon of the brackish Cenomanian containing abundant organic components. This horizon is characterized by an appreciable facial diversity. Higher up, the marine sediments are prevailingly medium-grained

TABLE II. PRODUCTION AND RECOVERABLE RESOURCES OF ECONOMICALLY EVALUATED DEPOSITS AS OF 1 JANUARY 1993

DEPOSIT	PRODUCTION	RESOURCES (tonnes U)				
		Cost Ranges	RAR	EAR-I	EAR-II	TOTAL
ROZNA	14800	<= $80/kgU	1650	1150	500	3300
		$80-130/kgU				0
		$130-260/kgU				0
		TOTAL	1650	1150	500	3300
BRZKOV	55	<= $80/kgU	900	200	300	1400
		$80-130/kgU	100	200	200	500
		$130-260/kgU				0
		TOTAL	1000	400	500	1900
HAMR-north	10500	<= $80/kgU	9400			9400
		$80-130/kgU	1500			1500
		$130-260/kgU	500			500
		TOTAL	11400	0	0	11400
STRAZ	13200	<= $80/kgU	3900			3900
		$80-130/kgU	2800	4200		7000
		$130-260/kgU				0
		TOTAL	6700	4200	0	10900
TOTAL	38555	<= $80/kgU	15850	1350	800	18000
		$80-130/kgU	4400	4400	200	9000
		$130-260/kgU	500	0	0	500
		TOTAL	20750	5750	1000	27500

"friable" sandstones of 20-30 m thickness and 30-40 m of sedimentary rocks ("fucoid" sandstones) ranging from silty fine-grained sandstones to sandy siltstones. The Cenomanian sedimentation is terminated by 0-3 m of argillaceous silty fine-grained sandstones with glauconite and by sideritic argillaceuos sandy siltstones. This Cenomanian rock sequence is covered by 80-200 m thick series of marls, marly sandstones and thick-bedded sandstones of lower and middle Turonian age.

The structure of the area consists of prevailing structural elements of NE-SW direction, represented by the Straz fault. This fault is accompanied by parallel faults which, partially, are filled with dykes of Tertiary basaltic and melilitic rocks. The intersections of these faults with the less frequent Lusatian structures of NW-SE direction sometimes contain larger bodies of Tertiary basaltoid eruptive rocks.

The uranium mineralization is represented by uraninite, uraniferous hydrozircon and ningyoite and occurs in the basal Cenomanian layers. It is concentrated mainly in the "washout" horizon (approx. 85% of the geological resources). About 10% of the resources are contained in fresh water Cenomanian and about 5% in the medium-grained sandstones. The age of the mineralization (U-Pb method) is 25 ± 3 and 6 ± 3 Ma. The northern part of the deposit is developed, from the morphological point of view, as the so-called simple mineralization represented by a continuous 2-12 m thick mineralized body occurring mainly in the wash-out horizon. The main ore minerals are uraninite, ningyoite and hydrozircon. All the mining operations are taking place in this part of the deposit.

A more complex morphological type of mineralization was developed in the southern part of the deposit. It is represented by a few (2-6) ore bodies of irregular thickness, which are distributed over all the three productive horizons. They contain mainly uraninite. These parts of the deposit are less favorable from the economic point of view. The average grade of uranium ore is between 0.08 and 0.15%. A technical and economical evaluation was made only in the northern part of the deposit. The results are given in Table II.

Analogically the recoverable resources of uranium in the southern part of the deposit were estimated by analogy based on the geological in situ resources (see Table III).

The only mining method used is the room and pillar method with a thorough backfilling of the mined-out space by solidifying backfill.

TABLE III. PRODUCTION AND RECOVERABLE RESOURCES OF ECONOMICALLY NOT-EVALUATED DEPOSITS AS OF 1 JANUARY 1993

DEPOSIT	PRODUCTION	RESOURCES (tonnes U)				
		Cost Ranges	RAR	EAR-I	EAR-II	TOTAL
HAMR-south	1400	<= $80/kgU				0
		$80-130/kgU		10000		10000
		$130-260/kgU		7000		7000
		TOTAL	0	17000	0	17000
BREVNISTE	1000	<= $80/kgU				0
		$80-130/kgU	2000			2000
		$130-260/kgU		2800		2800
		TOTAL	2000	2800	0	4800
HVEZDOV		<= $80/kgU			5000	5000
		$80-130/kgU			3000	3000
		$130-260/kgU				0
		TOTAL	0	0	8000	8000
OSECNA-KOTEL		<= $80/kgU				0
		$80-130/kgU		5600		5600
		$130-260/kgU		8800		8800
		TOTAL	0	14400	0	14400
TOTAL	2400	<= $80/kgU	0	0	5000	5000
		$80-130/kgU	2000	15600	3000	20600
		$130-260/kgU	0	18600	0	18600
		TOTAL	2000	34200	8000	44200

The other deposit under operation in the Cretaceous basin of northern Bohemia is the Straz deposit. It represents geologically a full equivalent of the Hamr deposit. The presence of the eruptive rock complex of Mt. Ralsko resulted in an intense disturbance by tectonic fault systems of different strikes and dips. They are frequently filled by dykes and diatremes of basaltic and melilitic rocks. The uranium mineralization, represented by ningyoite, uraninite and hydrozircon, is unevenly distributed in the deposit space. It occurs in the same three basal Cenomanian horizons as Hamr. The age of the mineralization is the same as in the Hamr deposit. The ore bodies of the whole Straz deposit represent,from the morphological point of view, full equivalent of the complex development ore type of the Hamr deposit. The technically and economically evaluated resources of the deposit are described in Table II.

The reason for the decision to develop the deposit by acid in situ leaching was the absence of thicker ore bodies with a good stratigraphic correlation.

The recoverable resources of the Brevniste deposit, which operated during 1982-1990, and of the Osecna-Kotel deposit, being estimated by drilling exploration only, were estimated solely on the base of the geological in situ reserves, analogically as in the Hamr deposit. The results of this evaluation are mentioned in Table Ill. The geological situation, composition and age are the same as in the Hamr deposit.

3.2. Undiscovered conventional resources (EAR-II & SR)

The undiscovered conventional resources of group EAR-II are located in the flanks of the deposits of western Moravia, especially at the Rozna and Brzkov deposits (see Table I).

If an ecologically admissible extraction technology is found the Hvezdov deposit would be economically feasible in the region of the north Bohemian Cretaceous basin. It may be possible, according to the attained degree of knowledge of the deposit (drilling net 400 × 400 m), to get recoverable resources of group EAR-II as shown in Table III (provided that there be an appropriate extraction technology). Analogical technical and economical parameters were considered in the recalculation of the resources in situ to recoverable resources as in the Straz deposit.

4. THE URANIUM PRODUCTION

The evolution of uranium production beginning in 1946 in the individual mining regions, identified by the name of the most important deposit, is shown in Fig. 3. The proportion of the

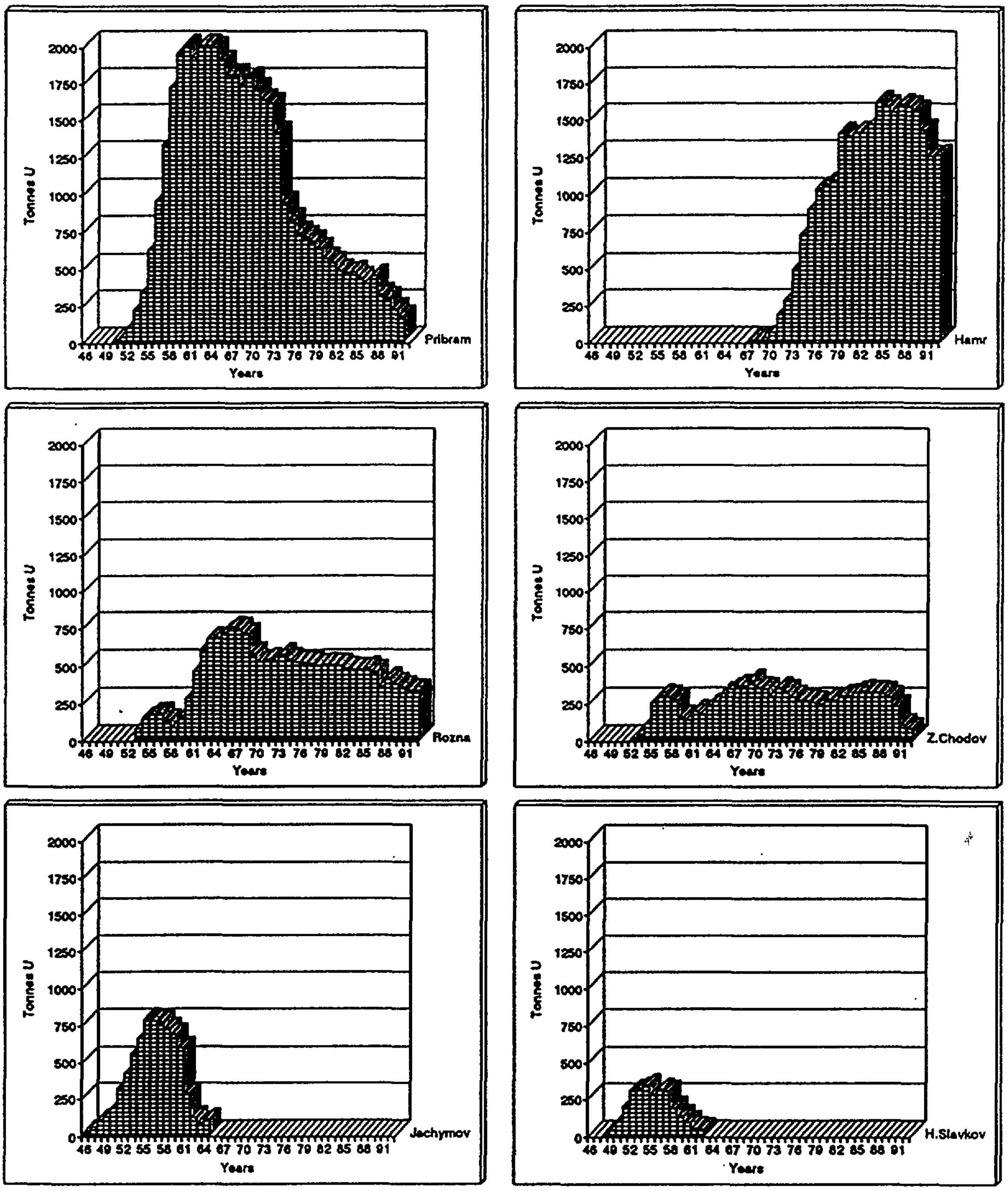


FIG. 3. Trends in uranium production in mining districts of Czech Republic (Main mining districts: 1946 - 1992).

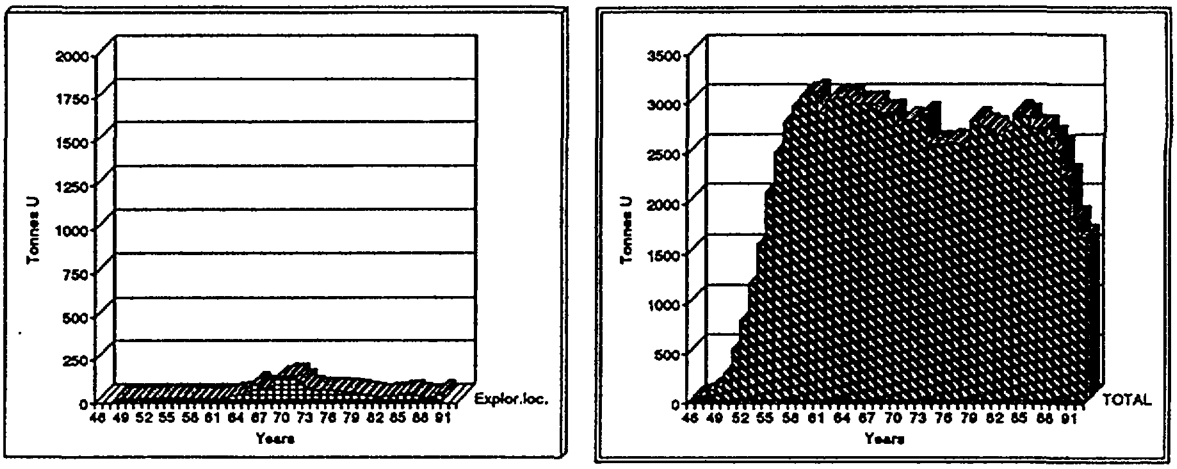


FIG. 3a. Trends in uranium production in mining districts of Czech Republic (Exploration and total: 1946 - 1992).

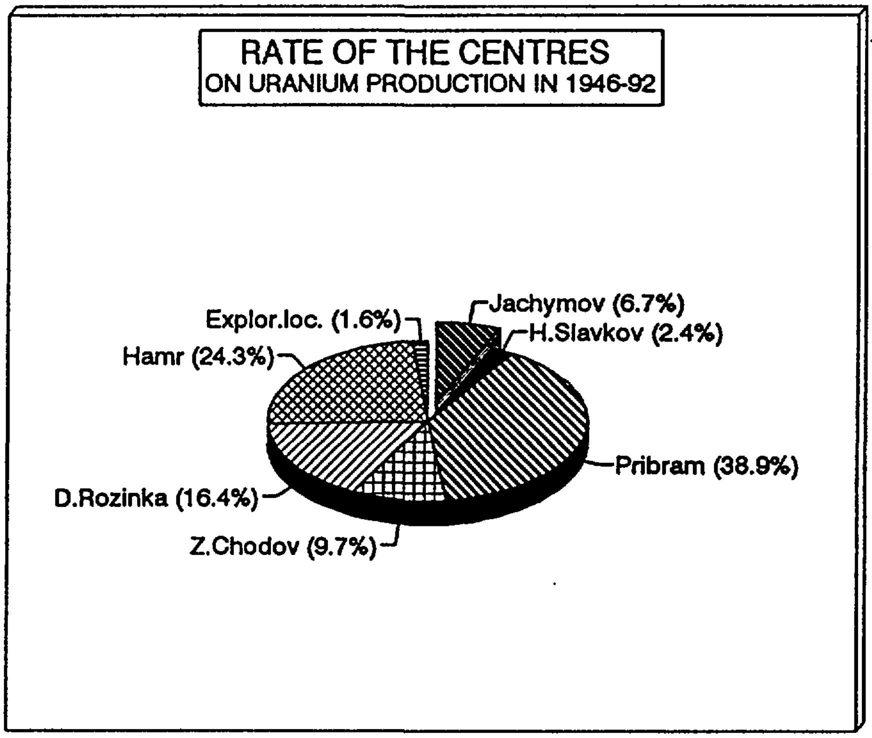


FIG. 4. Rate of the centres on uranium production in 1946 - 1992.

individual regions in the overall production including the exploration sections is seen in Fig. 4. It may be added more precisely that the Zadni Chodov region, except for the Zadni Chodov deposit, also includes the Vitkov II, Dylen, Okrouhla Radoun deposits and the Hajek, Oder and Ruprechtov deposits in the Tertiary basin of northwestern Bohemia. The Hamr region includes the Hamr, Straz and Brevniste deposits. The Dolni Rozinka region includes the Rozna, Olsi, Javornik-Zalesi, Chotebor, Slavkovice-Petrovice deposits and the Permo Carboniferous uranium deposits of the Intrasudetic basin (Rybnicek and Radvanice). The item "Exploration" includes the production from deposits with small resources which were not given over to the extraction organization (e.g. Predborice, Skrdlovice, Licomerice-Brezinka, Jasenice, Brzkov and other localities) with recoverable resources of less than 100 t.

The last four years are characterized by the extensive contraction programme of the uranium industry in the Czech Republic. This was caused by the restriction of the uranium delivery into the former Soviet Union and the restoration of market conditions in the Czech economy. Only the two deposits in northern Bohemia (Hamr, Straz) located in the basal sediments of the Cretaceous (sandstones) and the deposit Rozna in western Moravia (Moldanubian) remained in operation after the closure of mining in the Olsi (1989), Vitkov (1990), Okrouhla Radoun (1990), Pribram (1991), Dylen (1991) and Zadni Chodov (1992) deposits. This represent a decrease in uranium production from 2 500 t in 1989 to 1 539 t in 1992 and a further decrease to approximately 700-1 200 t in 1993.

All the exploration, extraction and processing activities were operated by the state for approximately 50 years. Today, the only uranium producer in the Czech Republic is the DIAMO state enterprise, based in Straz pod Ralskem.

The number of employees decreased from 12 200 in 1990 to 6 600 in 1992. This reflects both the overall contraction of the uranium extraction (see Fig. 3a) and the introduction rationalization measures in connection with the transition to market economy conditions in the Czech Republic.

The continuation of extraction is planned at the Rozna and Hamr deposits in the near future. The production of uranium is planned at the Straz deposit during the restoration activities.

The deposits where resources have been proven by mining works and which may feasibly be mined before 2000 are the Brzkov (resources of category RAR and EAR-I, western part of the Moldanubian of Moravia) and Hvezdov deposits (resources of category EAR-II, north Bohemian Cretaceous basin). The Osecna-Kotel and Brevniste deposits (north Bohemian Cretaceous) are not expected to be developed before 2000.

5. URANIUM REQUIREMENTS

In former Czechoslovakia uranium was produced only in the area of the Czech Republic. The Czech Republic produces more uranium, in consideration of its own nuclear energetic needs, after the splitting of Czechoslovakia. Together with contraction programme of this redundant capacity, the government accepted the strategy of buying some part of uranium production to the state stockpiles at the same time. In this way the Czech Republic is able to ensure the requirements of its own nuclear power plants from home production to 2000 at least. If we take into account the certain diversification of sources from abroad, we can move this boundary farther to the future.

PROGRESS IN GAMMA AND RADON DETECTION METHODS IN GEOPHYSICAL INVESTIGATION

M. MATOLIN
Faculty of Science, Charles University, Prague, Czech Republic

Abstract

Results of research in gamma ray spectrometry and radon detection technique are applicable in uranium exploration. Progress in establishment of calibration facilities and method of calibration of gamma-ray spectrometers unify reported data on K, U, Th concentrations in rocks among individual countries. Use of airborne and ground multichannel analysers enabled separation of the natural and fall out radionuclides in contaminated areas. Improved knowledge on radon in the air has been applied in corrections for its gamma radiation. Gamma-ray spectrometers stabilization eliminates undesirable errors in field U determination. Studies of radon soil air sampling, variations of radon in soil air due to climatic changes, methods of resolution of Rn-222 and Rn-220, calibration of radon detection instruments and the knowledge on radon vertical distribution in soils of different properties contribute to methods of U survey.

1. DEVELOPMENT IN GAMMA RAY SPECTROMETRY

Gamma ray spectrometry enables quantitative determination of K, U and Th in outcropping rocks and has been widely applied in U exploration since the 70's at different technical levels. Improvement has been reached in several fields of application.

Calibration facilities for airborne and portable gamma ray spectrometers are essential for conversion of equipment output count rates into concentration of K, U and Th in rocks. Method of calibration and results reporting has been suggested in the 70's [1], monitoring of calibration facilities in various countries showed the technical difficulties tied with the determination of calibration pads technical parameters [2], which were fundamentally surmounted by the IAEA project and manufacturing of certified geological reference materials for laboratory gamma ray spectrometry [3] enabling consistence in analyses of K, U and Th in various countries. Based on gained experience, the IAEA recommendation for the construction and use of calibration facilities was issued [4], with a description of calibration pads for portable (Fig. 1) and airborne gamma ray spectrometers. The use of the "blank" calibration pad has been proved an effective technique for the correction of detected count rates for the background radiation. Smaller transportable calibration blocks $1 \times 1 \times 0.3$ m has been described and used by Grasty [5]. Contemporary intercomparisons of measured K, U and Th concentrations show good results.

Back calibration has been developed to convert the older total count (TC) and gamma ray spectrometry (GS) data and maps, reported often only in relative output count rates, into gamma dose rate in air (TC), and concentration of K, U, Th in rocks (GS). The procedure of back calibration is based on repeated measurements with well calibrated instruments in previously measured areas [6]
.

Radiometric survey in contaminated areas has been studied intensively after the Chernobyl nuclear power plant accident. Nuclear fall out, deposited at the Earth s surface, and its gamma radiation limit substantially geophysical surveys carried out by TC instruments of usual low energy discrimination level, while gamma ray spectrometry can be applied also not earlier than after approximately 3 months after the nuclear fall out deposition, when high energy gamma ray emitting nuclear fall out radionuclides, with short and medium half-lives, disintegrate to acceptable level (Fig. 2). Contamination of the soil to the depth of ca 15 cm by Cs-137 (E 662 keV, half-life 30 years) and Cs-134 (E 604 keV and 796 keV, half-life 2.05 years) has been registered in many European countries. The use of airborne and portable multichannel analysers enable to distinguish well K, U, Th and nuclear fall out isotopes.

Atmospheric radon correction is applied with highly sensitive airborne gamma ray spectrometry eliminating errors in field U determination of the magnitude of several ppm U. Radon accumulated in the air under variable climatic conditions interferes by the gamma radiation of its daughter product Bi-214 with gamma radiation detected from rocks, used as specific for U determination. Method of atmospheric radon correction has been developed and described [7].

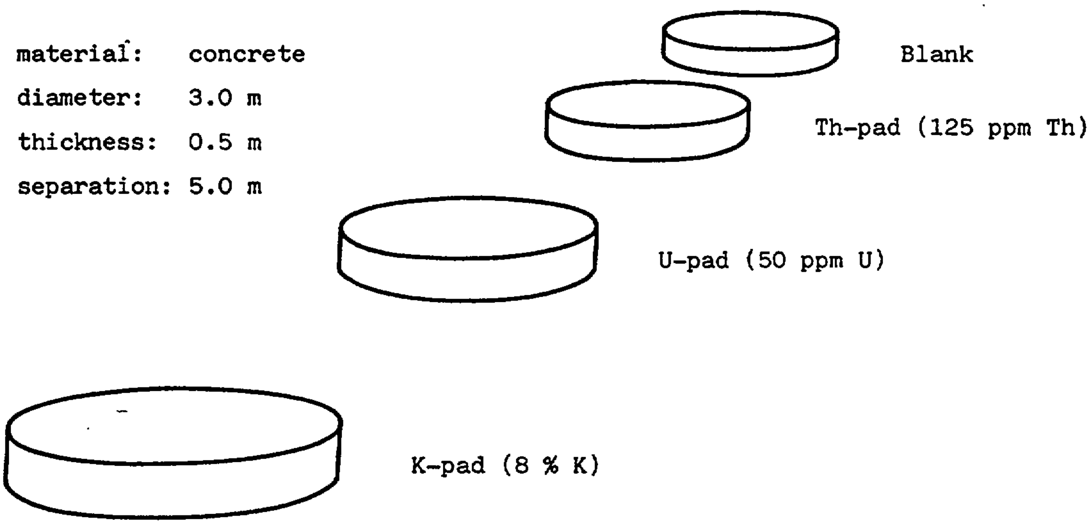
Energy stabilization of gamma ray spectrometers is required due to sensitiveness of equipment to temperature and power supply changes. Various approaches of equipment function stabilization were applied. Temperature stabilization and the use of reference isotopic gamma ray sources, such as Ba-133 and Cs-137, which limit the gamma ray energy intervals for detection of natural radiation, were for airborne spectrometers substituted by monitoring the gamma peak of K-40 natural radiation. New studies are focused on monitoring of fine changes of gain of detector electronic blocks and adequate correction. Portable gamma ray spectrometers, stabilized by means of isotopic sources Cs-137, are deviating from correct spectra stabilization on U anomalies, due to inteference of gamma-ray peaks 609 keV (Bi-214) and 662 keV (Cs-137).

Airborne flight path recovery and ground localization has been improved outstandingly by the introduction of now available global positioning systems, based on satellite navigation, reporting coordinates x, y with errors inferior to 10 m.

2. DEVELOPMENT IN RADON SURVEY

Calibration of radon detectors at reference radon chambers, that were established nowadays in many countries for radiohygienic environmental radon monitoring,improves the possibility of

material: concrete
diameter: 3.0 m
thickness: 0.5 m
separation: 5.0 m



detector NaI(Tl) 76x76 mm: count rates < 2000 c.s^{-1}
t = 10 min: accumulation 10000 counts in ΔE
~ 1 % relative error

K-pad: feldspar
U-pad: U-ore, high U/Th, radioactive equilibrium, low emanation power
Th-pad: Th-ore, high Th/U

FIG. 1. IAEA recommended calibration pads for portable gamma ray spectrometers.

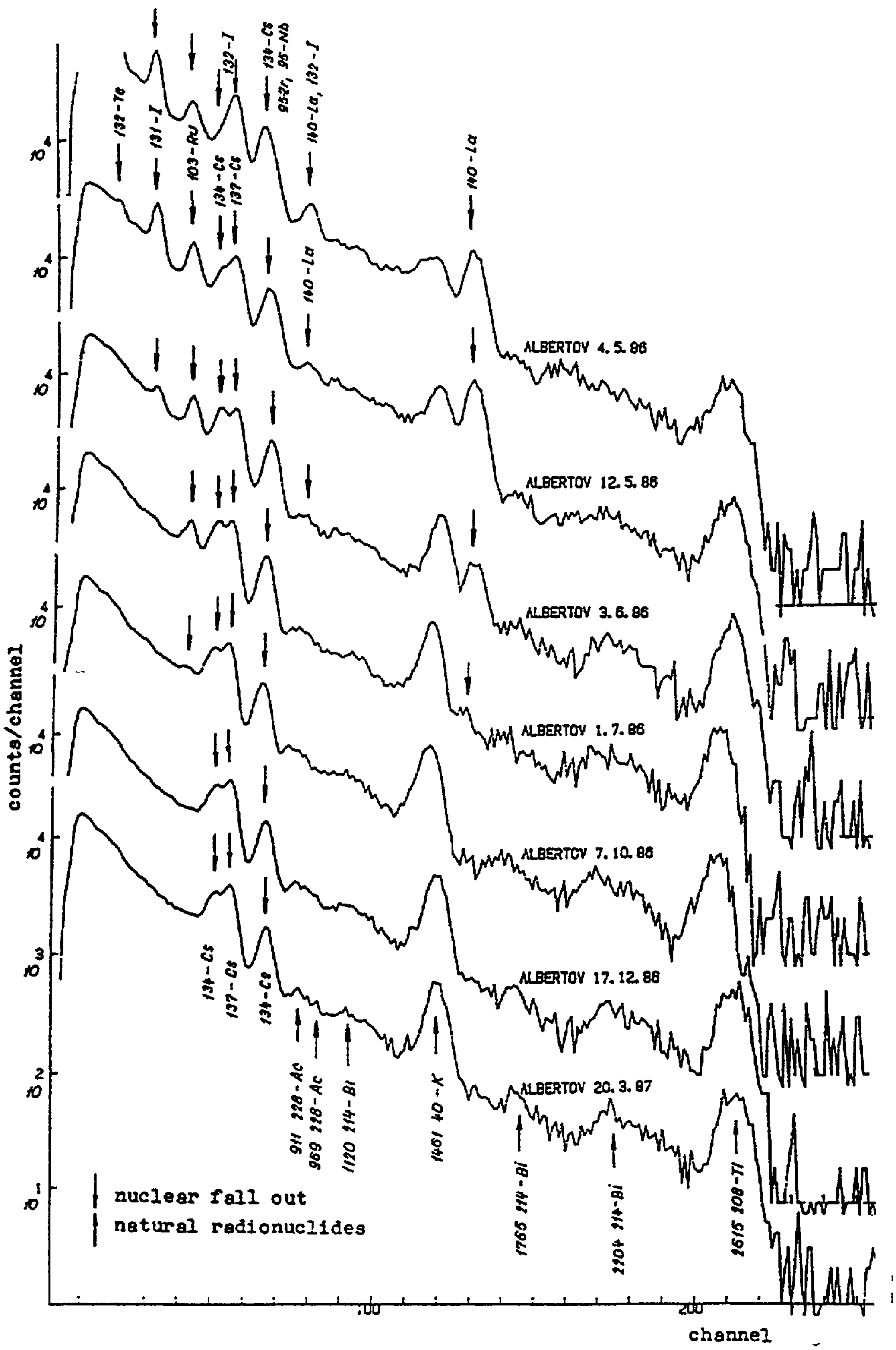


FIG. 2. Energy gamma ray spectra measured sequentially after 1986 nuclear fallout contamination on the Earth's surface at open area in Prague. GS-256 portable gamma ray spectrometer, detector NaI(Tl) 76 × 76 mm, t = 10 min.

reporting results of emanometric U surveys in radon volume activity in soil air, expressed in $kBq.m^{-3}$. Calibration is well applicable to instruments equipped with Lucas cells, exhibiting sensitivities around 6 $c.min^{-1}$ per 1 $kBq.^{-3}$ of Rn-222 in soil air, for the Lucas cell volume cca 150 cm^3 and immediate in situ measurement, while calibration of alpha track systems and active charcoal detectors is more complicated.

Soil air sampling affects significantly observed values of Rn-222 in soil air. Using the portable field emanometers, a soil air sample is transferred into the detection cell. Various systems of soil air sampling has been studied (Fig. 3). Dynamic soil air circulation technique dilutes the soil air samples, taken usually at low depths, with atmospheric air, and the determined volume activity of Rn-222 in soil air is up to 3 times lower. Suction of soil air from the whole vertical profile and volume of prepared hole gives lowered concentration of Rn-222 too. Suction of soil air sample from the end of a well sealed probe gives more representative quantitative information on investigated subsurface radon sources. Though relative values of anomalies are also indicative for U mineralization in U exploration, reliable quantitative values are more suitable for any interpretation.

Variation of radon volume activity in soil air due to climatic changes has been observed in numerous countries. Study and monitoring of these changes (Fig. 4) [8] showed the dependence of radon on temperature and moisture of the soil, which affects the soil permeability and subsurface vertical gradient of radon concentration. In U exploration, misleading high radon concentrations in soil can be observed in extremely moist soils and under temperatures below 0°C.

Resolution of Rn-222 and Rn-220, specially in highly radioactive magmatic rocks, is important for estimation of U potential. An economical field procedure is the measurement of emanation in situ in the field, immediately after the soil air sampling. Under these conditions, alpha radiation of Rn-222 (radon) and Rn-220 (thoron) is detected and the isotopes should be distinguished by means of successive measurements within first minutes. Analysis of this procedure shows that the Rn-222 volume activity in soil air can be determined, under usual radioactivity of rocks, with relative error 3-20% [9] .

Relation of radon and uranium in rocks has been studied for environmental purposes recently. Results of these investigations show that for a normal concentration of U in rocks of the Earth s crust, the correlation between radon and uranium has not been proved. At sites of enhanced emanation, interpretation of U subsurface geological bodies should be based on additional detail radon measurements. Positive signs are increase of radon concentration with depth, and Rn-222 character of the anomaly.

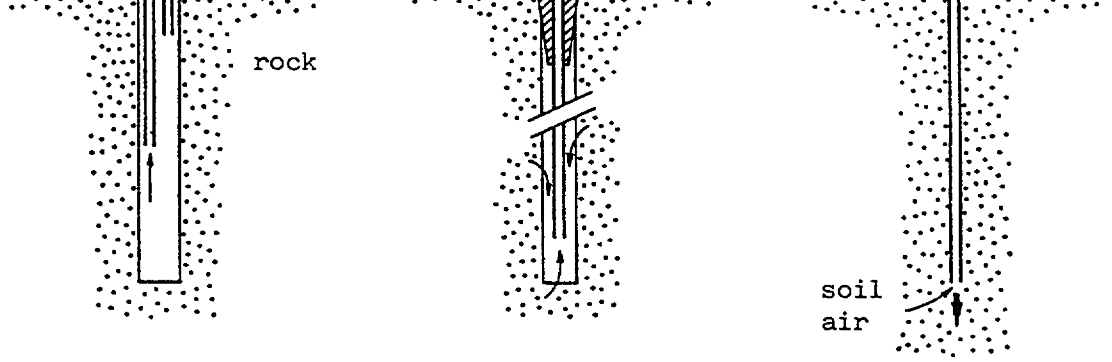


FIG. 3. Systems of soil air sampling: A-dynamic soil air circulation technique, B-suction of soil air from the whole volume of prepared hole, C-suction of soil air from the end of a well sealed probe.

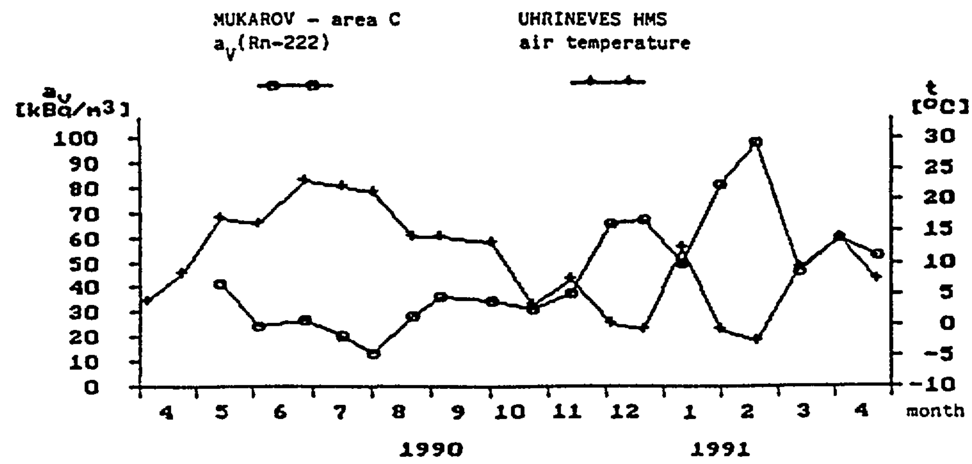


FIG. 4. Variations of temperature and radon volume activity in soil air at locality Mukarov, situated in granites, 25 km E of Prague, within a year climatic cycle.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiometric reporting methods and calibration in uranium exploration, Technical Report Series No. 174, IAEA, Vienna (1976).

[2] LØVBORG, L., The calibration of portable and airborne gamma-ray spectrometers - theory, problems and facilities, Risø-M-2456, Roskilde (1984).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Preparation and certification of IAEA gamma ray spectrometry reference materials RGU-1, RGTh-1 and RGK-1, report IAEA/RL/148, IAEA, Vienna (1987).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Construction and use of calibration facilities for radiometric field equipment, Technical Report Series No.309, IAEA, Vienna, (1989).

[5] GRASTY, R.L., HOLMAN, P.B., BLANCHARD, Y.B., Transportable calibration pads for ground and airborne gamma-ray spectrometers, GSC paper 90-23, GSC, Ottawa, (1991).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, The use of gamma ray data to define the natural radiation environment, IAEA-TECDOC-566, Vienna (1990).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Airborne gamma ray spectrometer surveying, Technical Reports Series No. 323, Vienna (1991).

[8] MATOLIN, M., PROKOP, P., Variation of radon volume activity in soil air in a year climatic cycle, Radon investigations in Czechoslovakia III, Geol. Survey Prague, Prague, (1992), 1-5.

[9] MATOLIN, M., PROKOP, P., KASPAR, J., Errors of Rn-222 determination at various measurement procedures, Radon investigations in the Czech Republic, Czech Geol. Survey, Prague, (1993), 9-11.

STRATEGY AND PERSPECTIVE FOR URANIUM EXPLORATION IN EGYPT

M.A. HASSAN, A.B. SALMAN, H.S. ASSAF, M.M. MAHDY
Nuclear Materials Authority, Cairo, Egypt

Abstract

Uranium exploration started in Egypt about three decades ago. This was performed by applying integrated airborne and ground radiometric prospecting. The latter was conducted upon selected areas having rather favorable geological criteria. These activities resulted in the discovery of great numbers of radiometric anomalies, with several uranium occurrences in various geologic environments in granitic and sedimentary rocks. Some of these uranium occurrences show good potential for developing into workable uranium deposits. Small-scale exploratory tunnelling and drilling works have been carried out at some of these occurrences. Leaching studies and pilot experiments were carried out on technological samples to evaluate ore's suitability for uranium extraction. However, no assured reserves of uranium have been reached yet. The demands for uranium to satisfy the near future Egyptian nuclear power generation necessitates some development in the national strategy for uranium exploration. This will be achieved through intense programmes for ground geophysics and drilling from surface and underground mining works, in addition to radon emanometry and logging of oil and gas wells. Moreover, non conventional procedures for uranium extraction such as heap-leaching may be followed to exploit small-scale uranium deposits. In this developed strategy, the present uranium occurrences are modellized and categorized following the IAEA classification. The characteristics of the present uranium occurrences will be utilized in prospecting new areas. Subsidiary resources in phosphorites, black sands and rare metal deposits could supply additional quantities of uranium, in addition to thorium and rare earth elements.

1. INTRODUCTION

Uranium exploration activities started in Egypt as early as 1956. The main exploration procedures followed were ground geologic and radiometric surveys as well as airborne radiometric and magnetic surveys. These activities led to the discovery of several occurrences of mineralization and high radiometric anomalies. This justified further detailed investigations in many areas. Limited exploratory drilling and mining works were carried out in areas having promising potentialities. Ground exploration works were always supported and supplemented by laboratory works including petrographic, mineralogical and geochemical studies. Bench scale recovery studies and pilot experiments were also conducted on technological samples of some ore types.

Although some of the discovered occurrences have good potentialities to develop into significant ore bodies, yet none has been evaluated to the stage of proved reserves in terms of tonnage and cost. However, with the growing interest in the nuclear power plants in Egypt, it is expected that uranium will be needed in the near future. This necessitates the development of the exploration strategy to reach proved reserves as soon as possible. The future perspectives should stem from two points:

- Present experience gained from past activities in which uranium occurrences and provinces were determined, and

- Geologic analogy to worldwide uranium deposits and occurrences.

Thus the present paper reviews the past experience in uranium exploration and their results, and proposes a perspective for future possibilities.

2. URANIUM OCCURRENCES AND POTENTIALITIES

The main results of the exploration activities are the discovery of several uranium occurrences (Fig. 1). In addition, a great number of radiometric anomalies with relatively high uranium contents

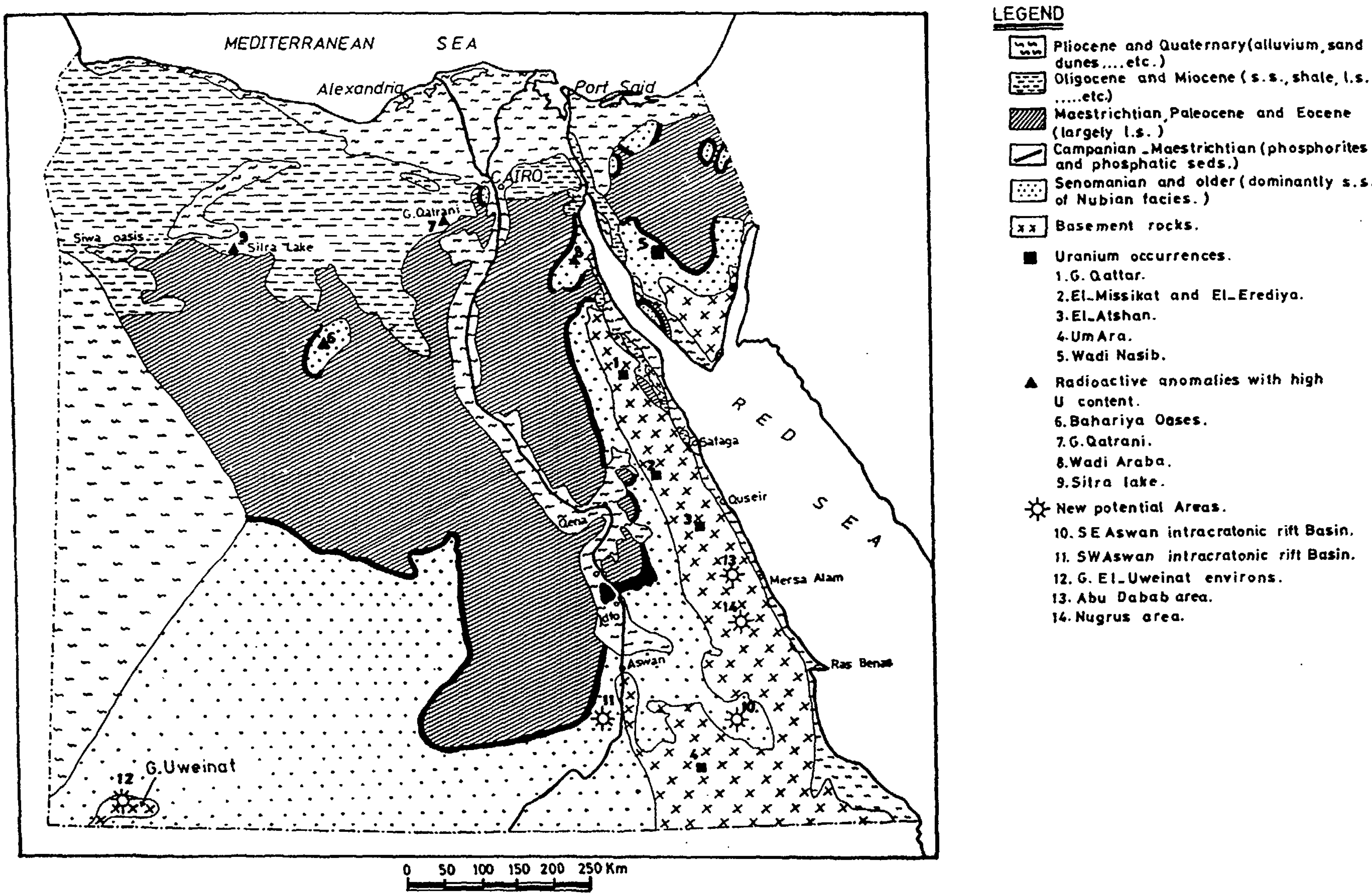


FIG. 1. A simplified map of Egypt with locations of uranium occurrences and areas of uranium potentialities.

were also identified. Fig. 2 shows a summary of the main uranium resources in Egypt. The main mineralogical, geochemical and recovery investigations carried out on the discovered occurrences are shown in Table I. Extraction of uranium concentrate (yellow cake) and other nuclear elements (Th, REE, Zr, etc.) from ore materials (granites, sandstone, siltstone, monazite, zircon and phosphorites) was carried out successfully by using various techniques on lab and pilot scales. A locally made pilot plant for uranium recovery and purification of yellow cake from conventional ores was constructed. Another pilot plant for the treatment of monazite was set up in the early 60's to separate REE, Th and U cakes. In addition, a physical upgrading pilot mill is successfully working on uranium ores and other raw materials including black sands, phosphorites and granitic rocks.

3. TYPES OF URANIUM RESOURCES IN EGYPT

The discovered uranium occurrences and anomalies can be correlated with the universally recognized uranium deposits as given by the IAEA and Dahlkamp [11] as follows:

3.1. Vein-type deposits

There are five such occurrences, namely Gabal Qattar, El Missikat, El Erediya, Um Ara and El Atshan occurrences (Fig. 1). In the first three occurrences, uraniferous veins occur as fissure fillings in late to post orogenic pink granites which are identified as belonging to the latest phase of the Pan African igneous activity (Hassan and Hashad [12]). The mineralized zones are mostly discontinuous and restricted to the peripheries of the granitic plutons. The uranium mineralization is invariably associated with sulfides of Fe, Cu, Pb, Zn and Mo together with fluorite and silica. At G.

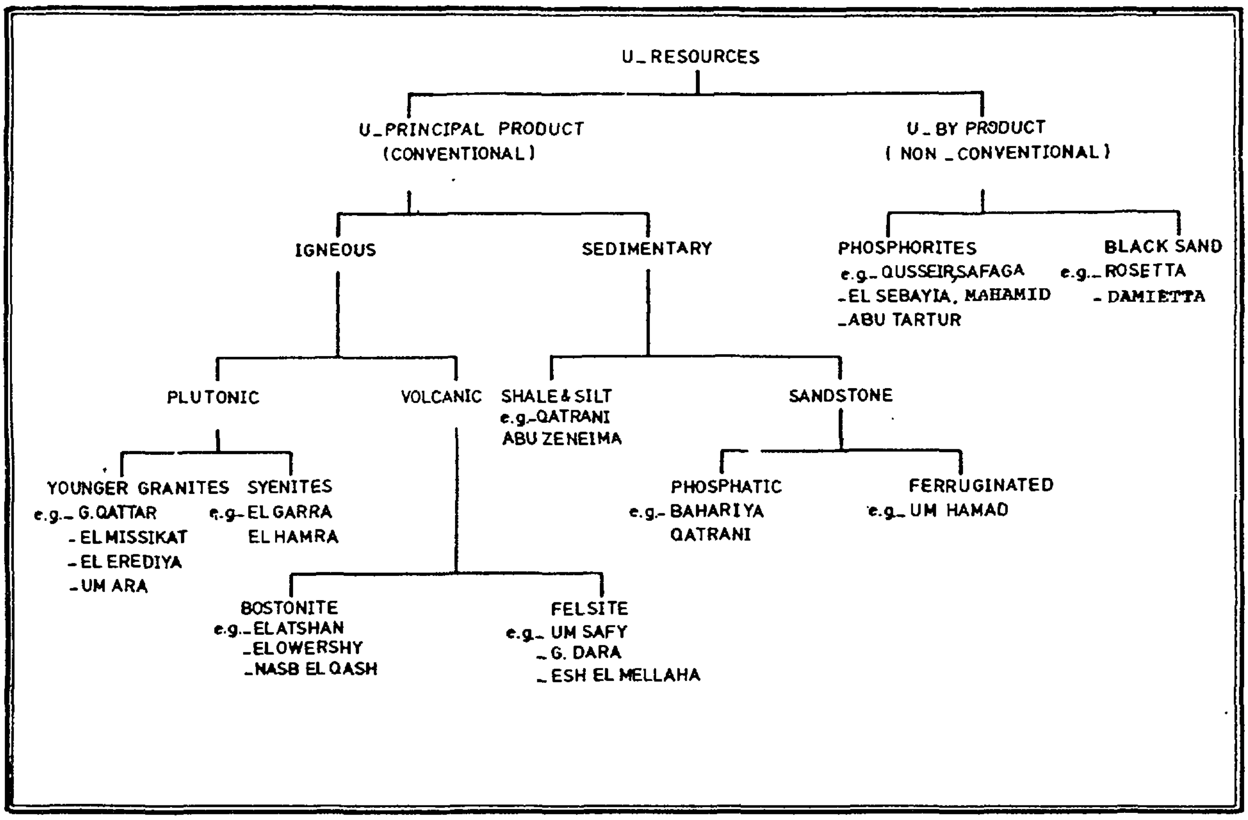


FIG. 2. Uranium resources in Egypt.

TABLE I. MINERALOGICAL, GEOCHEMICAL AND RECOVERY CHARACTERISTICS OF SOME URANIUM DEPOSITS IN EGYPT

Locality	Rock type	Principal U-Mineral	Mineral Assembelage	Geoch. Features	Uranium Recovery			
					Leach. Method	Ext. Method	Ext. Eff.	Scale
1- Gattar	Y. granite	Uranophane B-urano- phane	- Feldspars and quartz - Fluorite - Epidote - Hematite - Kaolinite	- SiO_2 66.9% - Al_2O_3 12.2% - Alkalis 4.6% - No relation with Mo-mineralization	Acidic Alkaline Acid. Perc. Alk. Perc. Heap	IX IX 	99% 70% 99% 99% 51%	Bench Bench Bench Bench Bench
2- Missikat	Y. granite	Uranophane Beta- Uranophane	- Feldspars and quartz - Sulphides - Kaolinite - Fluorite - Hematite - Kaolinite	- SiO_2 85.6% - CaO 4.2% - Presence of sulphides - Mo, Pb, REE as traces.	Acidic Acidic Alkaline	IX SX 	91% 72%	Bench Bench
3- Erediya	Y. granite	Uranophane Uraninite	- Feldspars and quartz - Sulphides - Fluorite - Hematite - Kaolinite	- SiO_2 85.3% - Al_2O_3 6.7% - Alkaline 2.2% - Presence of sulphides.	Acidic Acidic Alkaline	IX SX 	98% 96% 30%	Bench Pilot Bench
4- Um Ara	Y. granite	Uranophane Pitchblende	- Feldspars and quartz - Fluorite - Microcline - Kaolinite	- SiO_2 70.5% - Al_2O_3 15.1% - Alkalis 8.1%	Acidic Acid. Perc.	SX 	96% 92%	Bench Bench
5- Atshan	Bostonite	Uranophane	- Feldspars and quartz - Iron oxides - Carbonates.	- SiO_2 68.5% - Al_2O_3 13.5% - Alkalis 7.7% - Fe_2O_3 5.8%	Acidic Acidic Alkaline	IX IX IX	91% 98% 85%	Bench Pilot Bench
		Uraninite Coffinite	- Feldspars and quartz - Carbonates - Iron oxides - Sulphides	- SiO_2 62.1% - Al_2O_3 13.0% - Alkalis 11.4% - Fe_2O_3 4.1%	Alkaline Acidic	SX SX	98% 98%	Bench Bench

Sources: Ritcy [1], Mahdy [2,3], El Hazek [4], El Shazly [5], Mahdy [6], Ameer et al. [7], El Shazly et al. [8], Ibrahim [9] and Farag [10].

Table (1): Cont.

Locality	Rock type	Principal U-Mineral	Mineral Assembêlage	Geoch. Features	Uranium Recovery: Leach Method	Ext. Method	Ext. Eff.	Scale
6- Garra Hamra	Syenite	Thorogummite Bastanisite	- Feldspars - Aegirine - Hematite - Calcite - Traces of Th and REE.	- SiO_2 58.8% - Al_2O_3 19.1% - Fe_2O_3 4.0% - Alkalis 14.0%	Acidic	IX	99%	Bench
7- Abu Zeinema	Siltstone	Carnotite Zeippite Autonite Torbernite	- Clay minerals - Quartz - Iron oxides - Gypsum - Carbonates	- SiO_2 52.0% - Al_2O_3 16.0% - Fe_2O_3 7.0% - Alkalis 6.0%	Acidic Acidic Acid. Perc. Alkaline Alk. Perc.	IX SX	99% 98% 99% 99% 99%	Bench Bench Pilot Bench Bench
8- Qatrani	Shale		- Montmorillonite - Dolomite - Calcite - Gypsum - Hematite	- CaO 22.4% - SO_3 9.6% - CO_2 18.0% - Fe_2O_3 9.2%	Acidic Alkaline	IX IX	93% 99%	Bench Bench
	Phosphatic Red Sandstone		- Quartz - Iron oxides - Dolomite	- SiO_2 71.4% - Fe_2O_3 17.0%	Acidic Alkaline		97% 5%	Bench Bench
9- Sebayia	Phosphate		- T.C.P. - Quartz - Kaolinite	- CaO 49.7% - P_2O_5 23.3% - SiO_2 11.1%	Acidic	SX	97%	Bench
10- Rossetta	Black sand	Monazite	- Monazite - Quartz	- Ce_2O_3 26.6% - Re_2O_3 34.5% - P_2O_5 26.7% - SiO_2 2.4% - ThO_2 6.0%	Alkaline Alkaline	SX SX	88.5%	Bench

IX = Ion Exchange resin.
SX = Solvent extraction.
Acid. Perc. = Acidic Percolation leaching.
Alk. Perc. = Alkaline percolation leaching.
T.C.P. = Tri calcium phosphate.
Ext. Eff = Extraction effeciency %.

Qattar occurrence, secondary uranium minerals occur in dissected lenses in a 4 km long shear zone trending NNE-SSW, at an elevation of about 600 m above the wadi level, associated with fluorite and silica (Salman et al. [13]). Alterations of the granite enclosing the shear zones include silicification, hematitization, carbonatization and episyenitization. An adit was driven parallel to the main shear zone with some perpendicular crosscuts. Most of the surface uranium lenses are persisting in depth. To the north of the main shear zone, several other uraniferous lenses also occur in the granite and in the Hammamat sediments, particularly at the contact zone. Widespread leaching is rather common in the uraniferous parts.

In El-Missikat and El-Erediya occurrences, the mineralization is structurally controlled by faults and their feather joints which are associated with northeasterly trending shear zones (El Kassas [14], Bakhit [15], El Taher [16], Abu Deif [17]. Mineralization was introduced in more than one generation due to repeated rejuvenation of structures (Mohamed [18]). Associated alterations are silicification, kaolinization, hematitization and sericitization, which are zonally arranged along the veins. Uranium mineralization is concentrated within or adjacent to the faults and fractures together with jasper (in El-Erediya) or black silica and to a lesser extent jasper (in El-Missikat). Uraninite, the primary mineral identified in El Erediya, suffered intensive oxidation and probably leaching. Other black uranium minerals may also be present, but not identified. Secondary uranium minerals, mainly uranophane, are quite abundant. Exploratory tunnels of about 4000 m length were driven along some of the uraniferous shear zones to explore the mineralization at the wadi level. These showed the persistence of some of the mineralized sections on the surface in El-Missikat, but in El-Erediya, mineralized parts of the shear zones were not met in the tunnels, and highly mineralized parts in the tunnels do not persist to the surface.

At Um Ara, uranium mineralization is hosted in the northern periphery of a younger granite pluton characterized by abundant albitization, microclinization, silicification and extensive manganese oxide stainings (Hussein et al [19]). Secondary uranium minerals, mainly uranophane, occur as minute disseminations, stainings and fractures fillings of general north-westerly trend. Trenching with a total amount of about 3000 cubic metres of excavated raw material has been carried out.

In El Atshan occurrence, uranium mineralization is restricted to the contacts between bostonite dikes and Hammamat sediments (Assaf [20], El Ghawaby et al. [21], Obranović [22]). It occurs in the form of sooty pitchblende along micro fractures in the bostonites at the lower and upper contacts. It also contains accessory sulfides of Pb, Zn, and Fe (Abdel Gawad [23]). Secondary uranium minerals are widespread after the oxidation of the pitchblende. At this occurrence, exploration works including 3600 m of core drilling and 900 m of tunnelling have been carried out.

3.2. Surficial-type occurrences

These are broadly defined as uraniferous sediments, usually of Tertiary to Recent age which have not been subjected to deep burial, and may or may not have been calcified to some degrees. At Abu Zeniema, secondary uranium minerals occur in a fluvial to marginal marine siltstone bed of Early Carboniferous age, close to the contact with the Precambrian basement. This uranium is clearly supergene in origin and may have been derived from the nearby granitic rocks, or from partial leaching from detrital uraniferous minerals in the overlying sandy and gravely beds (Hussein et al. [24]). Although uranium has not proven to be of economic interest yet, it can be considered as a by-product to the famous manganese-iron ores and copper mineralization hosted in these sediments. Most workers agree that this occurrence is of the surficial type, however there is another view which believes that it is more related to the sandstone type (Afifi [25]).

3.3. Sandstone-type and sandstone related occurrences

Two important areas are included in this type: G. Qatrani area in the north Western Desert, and Wadi Araba area in the north Eastern Desert. In G. Qatrani area, concentrations of uranium are of wide extension in the lower part of the sedimentary Oligocene succession in various modes, mostly in phosphatic and red sandstones and in a carbonaceous clay bed (El Shazly et al. [26]). According to these authors no uranium or uranium-bearing minerals have been identified in the mineralized rocks except francolite having a high uranium content in the uraniferous phosphatic sandstone; otherwise uranium was found to be adsorbed by organic matter, iron oxides and clayey constituents.

In Wadi Araba area, a succession of sandstone, siltstone and shale of Carboniferous age occurs along a structural depression between two high plateaus to the north and south. The outcrops of the clastic beds are highly oxidized and ferruginated. Several high radiometric anomalies associated with relatively high uranium contents were recorded in these beds (Salman et al. [27]).

3.4. Other types

Rare metal mineralization (Nb, Ta, Sn, W, Zr, Th, U) was recognized in various parts of the Eastern Desert. Most important of which is the deposit of Wadi Nugrus area (Hassan [28, 29]). The mineralization is associated with the top 50 m of a psammitic gneiss formation capped by schist and amphibolite. Ore minerals include columbite, zircon, thorite, thorogummite, cassiterite and sulfides including arsenopyrite, pyrite, chalcopyrite, sphalerite and galena. Very high radioactivity and scarce secondary uranium minerals are associated with the mineralized gneiss. Several other rare metal mineralizations occur in the Eastern Desert associated with alkaline intrusives, dikes and ring complexes (Hussein [30]). Such deposits could yield by-product uranium, if they would be worked for rare metals.

4. NON-CONVENTIONAL RESOURCES

Two important non-conventional uranium resources occur in Egypt, namely: phosphorites and black sands. The phosphorites occur in an extensive belt of Late Cretaceous age (Fig. 1). Main deposits occur at Abu Tartur in the Western Desert, around Sibayia in the Nile Valley and along the Red Sea Coast. Average uranium content in several parts ranges from 60 to 150 ppm. However, near Luxur, siliceous phosphatic beds have up to 300 ppm U (Salman [31]. At present the Fertilizer Factory at Abu Zaabel, east of Cairo, is producing phosphoric acid which will make extraction of uranium from the phosphorite feasible.

The deposits of black sands occur along the Mediterranean shore between Rosetta in the west to Rafah in the east. They occur as beach placers as well as sand dune belts. Total heavy minerals content is quite variable, but the average ranges between 13 and 15%, and may reach up to 70% in some rich lenses. The main economic minerals are ilmenite, magnetite, zircon, rutile, monazite and garnet.

5. STRATEGY AND FUTURE PERSPECTIVES

The past exploration activities and results put Egypt near to the discovery of workable uranium deposits. With the growing interest in nuclear power plants, future perspectives for uranium exploration and evaluation of its occurrences must be developed and adopted (Saraswat [32]). Such a strategy must take in consideration the local conditions and the international experience in uranium geology and types of uranium deposits (Dahlkamp [11]. This will be based upon:

(a) Establishing a logical sequence of exploration phases and procedures.

(b) Conducting extensive programmes of ground geophysics and drilling from both the surface and subsurface.

(c) Applying the non-conventional techniques in uranium extraction, such as heap leaching.

(d) Delineating new areas with good potentialities depending upon characterizing and modellizing the present occurrences.

5.1. Proposed exploration phases

It is here proposed that the exploration activities for uranium goes into four phases as shown in Fig. 3, which is self explanatory. All information on each occurrence and anomaly should be evaluated in order to put it in its proper phase of that sequence. After that, a decision can be taken on the required further works. Other techniques should also be introduced such as radon emanometry and radiometric logging of all petroleum and other drill holes.

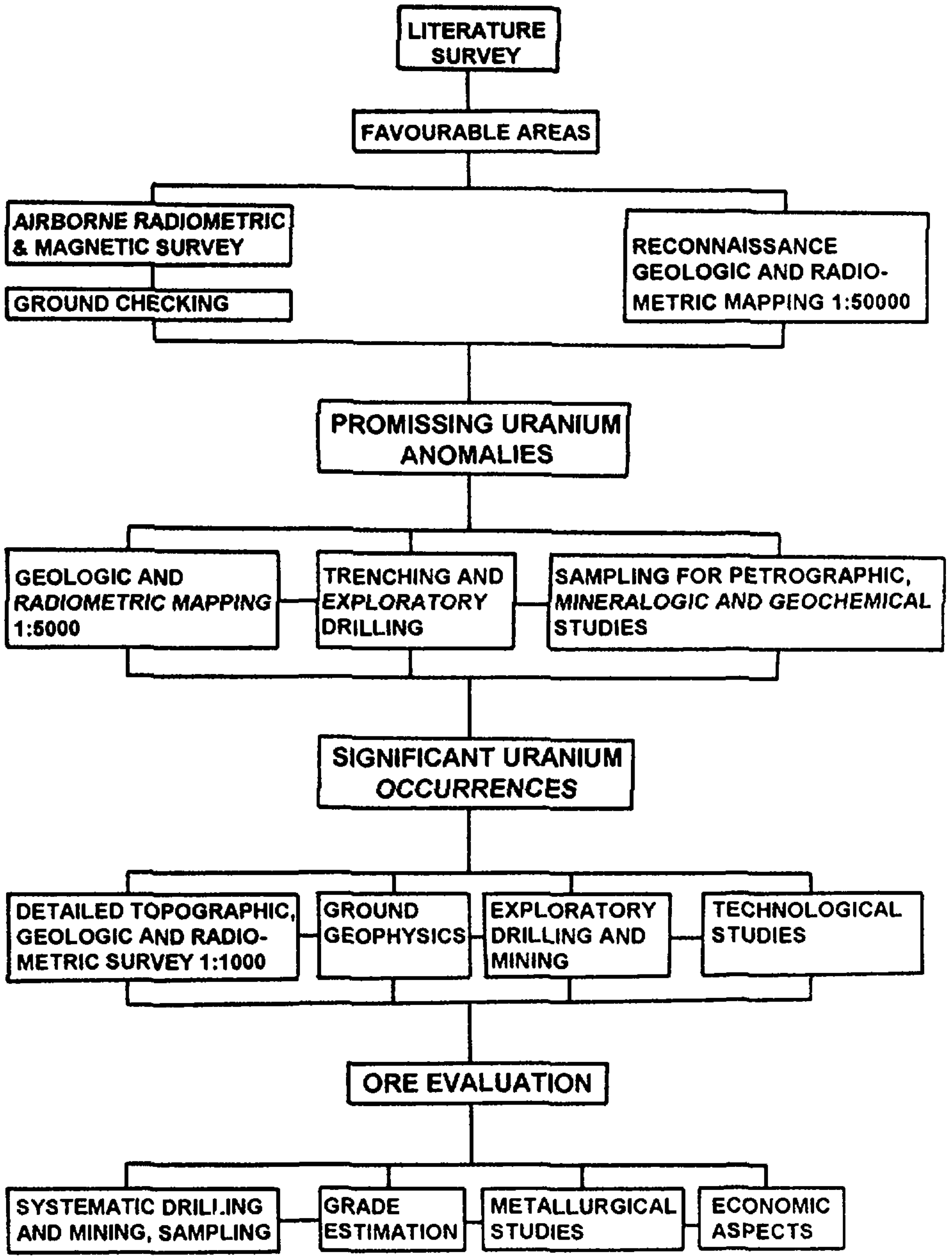


FIG. 3. Proposed phases of uranium exploration in Egypt.

5.2. Drilling programmes

A noteworthy point here is that drilling is a vital procedure in uranium exploration, particularly in desert regions, where highly oxidizing conditions demolish any primary minerals exposed at the surface, leaving behind only secondary minerals. Fig. 4, shows the relation between the total assured uranium reserves in tons to the total length drilled in meters specifically for uranium in 25 countries based upon information of uranium production in 1982 as an example. It shows that for each ton of proved uranium there should be at least one meter of drilling. Only three countries appear above the 1:1 line. For Chili, most uranium was produced as a by-product of other elements, so the exploration expenditure was assigned to these elements, particularly Cu. For UK, a similar situation was reported. For Denmark, a great part of the U proved occurs disseminated in a homogenous granitic body. At present, intensive drilling programmes are planned in most of the areas of uranium resources in Egypt, particularly in Um Ara and G. Qattar.

5.3. Application of non-conventional uranium extraction techniques

The non-conventional leaching techniques including heap and in situ leaching methods, seem attractive because they may be more suitable and less expensive for small-scale, low grade uranium ores than convention techniques. Bench scale and controlled pilot heap studies are now in progress to investigate the feasibility of these techniques for Um Ara and Abu Zeneima areas.

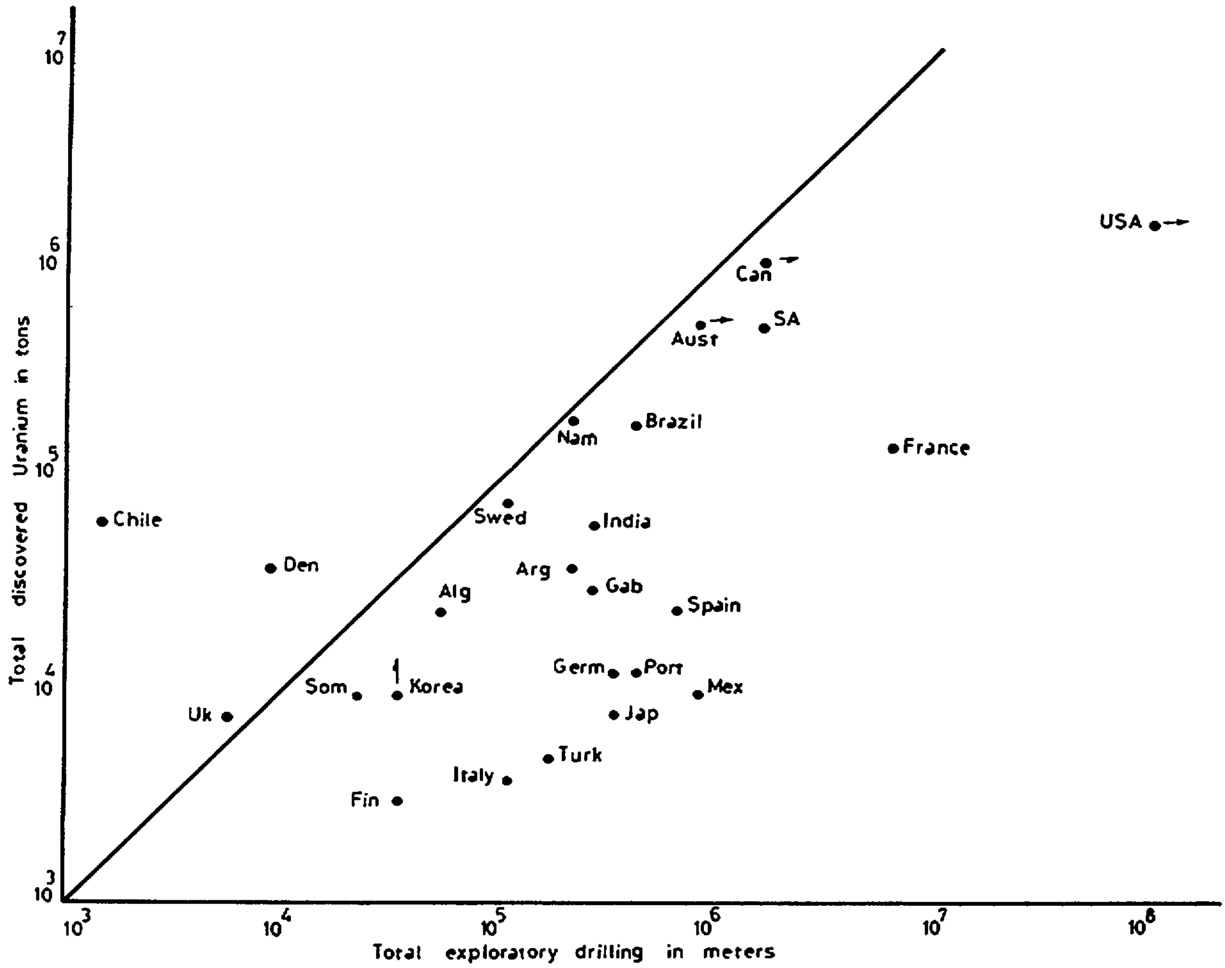


FIG. 4. Plot of total surface drilling for uranium exploration against total discovered uranium in 25 countries.

5.4. Future perspectives

Future perspectives for uranium exploration in Egypt should be directed towards the following targets:

1. As granites comprise about 40% of the total basement rocks in the Eastern Desert and Sinai and host the most promising uranium occurrences, they should be regarded as first target for U exploration.

2. The results at hand on the uranium bearing bostonites at El Atshan area indicate the presence of small scale uranium deposits. The occurrence of pitchblende associated with the graphitic Hammamat sediments and sulfide mineralization along the bostonite dike contacts is encouraging. Exploration to deeper levels should continue.

3. The early discovery of several radiometric anomalies and uranium showings in the Basement rocks turned the direction of most exploration activities towards granitic rocks. This policy was also encouraged by the failure to spot any significant uranium mineralization in sedimentary rocks. However the occurrence of the greatest part of the world reserves in sedimentary rocks should be taken in consideration. The Paleozoic sedimentary succession should be an important target in this respect. In addition, the extensive "Nubian" sandstone succession in the Western and Eastern Deserts are favourable target areas for systematic investigations.

4. There are two intracratonic rift basins in the Phanerozoic sediments which constitute suitable targets, but have not yet been investigated. Recent data indicate that in some parts of these rifts, the thickness of sediments reaches 4.5 km (Nagati [33]). It is expected that gas and oil may be found in these basins, so emanations from these reservoirs may act as reductants for fixing uranium in the sediments. In addition, these basins are surrounded by numerous granitic rocks which act as good sources for uranium.

5. The southwestern Desert Archean and Lower Proterozoic rocks in Gabal Uweinat environs may also be considered for unconformity related and conglomerate types of uranium deposits. The discovery of radiometric anomalies with high uranium contents on the Libyan side of Gabal Uweinat encourages this perspective (Hunting Survey Corporation [34]). A similar situation may occur in some domal structures in the Eastern Desert (Hassan and Hashad [12].

REFERENCES

[1] RITCY, G.M., Potential for yellow cake production, Ru-3597 on the project EGY/3/010 Vienna (1993).

[2] MAHDY, M.A., Extraction of uranium from El Eradyia uraniferous granite. (in preparation) (1993).

[3] MAHDY, M.A., Potential of uranium heap leaching in arid environment. (in preparation) (1993).

[4] EL-HAZEK, N.T., Studies on the leachability and uranium concentration of El Atshan and comparable ores in relation to mineralogical composition, M.Sc. Thesis, Ain Shams Univ., Cairo (1965).

[5] EL SHAZLY, E.M. and EL-HAZEK, N.T., Uranium leaching and recovery from the primary ore of El Atshan, Eastern Desert, U.A.R., in the recovery of uranium IAEA-SM-135/34 (1971).

[6] MAHDY, M.A., Physical, geochemical characteristics of uranium ores from west Aswan and extraction of uranium from these ores, M.Sc. Thesis, Cairo Univ., Cairo (1972).

[7] AMEER, T.E., MAHDY, M.A. and EL-HAZEK, N.T., "Potentialities of in situ leaching of uranium and copper ore in West Central Sinai, Egypt", Tech. Com. Meeting of in situ leaching, IAEA, Vienna held on 5-9 Oct., 1992.

[8] EL SHAZLY, E.M., EL-HAZEK, N.T., and ZAYED, Z.M., Leaching parameters on uraniferous shales and sandstones from Qatrani, Western Desert U.A.R. in the recovery of uranium IAEA-SM-135/34 (1971).

[9] IBRAHIM, E.A., Pilot studies on processes for by-product uranium recovery and separation of gypseous precipitate from phosphoric acid product of hemihydrate procedure, M.Sc. Theis, Alex. Univ., Alexandria (1993).

[10] FARAG, A.Kh., Recovery of Thorium, uranium and cerium from Egyptian monazite, M.Sc. Thesis Cairo, Univ., Cairo (1972).

[11] DAHLKAMP, F.J., Uranium ore deposits, A state of the art review: Reprint from Metallogenesis of Uranium Deposits Proceedings of a Technical Committee Meeting on Metallogenesis of Uranium Deposits Organized by IAEA, Vienna (9-12 March, 1987) 31p.

[12] HASSAN, M.A. and HASHAD, A.H., The Precambrian of Egypt, in The Geology of Egypt, R. Said, editor, ch. 12, A.A. Balkema, Rotterdam, Netherlands (1990) 201-245.

[13] SALMAN, A.B., EL AASSY, I.E. and SHALABY, M.H., New occurrence of uranium mineralization in Gabal Qattar, north Eastern Desert, Egypt, Annals Geol. Surv. Egypt, (1986-1989) V.16, 31-34.

[14] El Kassas, I.A., Radioactivity and geology of Wadi Atalla area, Eastern Desert, Ph.D. Thesis, Ain Shams University, Cairo (1974) 502.

[15] BAKHIT, F.S., Geology and radioactive mineralization of Gabal El Missikat area, Eastern Desert, Egypt, Ph.D. Thesis, Ain Shams University, Cairo (1978) 280.

[16] EL-TAHER, M.A., Radioactivity and mineralization of granitic rocks of El-Erediya occurrences and its comparison to El-Missikat-Rea El-Garra occurrences, Eastern Desert, Egypt, Ph.D. Thesis, Al-Azhar University, Cairo (1985) 133.

[17] ABU DEIF, A., Uranium mineralization along Qena-Safaga Road, M.Sc. Thesis, Al-Azhar University, Cairo (1985) 109.

[18] MOHAMED NABAWIA, A., Mineralogical and petrographical characteristics of some alteration product related to U-mineralization in El-Missikat, El-Erediya areas, Eastern Desert, Egypt. (M.Sc. Cairo University) (1988).

[19] HUSSEIN, H.A., KAMEL, A.F., and MANSOUR, S.I., "Disseminated type uranium mineralization in the granitic rocks of Um Ara area, south Eastern Desert, Egypt", Arab. Jour. Nucl. Sci. and Appl., Cairo (1985).

[20] ASSAF, H.S., Ground exploration and geological studies on some radioactive occurrences in the area south of Kosseir. M.Sc. Thesis, Faculty of Science, Ain Shams Univ., Cairo (1966).

[21] EL GHAWABY, M.A., SALMAN, A.B. and EL AMIN, H., On results of drilling at uranium occurrences of El Atshan locality, central Eastern Desert, Egypt: (Internal Report), Geology and Nuclear Raw Materials Dept., AEE (1963) 25.

[22] OBRENOVIC, M., EL KASSAS, I. and EL AMIN, H., Report on the results of detailed exploratory mining works at the uranium deposits in Wadi El Atshan locality, central Eastern Desert, Egypt: (Internal Report), Geology and Nuclear Raw Materials Dept., AEE (1965) 31.

[23] ABDEL GAWAD, A.M., Mineralogy, geochemistry and radioactivity of El Atshan No. 1 uranium deposit, Eastern Desert, Egypt. Internal Report, Geol. and Raw Materials Dept., Atomic Energy Establishment, Cairo, Egyp (1964) 1-10.

[24] HUSSEIN, A.H., ABDEL-MONEM, A.A., MAHDY, M.A., EL-AASSY, I.E. and DABBOUR, G.A. On the genesis of surficial uranium occurrences in West Central Sinai, Egypt: Ore Geology Reviews, 7 (1992), 125-134.

[25] AFIFI, Sofia, Y., Geochemical investigation of some radioactive Lower Carboniferous sedimentary rocks of Wadi Nasib area, West Central Sinai, Egypt: M.Sc. Thesis, Fac. Sc., Suez Canal Univ., Egypt, (1991), 250.

[26] EL SHAZLY, E.M., EL HAZEK, N.M.T., ABDEL MONEM, A.A., KHAWASEK, S.M., ZAYED, Z.M. et al., "Origin of uranium in Oligocene Qatrani sediments, Western Desert, Arab Republic of Egypt", 467-478.

[27] SALMAN, A.B. and EL AASSY, I.E., Radioactivity and uranium distribution in Wadi Araba late Paleozoic sediments, north Eastern Desert, Egypt: Annals of the Geol. Surv. Egypt (1983) V. 13, 53-60.

[28] HASSAN, M.A., "On the occurrence of columbite mineralization in Wadi Abu Rusheid area, Eastern Desert, Egypt", Egypt. J. Geol. (1972) 16/2, 238-191 .

[29] HASSAN, M.A., Geology and geochemistry of the radioactive columbite-bearing psammitic gneiss of Wadi Abu Rusheid area, Eastern Desert, Egypt, Annals Geol. Surv. Egypt (1973) 3, 207-255.

[30] HUSSEIN, A.A., "Mineral Deposits, in R. Said ed. The Geology of Egypt", ch. 26, A.A. Balkema, Rotterdam, Netherlands (1990) 511-566.

[31] SALMAN, A.B., Structure and radioactivity of some phosphate deposits, East Luxor area, Egypt: Ph.D. Thesis, Fac. of Sci., Ain Shams Univ., Cairo, Egypt.

[32] SARASWAT, A.C., Uranium exploration in India: Perspectives and strategy: Exploration and Research for Atomic Minerals v. 1 (1982) 1-1 1.

[33] NAGATI, M., "Possible Mesozoic rifts in Upper Egypt: An analogy with geology of Yemen-Somalia rift basins", EGPC 10th Exploration and Production Conference, Cairo (1990) 20.

[34] Hunting Geology & Geophysics Ltd., "Geology of G. Al Uwaynat area", Libyan Arab Republic. Unpublished Report IRC. Tripoli, Libya (1974).

ORE RESERVE ESTIMATE, THE NEED OF RECONCILLIATION TO IMPROVE THE EVALUATION: A CASE STUDY, THE TAZA DEPOSIT

J.R. BLAISE, C. DEMANGE
Cogema, Velizy Cedex, France

Abstract

During the mining in the Taza, Niger Uranium deposit, a discrepancy was observed between the initial ore reserve estimate (local evaluation of the recoverable uranium) and the actual production. Following a description of the deposit and the initial evaluation, we shall compare and analyse the evaluation and production figures. The new evaluation of the remaining part of the deposit will be based on new parameters, a different model and selectivity blocks.

1. INTRODUCTION

Uranium exploration in the Arlit area of Niger (Fig. 1) began in 1956 by the CEA (Commissariat à l'Energie Atomique) and then followed later by Cogema. Discovery of mineralized areas eventually led to the mining of the Arlette-Artois-Ariège deposits by Somair ad the Akoula-Akola deposits by Cominak. Exploration along the northwest extension of the Arlette flexure fault led to the discovery of the Taza deposit and eventually to the creation of Société Minière de Tassa N'Tagalgue (SMTT) (Fig. 2). In 1986 part of the mining rights of SMTT were assigned to Somair. Since 1988 the Taza deposit has been mined by open pit methods.

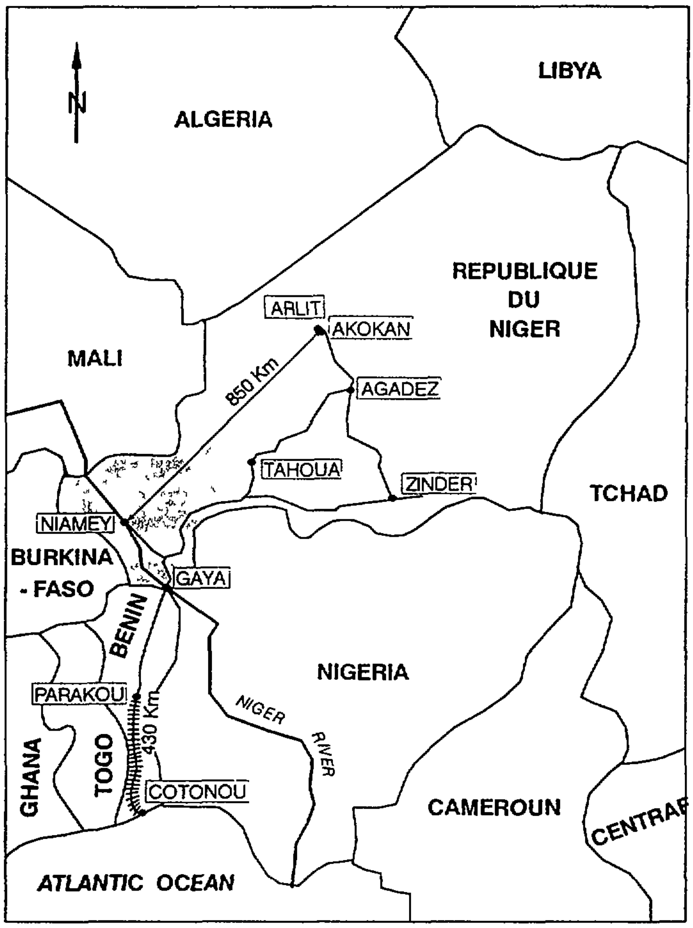


FIG. 1. Location map — Arlit, Niger.

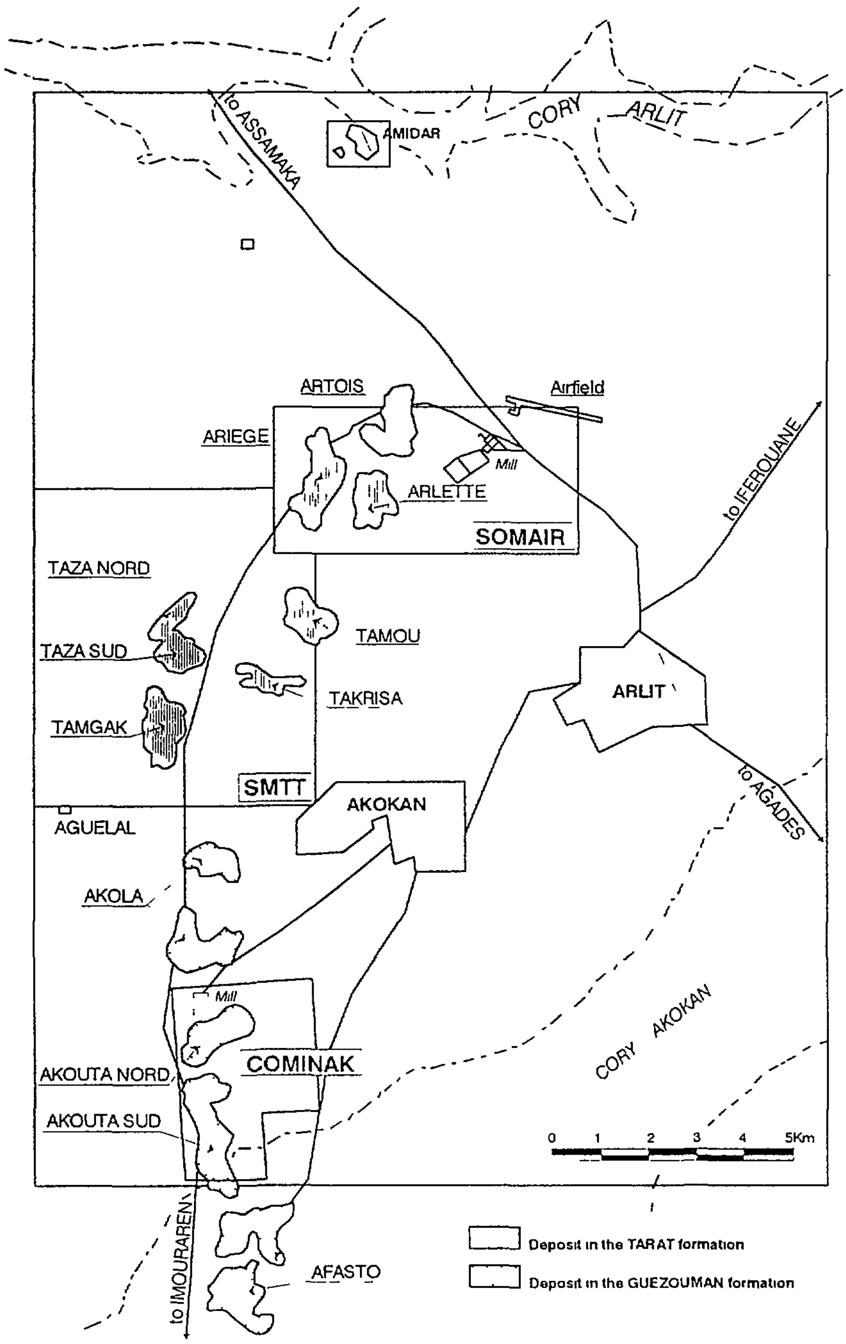


FIG. 2. Location map — Taza Sud Deposit.

2. GEOLOGY

Uranium mineralization of the Taza deposits is hosted in fluvio-deltaic sandstone and clay belonging to the lower carboniferous Tarat-Madaouela Formations and is controlled by tectonic, sedimentologic and hydrogeologic factors. Mineralization is located on the oxidation-reduction interfaces at the contact between fined-grained reducing facies, rich in organic matter and pyrite, and sandstones.

The mineralized bodies form discontinuous lenses, whose average vertical thickness is approximately 2 m; the horizontal dimensions varying between 15 and 35 m. These lenses can be part of larger bodies, up to 30 m thick and 500 to 600 m long.

The mineralization is fairly erratic at a decametric scale over the whole deposit. This variability is therefore a major parameter regarding the evaluation and mining.

3. FIRST ESTIMATION

The first evaluation of the Taza deposit was completed in 1987, and since the beginning of the mining in 1988 was used as a reference for the planification of the short and middle term production.

3.1. The data

The deposit has been evaluated with 585 drill holes (Fig. 3) including:

- 460 percussion holes drilled on a regular 25 × 25 m spacing
- 5 percussion holes drilled on 2 cross-shape profiles with a 5 and 12.5 m spacing
- 30 diamond drill holes on a 100 × 100 m grid.

Radiometric data were collected by down hole probing every 10 cm, and transformed into grades through the correlation curve

$T = 1{,}043\ Ra^{1{,}021}$
T = grade in ‰
Ra = radioactivity in AVP × 1000

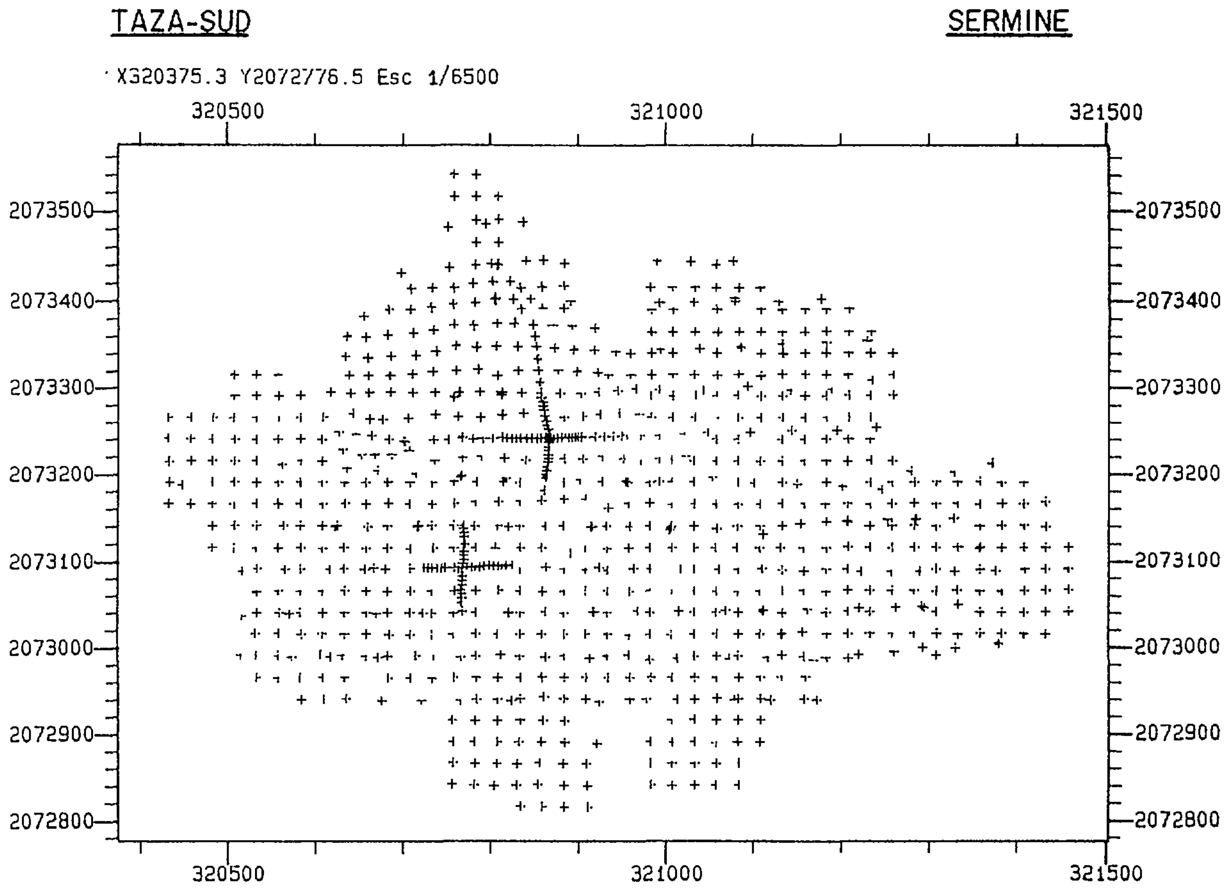


FIG. 3. Drill hole map — Taza Sud.

3.2. Estimation parameters

Compositing over 1 m.
Kriging of panels 25 × 25 × 1 m

Selectivity block = block size that corresponds to the selectivity of the mining method. Such a block does not have a real physical meaning since it is affected by several dilutions and sortings occurring between the blasting and the stockpiling.

A size of 7.5 × 7.5 × 1 m was adopted by analogy with other deposits in the same area.

The local recoverable reserves have been calculated using the "Service variables" method, for seven different cut-offs.

3.3. Definition of the estimated mining level

The study was limited to the area drilled on a 25 × 25 m grid. The surrounding holes, which were drilled on a 50 m grid, were not included. Vertically the evaluation was made on the whole unit without differentiating between the different sub-units.

3.4. Variographic study

The variograms were calculated along the main directions of the network: NS, EW and vertical. Data from the cross-shape profiles were used to calculate the first steps of the variograms (Figs 4 and 5). The variogram is fitted with a nugget effect and 2 spherical structures.

	Nugget effect	1 structure	2 structure
Sill	0.90	2.10	0.75
Range Horizontal	-	20	150
Range vertical	-	2	5

The variogram analysis shows a strong nugget effect (24% of the total variability) and short mineralized structures (20 m horizontally, 2 m vertically) .

Strong variations of the grade from one panel (25 × 25 m) to another could be predicted. The strong nugget effect in combination with a drilling grid too large to connect the structures did not permit a very high precision on the evaluation of each panel.

3.5. Local estimation of recoverable reserves

3.5.1. Gaussian anamorphosis

The grade Z(x) on a 1 m support does not match a simple known distribution la. It is therefore necessary to apply to the experimental distribution on anamorphosis transformation, which transposes each grade Z(x) into a gaussian equivalent.

In practice, one works with cumulated histograms called function of repartition. To each value of z is associated a y of identical cumulated frequency. The transformation Φ relating y and z is modellized with a Hermition polynomial development:

$$Z(x) = \Phi\ y(x) = \hat{\epsilon}\ \frac{\psi i}{i!}\ Hi\ (y) \tag{1}$$

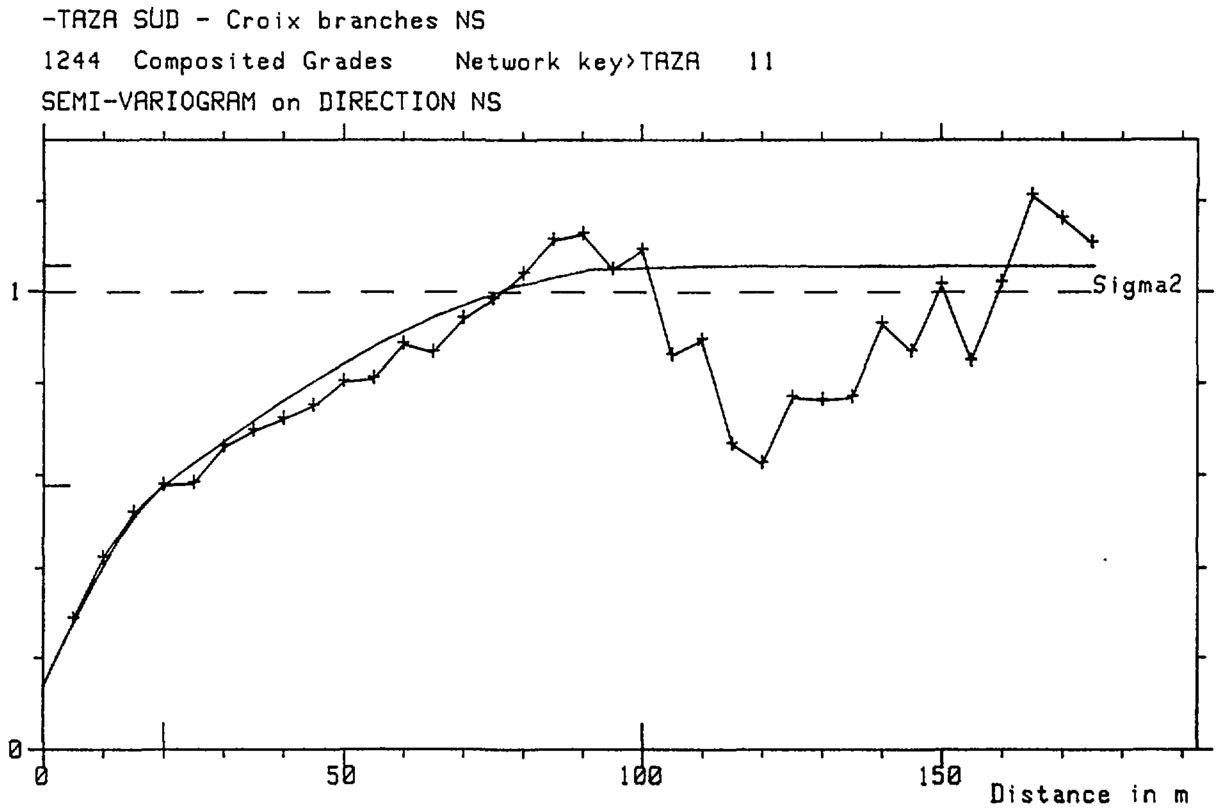


FIG. 4. Semi-varogram of composited grade in north-south direction.

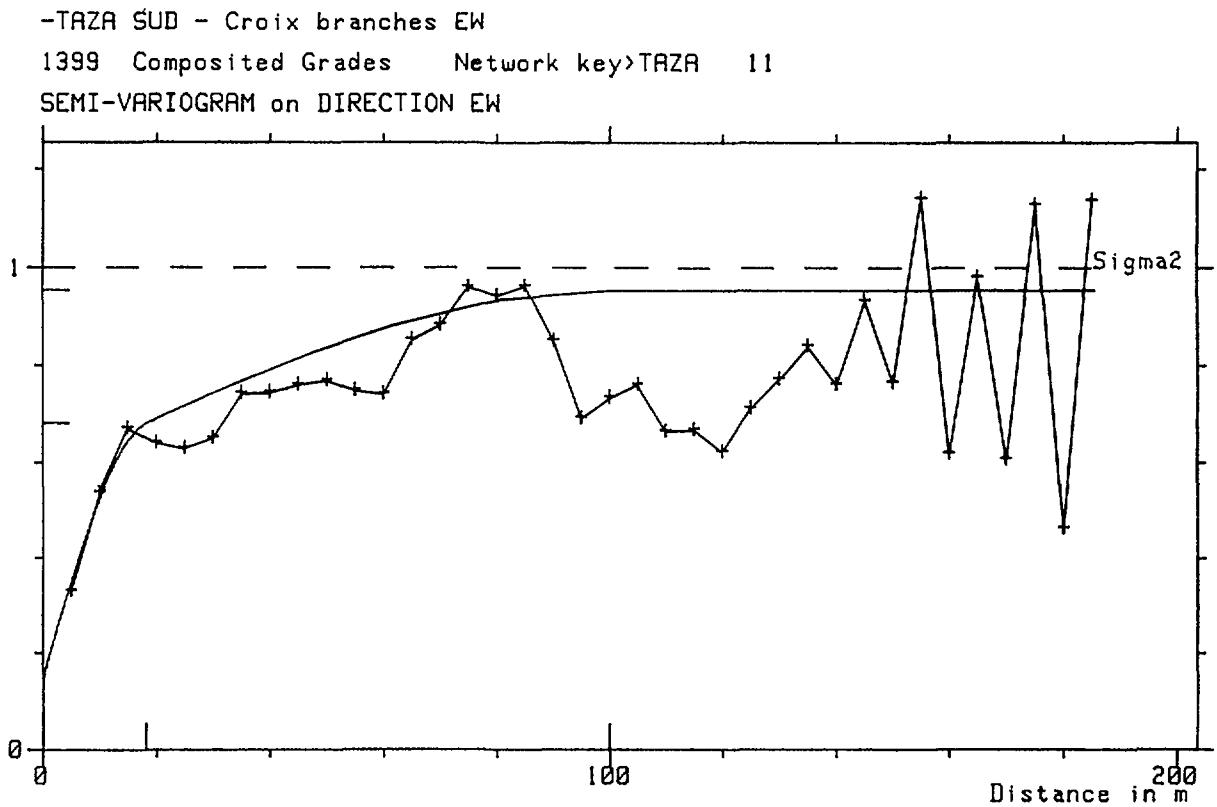


FIG. 5. Semi-varogram of composited grade in east-west direction.

i = o
with n = 59
Hi (y) = Hermitian polynonom
i = coefficient determined during the adjustment

The quality of the adjustment can be graphically appreciated by comparing the experimental curve z = phi (y) to the theoretically adjusted curve (Fig. 6).

3.5.2. Change of support

The change of support represents the subtraction of the histogram of selected V size blocks grades from the histogram of 1 m size support blocks grades. The variogram modellization allows the calculation of the distribution variances of the block V, using the following Krige relationship:

$$D^2(2v) = D^2(Z(x)\text{-}\gamma\ (v, v))$$

For a selectivity block $V = 7.5 \times 7.5 \times 1\ m^3$ we obtain:

D^2 (Zx) = dispersion variance of the regularized samples: 3.75 (‰)^2
D^2 (Zv) = dispersion variance of blocks v: 2.22 (‰)^2

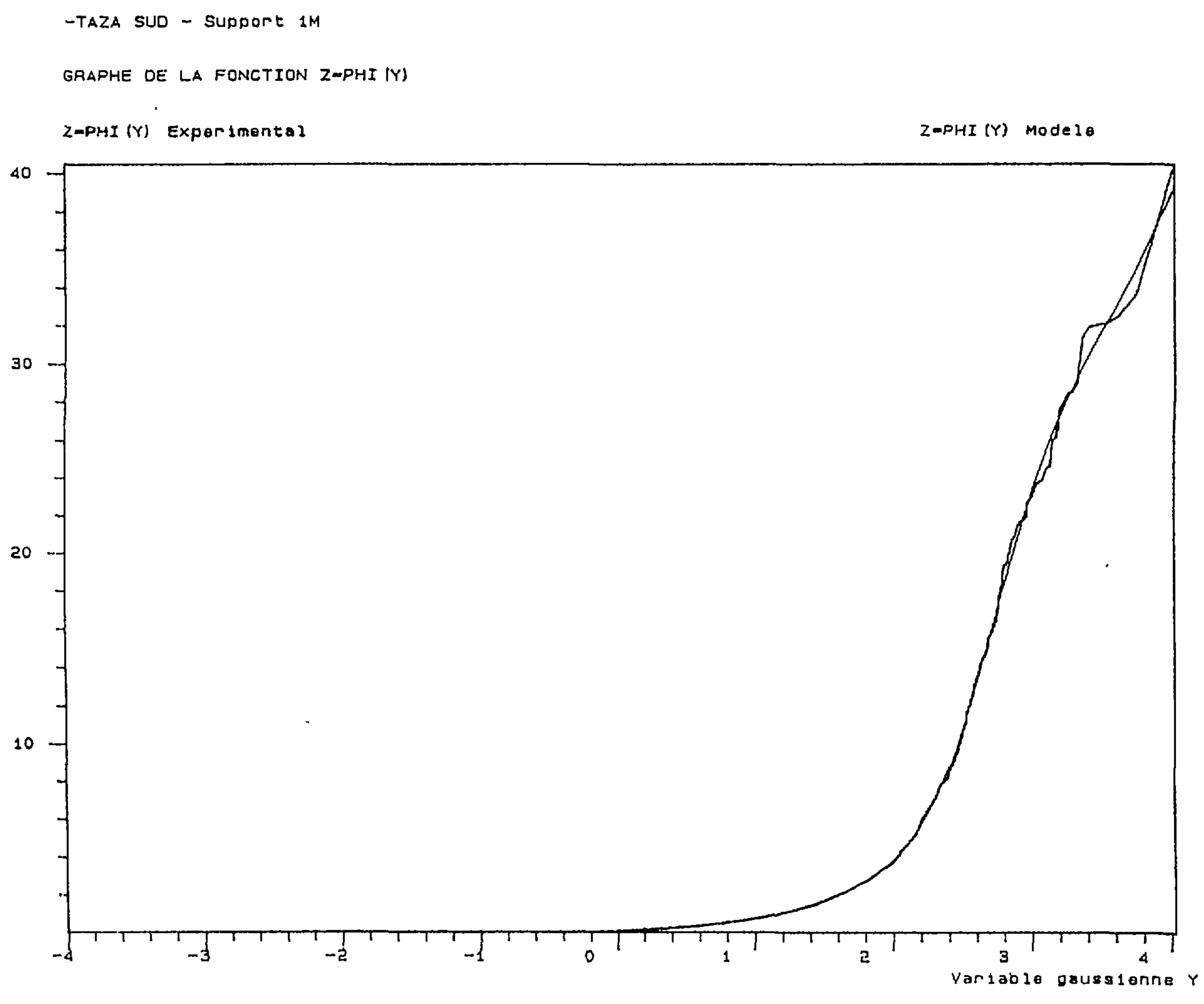


FIG. 6. Taza Sud graph of function; z = phi (Y)

The variance has decreased by 41%.
The change of support coefficient is r = 0.895.

Knowing the coefficient r allows the calculation of the block distribution.

3.5.3. Local estimation of recoverable reserves using the "service variables" method

Two variables are estimated in each 25 × 25 × 1 m^3 panel:

TMIN is the probable proportion of mineralized 7.5 × 7.5 × 1 m^3 blocks.
TREC is the corresponding quantity of metal.

The method is described by J.F. Bouchind'homme in his thesis and is summarized in appendix.

The TMIN and TREC variables are calculated for each 1 m sample at seven different cut-offs (0.6-0.8-1.0-1.2-1.4-1.6-2.1‰).

The TMIN and TREC variables are then averaged on a 3 m support in order to improve the horizontal continuity of these variables. The variograms of Service Variables TMIN and TREC are calculated and modellized with a nugget effect and two spherical models:

		Nugget effect	Spherical 1	Spherical 2
TMIN	sill	0.10	0.71	0.19
	range horizontal		40	150
	range vertical		7.5	10
		Nugget effect	Spherical 1	Spherical 2
TREC	sill	0.18	0.61	0.21
	range horizontal		35	150
	range vertical		6.6	10

The recoverable ore and uranium for each 25 × 25 × 3 m^3 panel is obtained by kriging the service variables TMIN and TREC defined on 3 m support, using the following pattern:

5 panels coplanar with the kriged panel;
1 panel on the upper and lower benches.

Results

Using a 1.6‰ cut-off, the following results on the southern part of the Taza deposit are obtained:

1 296 kt of ore at 4.12 ‰ = 5 337 t Uranium

3.5.4. Accuracy on the recoverable uranium

The kriging variances obtained for a sill normed to 1 are:
TMIN (ore): $\sigma^2 k$ = 0.99/6.99% of the local variance
TREC (uranium): $\sigma^2 k$ = 0.1111 /11.11% of the local variance

The higher the local variance, the higher will be the estimation variance, in absolute value, and the lower the accuracy.

On the TAZA deposit the square of the average grade is positively correlated with the variance. Consequently, the local accuracy will be poor for the richest zones.

Examples

For the following estimated panel values:

Ore	:	500 t
Grade	:	1‰
Uranium	:	0.5 t

The standard deviation would be 204 t on the ore and 0.4 t on the uranium.

If:

Ore	:	2 000 t
Grade	:	4‰
Uranium	:	8 t

The standard deviation would be 928 t on the ore and 4.2 t on the uranium.

The accuracy obtained on the evaluation of each panel is fairly low, as could be predicted from the variogram. The drilling grid is too wide spaced when compared to the range of the structures. For two standard-deviations the relative accuracy will generally be above 100% for the ore and 150% for the uranium.

4. RECONCILIATION OF THE ORE RESERVE ESTIMATE WITH THE PRODUCTION

4.1. Mining — production

The ore is mined on 3 m high benches. The blast holes are drilled on a 5 × 5 m pattern and are radiometrically probed. This information along with direct radiometric control during the mucking is used to load more or less homogeneous truck loads of ore at various grades.

Every ore truck is scanned outside the pit by an automatic scintillometric scanner, which calculates the grade using a radioactivity-grade correlation.

Only the ore whose grade exceeds 1.6‰ is currently processed at the mill. For this category the scanner data is adjusted to balance with those at the mill. The ore grading between 0.6 and 1.6‰ U is stockpiled.

4.2. Reconciliation of the ore reserve estimate with the production

The ore reserve estimate has been compared to the production for 9 panels (T4 to T12) (Fig. 7), which produced 2800 tonnes of uranium (52% of the estimated uranium of South TAZA).

The ore reserve estimate has been recalculated on the some volume as the production. The actual pit was digitized, and only the panels within this outline were computed (sometimes weighted by the percentage of volume within the contour).

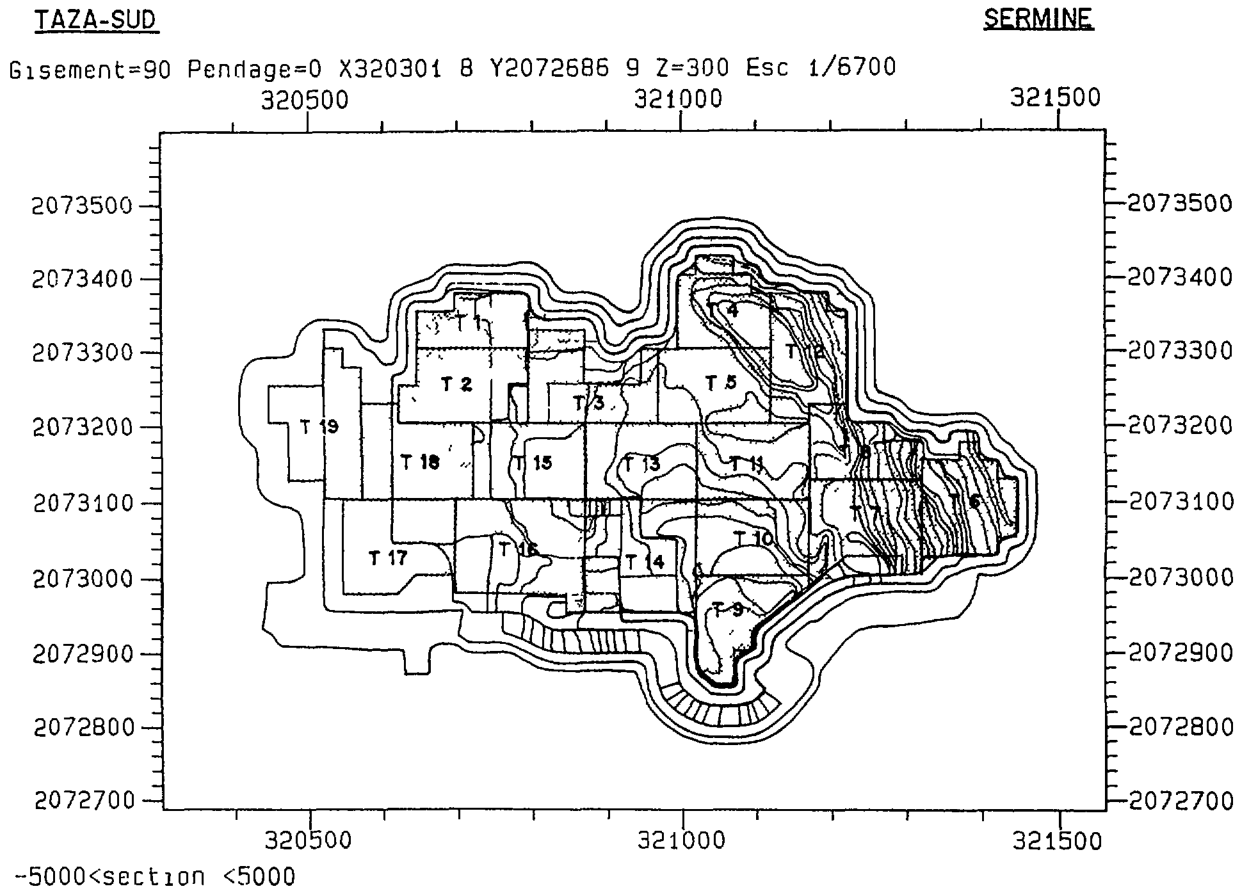


FIG. 7. Ore block map.

The results panel by panel for grades exceeding 1.6‰ U are given in Table I. The results for the different grade categories are in Table II and (Fig. 8) .

TABLE I. COMPARISON OF PANELS ESTIMATE (E) AND PRODUCTION (P) FIGURES: AT CUT-OFF 1.6 % U

Panel	Geostatistical estimate			Production			(P-E)/E		
	Ore	Grade	Uranium	Ore	Grade	Uranium	Ore	Grade	Uranium
T4	74,7	3,47	259,44	60,64	3,10	187,89	-18,9	-10,7	-27,6
T5	79,0	3,55	280,70	72,33	2,83	204,45	- 8,4	-20,5	-27,2
T6	83,7	4,33	362,20	116,68	3,62	422,79	39,4	-16,3	16,7
T7	115,3	5,42	624,60	161,10	4,23	681,76	39,8	-21,9	9,2
T8	68,3	4,16	284,16	64,66	3,70	239,29	- 5,3	-11,1	-15,8
T9	66,7	4,30	286,60	77,93	3,76	292,72	16,8	-12,6	2,1
T10	66,4	3,81	245,40	63,34	3,40	215,20	- 1,6	-10,8	-12,3
T11	54,5	3,82	208,10	56,92	4,12	234,65	4,5	8,0	12,8
T12	109,2	3,64	397,32	114,71	2,82	323,88	5,0	-22,4	-18,5
TOTAL	**715,8**	**4,12**	**2948,52**	**788,31**	**3,56**	**2802,63**	**10,1**	**-13,7**	**-4,95**

TABLE II. COMPARISON OF THE ESTIMATE (E) AND PRODUCTION (P) PER GRADE CATEGORIES: TOTAL OF ALL PANELS

GRADE CATEGORIES			P-E / E ORE	GRADE	URANIUM
Grade	>	1,6 °/oo	10	-14	- 5
1,2	-	1,6 °/oo	-14	0	-14
1,0	-	1,2 °/oo	-13	1	-12
0,6	-	1,0 °/oo	-35	4	-33

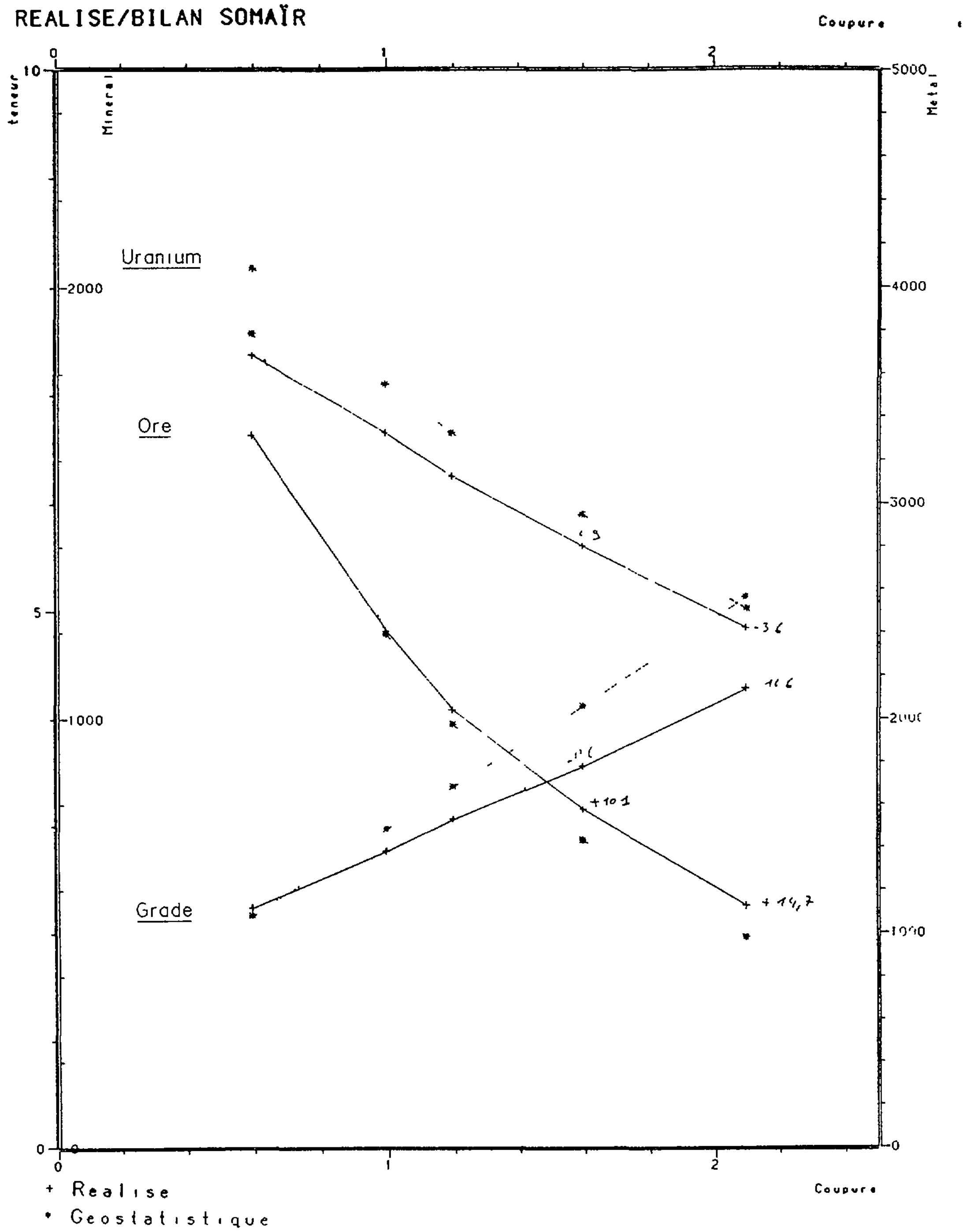


FIG. 8. Comparison of geostatistical estimate with observed uranium grade.

4.3. Ore

Comparison with the production shows a positive difference of about 10% for ore grading over 1.6‰ U but with a discrepancy of -1.6 to 39.8% on single panels. For ore grading between 0.6 and 1.6‰ U the difference is negative.

4.4. Uranium

The average difference between the production and the evaluation is -5%.

For the ore grading over 1.6‰ U the difference on single panels ranges from -27.6% to +16.7%.

For the other grade categories, the difference varies from -12 to -33%.

4.5. Grade

For the 9 panels the average difference between production and evaluation is -14%. The difference ranges between -22% and +5% (only one panel, T11, shows a positive difference).

For the grades ranging from 0.6 to 1.6‰ U, the difference is only 0 to -4%.

These results show that the first ore reserve estimate of south TAZA is inadequate for a correct short term planification of the exploitation.

What could cause these differences ?

- *the geological model*
  The differences on the ore estimate can be partly explained by an incorrect definition of the mineralized zone. The accuracy on the outline of the mineralized zone depends on the geological interpretations.

  The evaluation has been made on the whole mining unit without distinguishing the various sub-units. On the eastern part of the deposit, where the formations are dipping, high grade units can be used to krige panels on another unit resulting in an overestimation. The solution would be to estimate the different unit separately.

- *the drilling grid*
  The variogram interpretation shows a strong nugget effect and a first horizontal range of 20 m. However, the deposit is only recognized on a 25 m spacing. This development grid is not sufficient for an accurate local estimation. The production figures only reflect the confidence levels calculated from the available data.

- *block of selectivity*
  The size of the selectivity block (7.5 × 7.5 × 1 m^3) has been selected by comparison with other evaluations made on deposits located in the same geological environment (ARLIT deposits). However, it appears that the mineralizations of TAZA are less continuous and the current model is too selective compared to what is achievable in open pit selectivity.

- *bias on the representativity of the data base*
  The fact that the grade curve of the production does not fit the grade curve of the estimation shows that there could be a bias in the representativity of the data.

- the proportion of high grade values in the drill holes is higher than in reality;
- the radioactivity-grade correlation is too favorable in the high grade category;
- the production figures on the ore grading less than 1.6‰ U may not be properly measured. The scanner data cannot be adjusted to balance with those of the mill, as the ore is stockpiled for a possible treatment in the future.

5. NEW EVALUATION

Following the reconciliation between the ore reserve estimate and the actual production, a new evaluation was done on the remaining part of the south TAZA deposit, by using new parameters. Recommendations can then be made for the accurate evaluation of the north TAZA deposit.

5.1. Block of selectivity

Nine panels (T4 to T12) with a production of 788.3 kt at 3.56‰ = 2802.6 tu have been re-estimated using a selectivity block of $7.5 \times 7.5 \times 3$ m^3, which is less selective than the previous one.

At a 1.6‰ U grade cut of the result is: 799,2 kt at 3.55‰ U = 2839.6 tu. At the 1.6 and 2.1‰ U grade cut-off, we obtain a good correlation between the estimate and production figures. (Fig. 9) However, for the lower grade categories (0.6 to 1.6‰ U), a significant difference between estimation and production figures remains. At the present time this can only be explained by an inaccurate estimate of the production.

5.2. Geological model

A more conservative outline of the mineralized zone has been defined. For the various subunits of the Tarat Formation showing different geometrics, it has been necessary to design a geological mask fitted on the elevations obtained from resistivity logs interpretation. Each subunit can then be evaluated separately.

5.3. New evaluation

Implementing the new geological model, a less stringent selectivity, and using the same method as previously (Service Variables), the remaining ore of the South Taza deposit has been evaluated again.

We obtain the following results at a cut off of 1.6‰ U:

634.8 kT at 3.32‰: 2105 TU

Compared to the previous estimate, we observe:

a 18.3% increase on the tonnes of ore
5.0% decrease on the tons of Uranium
11.2% decrease on the grade

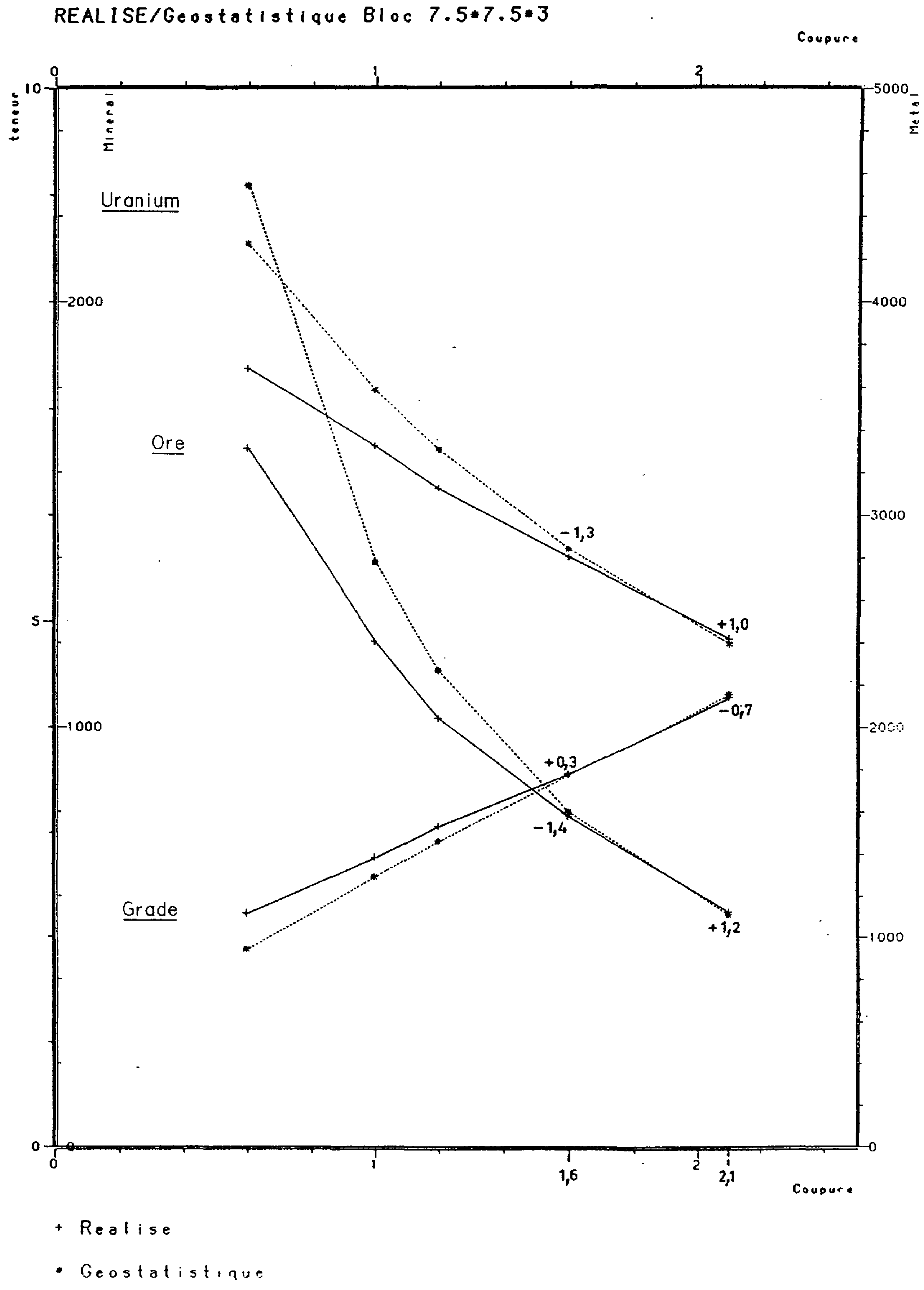


FIG. 9. Comparison of geostatistical estimate with observed uranium grade.

6. RECOMMENDATIONS FOR THE EVALUATION OF THE NORTH TAZA DEPOSIT

Along with the use of a more accurate geological model and of a $7.5 \times 7.5 \times 3\ m^3$ selectivity block, the ore reserves estimate of the North Taza deposit will include the computation of a new radioactivity-grade correlation using the results of the latest diamond drill holes.

These evaluations have been made using the SERMINE software, software built by COGEMA, which integrates a complete chain of programs whose applications range from acquisition of basic data to the most advanced geostatistical estimations and simulations.

BIBLIOGRAPHY

BOUCHIND'HOMME, J.F., Estimation de l'uranium récupérable sur les gisements sédimentaires stratiformes exploitables à ciel ouvert, Thèse de docteur ingénieur, Institut National Polytechnique de Loraine, 18 avril 1980.

COGEMA, internal reports.

APPENDIX

SERVICE VARIABLES METHOD

In a Gaussian model, two service variables are defined

- TMIN is the expectation of the proportion of small blocks higher than the cut off grade, knowing the grade of the central section
- TREC is the metal recoverable from these blocks.

1/ Determination of the cut-off Y_c

Knowing the raw cut-off Z_c to be applied to the block its Gaussian equivalent Y_c to be applied to the Gaussian histogram of the block v is computed, knowing that $Z_c = \Phi\, Y(c)$.

2/ Determination of cov (Z_0, Z_v)

Covariance between raw grade of the central sample and raw grade of its block v

$$\text{cov}\,(Zo,Zv) = D^2\,(Z) - \bar{\gamma}\,(Zo,Zv)$$

$D^2\,(Z)$ = sill of the variogram = dispersion variance of samples in the ore body

$\bar{\gamma}\,(Zo,Zv)$ = mean variogram between central sample and its block.

3/ Determination of cov $(Y_0, Y_v) = r_0$

It is assumed that the pair (Y_0, Y_v) is Gaussian
r_0 is the correlation coefficient between Gaussian grade of block V and Gaussian grade of central sample. r is the change of support coefficient.
r_0 is computed by applying to the n coefficients of the anamorphosis, the coefficient r_0 x r, which correctly reconstitutes cov (Z_0,Z_v)

$$\text{cov}\,(Zo,Zv) = \sum_{i=1}^{n} \frac{\psi_i^2}{i!}\,(r \times ro)^i$$

knowing r_0 we can obtain conditional law of Y_v knowing Y_0

4/ Computation of *TMIN and TREC at sample level.*

The following is considered :

- For the ore : the random variable TM = 0 if $Z_v < Z_c$
  TM = 1 if $Z_v > Z_c$
- For the metal : the random variable TR = 0 if $Z_v < Z_c$
  TR = Z_v if $Z_v > Z_c$

Using a Gaussian distribution allows to obtain a conditional law of TM, knowing $Z_0 = \Phi(Y_0)$ grade of the central sample.

Consequently TMIN = E (TM/Z_0) = E (TM/Y_0)
and TREC = E (TR/Z_0) = E (TR/Y_0)

We compute for each *sample value* Y_0 *according to its development* in terms of Hermite polynomials.

5/ Estimation of TMIN and TREC at panel level.

After modelling the TMIN and TREC variogram the mean values TMIN* and TREC* are estimated by kriging for each panel

6/ Computation of the tonnages and grade of recoverable material.

For each panel :

- Recoverable ore = TMIN* x Volume of panel x density
- Recoverable metal = TREC* x Volume of panel x density
- Recoverable grade = $\frac{\text{TREC*}}{\text{TMIN*}}$

7/ Change of cut off

Back to 1/

Next page(s) left blank

URANIUM RESOURCES ASSESSMENT AND THE MARKET

M. GIROUX, G. CAPUS
Cogema, Velizy Cedex, France

Abstract

Among nuclear fuel cycle issues, those dealing with the future supply of raw materials for the power reactors are on the agenda of this Technical Committee. As the newly extracted uranium is only part of the supply available to utilities, this paper will first discuss the prospects of future demand and supply, taking into account the medium term impact of the inventories and the increasing role of recycling. For the longer term the key issue will be the future production coming from uranium resources presently known in the ground. While the Red Book is the international reference on uranium resources, questions are raised by the production side of the industry on the value of these "official figures" and the future availability of these raw materials in the present market situation. The uranium reserves appraisal issue is detailed in the second part of this paper.

1. THE MARKET STATUS

1.1. 1992 picture

In the western world, 1992 is the eighth year in a row that uranium production lies below actual consumption (see data of Fig. 1). Last year the production deficit in western world reached nearly half of the reactors' demand. Increasing supplies from the large redistribution of inventories which took place since the early eighties, and more recently imports from the CIS countries allowed the western market to stay in balance, even while prices pursued their downward trend, as illustrated in Fig. 2. More recently and to a much lesser degree, the same trend has been observed in the rest of the world, namely, Eastern Europe, CIS countries and China. On an aggregated basis in the rest of the world, production of fresh uranium remained above consumption in 1992. On a worldwide basis the production deficit continue to build up, representing more than 30% of last year total demand.

		1960	1970	1980	1990	1992
GWe	INSTALLED CAPACITY	-	17	127	316	325
	western world	-	15	115	276	284
	rest of the world	-	2	12	40	41
ktU	WORLD PRODUCTION	43	43	62	50	37
	western world	31	19	44	28	24
	rest of the world	12	24	18	22	13
	REACTORS REQUIREMENTS	1,5	6	24	50	54
	western world	1-2	5	21	43	47
	rest of the world	-	1	3	7	7

FIG. 1. Natural uranium market: Historical perspectives.

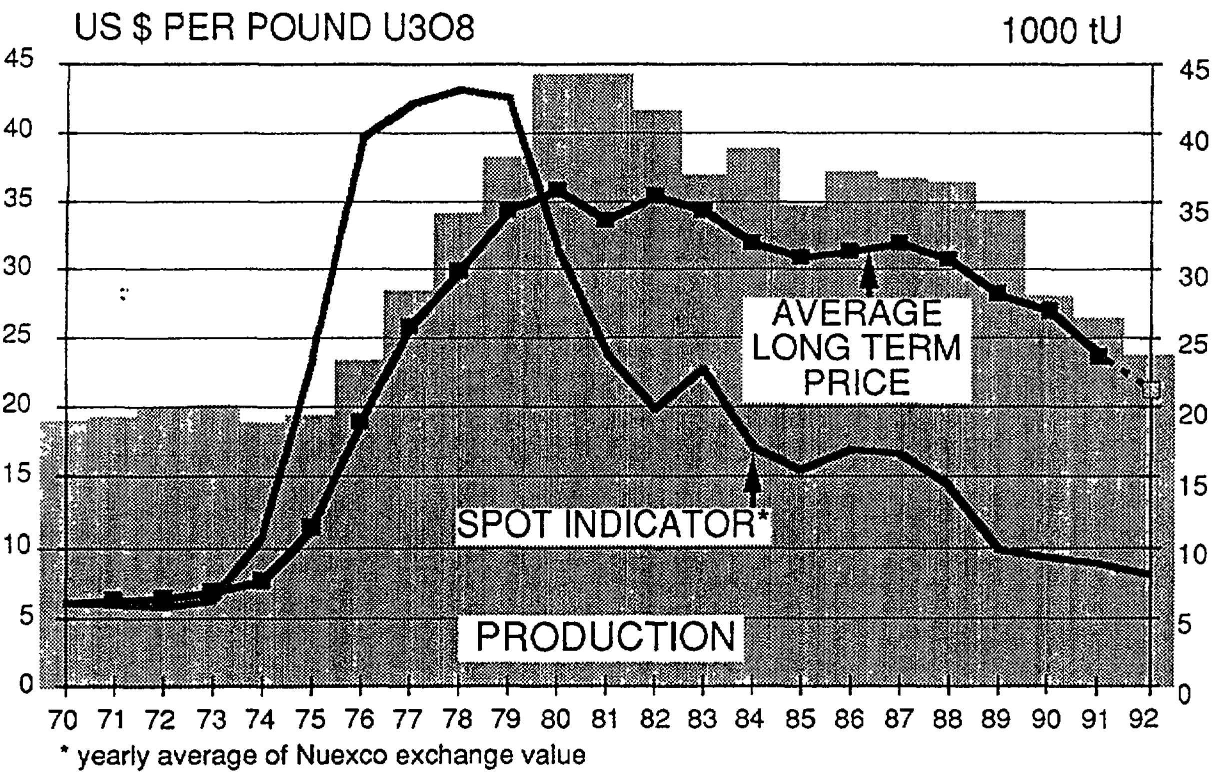


FIG. 2. Natural uranium production and prices in the western world.

1.2. The status of already extracted uranium

To-date, about one third of the 1,7 MtU extracted from the ground has been consumed in the Nuclear Power Plants. A nearly equal amount went through military hands, the bulk of it in United States and in CIS countries.

As it stands, the agreement between USA and RUSSIA calls for the export during the next twenty years of between 150 and 200 thousands equivalent tonnes U of CIS origin to the USA for consumption in the civil reactors. This material now in the form of highly enriched uranium will firstly be diluted below 5% U235 before being exported to USA for consumption in the civil cycle.

On top of that, there are still large quantities of materials in inventories (civil and military). According to various estimates, the total inventories accumulated worldwide amount to about 300 ktU.

1.3. The uranium supply and demand scenarios

1.3.1. The update of the 1991 scenario

The uranium supply prospect was addressed in the 1991 Technical Comittee on uranium resources. It was developed using both Red Book data, and an internal model developed by NAC. Fig. 5. is adapted from the TECDOC presentation. It integrates the saving resulting from the recycling of fissile materials (RepU and Pu) recovered during reprocessing of used fuels. According to this scenario, all available surplus will not cover the expected cumulated demand, and unless corrective measures are taken, a production deficit will occur in the late nineties.

	WORLDWIDE	*Western world share*
EXTRACTED FROM THE GROUND	>1700 ktU	1047 ktU
UTILIZATION		
MILITARY NEEDS	600 ktU (1/4 to 1/3 of this amount could come back to the civil cycle)	250 ktU (?)
NUCLEAR POWER PLANTS	700 ktU	600 ktU
INDUSTRIAL FACILITIES (working inventory)	100 ktU	
YET TO BE MOBILISED	>300 ktU i.e.: 5 years of worldwide reactors requirements	120 ktU

FIG. 3. Natural uranium market: Cumulated quantities (End of 1992).

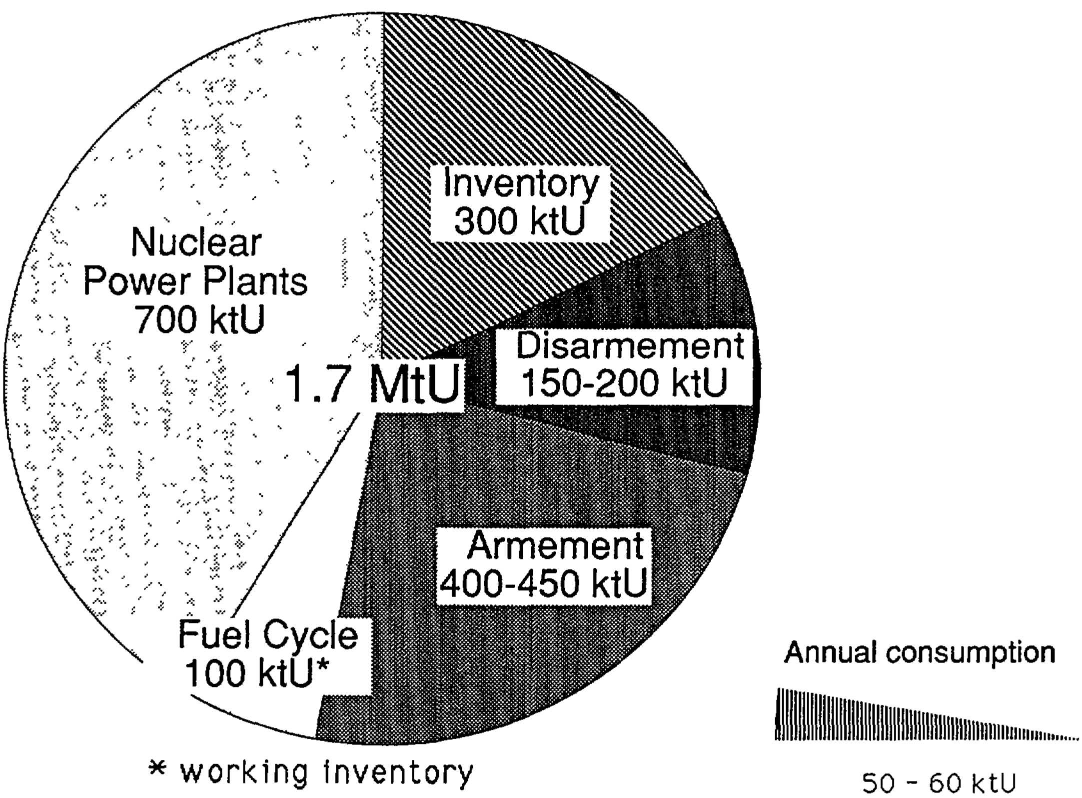


FIG. 4. End use of already extracted uranium.

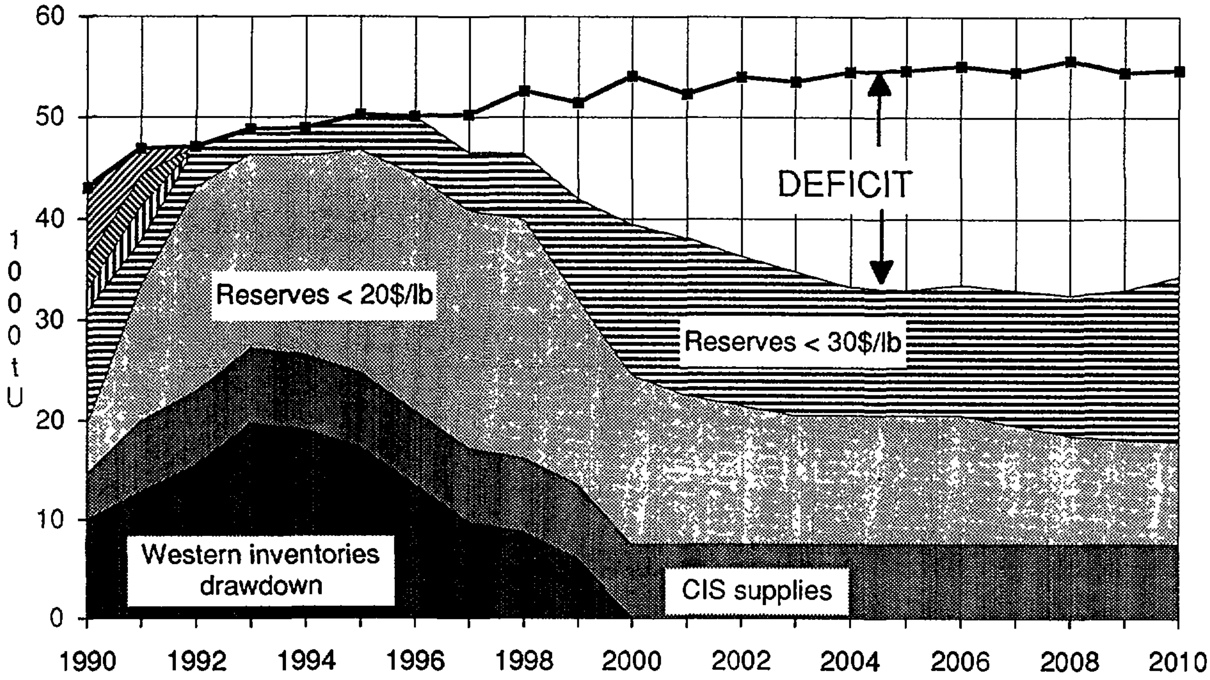


FIG. 5. Supply and demand of uranium in western world: Recycling not taken into account.

1.3.2. The effect of HEU recycling

In the 1991 scenario, the effect of the recycling of military materials in the civil cycle was not taken into account, the agreement between USA and Russia took place afterwards. This recent agreement, which leads to the recycling in US of reactors of Russian origin. Diluted HEU (highly enriched uranium) will provide the US consumers with an important supply source. If fully implemented, this agreement will modify the medium term supply and demand picture of the western world. Its full impact is illustrated in Fig. 6. In this case, the future demand addressed to fresh production is reduced and the deficit build-up pushed well beyond year 2000.

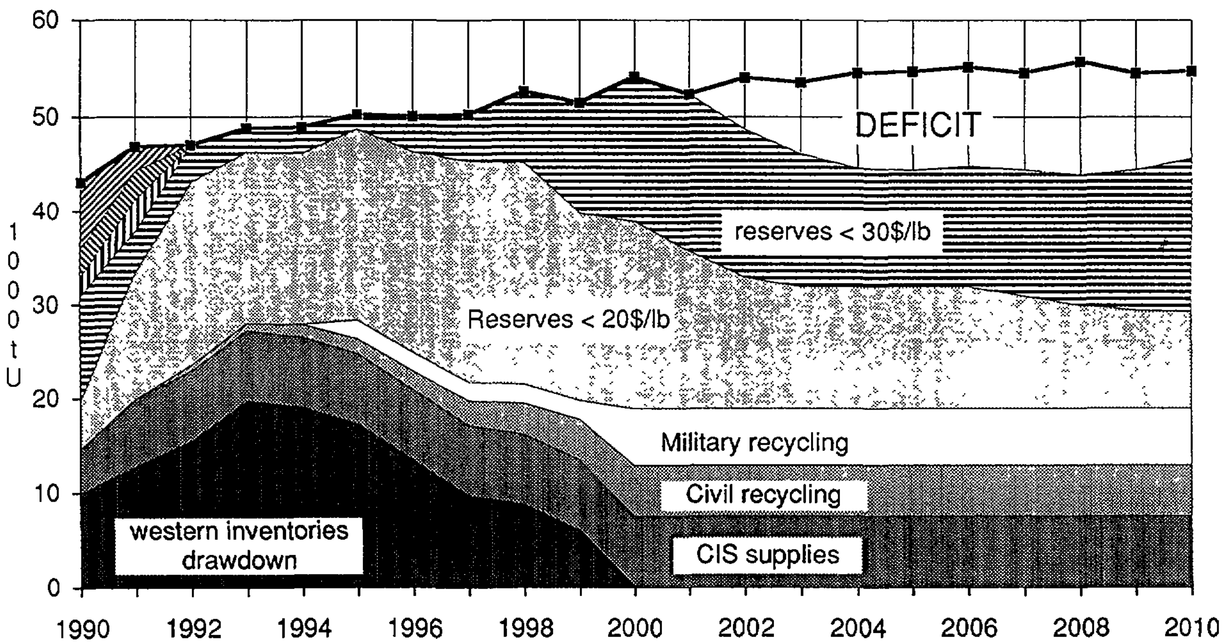


FIG. 6. Uranium supply and demand in western world: Including recycling of civil and military materials.

1.3.3. The likely impact

As the market may be overestimating the potential supply of external sources for consumption in power reactors, be they the recycling of military HEU, and/or a further drawdown of inventories, the probable production deficit may be at the turn of the century a middle point between both scenarios. To avoid such a deficit build-up, and allow for an increase of fresh production in western world to fill the gap, incentives will have to be provided. A price surge in the medium term is the prerequisite for the new capacities to be launched.

2. ASSESSMENT OF THE URANIUM FUTURE AVAILABILITY

2.1. The Red Book

The purpose of the Red Book exercise, initiated in the sixties, was to provide data to long term planners on the availability of uranium for the Nuclear Energy development they were foreseeing. Taking into account the time needed to:

(1) launch the construction,

(2) build the reactor,

(3) supply it during its expected 30 years life; it was really long term planning.

Today, nearly thirty years later, the picture is different. The power reactors that were planned are now operating, or no more planned. Few are still under construction.

Thanks to its two parents OECD and IAEA, the Red Book has much grown and improved, to the satisfaction of its readers. What is now questioned by industry participants, as illustrated by the work undertaken by the Uranium Institute, is its adequacy to present and future market needs in view of:

(1) a more or less stable and well known demand,

(2) availability of supply from sources other than fresh production

2.2. The uranium future requirements

Only part of the future reactor demand is covered by fresh production. Beside newly extracted uranium, other sources of supply include the redistribution of excess inventories, and/or the recycling either of reprocessed products or of materials of military origin. In the case of recycling, one can foresee that once available, this supply will likely be the first to be used, fresh production and redistribution of inventories fulfilling the remaining available demand.

Demand for fresh production in the medium term will be covered by presently operating mines. Taking into account the progressive reserves exhaustion of existing operations, and/or their premature closure for economic reasons, new mines will have to be developed to insure coverage of the longer term demand. As discussed above in the supply and demand scenarios, the need for new mines development and their share in the future supply mix will depend upon the implementation of the HEU agreement.

3.3. Dealing with uranium reserves

Sources of fresh uranium supply are:

- for the years to come, the reserves associated with existing operations,
- for the longer term the undeveloped known resources. With a high enough level of knowledge, the undeveloped resources can be classified as reserves.

Production wise, both reserves cannot be treated the same way:

- for existing operations, the driving force is the producer's contractual obligations.
- for future developments, the supplier guidelines are its market prospects and the expected ability of the foreseen project to challenge its competition.

3.3.1. Existing operations

The low prices presently prevailing on the spot market do not allow uranium mines having to sell all their production on this market to operate on a long term basis in a profitable manner. Most mines have developed various ways to face this situation. They can rely on prices they receive on their long term contracts, and/or reduce their average supply cost by complementing a part of their production with external supply acquired below their own cash cost. These various strategies are described below.

3.3.1.1. Long term contracts in force

In adjusting their production plan to their contractual obligations as long as the operation remains profitable, the existing mines are extracting reserves in an economical way. While any extra output will be produced at lower costs than the baseload, it will have to be sold at prices prevailing on the spot market. In present conditions, it will not likely be extracted with a profit.

If the supply originating from those profitable mines is assessed according to predefined thresholds, it might be not classified as reserves. Due to contractual obligations the extraction will take place, while hopefully making a profit.

3.3.1.2. Survival strategies

The two following strategies allow mining companies to cope with adverse market conditions in extending mine operations which otherwise would have to be mothballed.

- substitution of production:

  by substituting in deliveries a part of its production by supply acquired below its cash cost, an operation may be increasing its profits while apparently decreasing its minable reserves, taking into account that those remaining reserves once mined will have to find their way on the spot market.

- complementing production:

  a supplier, having a contractual obligation to be mining at least partly the materials it delivers, may find profit by complementing its production made at a loss with materials bought on the spot market. In the latter case its minable reserves are increased.

For mines operating that way, the economic assessment of reserves cannot only be based on cost thresholds.

3.3.2. Future mines

The reserves of undeveloped properties cannot be assessed the same way as those of existing operations. They have to gain a share of the market, while the bulk of the required investments for their development remain to be done.

A feasibility study is the minimum requirement to estimate the amount of recoverable reserves from a potential orebody. Even if mining and milling methods can be well defined at the feasibility stage, the cost of extracting the concentrates it contains can generally only be assessed within a range. Taking into account the nature of mineral concentrations the range obtained is not necessarily matching predefined thresholds.

On top of that, and enlarging the range are the unforeseen constraints that local authorities can impose on the future project once launched.

For undeveloped properties an improved cost thresholds system should allow a better knowledge of the really available reserves in present commercial conditions.

3.4. The Industry practice in reserves estimate

3.4.1. Stock-exchange reporting requirements

In countries such as Australia, Canada and the USA, publicly listed mining companies must locally report their metal reserves, as their other assets, in accordance with Codes of Practice devised by professional institutions in consultation with stock exchange bodies. Reporting reserves according to these standards provides for the potential investor, the statement of the commercially minable tonnes and grade of ore and recoverable uranium.

3.4.2. International mining companies, the COGEMA's approach

Apart from the reporting requirements above mentioned, international mining companies developed specific tools to assess their strategy and balance their investments decisions. Geostatistical estimate was retained within the COGEMA group in order to compare and aggregate numbers originating from various sources in a proper way.

The results of such an approach are described in the case history detailed in J.R Blaise and C. Demange's paper.

Reserves definition

- geological reserves: they are defined by a grade/tonnage curve. Each point of the curve is a set of three numbers: a given cut-off grade, an average grade and a tonnage for the reserves grading higher than the cut-off.

- Minable reserves: provided all extraction parameters are set up, including, production capacity, mining plan and production level, an extraction cost can be associated with a given cut-off grade. An average mining grade and the associated recoverable tonnage are as well estimated.

- Cost thresholds: On a theoretical basis, an estimate of minable reserves at a given cost can be performed on each set of geological data, provided all other mining parameters are as well adjusted to the case. Such an estimate, requires a lot of work and is very much time consuming. In practice, it is only undertaken on few selected points of the curve. Those points chosen according to the orebody characteristics do not inevitably match given cost thresholds.

4. RECOMMENDATIONS

The various ways which have been developed to assess reserves and resources of uranium lead to various sets of data, sometimes in a confusing manner for the outside observer used to dealing with the single numbers that the other extracting industries are releasing. The companies mining uranium have their own reporting system which can make their figures hardly comparable to those released through official channels in the Red Book.

Such a situation can raise heated discussions among technical people about respective values of data sets of various origin which have each their own merits.

To overcome such a situation, should not the interested parties in uranium reserves estimates share their efforts to increase the quality of the final product. The mining industry (via professional bodies, as the Uranium Institute) would be in charge of the assessment of minable reserves of existing and planned operations, while the Red Book effort would be focussed on the assessment of the longer term perspectives, taking care of the resources of uranium.

It is hoped that a shared effort like above proposed would lead to an improved appraisal of uranium future availability that should be welcomed by market participants.

BIBLIOGRAPHY

CAPUS, G., L'uranium, évolution et perspectives d'une industrie en crise, in ATOME ET GEOLOGIE, Ste Geologique de France 11/92 (to be published).

GIROUX M., MÜLLER-KAHLE E., PECNIK M., UNDERHILL D.H., Uranium supply-demand projections and their analysis, IAEA-TECDOC-650, Vienna (1992).

URANIUM INSTITUTE, Uranium Issues Nr. 4, February 1993.

THE THREE-DIMENSIONAL RESERVE/RESOURCE CLASSIFICATION SYSTEM — A PROPOSAL FOR URANIUM

D. KELTER, F. BARTHEL
Bundestalt für Geowissenschaften und Rohstoffe, Hannover, Germany

Abstract

In view of the lack of an internationally accepted convention for the classification of mineral resources a new scheme is proposed. This is based (1) on the existing classification for uranium resources applied by NEA and IAEA, (2) experience of the first author gained in exploration for coal deposits in Third World Countries, and (3) the Australasian Code for Reporting of Identified Mineral Resources and Ore Reserves, published in 1989. The proposal discusses the harmonization of classifications in use for resource estimates based on geological information only with those for which studies of various degrees of economic considerations (pre-feasibility study, feasibility study) are available. The present system of the NEA and IAEA for the classification of uranium resources already takes into account the amount of information on the economic availability of uranium resources and their costs of production. Therefore the harmonization with other classification systems should be possible. This proposal should be regarded as provisional, open for discussion to organizations dealing with resource classification.

1. INTRODUCTION

Many different systems for classifying mineral reserves and resources, with differing definitions, are in use throughout the world. Numerous efforts have been made in the past to standardize the different systems and thus set up a more internationally valid concept, but have so far failed. More recently, the trend has been away from harmonization of existing systems towards the introduction of new systems. The issue of reserve classification is thus becoming more and more complicated and confusing. At the same time the need for an international standard is increasing with the growing worldwide trade in mineral commodities.

In the short time available we can only cover some aspects related to the subject of reserve classification. We shall focus on the principle behind the classification in order to demonstrate the necessity to modify the existing systems, as we feel that it is not possible to establish an internationally acceptable classification without a basic change in the existing systems.

2. THE PRINCIPLE BEHIND THE EXISTING SYSTEMS

In spite of the fact that many classification systems are in current use, they are all based on the same principle for subdivision of the reserves, i.e. application of two criteria: degree of geological assurance and degree of economic feasibility.

The first criterion, the degree of geological assurance, is a function of the geological information available. This information is normally obtained in stages following a general procedure established for the investigation of a mineral deposit.

When a mineral occurrence is discovered or a geochemical or geophysical anomaly detected, a reconnaissance is normally undertaken. This yields the so-called hypothetical reserve figures, which have a low degree of geological assurance. This work is followed by widely spaced drilling and trenching, aimed at narrowing down the area of investigation to the most probable site of the mineralization. This stage yields figures for the tonnage(s) and grade(s) of reserves which have a moderate degree of assurance. Furthermore, genetic and structural models are developed and petrographic and mineralogical studies are undertaken, just to mention some of the additional approaches made. The final exploration step is the actual systematic, closely spaced drilling, detailed sampling, assaying and interpretation of the results, providing reserve tonnage and grade figures with a high degree of accuracy. These reserves are referred to as proved or measured.

Increasing the geological assurance as described above does not increase the economic feasibility or mineability of the reserves, as the two factors are not related.

The geologist delineates reserves and calculates tonnages and grades by applying cut-off values, i.e. minimum thickness of orebody or seam, minimum grade, maximum depth, etc. The cut-off values adopted are normally those used for mining the same mineral commodity under similar conditions elsewhere. At the same time they are of great importance as they separate reserves from waste, and thus constitute the initial, albeit provisional, assessment of the reserves. However, whether the reserves calculated by the geologist are mineable or not cannot be stated, as no specific information is available on which to base such a statement.

Existing reserve classifications, which subdivide reserves according to the degree of geological assurance and degree of economic feasibility or mineability, lack a reliable basis and are therefore unsatisfactory.

3. THE PRINCIPLE BEHIND THE PROPOSED THREE-DIMENSIONAL CLASSIFICATION

Reserves are normally quoted with respect to their degree of feasibility or mineability as: economic, marginally economic, and sub-economic. Any reliable appraisal of reserves on this basis is made by mining engineers and mining economists, who incorporate other specialists' assessments in the fields of beneficiation, transport, environmental impact, and mining law, just to mention a few aspects.

This complex set of investigations, for which we use the expression "technical and economic investigations", is normally also carried out in stages. After the initial appraisal, which is done by the geologist, a pre-feasibility study is usually carried out, in which the basic technical and economic factors of a future mining venture are looked into. The pre-feasibility study results in a statement on the mineability which has a relatively low but definable degree of assurance. The final stage is the so-called feasibility study, which gives a high degree of assurance to the economic mineability assessment.

The following classes of assurance about the degree of mineability are tied to the stage of investigation reached.

Class of assurance			*Stage of investigation*
I	high	(assessed in detail)	Feasibility study
II	medium	(sufficiently ass.)	Pre-feasibility study
III	low	(initially appraised)	Exploration report

In class III, since only the initial appraisal has been carried out, no statement about the mineability can be made, as it has not been defined as to whether the reserves are economically, marginally or sub-economically mineable. In this class, only one reserve figure is quoted as established by the geologist. This figure is defined as reserves that may be economically mineable, depending on the results of the technical and economic studies to be carried out sometime in the future. Class III in fact relieves the exploration geologist of the responsibility of making a statement about the mineability of the reserves that he is quoting in his report.

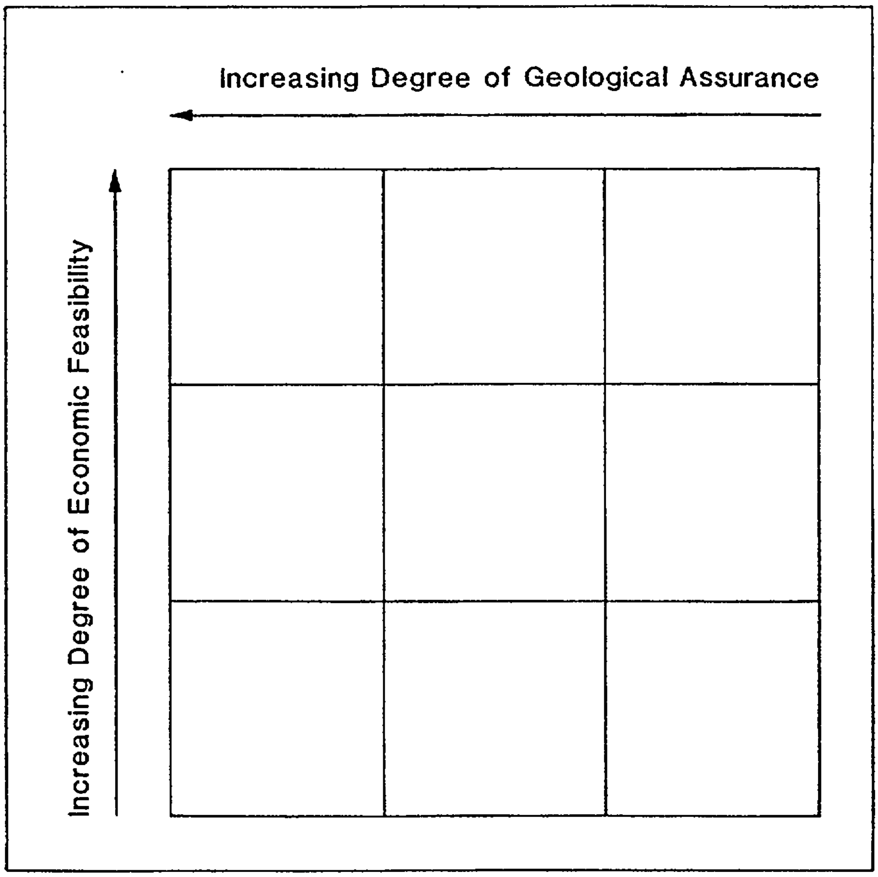


FIG. 1. Diagram showing the principle behind the classification systems.

Classes II and I are a measure of how thoroughly a deposit has been assessed from the technical and economic points of view, and provide a measure of assurance with which a statement of economic, marginal, or sub-economic is made.

We therefore propose incorporating a third vector (see Fig. 2) into the existing classifications, i.e. the degree of technical and economic assurance with which the mineability or feasibility assessment is made. The practical application of the three-dimensional classification system is simple, since the ranking into class I, II, or III is direct indication of whether a feasibility study, pre-feasibility study or only an exploration report has been completed; these reports of course contain the relevant data on mineability.

Our proposed addition to the classification will indicate how reliable the mineability assessment is. It has the advantage of being based on current practices. We feel therefore that it is worth discussing, and hope that it will be generally accepted.

The original idea to incorporate the state of knowledge about mineability, i.e. degree of assurance, derives from Prof. Fettweis and was published in Austria in the Österreichische Norm (ÖNORM) No.G 1050, 1989.

The Institution of Mining and Metallurgy, London (IMM) has recently also proposed a new method of subdividing reserves, following a quite similar concept as we do. In December 1991 IMM forwarded a revised classification system which incorporates the additional criterion of technical and economic consideration, distinguishing between geological reserve data and feasibility/pre-feasibility reserve data as well.

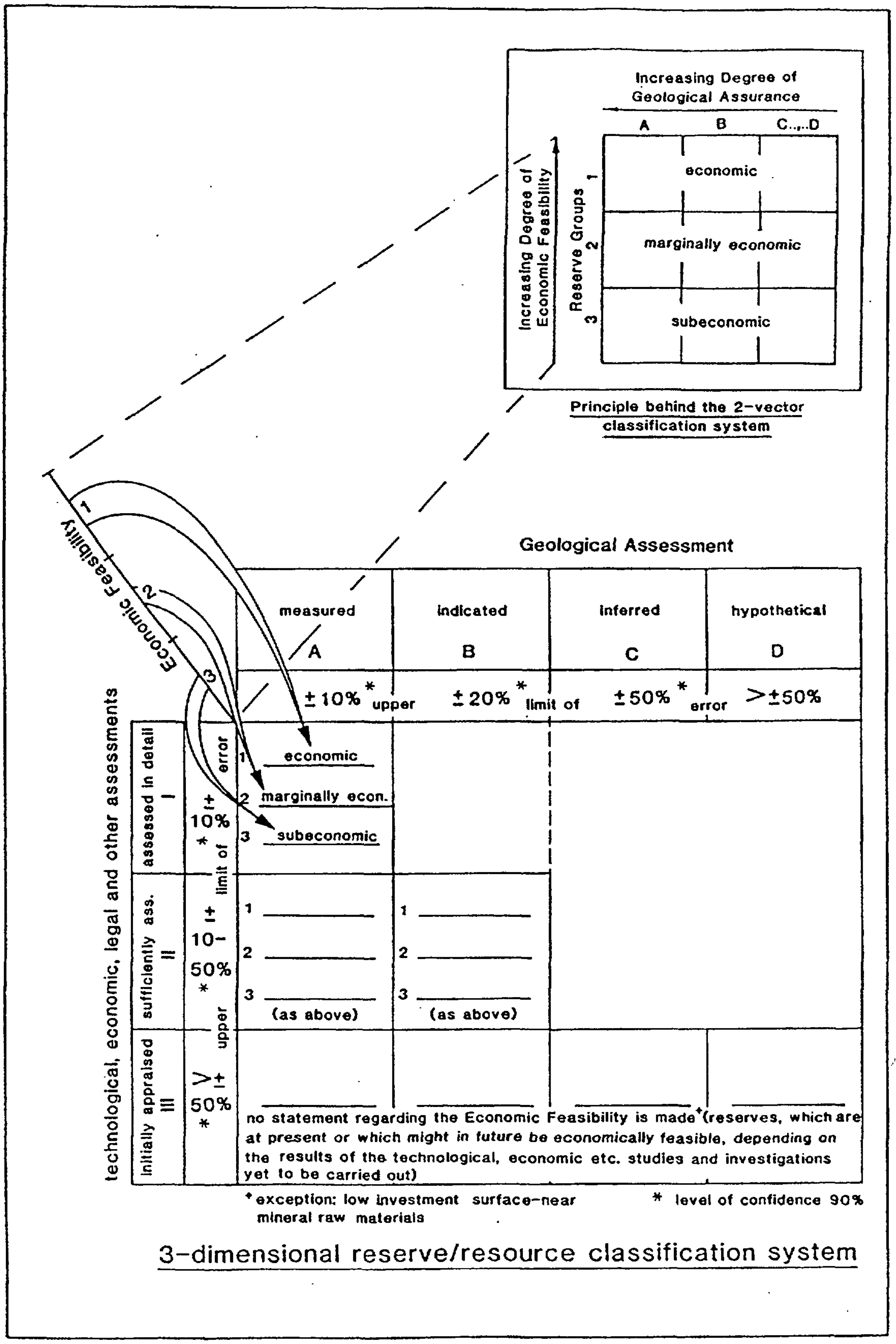


FIG. 2. Three-dimensional reserve/resource classification system.

In February 1989 a Joint Committee of the Australasian Institute of Mining and Metallurgy and the Australian Mining Industry Council published a report entitled "Australasian Code for Reporting of Identified Mineral Resources and Ore Reserves". The Code defines the terminology used for mineral resources and ore reserves, and distinguishes between identified mineral resources (in situ) and ore reserves (mineable). It defines a mineral resource as "an in situ mineral occurrence quantified on the basis of geological data and a geological cut-off grade only". Resources are subdivided into inferred, indicated and measured.

Ore reserves are defined as a part of measured and indicated resources which can be mined (taking mining dilution into account) and from which minerals can be recovered economically under conditions inferred to be realistic at the time of reporting. Ore reserves are subdivided into probable and proved ore reserves.

The definitions of the terms and the rules of reporting are explained. A resource report or ore reserve report including all relevant data must have been carried out and must have been prepared by qualified personnel under the direction of a competent person. The reporting terminology is given in Fig. 3.

	Identified Mineral Resources (in situ)		Ore Reserve (mineable)
increasing level of geological knowledge and confidence ↓	Inferred		
	Indicated	⟷	Probable
		consideration of economic, mining, metallurgical, marketing, environmental, social and governmental factors	
	Measured	⟷	Proved

FIG. 3. Reporting terminology: Australasian code for reporting of identified mineral resources and ore reserves.

The Committee states that its report unifies the industry's reporting of mineral resources and ore reserves and is complimentary to the Australian Code for Reporting Identified Coal Resources and Reserves used by Australian government organizations.

In a recent publication by A.C. NOBLE: Geologic resources vs. ore reserves (Mining Engineering, February 1993) this issue is discussed. Resource estimates resulting from the work of exploration geologists are often higher (by a factor of three to five) than ore reserves defined by subsequent detailed investigations; this commonly leads to problems in the evaluation of projects. Therefore it is aimed to introduce qualifiers into the process of resource estimation, allowing the exploration geologist to produce a better evaluation of the property. Examples of typical deposits are given.

For uranium resources, the definitions of resource categories are reported in the biennial publication "Uranium Resources Production and Demand" of the NEA/OECD and IAEA. From time to time the definitions have been revised. An approximate correlation between the classification systems throughout the world is shown in Fig. 4.

The relation between the resource categories described below is shown in Fig. 5.

The division of resource estimates into separate categories reflects different levels of confidence in the quantities reported.

4. DEFINITIONS OF RESOURCE CATEGORIES PRESENTLY USED BY NEA/OECD AND IAEA

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.

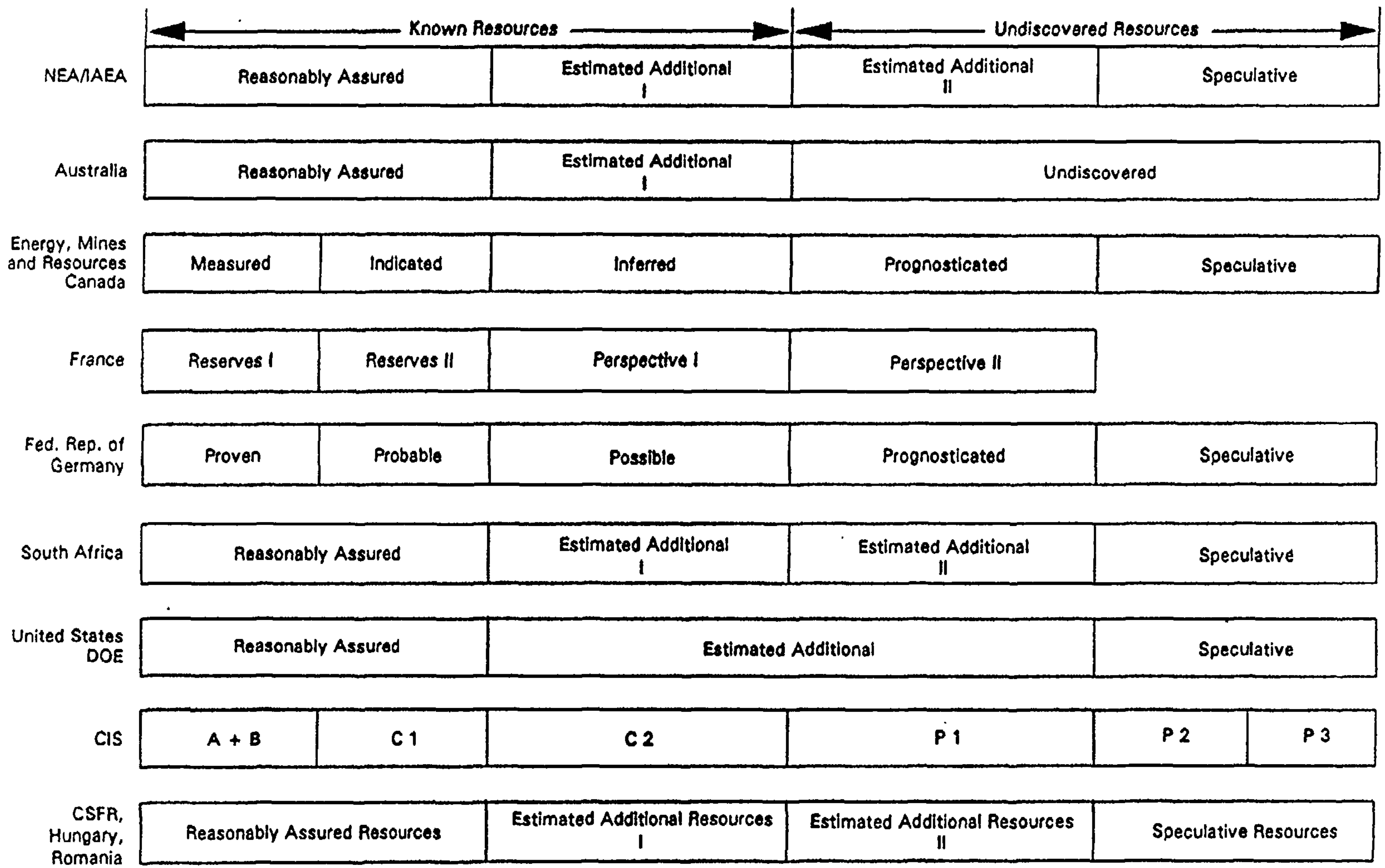
Estimated Additional Resources — Category I (EAR-I) refers to uranium in addition to RAR that is inferred to occur, mostly on the basis of direct geological evidence, in extensions of well-explored deposits, or in deposits in which geological continuity has been established but where specific data, including 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.

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 mineralization 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 extrapolations, 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.

Resource estimates are expressed in terms of recoverable tonnes of uranium, i.e. quantities of uranium recoverable from mineable ore or as quantities contained in mineable ore. In cases such figures are not available it should be mentioned that resource estimates are quantities in situ.

In addition, resource estimates of the above categories are expressed in cost categories. Since 1993 a new cost category of less than $ 40/kg U has been introduced reflecting changing market conditions. All cost categories are defined as cost of uranium recovered at the ore processing plant.



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

FIG. 4. Approximate correlations of terms used in major resource classification systems.

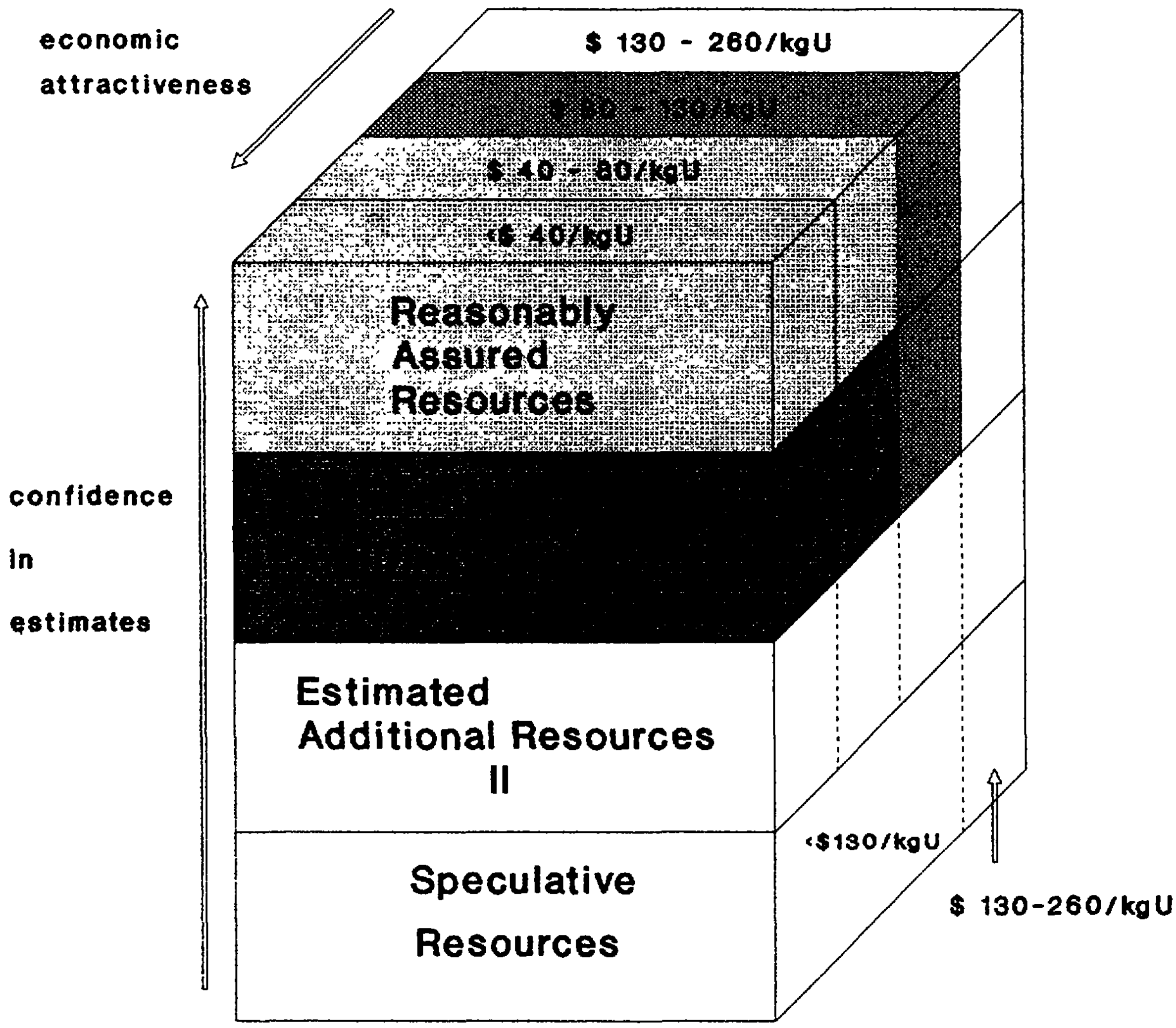


FIG. 5. Classification scheme for uranium resources (after NEA/IAEA).

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 were not normally taken into consideration.

The proposed modification of the existing scheme for classifying uranium resources is shown in Fig. 6. The front boxes show resources assessed in detail with regard to economic, technical, environmental, legal, and other aspects. They comprise categories RAR and EAR I at a cost up to $ 80/kg U and are currently considered to be economically attractive resources. They would correspond to Classes I and II.

The blank box at the back represents resources for which only geological information is available, corresponding to Class III.

Finally, in Fig. 7 a proposal for a classification of uranium resources is presented, which relates the degree of confidence of resource estimates to the technical and economic assessment, by which a resource can be upgraded into an ore reserve, taking different cost categories into account. The bottom box contains the resource estimate produced in the initial stage of assessment, with limited or no appraisal of economic aspects (equivalent to Class III).

The next step shows the resource estimate after additional information has been obtained, for example, by more closely spaced drilling, conceptual work on grade and tonnage of the mineralization, and further geological investigation (genetic model etc.)

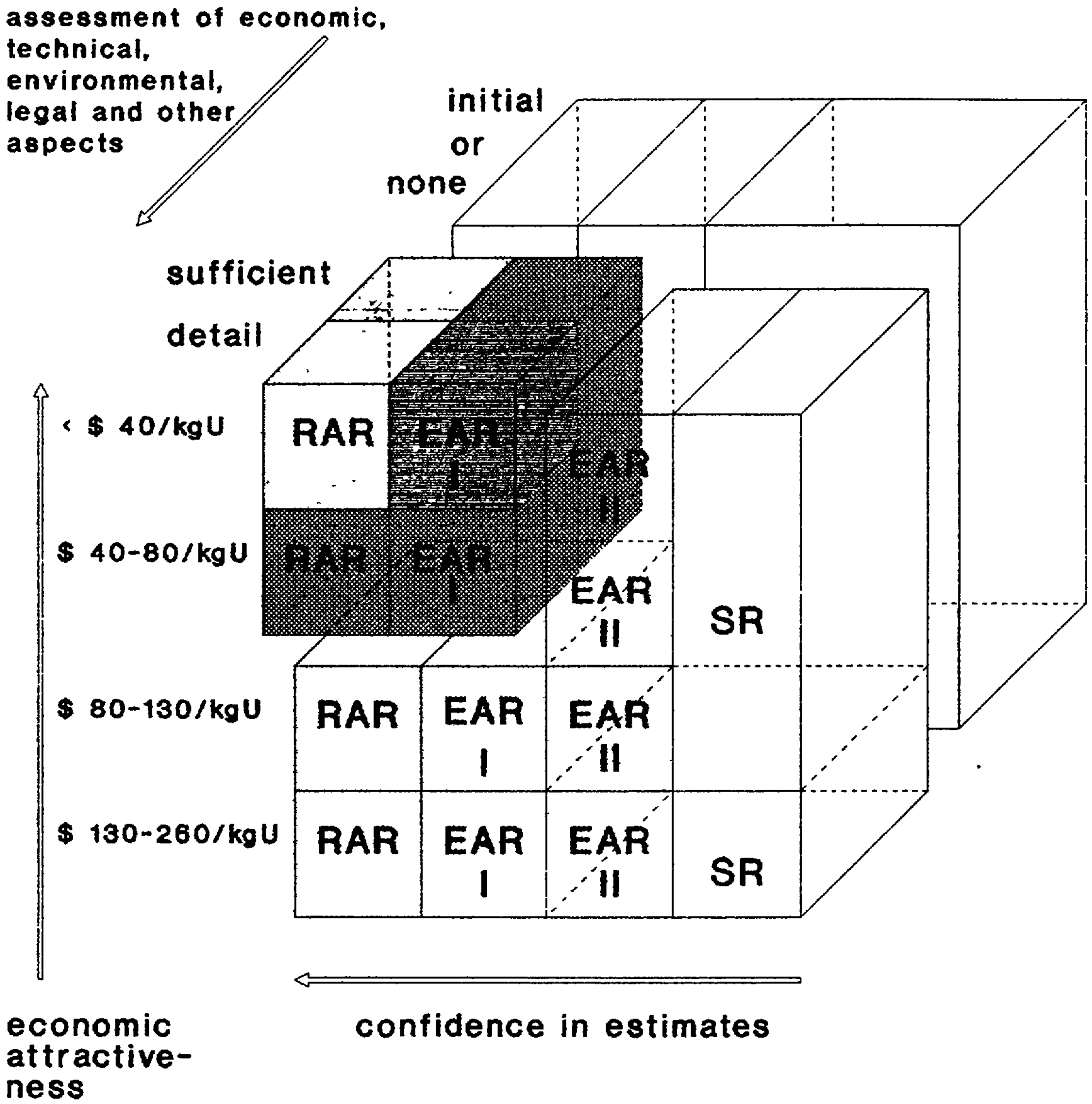


FIG. 6. Three-dimensional classification scheme for uranium resources (modified after NEA/IAEA).

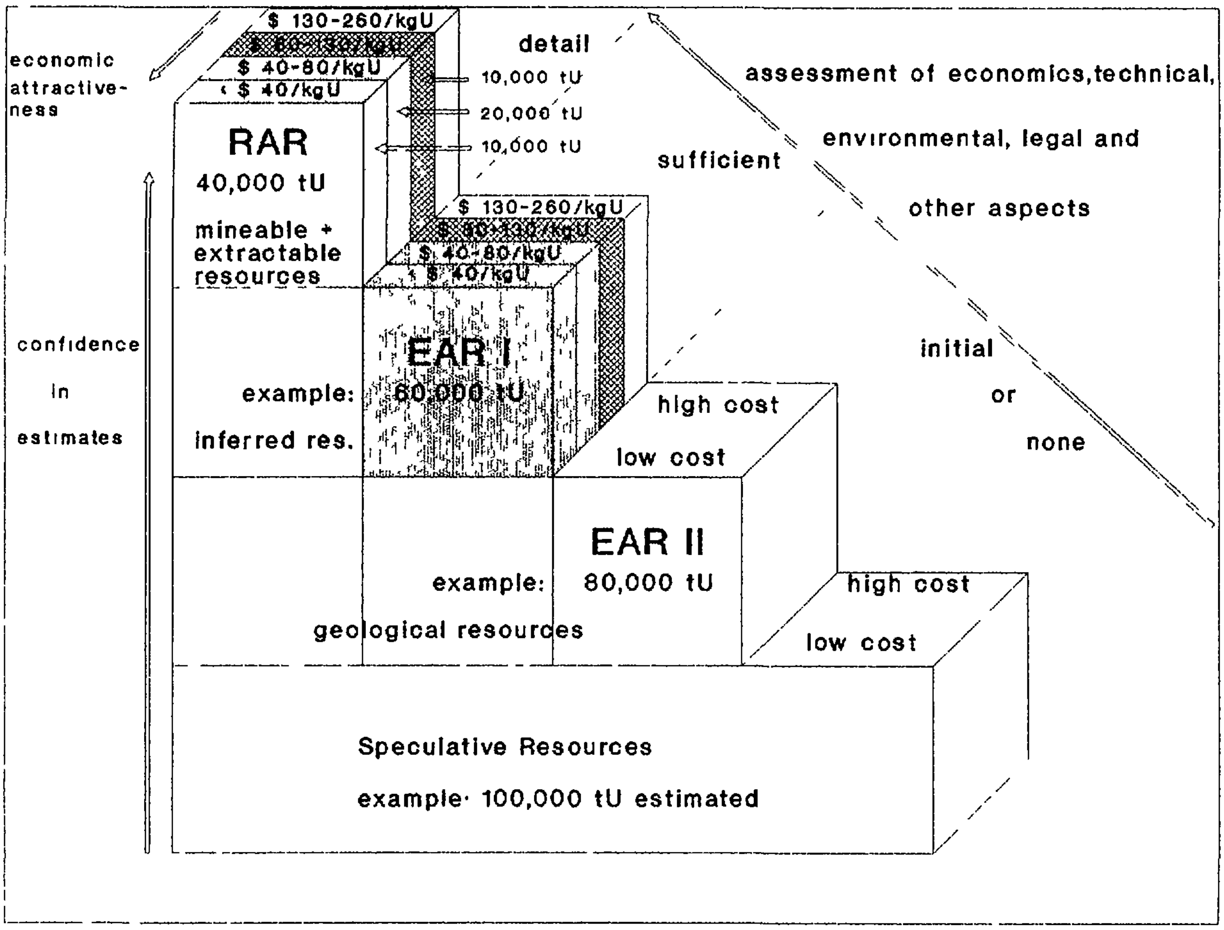


FIG. 7. Proposed classification scheme for uranium resources.

In the third step, estimates of resources are shown that are based on detailed investigation of grade and tonnage including specific work on mineability and recoverability, as in a pre-feasibility study (equivalent to Class II).

The final step in the top box represents estimates obtained via a feasibility study, proving the ore reserve as mineable and extractable with existing techniques (equivalent to Class I). Reserves in producing mines are to be classified under this class using the appropriate cost category.

The classification proposed here differs slightly from Kelter's system. Moreover, strictly speaking this proposal does not always reflect current practice in the mining industry. In practice, cases are known where ore is mined and metal extracted from deposits for which no detailed economic studies have been undertaken.

However, mining companies and government organizations are faced with the task of reporting resource estimates and ore reserves. It is hoped that the paper stimulates discussion, and that ultimately we shall be able to set-up a widely accepted model that can overcome the deficiencies of existing classification systems.

Finally, we should not forget the miners' saying You will only know how much ore is present when you have finished mining it.

BIBLIOGRAPHY

Australasian Code for Reporting of Identified Mineral Resources and Ore Reserves, Report of the Joint Committee of the Australasian Institute of Mining and Metallurgy and Australian Mining Industry Council, February 1989.

KELTER, D., Classification System for Coal Resources — a Review of the Existing Systems and Suggestions for Improvements, Geol. Jb. 76, A 127, Hannover (1991) 317 - 359.

KELTER, D., WELLMER, F.-U., Is the Introduction of a 3 Dimensional Coal Reserve/Resource Classification System desirable ? (1992) (in press).

NOBLE, A. C., Geologic resources vs. ore reserves, Mining Engineering, February 1993, 173 - 176.

ÖSTERREICHISCHE NORM, (ÖNORM) G 1050 (1989).

THE INSTITUTION OF MINING AND METALLURGY, London 1991, Definitions of reserves and resources (1991).

Uranium Resources, Production and Demand 1991.- Joint Report OECD Nuclear Energy Agency and International Atomic Energy Agency, Paris 1992, 255 p.

POSSIBILITY OF NEW URANIUM DISCOVERIES IN THE ENVIRONS OF DOMIASIAT, MEGHALAYA, INDIA

K.K. DWIVEDY
Atomic Materials Division, Hyderabad, India

Abstract

The discovery and proving of a large, near-surface, sandstone-type uranium deposit at Domiasiat, West Khasi Hills district, Meghalaya in the Upper Cretaceous Lower Mahadek Formation constitutes a major breakthrough in uranium exploration in the sedimentary environments in India. It has brightened the prospects of finding similar deposits elsewhere in India, notably in the areas adjoining Domiasiat. The most promising localities in this context appear to be those of the plateau areas bordering the ghats in Meghalaya where arenites overlying the fertile granitic basement, show distinctive fluviatile characteristics, and contain abundant reductants like carbonaceous matter and biogenic pyrite. So far, about 20% of the total exposed area (1100 km^2) of the Mahadek Formation in Meghalaya has been covered by radiometric surveys and numerous uranium anomalies have already been recorded in the contiguous areas. Exploratory and evaluation drilling of some 24 km^2 has enabled the proving of a medium-grade, fairly large tonnage, near-surface deposit at Domiasiat, amenable for open-cast mining. Based on the case history of Domiasiat uranium deposit and others along with exploration strategies evolved over two decades, a number of potential localities have been identified in areas adjoining Domiasiat. These include Nongmalang, Phlagdiloin, Rangjadong, and Mawkyrwat. Exploratory and evaluation drilling could prove significant additional resources in this part of the Meghalaya Plateau.

1. INTRODUCTION

Uranium exploration in the Mahadek Formation of Meghalaya was initiated in 1962, and the first radioactive anomaly was located near Dauki by radiation jeep survey. Exploration efforts in the Meghalaya Plateau are severely constrained by the hostile terrain (deep gorges), lack of road, communication, and logistic facilities, and inclement weather due to rains. In the initial years of exploration, the radioactive anomalies located were both uraniferous and thoriferous. A significant breakthrough was achieved in 1974 with the discovery of highly uraniferous horizons associated with the fluvial facies of the Lower Mahadek Formation in the Umrynga river section at Tarangblang in Jaintia Hills district, where a sample of coalified wood analysed 10% U_3O_8 [1]. Uranium anomalies were also located a year later near Gomaghat in the marginal marine facies rocks of the Lower Mahadek Formation [2]. Thus, the Upper Cretaceous, Lower Mahadek Formation, occurring all along the southern periphery of the Meghalaya Plateau, became a major and potential stratigraphic horizon for the search of sandstone-hosted uranium deposit [3].

Uranium investigations in the Upper Cretaceous, Lower Mahadek Formation of Meghalaya persisted and gained momentum with the discovery of large number of uranium occurrences resulting from the geological knowledge gained from existing prospects and developing the concept of geomorphic domains and their sedimentalogical characters [4]. Two geomorphic domains, namely the 'Plateau Domain' with a distinct fluviatile and the 'Ghat Domain' with marginal-marine characteristics were recognised. Exploration efforts were intensified in the 'Plateau Domain' which resulted in the discovery of impressive uranium anomalies around Phlangdiloin [5] and Domiasiat [6]. Subsequently, detailed investigation brought to light numerous potential blocks, namely, Killung, Rangam, Umla, Pyrnotbri, Jimrey and Tyrkhang spread over an area of 10 km^2 in and around Domiasiat [7]. Exploratory and evaluation drilling taken up in the Killung and Rangam blocks has established a commercially viable sandstone-type uranium deposit, so far the largest of its kind in India. This has enlarged the possibility of new uranium discoveries in the 'Plateau Domain' of Meghalaya, especially in the environs of Domiasiat.

The paper discusses in detail, the nature of uranium mineralization associated with the Lower Mahadek Formation of the Meghalaya Plateau with special reference to the genetic model developed for the Domiasiat uranium deposit. The possibility of locating new uranium discoveries based on the Domiasiat model is explored, especially in the West Khasi Hills adjoining Domiasiat.

2. GEOLOGY

The Meghalaya Plateau is a uplifted horst like feature, bordered by the E-W trending Dauki fault to the south and the Brahmaputra graben to the north. The plateau, considered to be the northeasterly extension of the Indian Peninsula, is comprised of Archaean gneisses and schists and the Middle Proterozoic Shillong Group of rocks with intrusions of Upper Proterozoic Mylliem (607 $\pm$ 13 Ma), Kyrdem (479 $\pm$ 26 Ma), Nongpoh (550 $\pm$ 15 Ma) and South Khasi (690 $\pm$ 19 Ma) granitic plutons (Fig. 1), [8, 9, 10, 11]. The generalized stratigraphic sequence of the Meghalaya Plateau is given in Table I.

The post-Cambrian landmass of Meghalaya experienced peneplanation until Jurassic (?), by the end of which the eruption of plateau basalts, the Sylhet Traps has taken place through E-W fissures i.e., Raibah fault along the southern margin of the plateau. Compositionally, Sylhet Trap includes basalt, alkali basalts, rhyolites, tuffs, and andesites [12]. These traps are overlain, with a pronounced unconformity, by a thick pile of Upper Cretaceous-Tertiary sedimentary rocks.

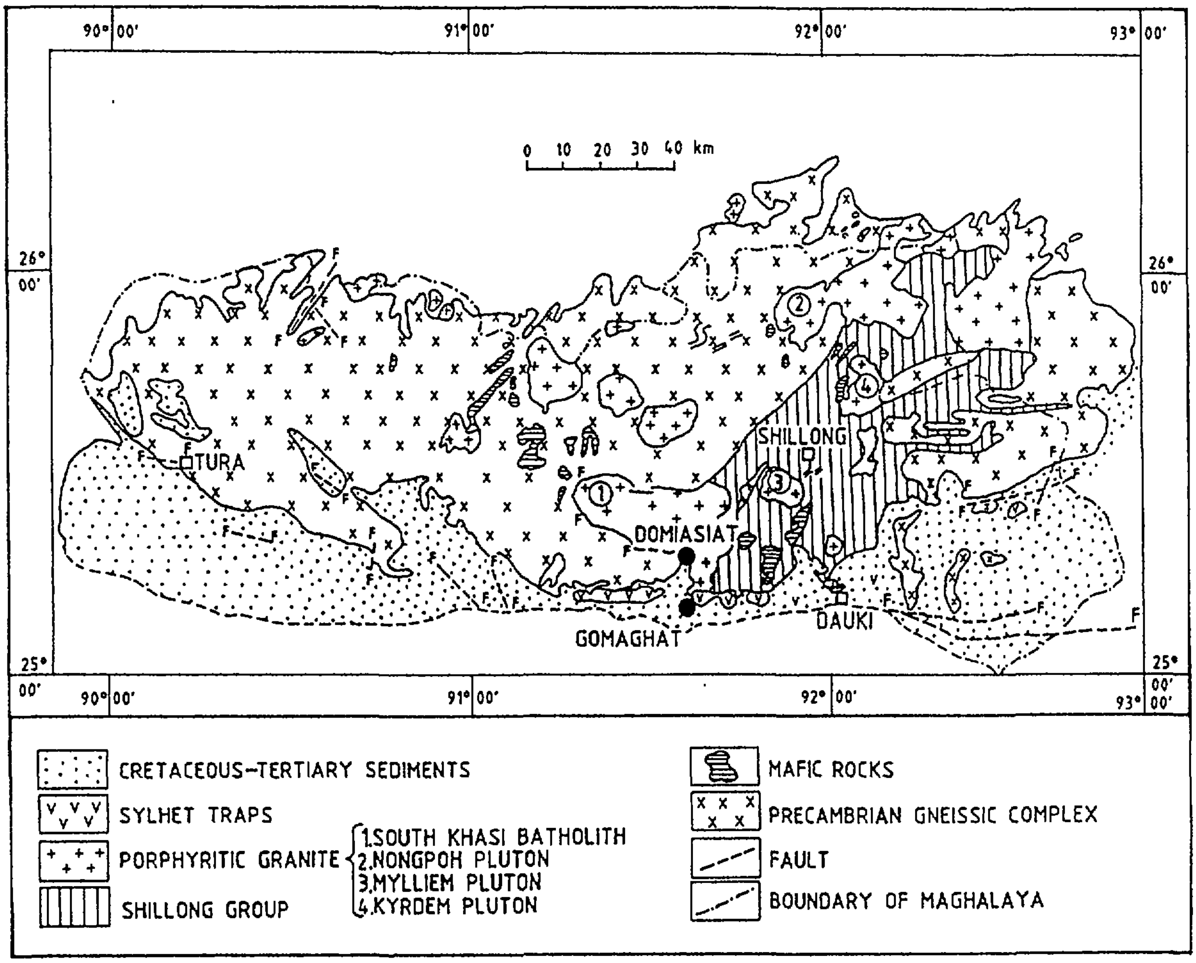


FIG. 1. Geological map of Meghalaya plateau.

TABLE I. STRATIGRAPHIC SUCCESSION OF THE MEGHALAYA PLATEAU (MODIFIED AFTER [13] AND [8])

Geological Age	Group	Formation	Lithology
Miocene Oligocene	Garo	Chengapara 700 m	Sandstone, siltstone, clay and marl.
		Baghmara 530 m	Feldspathic sandstone, conglomerate and clay.
		Kopili-Rewak 500 m	Shale, sandstone and marl.
Eocene	Jaintia	Shella 600 m	Alternation of sandstone and limestone.
Palaeocene		Langpar 50-100 m	Calcareous shale,sandstone and impure limestone.
Upper Cretaceous	Khasi	Mahadek 215 m	Upper, medium to fine-grained purple sandstone (ca.190 m)
			Lower gray, coarse to medium-grained sandstone (25 - 60 m)
		Jadukata 235 m	Sandstone-conglomerate alternations.
........................Unconformity...........................			
Jurassic	Sylhet Trap		Basalt, alkali-basalt, and acid tuff, Alkaline rocks and carbonatite complexes.
........................Unconformity...........................			
Late Proterozoic	Mylliem		Coarse,porphyritic granite, pegmatite, aplite, and quartz veins. Epidiorite and dolerite.
Middle Proterozoic	Shillong		Phyllite-quartzite sequence with basal conglomerate.
........................Unconformity...........................			
Archaean	Gneissic		Biotite gneiss, granite gneiss, migmatite, mica-schist, sillimanite-quartz schist, granulite.

The Upper Cretaceous - Tertiary sediments are affected mostly by basement controlled faults, and consist mainly of sandstone and shale (mudstone), except for the three well defined fossiliferous limestone horizons [13] The lowermost sedimentary sequence overlying the Sylhet Traps (Ref. Table I) is called the Jadukata Formation which is a marine facies comprising an alternation of conglomerate and sandstone (with characteristic zonal fossil — Inoceramus). These are overlain by the Mahadek Formation which is divisible into a relatively thinner (25-60 m) lower unit and thicker upper part (ca. 190 m).

The Lower Mahadek Formation consists of medium-to-coarse grained, grayish-green, feldspathic, fluviatile sandstone with abundant carbonaceous matter and framboidal pyrite indicating anaerobic environment at the time of deposition and diagenesis. The Upper Mahadek Formation, on the other hand is an oxidized, yellowish to purple brown, coarse arkosic sandstone.

The Mahadek Formation is overlain by the Jaintia Group of rocks with Langpar Formation (Upper Cretaceous-Palaeocene) followed by the Shella Formation of Eocene age. The deposition of these sediments marks the beginning of a stable shelf condition, which was firmly established later with the deposition of the Shella Formation (600 m thick), represented by the alternating limestone and sandstone sequence. Thereafter, the basin became shallow which is clearly indicated by the dominance of the arenaceous sediments with minor argillaceous and calcareous sediments of Garo Group during Oligo-Miocene time.

3. DEPOSITIONAL ENVIRONMENT

The depositional environment of the sandstone during Cretaceous was mainly governed by the evolution of the Meghalaya Plateau. The continued uplift of the Meghalaya Plateau resulted in N-S to NE-SW block faulting and the development of the subsequent NE-SW and N-S drainage.

By the end of Jurassic the southern margin of Meghalaya Plateau experienced eruption of the Sylhet Traps, through E-W fissures, i.e., Raibah fault which was a precursor to the major uplift of the plateau, and the later carbonatite activity along the NE-SW Tyrsad-Barapani rift system [14, 15]. Along the Raibah fault, the southern block subsided and the northern block moved upwards [8]. This was followed by a phase of marine transgression resulting in the deposition of the Jadukata Formation. Further uplift of the Meghalaya Plateau appears to have continued along the linear faults and rifts in a step-like manner which resulted in marine regression after which the fluviatile Lower Mahadek Formation was deposited. Subsequent fluctuation of the sea level led to the deposition of the marginal marine Upper Mahadek Formation.

The rate of subsidence gradually slowed down towards Palaeocene-Eocene times during which the area attained a stable shelf condition and the calcareous formations of the Jaintia Group were deposited. These fresh water and marine formations lie partly over the Sylhet Traps in the south and partly over the crystalline basement to the north of the Raibah fault. After the deposition of the Mesozoic and Tertiary sedimentary formations, there was a major down faulting along the E-W trending Dauki fault. This resulted in the down faulting of the Sylhet Trap along with Upper Cretaceous-Tertiary sediments and subsequently thick alluvium covered the Bangladesh plains (Figs 2 and 2a).

The granite and gneisses together with the Shillong Group of rocks have provided a fertile provenance for the deposition of uranium along the tectonic-cum-erosional depressions during deposition of the fluviatile Mahadek Formation. The reactivated basement floor and the fertile basin rim rocks also have contributed uranium to the basin.

At Domiasiat, due to the block faulting, a depression was formed in which the poorly sorted lithic fragments and coarse mineral fragments were deposited [16]. Rapid deposition and burial in such depressions precluded the oxidation of the carbonaceous matter with the development of iron disulphides.

The Lower Mahadek sandstones are medium-, to coarse-grained, poorly sorted, the mean size varies from 0.36 to 0.71, negatively skewed (fines exceeding coarse) and are commonly leptokurtic to mesokurtic [17]. The Lower Mahadek Formation represents deposition by a system of continuous current.

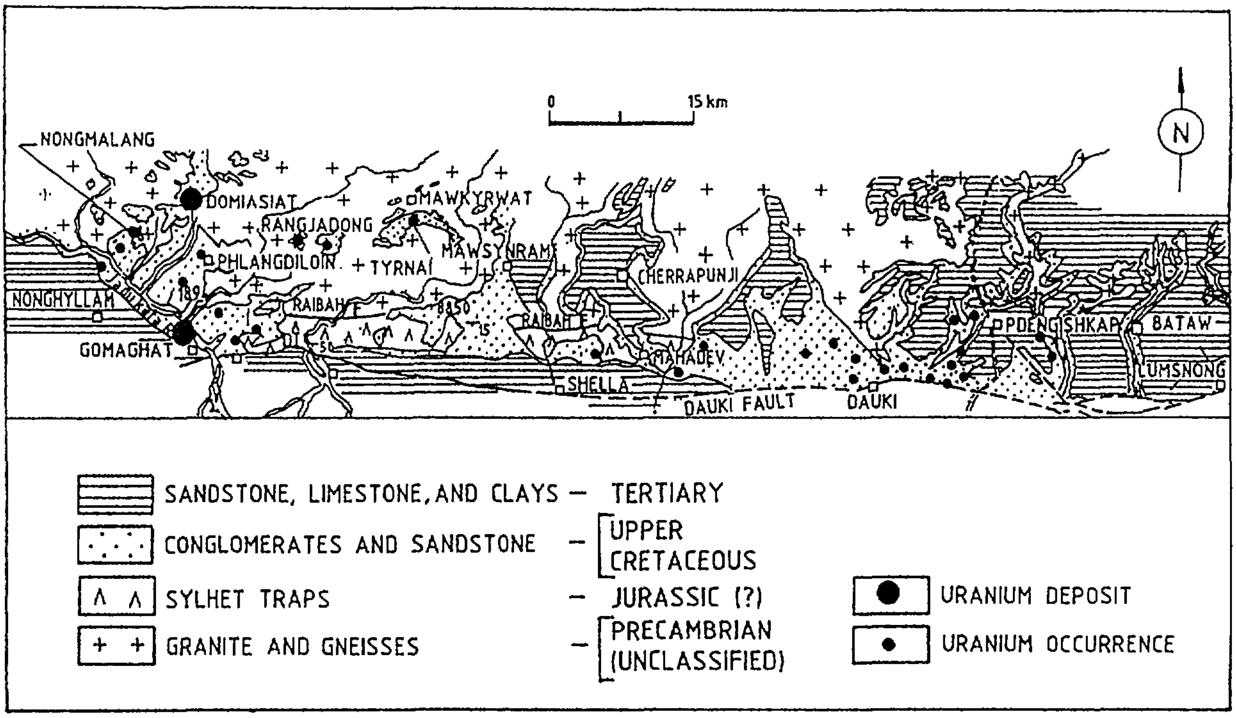


FIG. 2. Geological map of parts of West Khasi, East Khasi, and Jaintia Hills districts of Meghalaya.

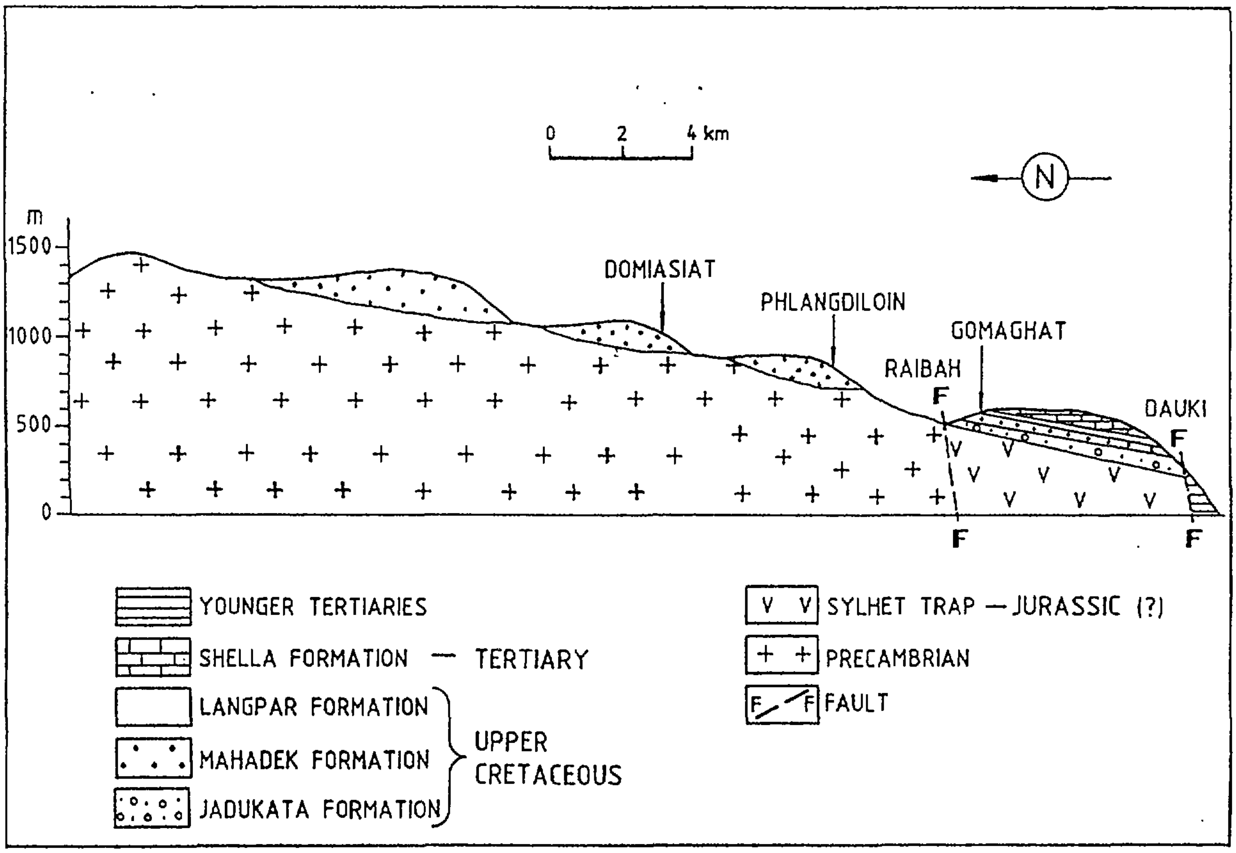


FIG. 2a. Generalized geological section along the north-south line of the southern part of the Meghalaya Plateau.

Generally the Upper Mahadek sandstones are medium to fine-grained, finely to coarsely skewed and meso-to-leptokurtic. The two sub-populations of saltation load indicate beach/offshore to shallow marine deposition (Fig. 3). The plots of graphic standard deviation against skewness for the Mahadek Formation indicate that the Lower Mahadek samples mostly lie in the fluvial environment and the Upper Mahadeks with beach environment (Fig. 4).

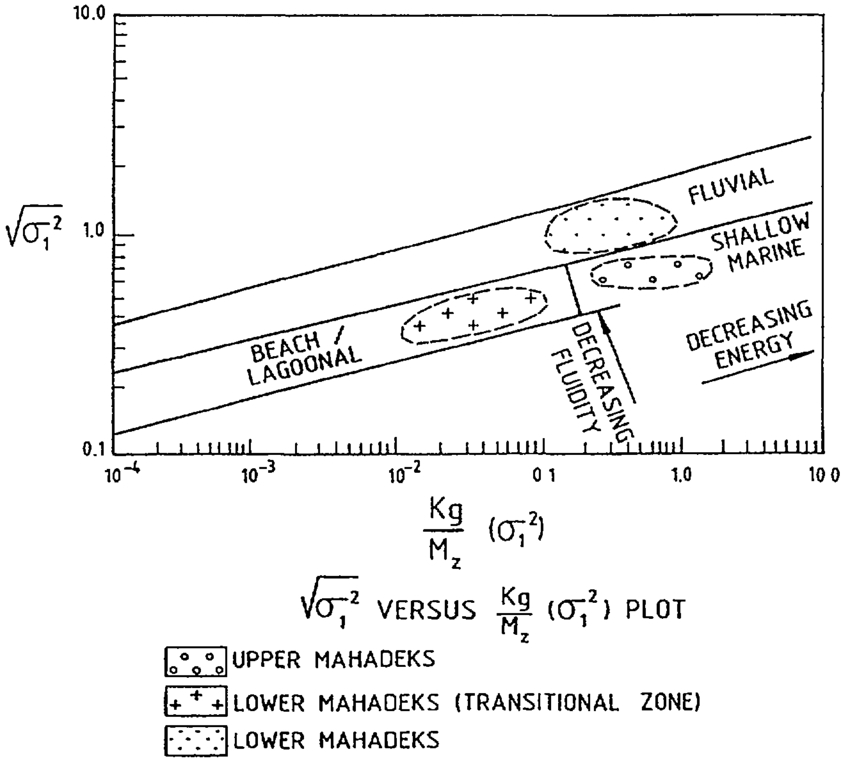


FIG. 3. Sedimentary environmental patterns in the Mahadek Basin.

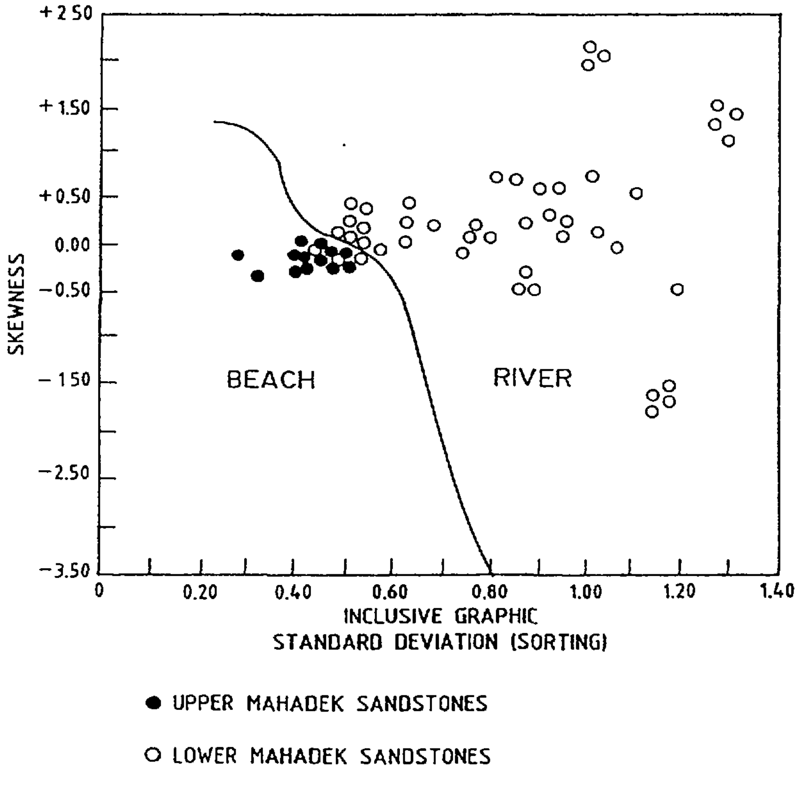


FIG. 4. Plot of skewness vs sorting coefficients of Mahadek sandstones.

Detailed work in and around Domiasiat has revealed two facies of Lower Mahadek sandstones, namely channel-filled, cross-bedded, unsorted, quartz arenite/feldspathic arenite with lithic fragments, flanked by massive sandstones corresponding to flood plain deposition (Figs 5 and 5a; [16] and [18]). The channel filled arenite abounds in carbonaceous matter and pyrite, and host the major uranium horizons, whereas the massive sandstones with lesser amounts of carbon and pyrite contain minor mineralized lenses.

4. URANIUM MINERALIZATION

4.1. Host rock

The Lower Mahadek sandstone is the main host rock for uranium mineralization. The mineralized sandstones are light to dark coloured depending mainly on the type and relative concentration of cementing material, such as carbonaceous matter, kaolinite, iron hydroxide [19]. It is friable to highly compact, medium to coarse and occasionally very coarse-grained (pebbly). At places like Domiasiat and Pdengshakap, variation from pebbly to medium grain size are seen within a shallow depth of 5-10 m, reflecting changes in energy levels of the transporting and depositing medium.

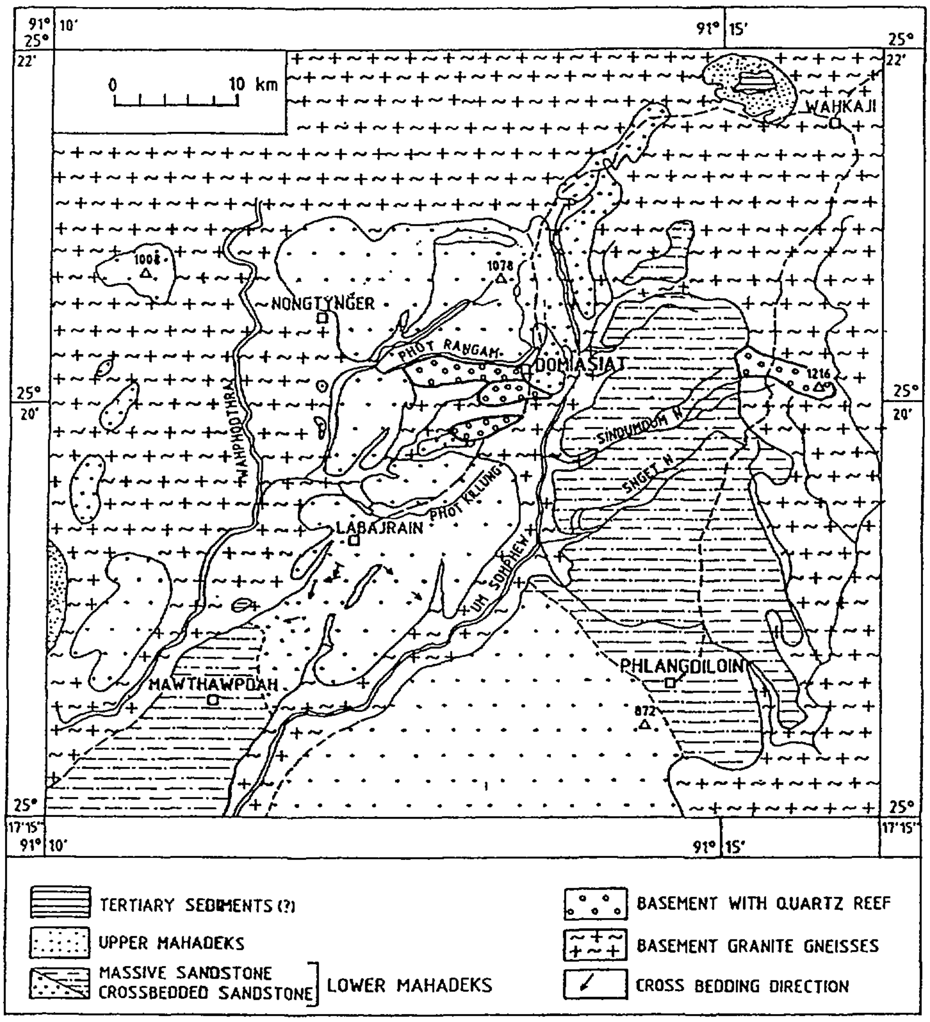


FIG. 5. Geological map of Domiasiat area.

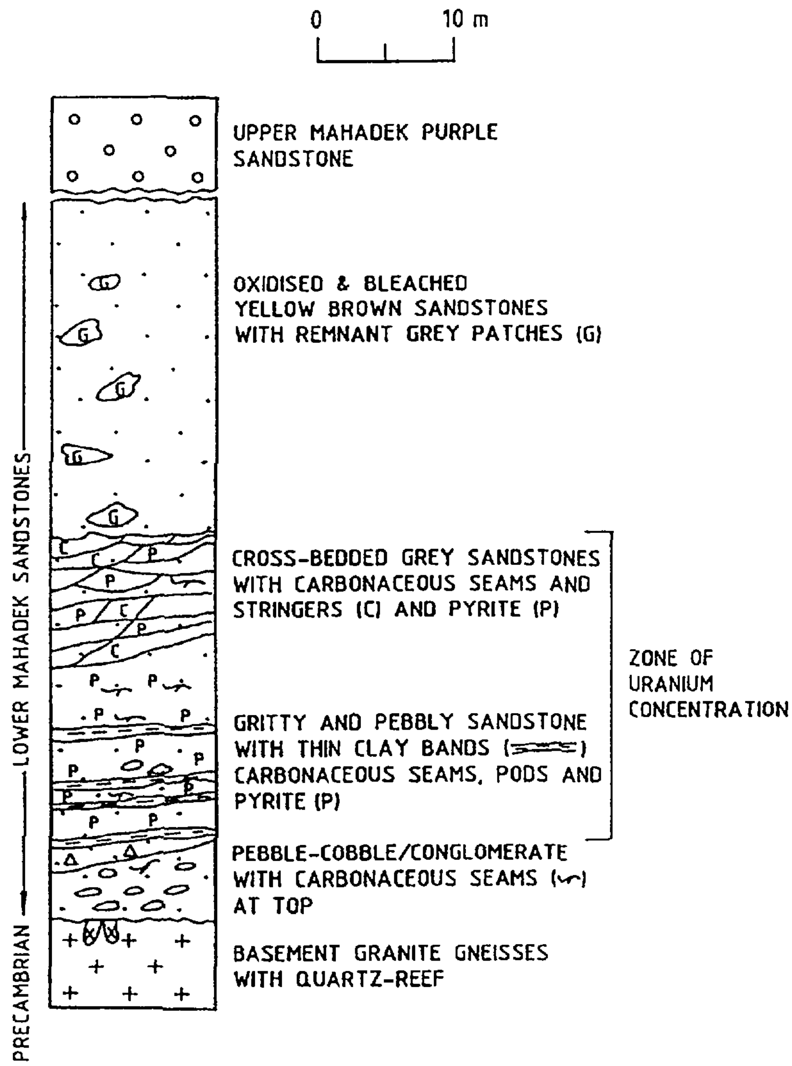


FIG. 5a. Generalized vertical litholog of the Domiasiat area.

Thin section study indicated that the sandstones at Domiasiat are composed of 90% clasts with about 10% matrix. Among the clasts, subangular to angular quartz is predominant (70-90%) followed by minor (5-15%) feldspar (microcline ± albiteoligoclase and perthite), and rock fragments (2-3%), with accessory minerals such as garnet, zircon, monazite, rutile, anatase, sphene, apatite, and opaque oxides. The sandstone of this composition corresponds to a quartz-arenite type [20].

The matrix which is usually low includes sericite (Pdengshakap), chlorite (Gomaghat) and chlorite plus mica (Domiasiat). Different types of cement occur in the sandstone and these include the commonly present carbonaceous matter and goethite. The carbonaceous matter with which most of the radioactivity is associated is a low rank coal of bitumen type. Pyrite is framboidal and colloidal (melnicovite) type, pointing to low temperature of its formation [19, 21]. The important diagenetic changes are the formation of different types of clays and cement.

4.2. Mineralogy

The alpha track distribution on CN film and microscopic studies reveal that uranium at Domiasiat is preferentially concentrated in organic matter and clay matrix, besides being present as pitchblende (11-12% reflectivity at 544 nm) and coffinite (8.5% reflectivity at 544 nm) within the organic matter [16]. Minor radioactivity is also contributed by nonmetamict zircon, monazite, goethite and leucoxene. The identification of the pitchblende is confirmed by X ray diffraction [22] and that of coffinite by UM_{α} and Sik_{α}electron microprobe X ray imaging [16]. The concentration of alpha tracks from parts of coal containing pyrite is more than the adjoining pyrite free parts, pointing out that uranium has precipitated from U-bearing solution when it encountered the reducing environment provided by either carbon or pyrite or both.

At Domiasiat, most of the uranium is present in hexavalent state, with high UO_3/ UO_2 ratios ranging from 4-7. These high ratios indicate that much of the adsorbed uranium in the carbonaceous matter occurs as uranyl ion. The low temperature of mineralization is corroborated by presence of framboidal pyrite and melnicovite pyrite (colloidal pyrite), besides low rank carbonaceous matter (bitumen).

4.3. Nature of mineralized horizons

In general, the ore body is tabular in majority of the areas where considerable amount of uranium mineralization has been established. At Domiasiat, the ore body is essentially tabular (Figs 6 and 7). The mineralized horizons occur mainly within the lower gray sandstone capped by the purple to red-brown oxidized sandstone. Ore zones occur somewhat perched, a few metres to some 10 m above the granitic basement. The thickness of the mineralized horizon varies considerably, ranging from 1 to 30 m both along and across the strike of the formation. The average thickness of the ore zone is 3.70 m. Uraniferous zones intercepted in the boreholes consist of two well correlated principal lodes, designated as the hanging wall and the main lode. A third lode, named as the footwall lode, is prominently marked in the eastern side of the Killung block (Fig. 8). Besides these three lodes, there are several subsidiary mineralized bands of limited extent.

The thicker horizons have a central or core part which is relatively more mineralized with higher grade. The cap rock (overburden) is from a few metres to about 20 m with an ore to overburden ratio of 1 : 6.7, thus making the deposit easily amenable to open cast mining.

5. GENETIC MODEL

The genesis of uranium mineralization has been discussed by several workers [3, 16, 18, 23, 24]. These studies revealed a dominantly continental fluvial environment for the Lower Mahadek Formation in the 'Plateau Domain' which hosts the bulk of the known uranium mineralization and a fluviatile - marginal marine Lower Mahadek Formation in 'Ghat Domain'. In general, the uranium mineralization appears to be intimately associated with organic matter in the 'Plateau Domain' whereas in 'Ghat Domain' redox interface appears to have played an important role.

The sandstone hosted uranium deposit at Domiasiat appears to have formed, as a result of several favourable factors, normally encountered in a large majority of the sandstone-type uranium deposits [25]. The bulk of the uranium was introduced into the basin from extrinsic sources followed by remobilisation. The South Khasi batholith and Mylliem granite contain anomalous uranium (7 to 110 ppm) and have apparently provided uranium-rich detritus to the Mahadek sediments. The confluence of braided system channels provided the ideal sites for greater accumulation of organic and plant debris. The diagenetic compaction and gradual removal of water from these sediments caused the enrichment of uranium in the connate water [18]. The interaction of connate water, rich in soluble uranium complex at the confluence of braided channels, with abundant decaying plant matter and H_2S led to the precipitation of pitchblende and urano-organic complexes. The close association of U- phases and pyrite in organic matter with negative δ S^{34} values (-1.1, -4.0, and -3.2 per mil), relative to the Canyon Diablo Standard are suggestive of common biological processes.

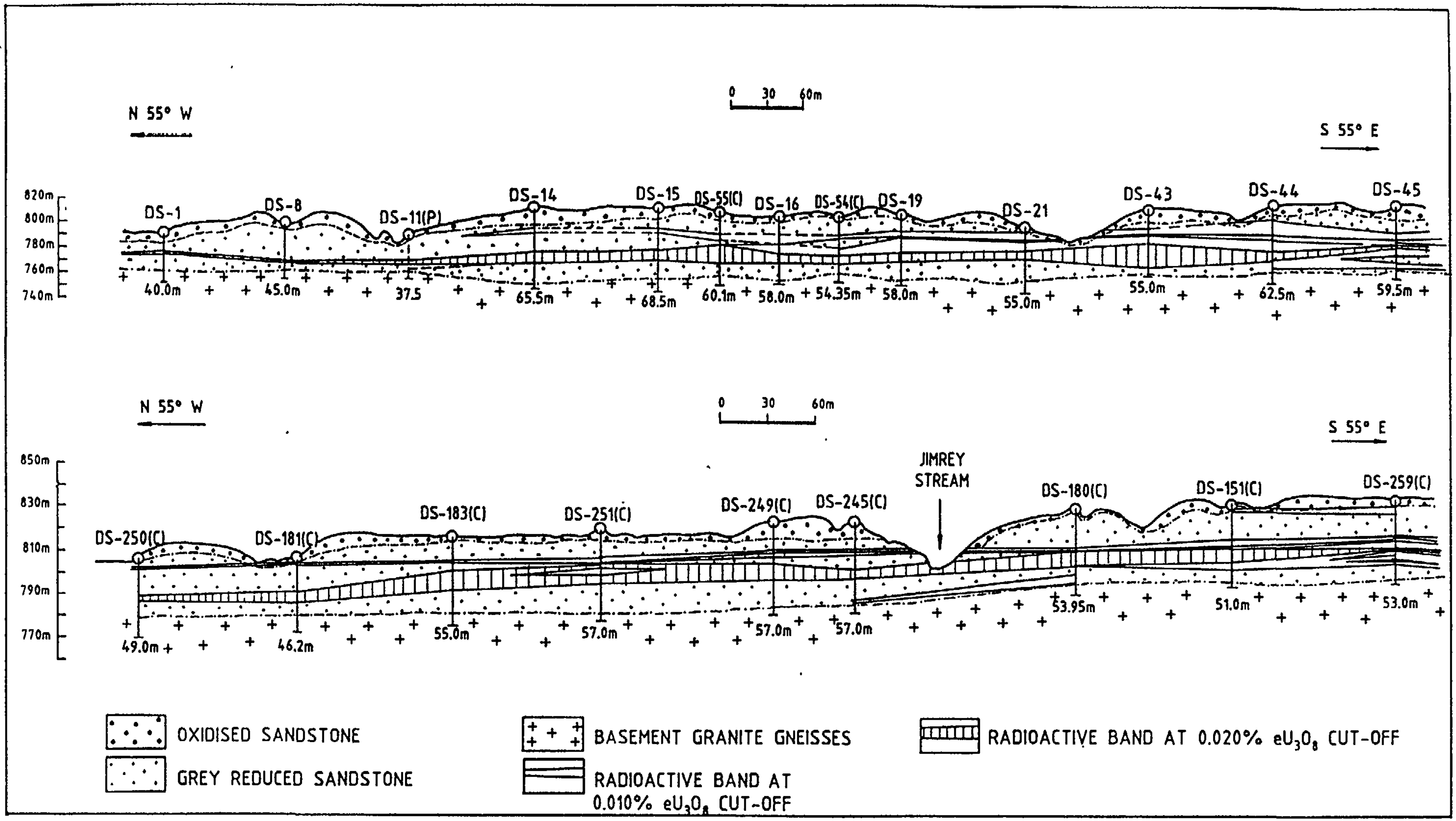


FIG. 6. Strike section of the Domiasiat ore body.

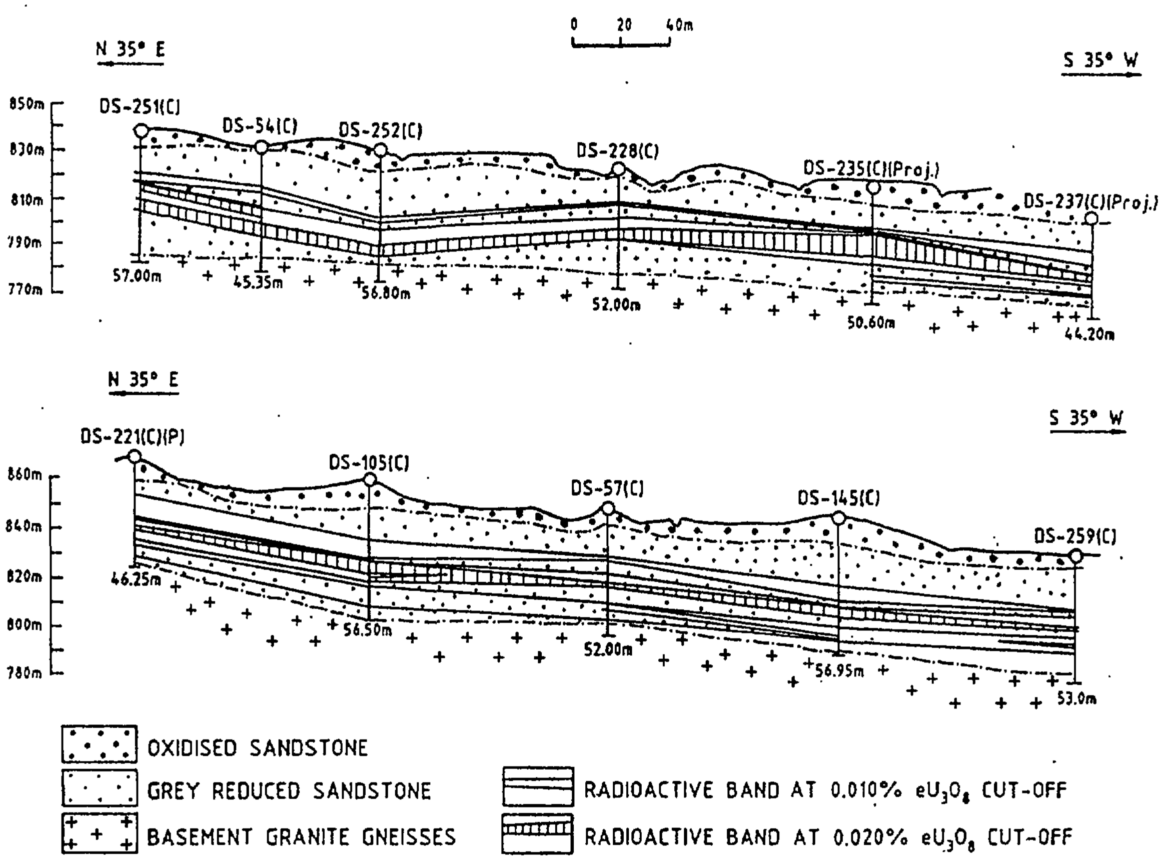


FIG. 7. Dip section of the Domiasiat ore body.

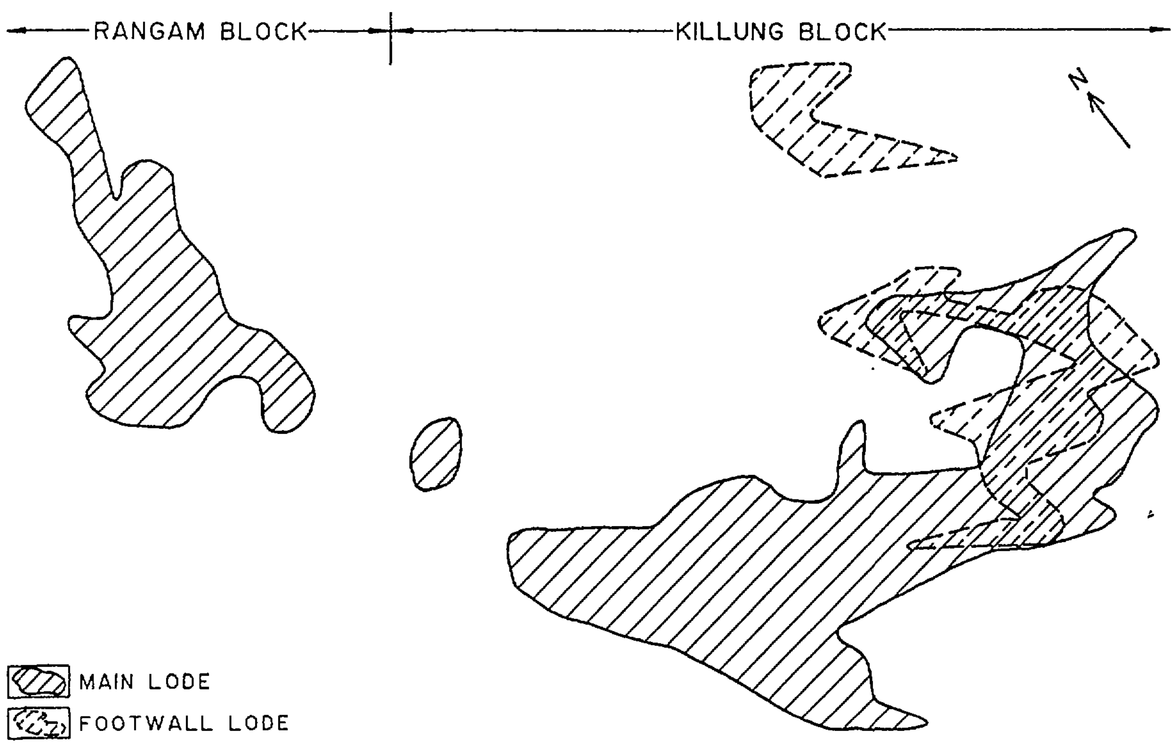


FIG. 8. Configuration of the ore body in Killung and Rangam blocks of the Domiasiat uranium deposit.

The continued uplift of the Meghalaya Plateau may also have provided fresh pulses of uranium bearing solution to the basin. Basement faults, which control the channels, have facilitated solution movement. The presence of oxidized cap rocks, with relict (?) mineralized horizon and gray sandstone patches in some of them suggests that uranium has also been leached from them by oxygenated ground water that percolated down along the hydraulic gradient encountering a reducing environment provided by the sandstones containing organic matter derived from the decay of plants below the water table.

Sandstones with intercalated siltstones and clay-rich horizons provided localized permeability barriers and enabled large quantities of uranium-rich solution to interact with greater volumes of organic matter and pyrite-bearing horizons, resulting in thicker mineralized zones and higher grades [16].

Thus, there are several important factors that have contributed to the formation of the uranium deposit at Domiasiat. These include:

(i) close proximity to the fertile granitic provenance,
(ii) activation of basement faults,
(iii) typical proximal sandy, braided-type fluviatile environment,
(iv) presence of appreciable amounts of strong reductants like carbonaceous matter and biogenic pyrite, and
(v) permeability barriers like siltstone and clay-rich horizons associated with sandstones.

In addition, the basement highs and palaeo-lows, together with the low angle dips of the sedimentary beds may also have played a significant role in uranium enrichment.

6. POTENTIAL AREAS

Based on the case history of Domiasiat uranium deposit and understanding of the different sedimentological and geomorphological controls vis-a-vis uranium mineralization, exploration strategy in the extension areas of Domiasiat was undertaken. Out of the several criteria, the foremost was the geomorphological one, i.e., demarcating the Meghalaya Plateau into two domains namely the 'Plateau' and 'Ghat' domains [4]. This was followed by the study of host rock character, sedimentological features, proximity to provenance and the nature of uranium mineralization in the anomalous zones. Other inputs such as remote sensing techniques were also used, especially to decipher different lithologies, structures, and geomorphological features (small semicircular mounds) that are favourable to ore formation and preservation [26]. In addition, geophysical surveys were also conducted to decipher basement topography and palaeo channels which have controlled the depositional trend vis-a-vis uranium mineralization [27].

The 'Plateau Domain' comprises the areas lying north of the Raibah fault, an east-west trending boundary fault, roughly along Lat. 25°15' in the East Khasi Hills and West Khasi Hills districts (Ref. Fig. 2). Thereafter, it takes a south easterly turn in the Jaintia Hills district, separating the Jurassic Sylhet Trap in the south and the Precambrian in the north [24].

A variety of features in the 'Plateau Domain', as deciphered for the Domiasiat deposit, were considered in order to select the most favourable areas for exploration, and in assigning priority to a particular sector. A number of such sectors have been identified for detailed exploration including drilling which could augment existing uranium resources. The salient features of these sectors along with anomalies discovered are given in Table II.

TABLE II. POTENTIAL SECTORS OF URANIUM MINERALIZATION IN AREAS ADJOINING THE DOMIASIAT URANIUM DEPOSIT.

S.No.	Sector*	Host rocks	Uranium anomalies**	Salient features	Remarks
1.	Domiasiat	Feldspathic sandstone	Exposed along stream sections at Killung, Rangam, Umla, Pyrontbri, Jimrey, and Tyrkhang (0.013-0.4% U_3O_8)	Sediments 30-60 m thick. Proximal, sandy, braided type with palaeo-highs and lows. Gray, immature sandstone and conglomerate with impersistant clay bands. Abundant carbonaceous matter and pyrite. Geomorphological features namely semi-circular mounds, sub-dendritic drainage and direct contact with basement granite along the cuesta slope are observed.	About 23,975 m have been drilled by completing 550 boreholes which resulted in establishment of a mineable uranium deposit at Killung and Rangam Block.
2.	Nongmalang	Feldspathic sandstone	Napsier, Phut Yapsir, Unatong Thawke, Phut Shamran, Wah Blei, Wah Ding Rang (upto 20 x bg)	West of Domiasiat Thickness of sediments gradually increases in south, reaching 60-65 m. The sandstones are medium to coarse grained and cross bedded with abundant carbonaceous matter and pyrite. Similar geomorphological features, as that of Domiasiat are observed in the Wah Blei area.	Taken up for survey in 1993.
3.	Phlangdiloin	Feldspathic sandstone	Phlangdiloin, Langpa, Phlangmawphra, Phud Mawrang, Phud Khandrowo, Sateek Photsophei, Luiyang (0.01% - 0.25% U_3O_8)	East of Domiasiat. Abundant carbonised wood and disseminations of carbonaceous matter. Cross bedding is common. Similar geomorphological features, as that of Domiasiat are observed in the south and south east of Phlangdiloin.	About 20,535 m has been drilled by completing 343 boreholes which resulted in proving a small tonnage uranium deposit at Sateek Block.
4.	Rangjadong	Feldspathic and argillaceous sandstones	Mawkhorang, Phud Ktiti, S. Rangjndong, Lav Lyngdoh, Phud Didoh, Phud Rang. (upto 20 x bg)	Sandstones with appreciable amounts of carbonaceous matter and pyrite.	Taken up for survey in 1993.

Table 2 continued

S.No.	Sector*	Host rocks	Uranium anomalies**	Salient features	Remarks
5.	Mawkyrwat	Feldspathic and argillaceous sandstones	Tyrnai, Nonglong, Nongmawmairang, Rangmaw, Phud Haap, Phud Rethli, Phud Siaith (0.013% - 0.2% U_3O_8)	Tabular sheet-like body. Two distinct sedimentary units are recognised, viz., the cross bedded and massive unit. Carbonaceous matter, pyrite and honey coloured resin is very common. Uranium minerals identified are coffinite and davidite.	Limited amount of drilling (7130 m) has been completed by drilling 144 boreholes. A small tonnage of uranium oxide is estimated at Tyrnai block.
6.	Mawsynram	Calcareous sandstone	Kenshluid and Juneo (0.011% to 0.13% U_3O_8)	There is a major fault trending NNW-SSE just south of Mawsynram and the litho-units differ on both the sides.	Unlike Domiasiat, uranium anomalies are associated with Langpar and Jadukata Formations.
7.	Cherrapunji	Arkosic, gritty sandstone	Mawsahew, Palang, Mynteng, Nongriat, Thymmai (0.005% to 0.18% U_3O_8)	Coarse-gritty sandstone grades into greenish grey massive sandstone.	Exploratory drilling has been taken up in 1993. The Mahadeks are overlain by Langpar and Shella Formations. Geophysical surveys would be rewarding.
8.	Pdengshakap-Tarangblang	Arkosic sandstone	Umrynga Valley, Umbeng stream, Umtryngai, Umrethneng (0.010% to 0.030% U_3O_8)	Radioactivity confined to the top and bottom parts of sandstone and associated with carbonaceous matter. The sediments are fluvial in north, grading into marginal-marine (glaûconite) sandstone towards south; Uranium mineralization is lensoidal in nature. Uraninite and coffinite are identified.	In all 16 boreholes with 2450 m drilled in this sector. The gamma-ray logging indicate very lean, uncorrelatable mineralisation. The Mahadeks are overlain by Langpar and Shella Formations. Geophysical surveys would be rewarding.
9.	Bataw - Borghat	Arkosic sandstone	Umthren, Tympiaksu, Pahngi, Umtelia (0.005% to 0.053% U_3O_8)	The radioactivity is essentially associated with carbonaceous matter.	Uranium mineralization is localised. The Mahadeks are overlain by Langpar and Shella Formations. Geophysical surveys would be rewarding.

* Delineation based on similarity in geology, structure, and geographic/physiographic features, and proximity to the fertile provenance.

** Assay values given in parenthesis are the range of average values for the different blocks in sectors at S.No. 1,3, & 8 and range of values in rest of the sectors.

7. SUMMARY AND CONCLUSIONS

Uranium exploration in the Mahadek Formation of the Meghalaya Plateau is over three decades old. Exploration efforts have been sustained and continued in spite of severe constraints and lack of spectacular success imposed by the hostile terrain and inclement weather during most of the year. The identification of the Upper Cretaceous Lower Mahadek Formation as a potential host rock for uranium during the 1970s, and the discovery and proving of the Domiasiat uranium deposit in early 1980s represents a major breakthrough in the uranium exploration in the sedimentary environments in India, and notably in the Meghalaya Plateau.

The most important factors that guided the successful exploration programme include understanding the evolution of the Meghalaya Plateau and identification of two geomorphic domains, namely the 'Plateau' and 'Ghat', which have an important bearing on the sedimentary environment and uranium mineralization. The sedimentary environment of these two domains had an important role in providing favourability for localizing uranium mineralization. The identification of the fluviatile environment, notably the proximal, sandy-braided channel-type of Domiasiat, its location in close proximity to the fertile granitic provenance with immature quartz arenite, and abundant carbonaceous matter as reductants have been important factors. Detailed geological, and mineralogical studies at Domiasiat have contributed to a better understanding of the genetic evolution of the deposit.

Exploration strategy based on the Domiasiat example as well as direct and remote sensing techniques has led to the identification of a number of sectors such as Nongmalang, Phlangdiloin, Rangjadong and Mawkyrwat which along with the Domiasiat sector appear to be the most promising. The possibilities of finding additional resources in several of these sectors are very bright.

ACKNOWLEDGEMENTS

The author expresses his gratitude to Dr. R.Chidambaram, Chairman, Atomic Energy Commission, India for permission to present this paper. He thanks his colleagues in the North Eastern Region and in the laboratories of the Atomic Minerals Division for their contributions on various aspects of geology and uranium mineralization. The assistance received from S. Hamilton and P. Krishnamurthy during the preparation of the manuscript, and the Drawing section in the preparation of the illustrations are thankfully acknowledged.

REFERENCES

[1] GUPTA, R.K., and VEERABHASKAR, D., Detailed radiometric survey, geological mapping and exploratory drilling for uranium in parts of Jaintia Hills district, Meghalaya. Unpubl. Rept. At. Minerals Div., Hyderabad, India (1975).

[2] ALI, M.A., and SINGH, A.K., Report for the field season 1975-76. Unpubl. Rept. At. Minerals Div., Hyderabad, India (1976).

[3] SARASWAT, A.C., RISHI, M.K., GUPTA, R.K., and BHASKAR, D., Recognition of favourable uraniferous areas in sediments of Meghalaya, India. In: Recognition and Evaluation of Uraniferous Areas, Internatl. At. Energy Agency, Vienna (1977) 165-181.

[4] RAJENDRA SINGH, Status report on uranium explorations in Mahadek Formation of Meghalaya for Field Workshop. unpubl.Rept. At. Minerals Div., Hyderabad, India (1986).

[5] TANEJA, P.C., MAITHANI, P.B., GAJAPATHI RAO, R., DIKSHITULU, G.R. and KHARE, M.K., Preliminary report on uranium occurrences in Lower Mahadek sandstones around Phlangdiloin-Langpa areas, West Khasi Hills, Meghalaya. Unpubl. Rept. At. Minerals Div., Hyderabad, India (1983).

[6] SUNIL KUMAR, DIKSHITULU, G.R. and BIKASH SENGUPTA, Investigations for uranium in Phlangdiloin-Langpa - Domiasiat-Mawthapdah area, West Khasi Hills, Meghalaya. Unpubl. Rept. At. Minerals Div., Hyderabad, India (1984).

[7] SENGUPTA, B., BAHUGUNA, R., SUNIL KUMAR, RAJENDRA SINGH, and KAUL, R., Discovery of a sandstone-type uranium deposit at Domiasiat, West Khasi Hills district, Meghalaya, India. Curr. Sci. v.61 (1991) 46-47.

[8] GEOLOGICAL SURVEY OF INDIA, Geology and mineral resources of India, Misc. Publ. 30, Geol. Surv. India (1974) 77 pp.

[9] MAZUMDAR, S.K., A summary of the Precambrian Geology of the Khasi Hills, Meghalaya. Geol. Surv. India. Misc. Pub. no.23 (1976) 311-334.

[10] ACHARYYA, S.K. and CHAKRABORTY, S., Proterozoic crustal evolution of northeast part of the Indian Continent. Seminar on Evolution of Precambrian crust in India, Geol. Surv. India, Calcutta. Abstract vol. (1990) p.1.

[11] GHOSH, S., CHAKRABORTHY, S., BHALLA, J.K., PAUL, D.K., SARKAR, A., BISHUI, P.K., and GUPTA, S.N., Geochronology and geochemistry of granite plutons from East Khasi Hills, Meghalaya. Jour. Geol. Soc. India, v.37 (1991) 31-342.

[12] TALUKDAR, S.C., Rhyolite and alkali basalt from the Sylhet Traps, Khasi Hills, Assam. Curr. Sci., v.36 (1967) 238-239.

[13] CHAKRABORTHY, A. and BAKSHI, S., Stratigraphy of the Cretaceous-Tertiary sedimentary sequence, southwest of Shillong Plateau. Quart. Jour. Geol. Min. Metall. Soc. India. v.44 (1972) 109-127.

[14] TALUKDAR, S.C. and MURTHY, M.V.N., The Sylhet Traps, their tectonic history and their bearing on problems of Indian flood basalt provinces. Bull. Volcanol, v.33 (1971) 602-618.

[15] VEENA KRISHNA, PANDEY, B.K., KRISHNAMURTHY, P., and GUPTA, J.N., Rb-Sr and Nd isotopic systematics of Sung Valley carbonatites, Meghalaya, India : Implications for contemporary sub-crustal upper mantle characterisation. In: Preprint volume, Fifth National Symposium on Mass Spectrometry. Physical Research Laboratory, Ahmedabad, India (1991) 19/1 - 19/4.

[16] KAUL, R. and VARMA, H.M., Geological evaluation and genesis of the sandstone-type uranium deposit at Domiasiat, West Khasi Hills district, Meghalaya, India. Explor. Res. At. Minerals v.3 (1990) 1-16.

[17] MOHAMMAD, H., A petrologic and genetic study of the Mahadek sediments of Cretaceous age in parts of Khasi and Jaintia Hills districts, Meghalaya. Unpubl. Petrol. Rept., At. Minerals Div., Hyderabad, India (1978).

[18] SUNIL KUMAR, RAJENDRA SINGH, BAHUGUNA, R., SENGUPTA,B., and RAVI KAUL, Geological environment of the sandstonetype uranium deposit, Domiasiat area, West Khasi Hills district, Meghalaya, India. Explor. Res. At. Minerals, v.3 (1990) 17-26.

[19] DHANA RAJU, R., PANNEER SELVAM, A., and VIRNAVE, S.N., Characterisation of the Upper Cretaceous Lower Mahadek sandstone and its uranium mineralization in the Domiasiat-Gomaghat Pdengshakap area, Meghalaya. Explor.Res. At. Minerals, v.2 (1989) 1-17.

[20] PETTIJOHN, F.J., POTTER, P.E., and SIEVER, R., Sand and sandstones (2nd Ed.), Springer-Verlag, New York (1987) 553.

[21] NARASIMHAN, D., SUNIL RUMAR, T.S., and KRISHNA RAO, K., Petrographic studies, Unpubl. Ore Dressing Section, Bhabha Atomic Research Centre, Hyderabad, India (1991).

[22] SINGH, K.D.P., Unpubl. Rept. No. XBNE-30/90 XRD Laboratory At. Minerals Div., Hyderabad, India (1990).

[23] KAK, S.N. and MOHAMMAD, H., Genesis and characteristics of uranium mineralization in Mahadek sandstones. Ind. Jour. Earth Sci., v.6 (1979)152-161.

[24] ALI, M.A. and SINGH, A.K., A note on the uranium mineralization in Cretaceous sedimentary rocks near Gomaghat, Khasi Hills, Meghalaya. Rec. Geol. Surv. India, v.112, pt.4 (1982) 17-20.

[25] FINCH, W.I. and DAVIES, J.F., Sandstone-type uranium deposits - an introduction. In: Geological environments of sandstone-type uranium deposits, International Atomic Energy Agency, Vienna (1985) 11-20.

[[26] SHARMA, P.K., MAMALLAN, R., KAK, S.N. and DWIVEDY, K.K., Exploration target identification by remote sensing techniques - A case study from Meghalaya. Proc. Nat. Symp. on Remote Sensing for Sustainable Development, Lucknow (1992) 233-238.

[27] TIKU, K.L., SUBBA RAO, J.R., ANANTHARAMAN, K.B., and BHALLA, N.S., Magnetic survey at Pdengshakap area, Jaintia Hills district, Meghalaya. Unpubl. Rept. At. Minerals Div., Hyderabad, India (1977).

URANIUM RAW MATERIAL BASE OF THE REPUBLIC OF KAZAKHSTAN

A.A. ABAKUMOV
KATEP, Alma-Ata, Kazakhstan

Abstract

The report is composed of three sections: 1) development history of the uranium raw material base in Kazakhstan, 2) commercial genetic types of uranium deposits of Kazakhstan and 3) general uranium reserves and resources of the Republic of Kazakhstan. Section 1 gives a survey of stage-by-stage implementation of prospecting and exploration works on the territory of Kazakhstan as well as of forming of uranium ore provinces and formation of uranium raw material base. Section 2 gives a summary of commercial types of uranium deposits from genetic positions. The uranium deposits of Kazakhstan are divided into two major series: endogenous deposits in pre-Mesozoic formations and exogenous deposits in Mesozoic and Cainozoic formations. The endogenous series contains vein-stockwork deposits in Proterozoic and Paleozoic complexes within the Kokshetav uranium ore province and vein-stockwork deposits in land volcanogenous complexes of the Probalkhash uranium ore provinces. The exogenous series contains -phosphate uranium ore formation (deposits of Pricaspian province), epigenetic uranium ore formation of regional zones of stratum oxidation (deposits of Chu-Saryssu and Syr Darya provinces) and epigenetic uranium ore formation of zones of ground-stratum oxidation (deposits of Ily province). Section 3 is dedicated to uranium reserves and resources distribution on the basis of provinces, degree of exploration and cost.

1. HISTORY OF CREATION OF URANIUM MINERAL RAW MATERIAL BASE IN KAZAKHSTAN

Prospecting of uranium was started in Kazakhstan in 1943. During the initial stage of execution of works (1943-1957) most of the territory of the Republic was covered by area land and aeroradiometric prospecting. The works resulted in discovery of several commercial uranium deposits which were originally located in three uranium ore provinces: Kokchetav, Pribalkhash and Pricaspian.

In 1951 in Kendyktas, Central Kazakhstan, the first commercial uranium deposit -Kurdai - was discovered. In 1953-1957 Botaburum and Kizilsai deposits were discovered in effusives of Devonian volcanic belt of Chu-Balkhash watershed.

Since 1953 mining operations of Kyrgyz ore mining combine (future "Yuzhpolymetal" production enterprise) have successfully operated on the basis of discovered deposits in an area called Pribalkhash or Kendyktas-Chuily-Betpakdala uranium ore province.

In 1953 Kubassadyrskoye, Balkashinskoye and Shatskoye uranium deposits were discovered in Northern Kazakhstan. These discoveries gave start to creation of Kokchetav (or Nothern Kazakhstan) uranium ore province. In 1954-1955 Manybaiskoye, Ishimskove and Zaozernoye deposits were discovered here. Later several dozens of deposits were discovered within the Kokchetav uranium ore province, including large deposits such as Vostok, Grachevskoye and Segyzbai.

Since 1957, the Tselinny Mining and Chemical Combine has been operating here. It is involved in mining and uranium ore processing.

In 1954 the large deposit Melovoye was discovered on the Mangyshlak Peninsula, south-west of Kazakhstan, on the basis of which Pricaspiski Mining and Metallurgical Combine (PMMC) has been operating since 1959. Tamakskoye, Tasmurunskoye and Taibagarskoye uranium deposits were discovered during the same period. The region represents a separate uranium ore province which continues to be a raw material base for PMMC.

The next period, from 1957 up to 1968, was a transition stage on the way to discovery of basic uranium resources in the regional alpine depression structures. It is during this period that fundamental concepts on the role of oxidation-reduction processes in localization of uranium mineralization on pinching out of stratum oxidation zones were theoretically substantiated.

During prospecting works in Ily depression, the Koldjatskoye and Kizhneilyskoye uranium deposits were discovered. These deposits are not mined. During the same period Uvanas and Zhalpak deposits were discovered in Chu-Saryssu depression. These deposits are considered to be non-commercial objects for mining.

In 1970-1971 an experiment on uranium extraction using ISL was successfully carried out on Uvanas deposit. Since that period the amount of prospecting and exploration works increased greatly within Mesozoic and Cenozoic depression structures. Experimental works resulted in an identification of Uvanas deposit as the first large commercial site for uranium mining using ISL method. Kanshugan and Moinkum deposits were discovered in Paleogene sediments in the southern area. Mynkuduk deposit, unique by its size, was discovered and estimated in the sediments of the upper Cretaceous period in the northern area along with several other sites. Large commercial sizes of Zhalpak deposit are defined. The Big Chu Saryssu province was established on the basis of these deposits. Stepnoye and Central mining groups are carrying out mining works within this province.

In 1970-1975 North Karamurun and South Karamurun, Irkol and Zarechnoye deposits were discovered in the central part of Syr-Darya basin. In 1986 North Karamurun deposit was subjected to commercial development by the Vostochny Mining and Chemical Combine of rare metals.

Discovery of several large commercial deposits in Paleogene and Cretaceous sediments of Chu-Saryssu and Syr-Darya basins during the 70s-80s significantly increased the uranium raw material base of Kazakhstan.

The amount of basic geological exploration works in 1991-1992 concentrated in Chu-Saryssu and Syr-Darya Mesozoic-Cenozoic depression structures. These works resulted in substantial increase of earlier discovered Kanzhugan, Moinkum, Mynkuduk, Karamurun and Irkol deposits sizes. Estimation of general uranium resources and new deposits prospecting continued within these areas. Also prospecting exploration works continued within the Kokchetav uranium ore province.

Prospecting and exploration works ere carried out by specialized geological exploration organizations "Volkovgeology", "Steppgeology" and "Krasnoholmgeology".

2. COMMERCIAL AND GENETIC TYPES OF URANIUM DEPOSITS OF THE REPUBLIC OF KAZAKHSTAN

Uranium raw material base of Kazakhstan is represented by well diverse deposits as for their genetic position associated with structural formational complexes of different age. On the whole known commercial uranium deposits of Kazakhstan may be divided into two basic series:

- Endogenous deposits in Pre-Mesozoic formations;
- Exogenous deposits in Mesozoic and Cenozoic formations.

Common characteristics as regards the geological positions and genetic features, regional territorial isolation make it possible to point out the following uranium ore provinces on the territory of Kazakhstan: (Kokchetav), Northern Kazakhstan and (Pribalkhash) Kendyktas-Chu-Ily-Betapakdala provinces of endogenous deposits; Chu-Saryssu, Syr-Darya, Ily and Pricaspian provinces of exogenous deposits (Fig. 1).

2.1. Endogenous series

Endogenous series deposits are wide-spread on the territory of Kazakhstan. They are represented by vein-stockwork deposit of two isolated subtypes, one of which is linked with ore formation processes in Proterozoic and Paleozoic folded complexes and the other in volcanogenous complexes.

2.1.1. Vein-stockwork deposits in proterozoic and paleozoic complexes

This genetic subtype includes a total of 26 uranium deposits within the Kokchetav median mass and its line in Northern Kazakhstan (Kokchetav) uranium ore province (Fig. 2).

The deposits occur in various rocks: shales, arkose, jasper, limestone, granite aged from Silurian to Devonian and connected with Paleozoic periods of orogenesis and activating.

Mineralization is mainly associated with metasomatic formations of beresite and other alkali metasomatic changes which are considered to be parts of a single hydrothermal-metasomatic row. Decisive factor of localization of uranium mineralization is its link with fractural dislocations, mainly with clusters of crossing and coupling of long-aged faults.

Ore deposits occur in the form of flat line lenticular or tube-shaped stockworks, developing along the tectonic zones of crushing. Nasturan is a main uranium mineral at the majority of deposits and it often occurs along with coffenite. In some deposits uranium mineralization is partially represented by uranium bearing apatite.

All the deposits of the province are characterized by ordinary ores. According to the reserves, the deposits may be divided into large (Vostok, Manybai, Grachevskoye, Zaozernoye, Semizbai), about 20 000 t U each, and relatively small one (Balkashinskoye, Tastykolskoye et.al.), about 3 000 t.

Total uranium reserves in the area are about 208 000 t, including proven ones - 99.2 thousand t. Within the proven reserves 73% are reserves with uranium production cost of $80/kg.

The production of ore from the deposits of this province is carried out at the production site "TSELINNY MINING & CHEMICAL COMBINE" with ammonia paramolybdyte and phosphor fertilizers as by-products. The Ishimskoye, Balkashinskoye, Tastykolskoye and Manybaiskoye deposits are mined out. Grachevskoy, Zaozernoye and Vostok deposits are in operation now.

2.1.2. Vein-stockwork deposits in continental volcanogenous complexes

Deposits of this genetic type are located within the Pribalkhash (Kendyktas-Chuily-Betpak-Daynskaya) uranium ore province. Deposits of the Pribalkhash province are the second raw material base in Pre-Mesozoic formations in Kazakhstan, though not so large as the Nothern Kazakhstan one, but is has played an important role of one of the first suppliers of uranium raw material for atomic industry.

The most important feature of the province is that it is related to a large Devonian volcanic belt represented by wide-spread acid effusives and pyroclasts with numerous subvolcanic bodies.

Uranium deposits of the province are related to the vein-stockwork hydrothermal type. They are closely connected (in space and time of formation) with volcanic complexes of liparite composition. Main deposits of the area (Botaburum, Kyzylsai, Kurdai, Djidely) are similar from the geological point of view. Kurdai deposit is localized in granites, but structurally it is connected with volcanic necks. Other deposits are located directly in volcanic processes (Fig. 3).

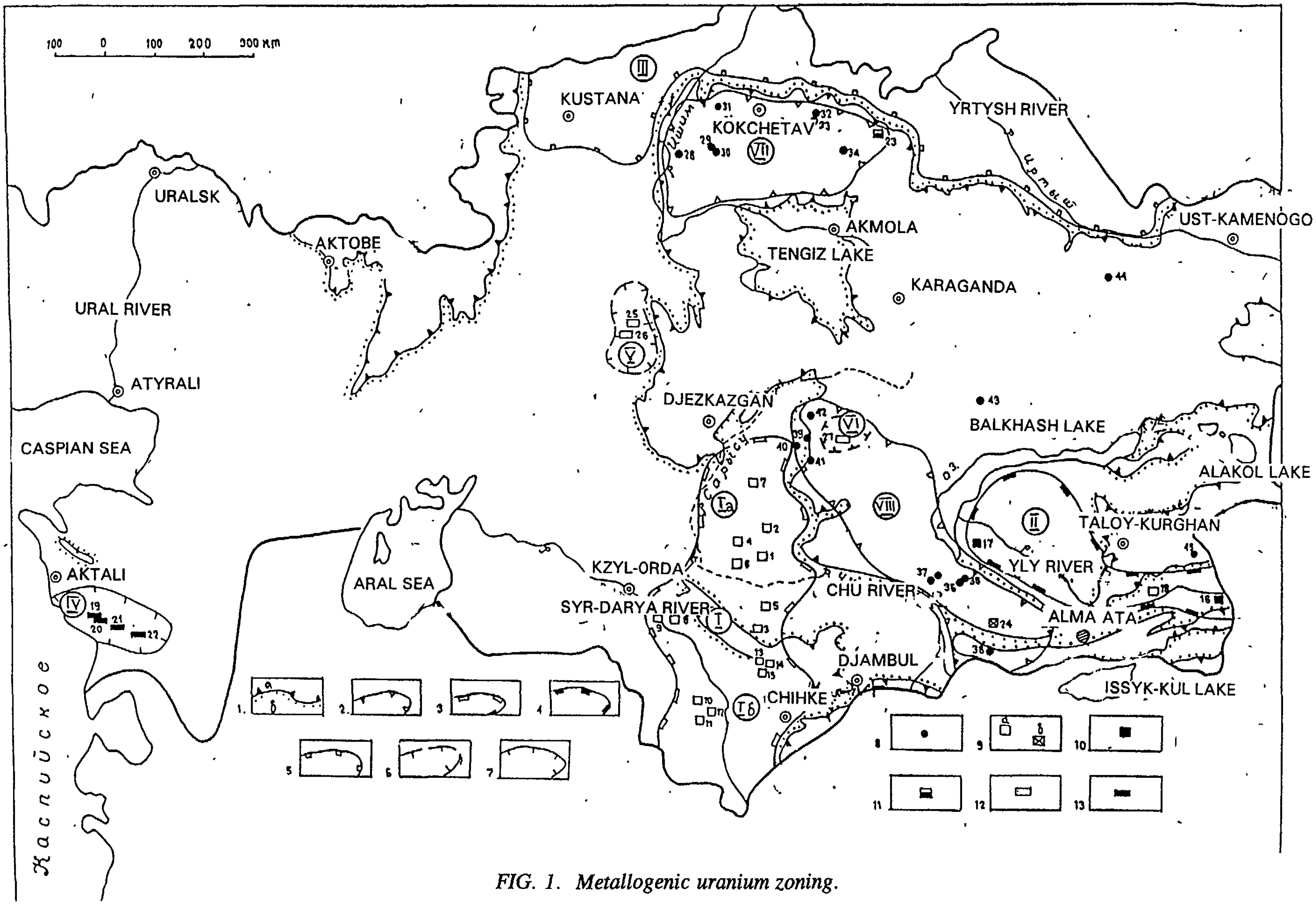
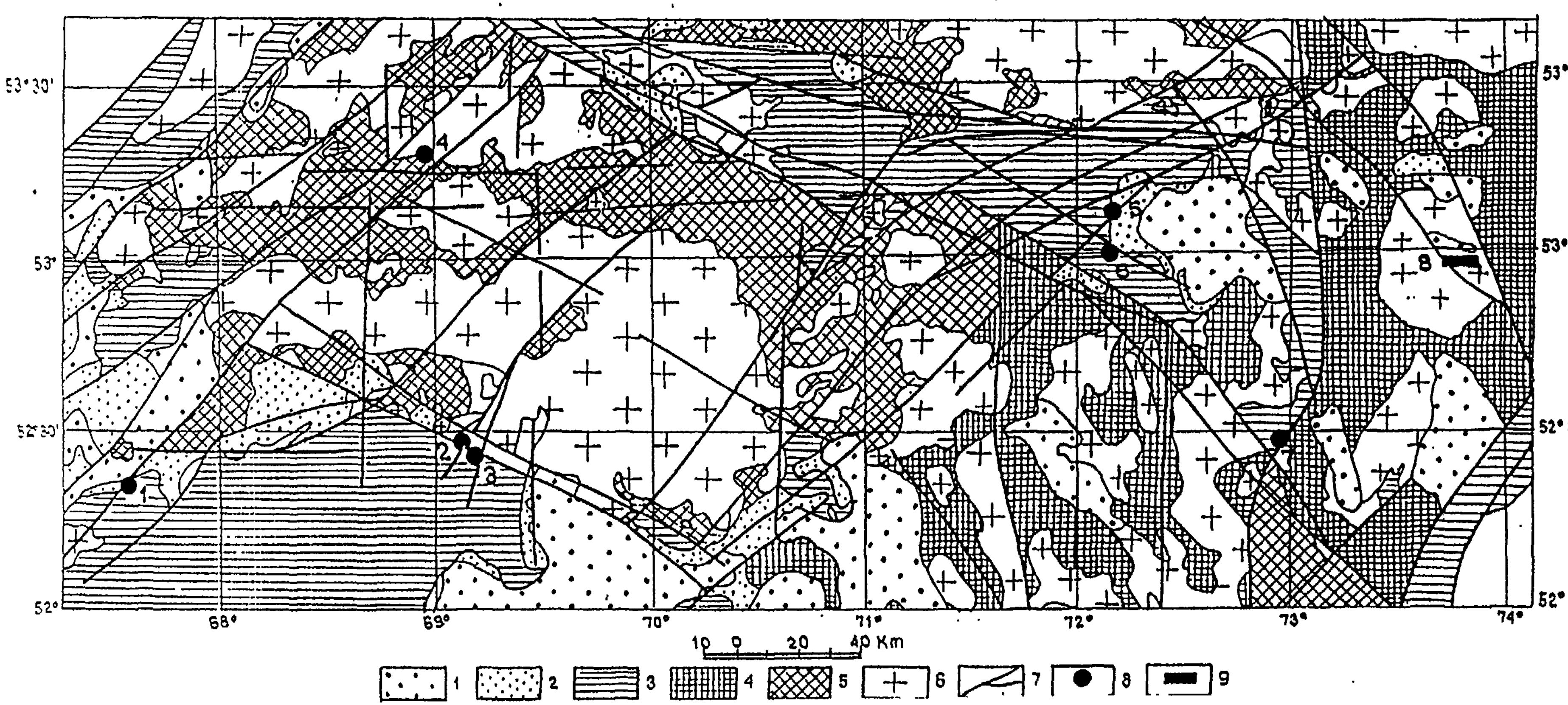


FIG. 1. Metallogenic uranium zoning.

1 - boundaries of pre-Mesozoic and Mesozoic-Cenozoic formations;
2 - 7: metallogenic (for uranium) subdivisions boundaries:
2 - hydrothermal deposits provinces in pre-Mesozoic formations (VII - Northern Kazakhstan, VIII - Kendyktas - Chuily - Betpak Dala);
3 - 7: of metallogenic subdivisions with exogenous deposits in Mesozoic - Cenozoic formations, including:
3 - of provinces with uranium ore formation deposit of regional stratum oxidation zones (1- eastern-Turan megaprovince and provinces within this megaprovince; 1a - Chu-Saryssu; 1b - Syr-Darya)
4 - province with the deposits of uranium-coal type in Jurassic formations; (II - Ilyskaya subprovince)
5 - of uraniferous areas with stratum-ground-infiltration deposits in sand-clay sediments of late Jurassic - early Cretaceous paleovalleys. (III - Turgai - Priyrtysh area);
6 - of uraniferous areas with exodiagenetic deposits in lignite-bearing sediments of paleovalleys of Cenozoic age (V - Zhalanshiksky region, VI - uraniferous field "Granitnoye");
7 - of uranium ore areas with deposits of phosphate-organogeneous type;
8 - 13 - uranium deposits, including:
8 - hydrothermal with various ore formations;
9 - tabular-infiltration type of Cenozoic (a) and Paleozoic (b) age;
10 - uranium-coal;
11- tabular-soil-infiltration in the sediments of late Jurassic - early Cretaceous Paleovalleys;
12 - exodiagenetic in the sediments of Cenozoic paleovalleys;
13 - phosphate-organogeneous.

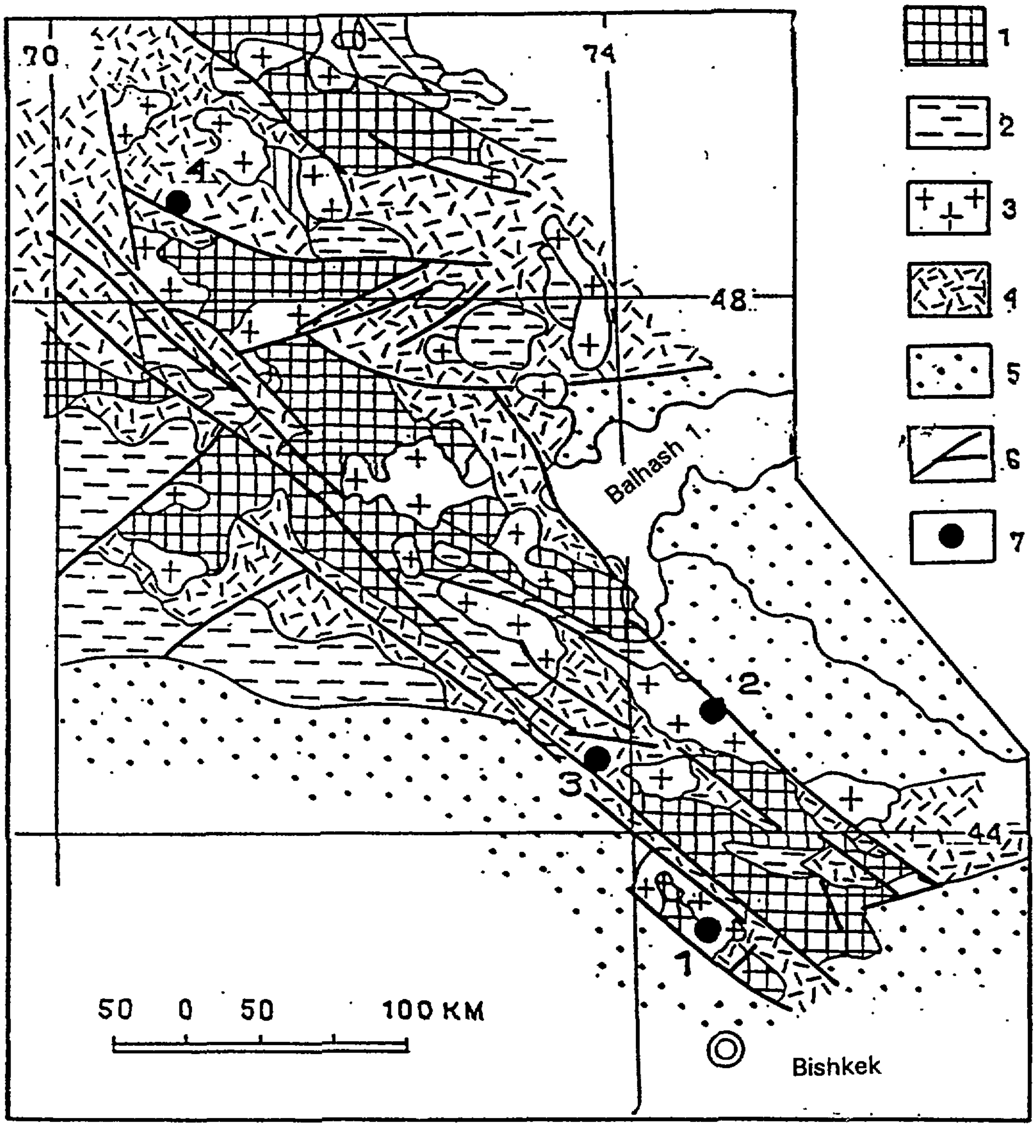
1 - Uvanas;
2 - Zhalpak
3 - Kanzhugan
4 - Mynkuduk
5 - Moynkum
6 - Sholak-Espe
7 - Karakoyn
8 - Northern Karamurun
9 - Irkol
10 - Zarechnoye
11 - Assarchik
12 - Zhautkan
13 - Kyzylkol
14 - Chayan
15 - Lunnoye
16 - Koldjat
17 - Nizhe Ilyskoye
18 - Suluchekinskoye
19 - Melovoye
20 - Tasmurun
21 - Taibagar
22 - Karyntarynskoye ore field
23 - Semizbai
24 - Kopalysai
25 - Lunnoye (Syr-Darya uranium ore province)
26 - Lazarevskoye
27 - Granitnoye; Talas
28 - Ishimskoye
29 - Vostok
30 - Balkashinskoye
31 - Grachevskoye
32 - Zaozernoye
33 - Tastykolskoye
34 - Manybaiskoye
35 - Botaburum
36 - Djussandalynskoye
37 - Kyzylsai
38 - Kurdai
39 - Djidely
40 - Kostobe
41- Daba
42 - Bezymyannoye
43 - Kyzyl
44 - Ulken-Akzhal
45 - Panfilovskoye

FIG. 1. Metallogenic uranium zoning.



1 - platform complex (D3 - Kz)
2 - orogenic complex (S - D2)
3 - preorogenic complex (E - O)
4 - preorogenic complex of reduced capacity on metamorphic basement
5 - complex of metamorphic basement (Pt)
6 - granitoids of preorogenic complex
7 - faults
8 - uranium deposits of endogenic series (1-Ishmiskoye; 2-Vostok; 3-Balkashinskoye; 4-Grachevskoye; 5-Zaozernoye; 6-Tastykolskoye; 7-Manybai)
9 - Uranium deposits of exogenic series (8-Semizbay)

FIG. 2. Geological map of the Kokchetav uranium ore region.



1 - Platform complex (Mz-Q)
2 - 3 - orogenic complex (Pz_2 - Pz_3)
2 - acid volcanites
3 - granites

4 - 5 - pre-orogenic complexes
4 - folded continental volcanogeic rocks (Pz_1-Pz_2)
5 - metamorphics (PR ?)

6 - fault
7 - uranium deposits of endogenous series (1: Kurday; 2: Botaburum, 3: Kyzylsay, 4 - Dzhideli)

FIG. 3. Geological map of the Pribalkhash uranium ore region.

Position of orebodies is defined by a combination of tectonic fractures and contacts of volcanic lithofacies.

In this type, the ores are uranium molybdenum. Average uranium content is 0.1- 0.3%. At the Djidely deposit in some blocks there occurred unique high grade ores (with U content more than 10%). During ore processing ammonia paramolybdate is produced as a by-product.

Uranium resources of the province are about 120 000 t, including explored ones of 21.9 thousand t.

During the period of 1953-1990 deposits of the Pribalkhash uranium ore province were mined by "Yuzhpolymetal" production enterprise (Bishkek City, Kyrgyzstan). At present uranium mining from the deposits of the Pribalkhash uranium ore province is stopped.

2.2. Exogenous series

Exogenous series of Kazakhstan deposits is represented by three uranium ore formations:

- Organogenous-phosphate type (Pricaspian uranium ore province),
- Epigenetic uranium ore formation of regional stratum oxidation zones (Chu-Saryssu and Syr-Darya uranium ore provinces),
- Epigenetic uranium ore formation of soil-stratum oxidation zones (Ily uranium ore province).

2.2.1. Organogenous-phosphate type formations

Pricaspian (Mangyshlak) uranium ore province is located on the eastern coast of the Caspian Sea on the Mangyshlak Peninsula. Aktau city is situated in the centre of the area where Pricaspiski Mining-Metallurgical Combine is operating, processing ore from the local deposits (Fig. 4).

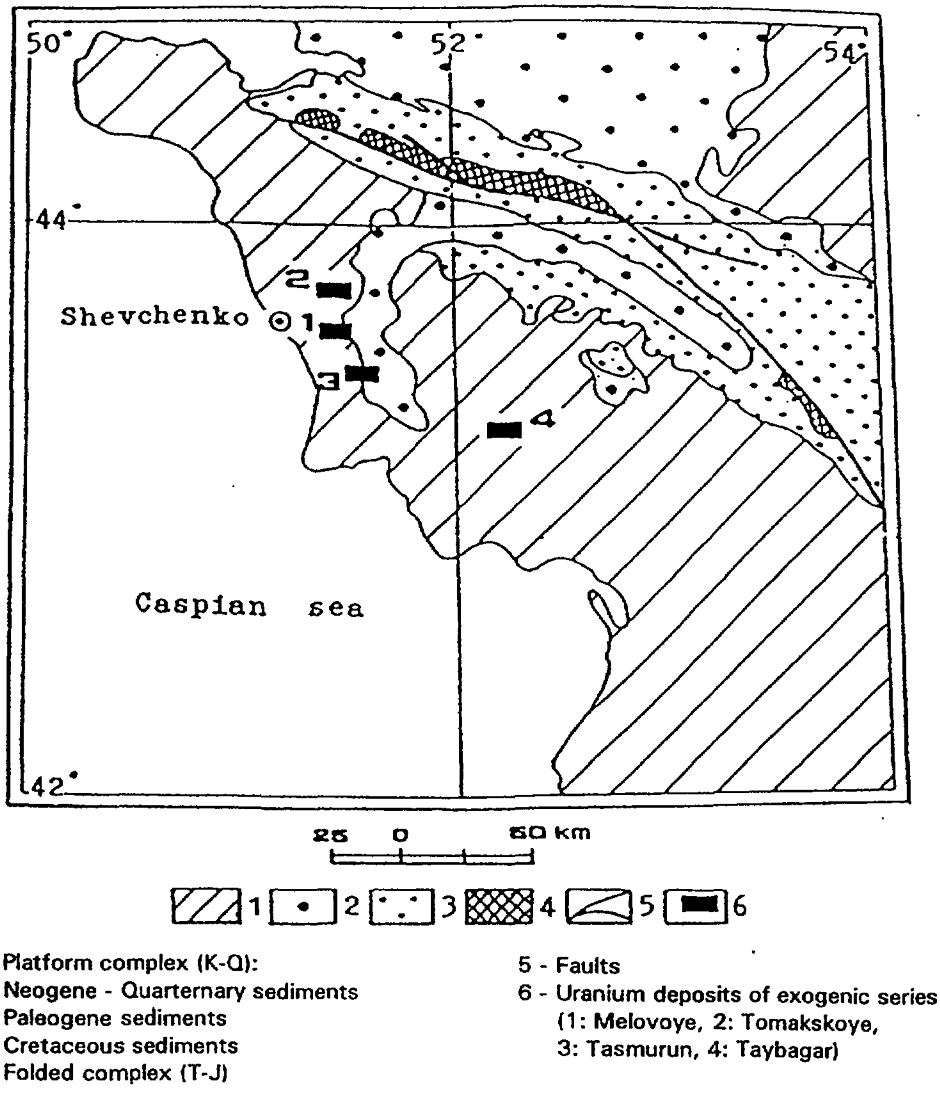


FIG. 4. Geological map of the Pricaspisky uranium ore region.

From the geological point of view the area is a relatively young platform. The basement of which is formed by folded sedimentary complexes of permotriasss, and its cover is formed by sediments of Cretaceous-Paleogenous-Neogenous periods. The Maikoi formation has an age of Oligocene-lower Miocene. Uranium mineralization if represented by a unique type of deposit - by accumulation of phosphatized bone detritus of fossil fish in pryite-bearing clays.

Ores of this type of deposits have low U content (0.03-0.05%), however, bone *detritus is* easily separated by washing. Uranium content in detritus concentrate increases by 2-3 times, and phosphoreal anhydrite content achieves 30%. In addition to uranium and phosphorus there are rare earth and scandium in detritus which are also extracted during processing.

Melovoye is the largest deposit (43.8 thousand t). Other deposits reserves (Tomakskoye, Tasmurunskoye, Taibagarskoye) are from 4 000 t to 9 000 t in each. Accumulation of uranium-bearing bone detritus in a certain horizon of paleogenous sediments occurs both to the south of the area and on the western coast of the Caspian Sea. However on the rest of the territory productive horizon occurs in the depth which includes the possibility of economically justified deep mining. Therefore the prospects of this peculiar type of deposit are limited by proven reserves of the known deposits or the area (64.4 thousand t).

2.2.2. Epigenetic uranium ore formation of regional stratum oxidation zones

2.2.2.1. Chu-Saryssu ore province

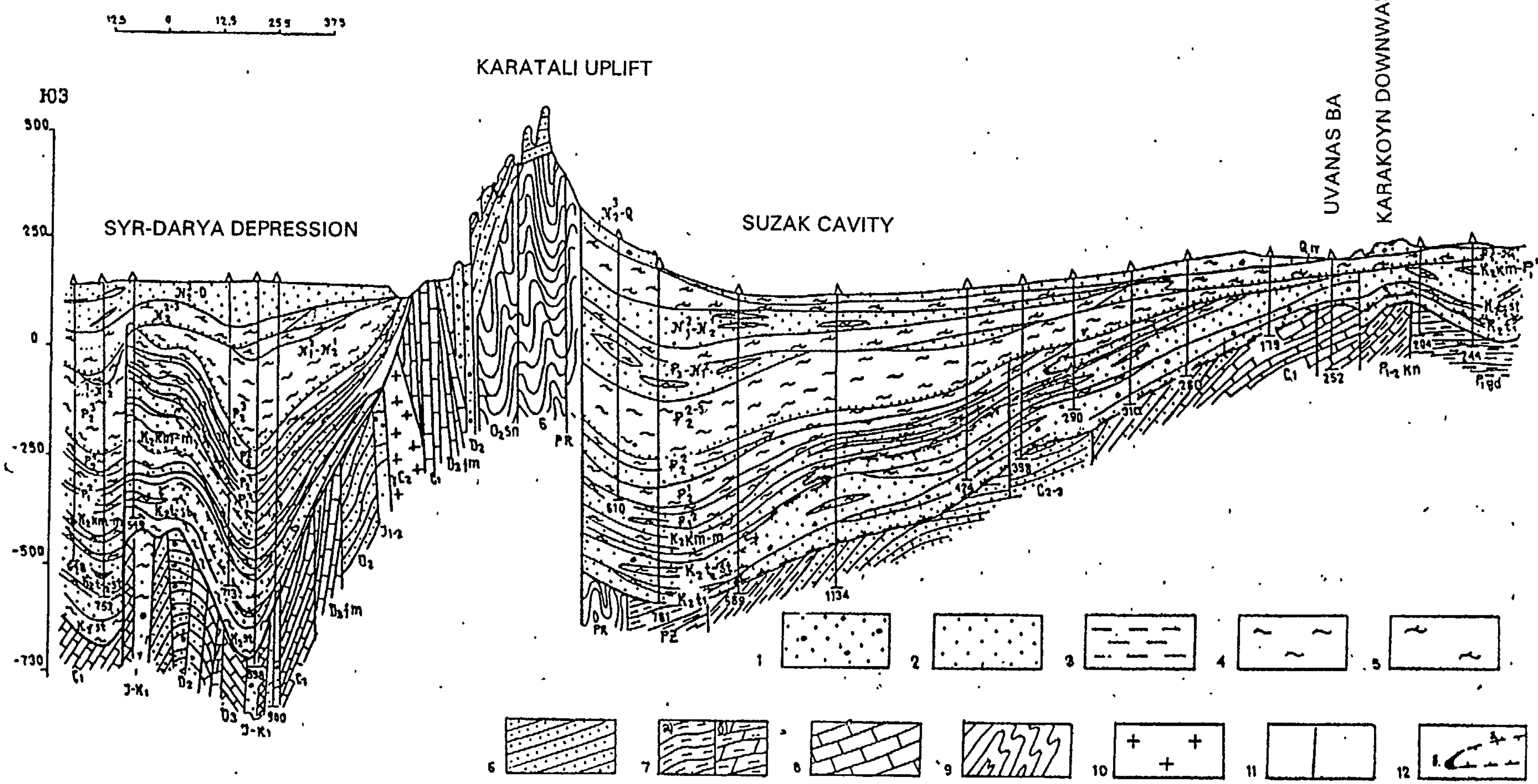
Chu-Saryssu uranium ore province is located in the central part of Meso-Cenozoic depression structure of the same name, which has been formed on the place of middle-upper Paleozoic basin. Depressions bed consists of sub-platform terrigenous sediments of medium-late Paleozoic period. Mesozoic-Cenozoic formations are represented by two structural formational complexes: platform Cretaceous-Paleogenous, which is ore host, and by overlapped activated late Oligocene-Neogene. Tectonic structure of Mesozoi-Cenozoic basin cover is monocline gently sloping in the south-western direction to the Karatau mountain range complicated by big sedimentary uplift of north-western orientation as well as by more local brachyanticline (Fig. 5).

Chu-Saryssu depression is an artesian basin formed by water-bearing complexes of upper Cretaceous period and Paleocene-Eocene.

Mass of sea clays of upper Eocene serves as a regional upper aquiclude. During the activating (neo-tectonic) stage in the course of late-Oligocene-Neogene period the artesian basin has been developed mainly in an infiltration regime. This resulted in wide development of stratum oxidation zones in water-bearing horizons. Their boundaries form systems of regional fronts in the horizons of host ores complex as a whole in near-meridional direction.

Commercial uranium mineralization is linked with the boundaries of stratum oxidation zones in six-water-bearing horizons (from lower Turan to middle Eocene). Upper Cretaceous and Paleocene formations are represented by sand and gravel-sand sediments of lacustrine-aluvial plain, Paleogene are represented mostly by delta and underwater-delta clay-sand formations. Each horizon forms sedimentary macrocycle with thickness of 50-70 m. The horizons are divided by continuous or dotted clay aquicludes.

In plan the ore deposits are winding, often very prolonged (up to 10-20 km) bands, and more rarely they have a form of irregular or isometric shape. The width of deposit varies from several dozens of metres up to 1-1.5 km. In cross-sections ore deposits have a form of asymmetric rolls and lenses. Their thickness changes from several metres to 15-20 metres and in some cases more than that. As for the uranium content the ores are low-grade (0.02-0.05%), though there are ores in all the deposits with the content of 0.1-0.3% and more rarely up to integer per cent. Depth of occurrence of orebodies varies form 80-100 m to 400-600 m. Mineralization is mainly monometal, rhenium (and seldom selenium) being an accompanying element.



1 - sands of different grain sizes, gravel
2 - medium grain and fine-grain sands
3 - alevrites
4 - clays and alevropalites
5 - limestone clays

6 - sandstones
7 - alevrolites (a) and limestone alevrolites (b)
8 - limestones
9 - cristallic shales
10 - granitoids

11 - fragmentary faults
12 - boundaries of stratum oxidation zones (a) and uranium mineralization connected with them

FIG. 5. Geological cross-section of the sediments of the Syr-Darya and Chu-Saryssu Mesozoic-Cenozoic depressions.

Uranium mineralization is represented by fine dispersion coffenite and nasturan, in various correlation, developing in porous clay-alevrite filler of quartz and feldspar-quartz sands in micro-fractures of fragmentary minerals and in a form of pseudo-morphosis along the plant remains.

Ore deposits are characterized by high permeability and porosity. Filtering coefficient is usually 5-10 m per day and higher. Practically all deposits are good for using ISL method, and this fact is confirmed by a number of trial operations of the deposits. The largest commercial sites of the Chu-Saryssu uranium ore province are: in Paleogene sediments — Uvanas, Kanzhugan, Moynkum deposits, in Cretaceous — Mynkuduk and Zhalpak deposits. According to the uranium reserves the largest explored site of the area is Munkuduk deposit (127 000 t). Uranium reserves at the Moynkum deposit is 82.5 thousand t, Kanzhugan — 50 000 t, and Uvanas — 20 000 t.

Uvanas, Kanzhugan and Mynkuduk deposits at present are mined by Stepnoye and Central Ore Groups.

Total resources of the Chu-Saryssu uranium ore province are defined to be 500 000 t, including proven ones — 221 000 t, additional — 74 000 t, and prognosticated no less than 205 000 t. Prospecting - exploration works in this area are underway.

2.2.2.2. Syr-Darya uranium ore provinces

Syr-Darya uranium ore province occupies the territory of Syr-Darya basin with complicated composition and is separated from the Chu-Saryssu basin by Karatau uplift in the north-east and by Chatkalo-Kuraminsky uplift from the Northern-Fergana uranium ore area situated on the territory of Uzbekistan and Kyrgyzstan.

Syr-Darya depression mainly consists of sediments of Cretaceous. Paleogene and Neoge periods with width of 2.5-3.0 km. Uranium ore area is concentrated in the eastern and south-eastern parts of the depression.

Uranium mineralization is controlled by systems of regional fronts of stratum oxidation zones in water-bearing horizons of upper Cretaceous period and Eocene which are the southern continuation of oxidation fronts showed in the corresponding horizons of the Chu-Saryssu province. The most widely ore-monitoring regional stratum oxidation is developing in the sediments of upper Turon, Cognac, Santon and Campan. High permeable sediments of continental clay-gravel-sand formation filling south-eastern part of the depression were favourable for the development of stratum oxidation processes. Within the Syr-Darya uranium ore area North-Karamurun, South-Karamurun, Irkol and Zarechnoye deposits were discovered, as well as a number of other sites less studied.

The most significant commercial sites are concentrated within the Karamurun ore field in the lower flow of the Syr-Darya river near south-western spurs of the Big Karatau mountain range.

Ore deposits are situated in the sand and gravel-sand sediments divided by clear impermeables. Ore deposits have a length of 750-5 500 m and width of 25-50 m up to 300-650 m. In plan they have a form of winding bands with variable width.

In cross-sections ore deposits consist of rolls, lenses, stratum bodies with complicated composition with each other. Uranium contents vary from thousandth of shares up to integer per cent and are, in average, 0.05-0.07% at orebodies width of 6-24 m. Depth of orebodies occurrence from the surface varies from 300 m to 700 m increasing from north to south.

As a rule, ores are complex uranium-selenium. Uranium minerals are represented by half-oxidized uranium pitchblende, fine-dispersion coffinite, and nasturan. Selenium occurs in a form of needle-shaped appearance of nugget element and being absorbed and accumulated in ferrum hydroxides.

All known uranium deposits of the area are located below the level of waters in high permeability rocks (filtering coefficient being 1-12 m per day). Host water-bearing horizons are usually separated from the upper and the lower horizons by sufficiently strong impermeables. Uranium mineralization is represented by easy-soluble minerals.

All these qualitative and technological characteristics of the deposit make them rather favourable for mining using ISL method. The most significant among the explored sites of the Syr-Darya uranium ore province are the following deposits: Irkol (37 000 t), North-Karamurun (28 000 t), Zarechnoye (23 000 t). Total uranium reserves of the Syr-Darya province are 143 000 t, including proven reserves of 77.3 thousand t, additional ones of 10.7 thousand t, and prognosticated of 55 000 t.

2.2.3. Epigenetic uranium ore formation of soil-stratum oxidation zones

The Ily uranium ore province is situated in the south-east of Kazakhstan and occupies the territory of two large basin structures - Ily and Balkhash which was formed during Mesozoic-Cenozoic stage of development. Development of continental coal-bearing sediments of early-middle-Jurassic age in south-eastern part of the Ily basin and in north-western part of the Balkhash cavity is a characteristic peculiarity of the area.

Coal-bearing sediments of the Ily depression have formed in subplatform conditions and have a form of a large inherited cavity in a Paleozoic basement. Coal-bearing structure occurs on the territory of Kazakhstan along the strike of 20-30 km and along the dip of 30 km. Main area of its spreading is located on the neighbouring territory of China. Coal-bearing sediments dip in the northern direction under the angle of 5-7 degrees. In the southern Ily basin they occur on the surface, and in the axial part the depth is about 1500 m and more.

The Ily coal-bearing basin is linked with the coal-bearing sediments of the observed basin, in the south-western foredeep part of which the Koldjat uranium coal deposit is situated.

Uranium mineralization is observed both in coal seams and in host sand-conglomerate sediments. Molybdenum mineralization in commercial concentrations is developed only in the uranium orebodies in coal seams. Uranium content varies in wide uranium limits from 0.05% to 1.0-1.5%. Uranium mineralization is represented mainly by nasturan with subordinate amount of coffinite and uranium half-oxidized pitchblende. Molybdenum mineralization is represented by molybdenite, ilzemanite and iordizite. Uranium reserves at the Koldjatskoye deposit are 37 000 t. The deposit is not mined.

Coal-bearing sediments in the north-western part of the Balkhash basin were formed in local block structures of graben (rift) type attached to crossing clusters of the system of deep faults of north-western and near-longitude direction. The Jurassic coal-bearing sediments were formed in down faulted blocks. The depth till the cover of Jurassic sediments varies from 100 to 500 m. The thickness of coal-bearing sediments is 125-260 m.

The Nizhne-Ilysky coal-bearing basin is linked with the coal-bearing sediments of the described area, with the coal resources being 20-24 billion t, and the uranium coal deposit of the same name. Within the Nizhne-Ilysky deposit the Mesozoic-Cenozoic complex of terrigenous sediments with the width of 400-500 m, forms a buried graben structure with length of about 100 km and width of 15-20 km. Uranium mineralization at the deposit is localized in cover part of the coal seam on the boundaries with overlapping permeable sandstones and gritstones. Mineralization is formed in the zones of ground and stratum oxidation development. Deposits have simple stratum form with areal sizes from 0.1 to 3.2 square km. Uranium content varies from 0.05% to 1.0-2.0%. Uranium mineralization is represented by nasturan and coffinite. Molybdenum mineralization is in close connection with uranium one, and it is represented mainly by ilzemanite, iordisite and more rarely by molybdenite. Uranium reserves at the deposit are 60 000 t.

Besides uranium coal type of deposits, which are the basis of the Ily uranium ore area stratum-infiltration uranium deposits of sandstone type (Suluchekinskoye, Kalkanskoye, Aktau) were discovered within it. Uranium mineralization at the deposit is connected with sand horizon of Campan-Paleocene age and is controlled by the boundaries of stratum oxidation zones pinching out. Suluchekinskoye deposit is the largest among them with reserves of 33 000 t.

Total proven reserves of the Ily uranium ore province are 92.9 thousand t, and additional ones are 37 000 t. The province is a large active coal reserve of the Republic of Kazakhstan.

3. TOTAL URANIUM RESERVES AND RESOURCES OF THE REPUBLIC OF KAZAKHSTAN

Total uranium reserves and resources of Kazakhstan are 1 168 000 t. The summarized amount of proven reserves (B+C1+C2 category) is 575 700 t, which is 49.4% from the total reserves and resources. 417 500 t (72.4%) of this amount are within the cost category of $80-$130 per kg. Table I gives a distribution of proven reserves for each uranium ore province.

TABLE I. PROVEN RESERVES (IN TONNES OF U)

Uranium ore province	Cost range		Total less $130/kg	
	less $ 80/kg	from $80 to $130/kg	in t	%
Pribalkhash	17 900	4 000	21 900	3.8
Kokchetav	72 400	26 800	99 200	17.2
Pricaspikaya	-	64 400	64 400	11.2
Chu-Saryssu	221 000*	-	221 000	38.3
Syr-Darya	77 300	-	77 300	13.4
Ily	28 900	64 000	92 900	16.1
Total Republic of Kazakhstan	417 500	159 200	576 700	100

*Note: including 124 800 t at the cost of $52-$80 per kg.

Estimated addtional resouces (EAR 1) are 211 300 t (i.e. 18.1% of the total reserves and resources of the Republic). 147,900 t of this amount are within the cost category till $80/kg and 63 400 t in the cost category from $80 to $130/kg. Table II gives a distribution of estimated additional resources (EAR 2) for each uranium ore province.

TABLE II. ESTIMATED ADDITIONAL RESOURCES (IN TONNES OF U)

Uranium ore provinces	Cost range		Total less $130/kg	
	less $80/kg	from $80 to $130/kg	in t	%
Pribalkhash	50 000	-	50 000	23.7
Kokchetav	9 200	30 400	39 600	18.7
Chu-Saryssu	74 000	-	74 000	35.0
Syr-Darya	10 700	-	10 700	5.1
Ily	4 000	33 000	37 000	17.5
Total Republic of Kazakhstan	147 900	63 400	211 300	100

Total proven and additional resources are 788 000 t or 67.5% of total reserves and resources estimation in Kazakhstan. Prognosticared and estimated additonal resources — category 2 (EAR2) are 380 000 t and practically all of them are connected with already known uranium ore provinces.

Surmised resources connected with other than known genetic types of deposits and new uranium ore provinces are not distinguished. Geological prospects of discovering new uranium deposits on the territory of Kazakhstan are high enough, but all of them are connected with already known uranium ore provinces and first of all with those of Chu-Saryssu, Syr-Darya and Kokchetav.

THE URANIUM RESOURCES OF MONGOLIA

Y.B. MIRONOV, S.S. NAUMOV
Geologorazvedka Concern, Moscow, Russian Federation

G. JAMSRANDORJ, O. CHULUUN
Ministry of Geology and Mineral Resources of Mongolia, Ulaanbaatar, Mongolia

Abstract

This report contains maps and results of reports on uranium survey of the country's geological structure and mineralization, uranium ore formation and epochs of uranium mineralization. It also includes descriptions of known deposits and best studied uranium-bearing districts. Uranium mineral deposits, uranium occurrences were prospected covering eight mineral formation. The territory of Mongolia can be divided into four main districts: Mongol-Priargun, Gobi-Tamtsag, Hentii-Daur and North-Mongolia. The main industrialized works have been carried out at detail explored Dornod deposit of nasturan-coffinite ore with stockwork type of mineralization occurred in from 30-50 to 500-600 m depth in a gently slopping position and Gurvanbulak deposit of coffinite-nasturan ore with bedlike morphology. Also based on materials where prospected mineral deposits in the east Dornot, Gurvanbulak, Mardaingol, Nemer; in south Haraat, Nars determined estimated reserves (RAR + EAR 1). In the present total estimated uranium reserves accounting 1 470 000 t in Meso-Cenozoic depressions related to surface oxidation connected with hydrogenic ore formation. Proved resources account 4.0% (59 000 t) of total uranium resources (RAR + EAR 1). A new large deposit area with uranium-rare metal complex ore occurred near ground surface has been discovered in Eastern Gobi. The total estimated of uranium resources of Mongolia allows it to be considered as one of the leading countries in the world in terms of this kind of raw materials. The presented information is based on most reliable, actual materials and may be best used in planning of geological exploration works and development of uranium mining industry in Mongolia.

Geological prospecting for uranium began in Mongolia after World War II with a re-appraisal of deposits of various minerals. From 1945 till 1960 a series of small occurrences of uranium were discovered in lignite deposits in the eastern part of the country.

Planned uranium exploration was carried out between 1970 and 1990 on funds made available from the USSR State Budget according to a bilateral agreement between the USSR and Mongolia. The survey was carried out by the Mongolian Survey Expedition, a division of the USSR Ministry of Geology, in collaboration with a host of scientific research institutes. During that period a significant amount of work was carried out with the aid of airborne gamma ray spectrometric survey (scale of 1:25 000-1:50 000 over an area of almost 420 000 km^2, or 27% of the country's territory, and an additional area of 450 000 km^2, or 28%, on a scale of 1:200 000). The highlands of Khangai, Mongolian Altai as well as the desert regions of South Gobi (224 000 km^2, or 14% of the country's total area) were surveyed on a scale of 1:1 000 000 (Fig. 1). No aerial gamma spectrometric surveys were conducted along the border with China or over inaccessible highlands in the central part of the country (30% of Mongolia's surface area). Metallogeneic analyses (survey scale 1:50 000-1:200 000) were carried out over an area of 500 000 km^2, in addition to extensive prospecting, evaluation and detailed exploration surveys, including drilling and underground workings.

Four uranium-bearing provinces were discovered as a result of special surveys. They are: the Mongolian-Argun, Gobi-Tamtsag, Khantai-Daurian and the North Mongolian provinces, within the combined area of which 6 deposits, almost 100 ore occurrences and 1 400 points of uranium mineralization and radioactive anomalies have been discovered. Each of these provinces contains several uranium-ore-bearing or potential uranium-ore-bearing regions, as well as complexes of deposits and occurrences with genetical features typical for these provinces (Fig. 2).

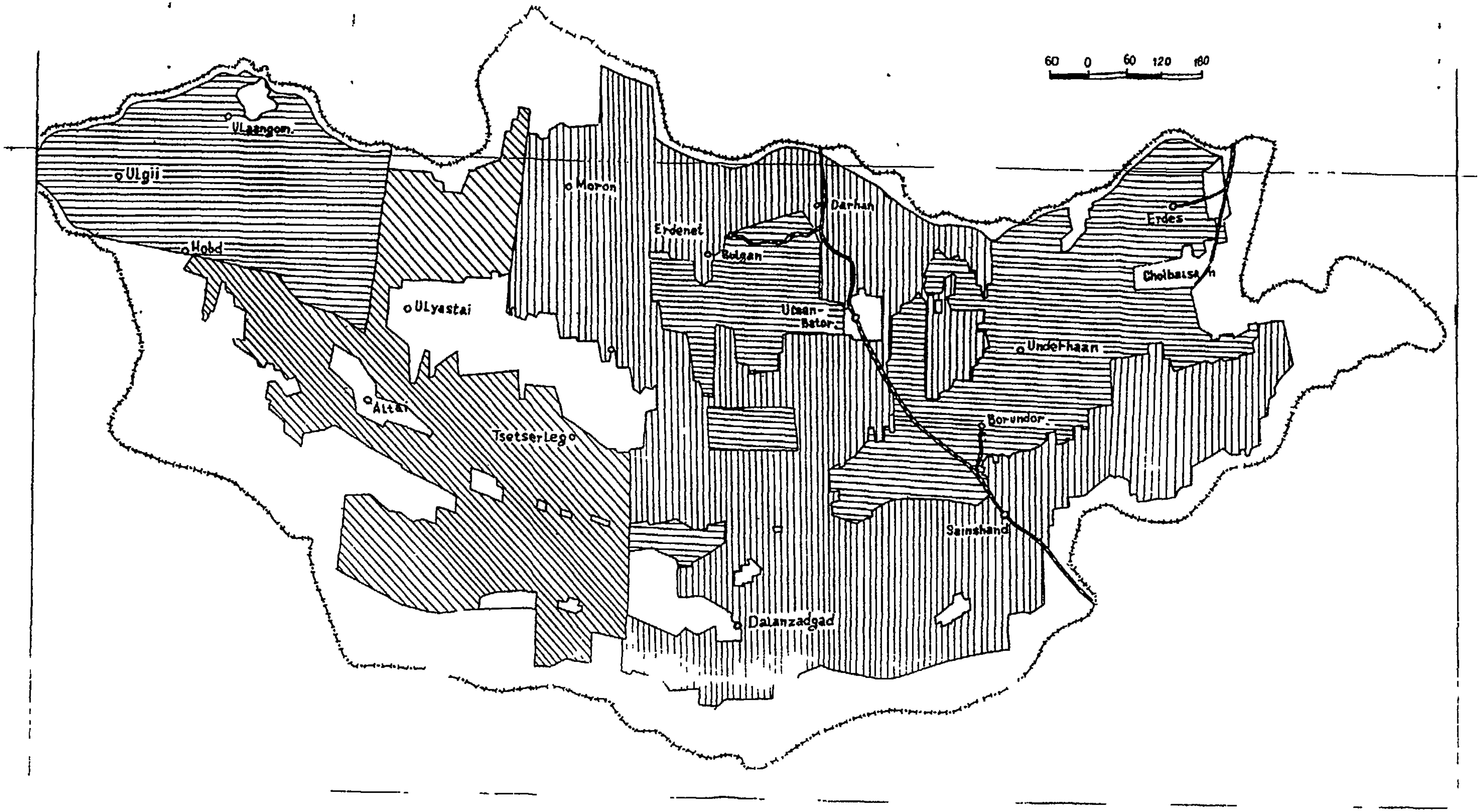


Fig. 1. Cartogram of study by AGSM survey.

The Mongolian-Argun province is located in the eastern part of the country and coincides in area with the likewise named intracontinental volcanic belt, extending over 1 200 km with a width of 70-250 km, beginning from the outskirts of Mongolian Altai and stretching to lower Argun.

The most widespread type of uranium deposit here are ore stockwork or veins in continental volcanogenic complexes with commercial analogues in Russia (Zabaikal region), as well as stratimorphic (found in sandstones related to ground and bed oxidation), similar to the well-known deposits in Kazakhstan and Central Asia.

Within the Mongolian-Argun province the following ore-bearing districts are notable: the North Choibalsan uranium-ore district, in addition to the Bekhin and East Gobi potential uranium-ore-bearing district with an area of several tens of thousands of square kilometres.

Several ore-bearing complexes have been studied in the North Choibalsan district. Of commercial value is the Dornot ore-bearing complex with an area of almost 2 000 km^2, enveloping one of the largest structures in the Mongolian-Argun volcanic belt, namely the Dornot volcano-tectonic structure. The latter is filled with a thick bed of volcanogenic sedimentary rocks (rhyolites, andesitic basalts, sandstones and conglomerates) of the Jurassic and Cretaceous periods, with a total thickness of 1 000 to 1 500 m. Over the area of the Dornot ore complex the following have been discovered: the Dornot, Gurvanbulak, Mardaingol and Nemer uranium deposits, as well as two gold-bearing, one fluorite deposit, and a host of ore occurrences of molybdenum, gold, fluorite and ceolites. On the basis of the estimated uranium reserves of the Dornot complex the first phase of the Erdes Mining Enterprise with a projected annual capacity of 2 million tonnes of ore was erected and mine works began in 1989. Owing to the lack of demand in Russia the current output is around 1 000 000 t of ore.

The Dornot uranium deposit is located along the northern flanges of the Dornot volcano-tectonic structure, filled with coatings of volcanites and beds of sedimentary rocks (late Mesozoic), having a total thickness of 1 200 m (Fig. 3). The structure's foundation consists of gneissoides, granites as well as diorites of the late Paleozoic, containing a large amount of skialitus of metamorphic rocks of the Proterozoic Eon.

The Dornot deposit is undoubtedly the largest in the entire ore-bearing complex. Commercial grade uranium ore is spread over an area of some 20 000 km^2, occurring within several levels of the section and consisting of 13 ore deposits of stratal levels of the section and consisting of 13 ore deposits of stratal and stockwork-like morphology. The largest (almost 15 000 t) is stratal deposit 7, which coincides with the cushion level of andesitic basalt lavas within the lower parts of the geological section of the ore-bearing rocks common to the south-western flanges of the deposit. The uranium minerals encountered here are: brannerite, coffinite, uranium titanates, uranium-bearing leucoxene and pitchblende. The average uranium content within the ores of the deposit is 0.282%. In the central parts there is an area with uranium contents of 0.424% Several ore occurrences of a lower size and with uranium content of between 0.06 and 0.582% are located at different stratigraphic levels within strata of tuffogenic sedimentary rocks in the central part of the geological cross-section. The major ore minerals here are coffinite and pitchblende.

Ore occurrences resembling stockworks are common within the zones of fracture in the rhyolite coverings. The uranium content of the ores ranges from 0.06 to 1%, with an average value of 0.2%. The total proved (explored) uranium reserves of the Dornot deposit constitutes 29 000 tonnes, in addition to 4 000 t of ore at a price of 80-120$/kg.

In view of their low sulphide and carbonate concentration these ores may be classified as the aluminium silicate type. A large part of the ore bodies may be exploited by means of underground workings without the need for cavinings. Water influx into the mine workings is estimated at 25-80 m^3 per hour. The ore from bodies 2A, 2B, 2C located near surface are currently extracted through open castings.

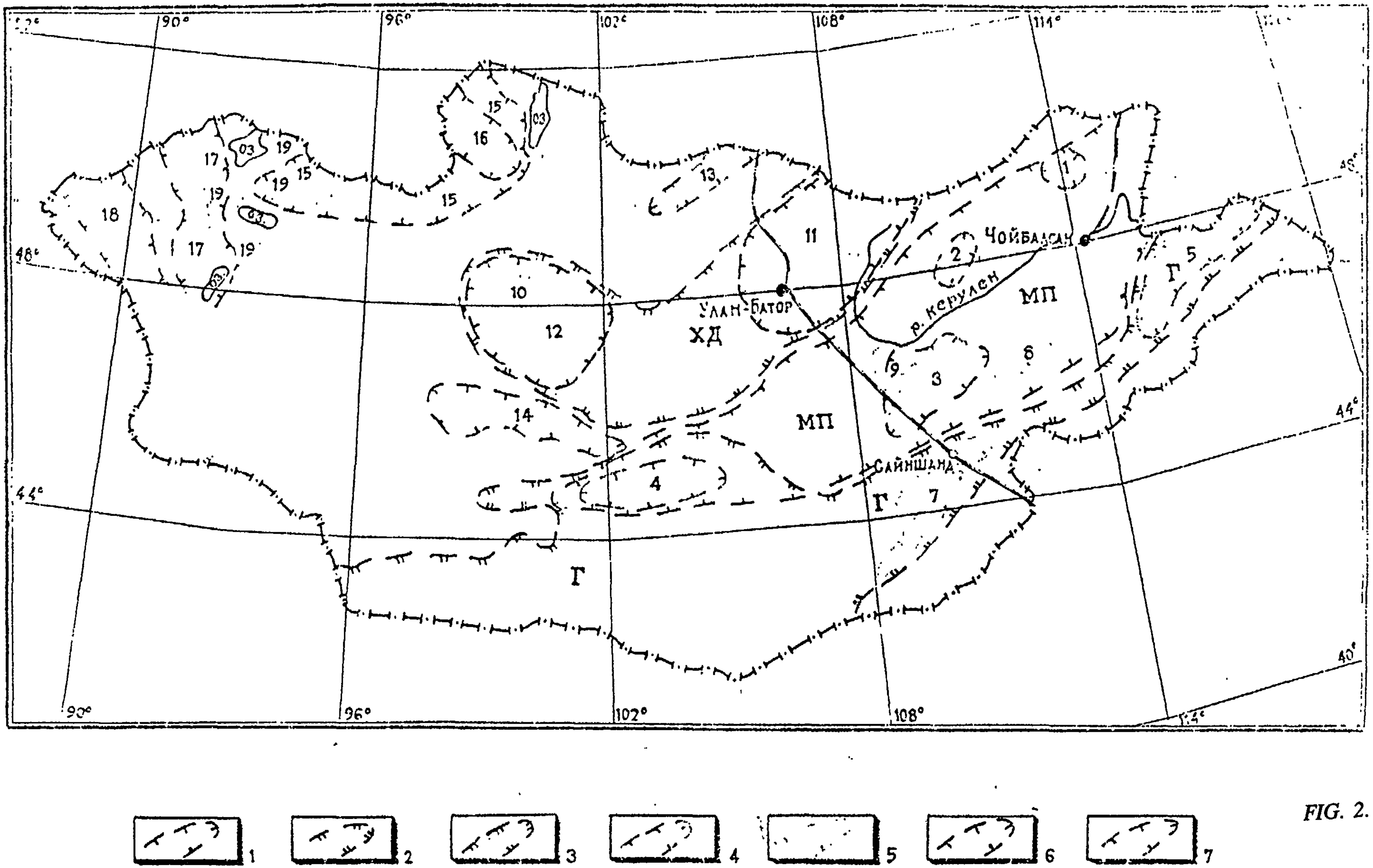

90°
96°
102°
108°
114°
48°
44°
40°
Чойбалсан
р. Керулен
Улан-Батор
Сайншанд
МП
ХД
Г
1
2
3
4
5
6
7
9
10
11
12
13
14
15
16
17
18
19
03

FIG. 2.

FIG. 2. Mongolia's uranium metallogenic division scheme; scale: 1: 1 000 000, 1985.

Boundaries:

1- Mongolian-Argun (MA) uranium-ore-bearing province;
2- The gobi (G) potential uranium-ore-bearing province;
3- The Khentei-Dauria (Kh.D) potential uranium-ore-bearing province;
4- uranium-ore- and potential uranium-ore-bearing districts of the fluorine-molybdenum formation;
5- potential uranium-ore-bearing districts and uranium-bearing basins related to exogenic ore formation;
6- potential uranium-ore-bearing districts of the uranium formation in fracture zones of leucocratic granitoids;
7- potential uranium-ore-bearing zones and districts of other uranium-ore formations;

Numbers[1]:

1- North Choibalsan district
2- Berkhin district
3- East Gobi district
4- Mid-Gobi district
5- Tamtsag basin
6- Sainshand district
7- Dzunbain system of basins
8- Uldzuitin depression
9- Choir-Nilgin system of depressions
10- Chulut district
11- Khentei region
12- Khangai region
13- Butulinur zone
14- Bayankhongor
15- Khubsugul region
16- Aragol zone
17- Tsaganshibet zone
18- Mongolian Altai zone
18- Ubsanur region

---

[1] These numbers refer to main uranium ore- and potential uranium-ore-bearing districts, zones, basins and depressions.

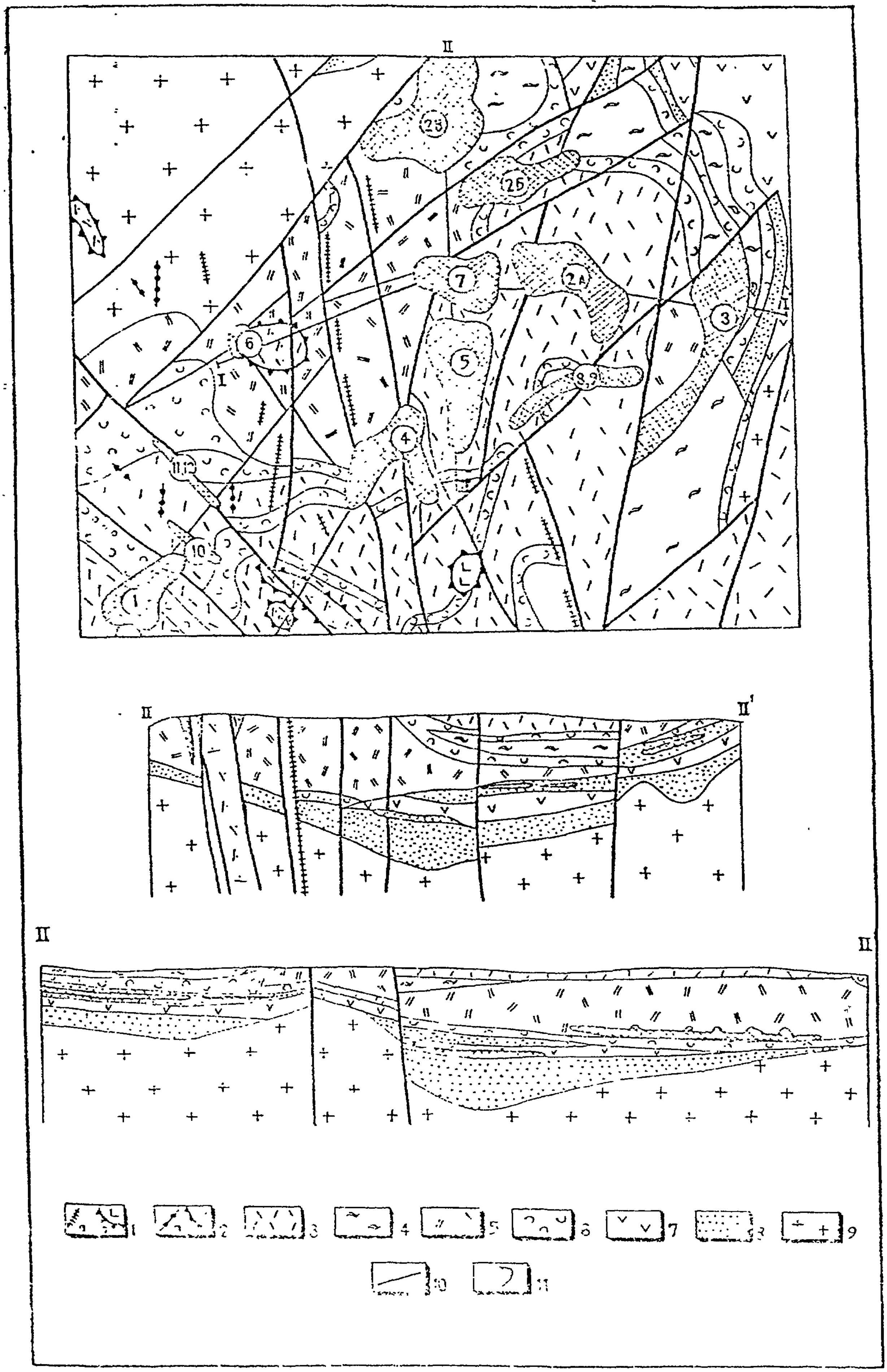


FIG. 3.

FIG. 3. The Dornot uranium deposit — geological schematic map.

1-8:
late Mesozoic volcanites and sediments:
1- dykes (a) and extrusions (b) of andesitic basalts;
2- dykes (a) and extrusions (b) of rhyolite

the upper bed:
3- feldspathic rhyolites
4- lithoid ignimbrites
5- oligophyric rhyolites
6- rhyolite tuffs;

lower bed:
7- andesitic basalts
8- sandstones, aleurolites, conglomerates, tuffites
9- granodiorites of the early Paleozoic;

10- main faults;
11- ore bodies (shown on the geological scheme as projections on the earth surface)

The Gurvanbulak uranium deposit is also located on the norther part of the Dornot volcano-tectonic structure (Fig. 4), the geological section of which comprises two beds: a lower bed of a thickness of 100-400 m, with rhyolite, trachydacite and andesitic basalt covers and horizons of tuffogenic sedimentary rocks, as well as an upper bed of a thickness of 300-800 m, covered with acid volcanites and their tuffic derivatives.

The deposit is made up of three isolated sectors covering an area of 9 × 1.5-4 km and extending along the north-eastern flanges of the volcanic structure. Uranium mineralization occurs along the entire geological section, within six lithostructural layers at a depth of 15-40 to 720 m. The major ore occurrence is related to massive flat-dipping fault zone at the boundary between the upper and lower beds. The fault consists of two converged tectonic seams, with an entrapped stratum of volcanic rocks of a total thickness of 5-20 m serving as cushion for a covering of ignimbrites. Tectonic seams closely hold two ore occurrences in position over a total area of 3 km^2. The largest deposit (80% of the total reserves) occurs at the level of ash-flow tuff within the lower tectonic seam at a depth of 40-100 m.

The deposit consists of 17 ore bodies of varying size and configuration, separated by sections of non-commercial-grade ore of a width ranging between several tens and a few hundreds of metres. The total area over which the deposit is spread constitutes 1 500 km^2, with an average thickness of 3.5 m and a uranium content ranging between 0.05 and 1.3% (with a mean value of 0.127%). Sometimes the ore bodies contain molybdenum, lead, zink, zirconium, copper and silver in high concentrations. In view of the stable chemical composition of the ores of this deposit they may be classified into the aluminium silicate category. Uranium extraction by means of sulphuric acid leaching is highly effective (96.9-97.8%). The main uranium reserves of the Gurvanbulak deposit is 10 000 t, secondary reserves - 6 500 t, at a price of 80-120$/kg.

In the northern part of the Dornot ore complex the Mardaingol and Nemer occurrences have been studied in detail, their geological composition being mainly similar to the Dornot and Gurvanbulak deposits.

Apart from the Dornot ore complex, a few other occurrences have been discovered. They are the Ugtam, Turgan and Engershand potential ore-bearing complexes. The total estimated uranium resources within the district is 90 000 t, including 51 000 t of proved reserves and 6 000 t secondary.

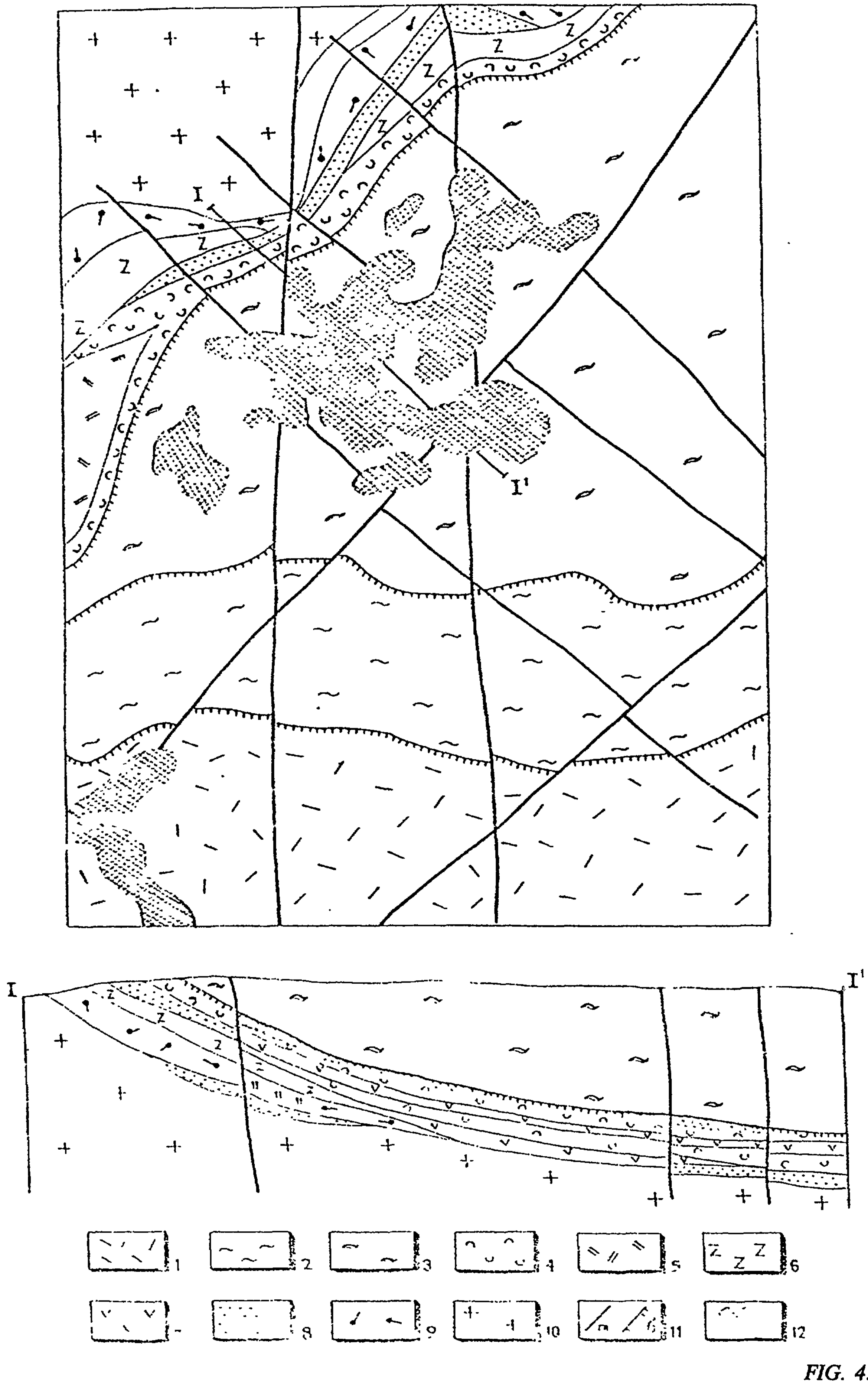


FIG. 4.

FIG. 4. The Gurvanbulak uranium deposit — geological schematic map.

1-9:
late Mesozoic volcanites:

1-	sanidinean trachyrhyolites
2-	fine fluid ignimbrites
3-	massive ignimbrites
4-	rhyolitic tuffs
5-	oligophyric rhyolites
6-	trachydacites
7-	andesitic basalts
8-	sandstones, conglomerates
9-	quartz-feldspar rhyolites
10-	Proterozoic and Paleozoic granodiorites and diorites, metamorphic rocks
11-	main faults: a) steep b) regular
12-	uranium-ore bodies (shown on the geological scheme as projections on the earth surface)

Within the Mongol-Argun province the uranium mineralization of significant commercial value is connected with zones of ground and bed oxidation, a typical example of which is the Kharat deposit.

The Kharat deposit is located within the East Gobi uranium ore province and coincides with one of the largest late Mesozoic structures in the district — the Choir basin, which stretches over 150 km within a width of 10-25 km. The foundation as well as frame of this basin are composed of Proterozoic crystalline shales, gneisses, marbles and a cap of granitoids, in addition of Paleozoic and Mesozoic volcanites. The trough is filled with coal-bearing sediments of the lower Cretaceous (thickness of up to 1 500 m) and a stratum of sands, clays, aleurolites, argilites, gravelites, pebby conglomerates with layers of lignite, overlapped on the eastern flange by mottled coarse-grained sandy gravel formations of the upper Cretaceous, with an underlying layer of gravelites and brecia-conglomerates within a cement of ferruginous sandstone. Uranium mineralization occurs within the upper part of the cross-section in lower Cretaceous layers underneath overlapping sediments of the upper Cretaceous (Fig. 5). The ore-bearing member consists of inter-stratified gritty and argillaceous sandstones of the alluvial-proluvial complex of bed thickness ranging from 0.2 to 20 metres, with an impregnation of sulphides, large quantities of finely dispersed vegetable debris as well as thin streaks of fusainized coal. The ore-bearing rocks are intensively oxidized (depth of 1-2 to 25-30 metres). Within the zone of surface oxidation the rocks are wholly covered with limonite, while further below the surface the effect of limonite treatment is restricted to spots on the permeable rocks. Uranium mineralization leads to the formation of a huge band-like deposit along the old river valley,which extends for more than 20 km on the eastern flanges of the valley, with a depth of between 0.5 and 2 km and a thickness of 1-2 to 33 metres. The deposit is located at a depth of 0.5 to 45 metres from the surface. The average content of uranium in the ores ranges from 0.01 to 0.04%. In the enriched parts extending for over 400-2 500 metres (width 50-300 m) the uranium content rises to 0.03-0. 2%, with a maximum value of 2-4% within lenses found in the thalwegs of the paleichannel. Ores with a uranium content greater than 0.05% constitute almost 30% of the total reserves.

The main uranium minerals in the oxidized ores are those found in the group of autunite, torbernite and schroeckingerite. Uranium is chiefly encountered in carbonificated residues in the form of fine-polished globular oxides. The presence of uranium both in the form of uranyl and oxide leads to non-stable radioactive equilibrium, with a coefficient that varies within the range of 15-300%, with an average value of 124%.

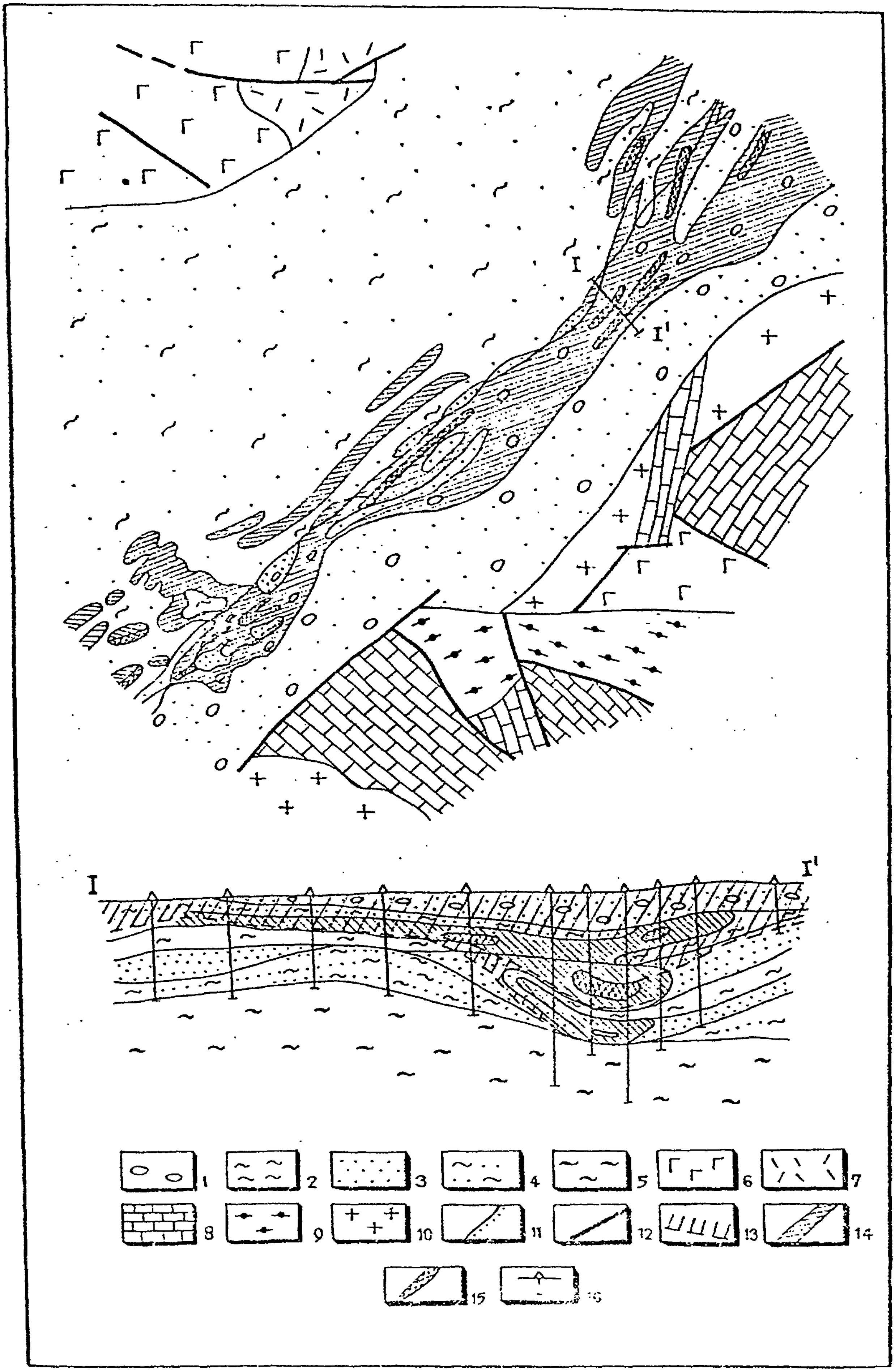


FIG. 5.

FIG. 5. The Kharat deposit — geological schematic map.

1-	upper Cretaceous mottled sandstone and pebby sediments
2-5-	lower Cretaceous grey coal-bearing sandy-clay deposits:
2-	undivided
3-	sandstone
4-	sandy clays
5-	clays
6-	upper Mesozoic basalts
7-	late Mesozoic acid volcanites
8-9	Proterozoic metamorphic rocks:
8-	limestones
9-	crystalline shales, gneisses
10-	Paleozoic leucocratic granites
11-	contact of sedimentary complexes
12-	tectonic dislocations
13-	zone of soil oxidation (shown in cross-section)
14-15-	projections of ore bodies:
14-	with uranium content 0.01 - 0.5%
15-	more than 0.05%
16-	bore holes (shown in cross-section)

The ores of the deposit are rich in cerium (0.2-0.3%), lanthanum (0.017-0.17%), scandium (0.7-60 grams/tonne), yittrium (26-300 grams/tonne), yitterbium (2-12 grams/tonne), rhenium (0.1-8 grams/tonne) and germanium (10-90 grams/tonne), as well as small quantities of molybdenium (up to 0.01%) and silver (up to 3 grams/tonne).

Geotechnical laboratory studies have established the feasibility of leaching as a means of extracting uranium, rhenium, scandium and other rare earth elements from the ores of the Kharat deposit, with an extraction of 80-94%. The most effective way of exploiting the deposit is thus by means of heap leaching, using natural underground water as solvent. In the Choir basin almost 10 occurrences of uranium ore have been discovered, all being geologically and genetically similar to the deposit of Kharat, differing only in terms of the extent to which they have been studied.

Uranium resources of the Kharat deposit are estimated at 22 700 t, including 8 000 t proved, and some possible 7 600 t. The total estimated reserves of the Choir basin is 90 000 t, including 45 0000 t with uranium content of more than 0.05%.

Beside the Choir basin, occurrences of uranium mineralization and other ore formations have been discovered in the East Gobi district. They are in the Baganuratin, Ulannur, Alagtsab and Tabunsubat basins. Practically all the mineralizations are poorly studied and no exploratory surveys or feasibility studies have been carried out on the areas of interest. It may be said with certainty that with the aid of limited exploratory work this promising region (with forecast reserves of 170 000-200 000 t) may be raised to the status of unique and one of the most interesting for the profitable extraction of hydrogenic uranium.

The Gobi-Tamtsag (Gobi) uranium province is located in Southern Mongolia and consists of numerous uranium ore formations in grey and mottled terrigenic sediments connected to oxidation and reduction (redox) zones.

The province enlists the Sainshand potential ore-bearing district in the south, the Nars deposit, a series of potential uranium-bearing basins (the Tamtsag, North-Sainshand, Dzubain and Undurshilin), in addition to numerous ore occurrences.

The Nars deposit is located in the southern part of the Sainshand Cretaceous basin, The basin's foundation consists of metamorphized riphean sediments, acid and alkali volcanites of the Paleozoic eon, and mollasic formations dating to early Mesozoic. The inner parts of the basin contain weakly lithified Cretasean-Paleogenic sediments of thickness of up to 1 500 m. A rhythmically interbedded series of sand and clay deposits the lower Cretaceous, superimposed with terrigenic formations of the upper Cretaceous. The upper sediments, which are the main ore-bearing borides, consist of levels of grey, greenish, mottled, sparsely reddish sands, clays and gravel.

Uranium mineralization is restricted to permeable fine gravel and sandstone level of thickness ranging from 30-35 to 80-100 m, separated by an impermeable horizon of reddish and mottled clays. The ore-bearing layers cover a length of between 800 and 1 700 m, with a breadth of 100 to 400 m. A spatial, multi-level system of complex morphology is formed by the ore-bodies of a thickness of 0.3-7 m. The uranium content is non-uniform, ranging between 0.01 and 0.1%, with an average value of 0.052%. The ores of the deposit may be classified as pitchblende-kerite, pitchblende with amorphous oxides or pitchblende-coffinite in type. They contain galenite, noticeable concentrations of lanthanum, chromium, vanadium, zinc, arsenic, wolfram, copper, germanium and strontium (0.02 - 0.09%), molybdenum (0.002-0.009%). The ores date back to 20 million years. With the aid of laboratory studies it has been proven that the uranium in the ores of the Nars deposit may be easily extracted, leading to the supposition that mining by way of underground leaching would be most preferential.

Another uranium mineralization has been discovered in the same area, related to the oxidation zones of Cretaceous sediments similar to the well-known ore formation in the Kharat deposit (Choir basin). Uranium mineralization is restricted to the area near the surface of the geological section composed of grey sand and clay sediments rich in organic materials dating back to lower Cretaceous and located near a cushion of superimposing mottled coarse-grained residues of the upper Cretaceous. In the Nars occurrence uranium is localized within thin bands 50-250 m long with a thickness of 0.2-1.5 m. A total length of tracked bands is 11 km. The uranium content ranges between 0.01 and 0.34%. Uranium mineralization is in the form of autunite, urophane and schroeckingerite. Selenium (up to 18 grams/tonne), lanthanum (up to 30 grams/tonne) and scandium (up to 10 grams/tonne) are present in the ores.

The forecast resources of exogenic epigenetic uranium mineralization in the Sainshand district, extractible by means of heap or underground leaching is estimated to be 30 000 t.

The remaining uranium-bearing provinces in Mongolia are rather poorly studied, despite their fairly high potential.

Within the Khentei-Daur province uranium ore formation occurs within fracture zones of Mesozoic leucocratic granites. Mineralizations such as the Khangai and Khentei roofs (vaults) are typical examples. Their location is mainly restricted to the central potential ore-bearing district (Zhanchubon massive and others); their commercial-grade analogues are found in Zabaikalje in Russia.

The North-Mongolian uranium-bearing province, within which the oldest structures in Mongolia are found, contains predominantly uranium-thorium-rare-earth and thorium-uranium ore formations in metasomatic rocks. Uranium reserves evaluation based on explored deposits and forecast estimates covering the entire geochemical probe analyses, has been carried out, based largely on the results of special works carried out by Soviet geologists. The total reserves and resources of the country may be estimated at 1 470 000 t. Data on estimates of reserves and resources by province and type of deposit are given in Table I and II. An analysis of the distribution of uranium reserves and resources shows that the proved and secondary components amount to 80 000 t, i.e. 5.4% of the country's entire estimated resources.

The bulk of Mongolia's total estimated ore base (757 000 t, or 52% of the total) is made up of occurrences and deposits of the stratimorphic mineralization type in sandstone (late Mesozoic eon) connected with zones of soil and bed oxidation. Of these the grater part is found in objects in the Gobi-Tamtsag and Mongolian-Argun provinces: the Choir basin (East Gobi district) with some 90 000 t, or 12% of the total estimated value of this ore type, and the Ongiyngol system (chain) of basins in the Mid-Gobi district, with 115 000 t (15%). These objects were discovered only lately and have been studied rather poorly. Nevertheless, this ore type seems to be the most promising in terms of commercial value, among all those currently known in Mongolia. Ore formation occurs near the surface, extraction by means of rather cheap heap or underground (bore-hole) leaching very feasible. The resources of the Kharat deposit as well as similar ore occurrences in the Choir and other basins of the East Gobi district may be graded as 80$/kg (cost) or less.

In commercial terms the next prominent type of ore formation are veins and stockworks found in volcanogenic complexes of continental origin, the estimated total of which reserves is about 313 000 t (21% of the country's total). Of the objects in this formation those concentrated in the North Choibalsan uranium-ore district has been studied in detail. The total figure for explored and secondary reserves is 57 000 tonnes. Here the use of shafts is recommended as an efficient method of extraction, the ore being of the grade extricable at a cost of 80-120$/kg. The remaining ore formations (about 256 000 t) may be classified into this group.

Within the fracture zones of Mesozoic granitoids, of substantial commercial value are appearances of uranium formations (reserves estimated at 180 000 t, or 12% of the total). The combined effect of the feasibility of ore dressing by means of radiometry and favourable mining conditions places the ore in the grade at a cost of 80-120$/kg.

Other types of uranium mineralization in Mongolia are rather poorly studied and account for just 15% of the country's total reserves. They are mostly located in the inaccessible parts where severe natural conditions prevent their exploration. The cost of exploitation of such ores is estimated at 120$/kg or more.

Thus, available information allows a division of Mongolia's uranium resources into the following categories (in terms of ore cost): <80$/kg: 205 000 t; 80-120$/kg: 579 000 t and >120$/kg - 687 000 t.

In conclusion it must be pointed out that the estimates of uranium resources were made based on data obtained from such districts of the country where special surveys and analyses could be carried out. No surveys or analyses were undertaken over a significant part (40%) of Mongolia's territory, except for certain areas covered by airborne gamma spectrometer survey (scale 1: 1 000 000). From available geological data it may be concluded that the country holds good prospects for up-to-date and undiscovered reserves that special attention be paid to areas which have either been ignored during previous surveys or have been studied to a small extent only.

TABLE I. DISTRIBUTION OF URANIUM RESERVES AND RESOURCES OF MONGOLIA (ACCORDING TO DEPOSIT TYPES)

N	Type of deposit	Location of deposit	Reserves and resources (thousand tonnes)									Example of deposit	Characteristics of deposit	
			Total	%	Proved			Secondary (probable)			Fore-cast		Uranium content in ore	Reserves
					Total	up to 80$/kg	80-120$/kg	Total	up to 80$/kg	80-120$/kg				
1	Veins or stockworks in continental volcanogenic complexes	North Choibalsan, Berkhin, etc.	313	21	51	-	51	6	-	6	256	Dornot, Gurvanbulak etc..	0.03 - 0.30%	up to a few thousand tonnes
2	Stratimorphic, in sandstones connected with zones of soil and bed oxidation	East Gobi, Central Gobi , Sainshand, etc.	757	52	8	8	-	11	11	-	738	Kharat, Nars, etc.	0.01-0.04%	-"-
3	Other types		400	27	-	-	-	-	4	4	396			
	In all:		1470	100	59	8	51	21	11	10	1390			

TABLE II. MONGOLIA'S URANIUM RESERVES AND RESOURCES (BY ORE PROVINCE)

N	Name of metallogenic subdivisions	Reserves and resources (thousand tonne)							
		Total estimate	Proved			Secondary (probable)			Forecast
			Total	up to 80$/kg	80-120$/kg	Total	up to 80$/kg	80-120$/kg	
1	2	3	4	5	6	7	8	9	10
1	Mongolian-Argun Uranium ore province	470	59	8	51	14	8	6	397
	Type of metallogeny:								
	- vein/stockwork in continental volcanogenic complexes	303	51	-	51	6	-	6	246
	- stratimorphic in sandstones	167	8	8	-	8	8	-	151
2	Gobi-Tamtsag potential ore-bearing province	500	-	-	-	3	3	-	497
	Type of metallogeny:								
	- vein/stockwork in volcanites	10	-	-	-	-	-	-	10
	- stratimorphic in sandstones	490	-	-	-	3	3	-	487
3	Khentei-Dauria potential ore-bearing province	15	-	-	-	4	-	4	146
	Type of metallogeny								
	- paleo-channel sediments	30	-	-	-	-	-	-	30
	- within granite fracture zones	120	-	-	-	4	-	4	116
4	North Mongolian potential ore-bearing province	350	-	-	-	-	-	-	350
	Type of metallogeny:								
	- stratimorphic in sandstones	100	-	-	-	-	-	-	100
	- uranium-thorium-rare-earth within metamorphites of alkali rocks	115	-	-	-	-	-	-	115
	- within shale chert sediments	69	-	-	-	-	-	-	60
	- thorium-uranium in meta-somatites	15	-	-	-	-	-	-	15
	- within granite fracture zones	60	-	-	-	-	-	-	60
	In all:	1470	59	8	51	21	11	10	1390

Next page(s) left blank

URANIUM EXPLORATION AND PRODUCTION IN ROMANIA: CASE HISTORIES AND PROSPECTS

C. BEJENARU, D. CIOLOBOC
Regie Autonom for Rare Metals, Bucharest, Romania

Abstract

This paper gives the history of uranium explorations and exploitation in Romania from 1950 to present. It describes the geological characteristics of some of the most important deposits in the three metallogenic provinces hosting uranium. The paper also discusses the required technological and operational improvements that are necessary to modernize the Romanian uranium industry and to reduce production costs.

1. URANIUM EXPLORATION

Uranium research works in Romania started in 1950, and in their evolution there are three distinct stages depending on the way of organizing. The founding of the Romanian-Russian joint venture SOVROM-CUARTIT marks the beginning of the first period which ended in 1961 when the Soviet consultants left the country. The second stage extended from 1961-1989, when the activities in this field were organized in the Rare Metals Enterprise, a state organization with industrial profile. Since 1990, in the conditions of a free economy, the entire uranium exploration and production activity has been organized within the Rare Metals Autonomous Regie.

The first period is characterized by the development of ample geological surveys, air and land radiometric works, research studies in the underground mines and drillings executed for the exploration of other metals. Thus two uranium metallogenesis provinces have been outlined in the western part of the country in the Apuseni Mountains and Banat Mountains respectively (Fig. 1). Even during the first period within these two areas, four medium size uranium deposits (Ciudanovita, Natra, South Dobrei and Avram Iancu) and a large one Baita-Bihor, known at that time as the richest deposit in the world, were discovered.

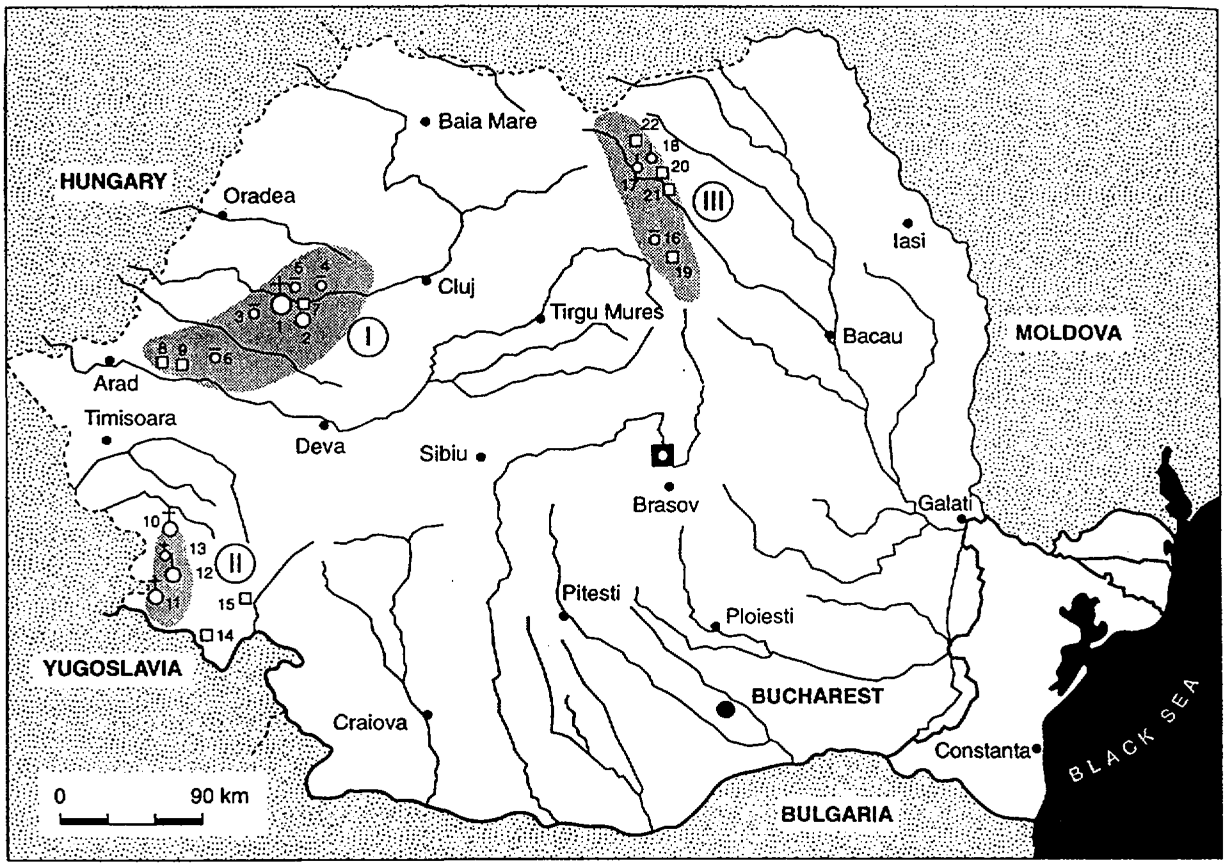
Regarding the spatial distribution of the uranium deposits in the north-west of the Apuseni Mountains the last metallogenetic events was in the Laramic phase of the Alpine- orogenesis with an intense magmatic activity which resulted also in the location of the granite batholith as the region foundation (Fig. 2). The central area of the batholith is situated under the Baita-Bihor deposit and has the composition of high alkali adamellitic granite and leucogranite.

Covering this batholith, the Paleozoic and Mesozoic rocks have been subjected to different metamorphic processes: dislocations, contact and hydrothermal metamorphism.

The hydrothermal metamorphism has the greatest implications in the transport and the location of uranium mineralizations which in this region has the following forms :

- veins in metamorphic rocks were uranium is associated with Co, Ni, Cu, Pb, Zn;
- tabular type lying in metarhyolites in which uranium is associated with Mo. and rarely with Pb and Zn;
- tabular type in sandstone in which copper with low grades is also found.

Uranium deposits in Romania



I. APUSENI MOUNTAINS

Deposits
1. Baita Bihor
2. Avram Iancu
3. Ranusa
4. Rachitele
5. Budureasa
6. Paiuseni

Occurrences
7. Arieseni
8. Milova
9. Conop

II. BANAT MOUNTAINS

Deposits
10. Ciudanovita
11. Natra
12. Dobrei South
13. Dobrei North

Occurrences
14. Ilisova
15. Mehadia

III. EASTERN CARPATHIANS

Deposits
16. Tulghes
17. Crucea
18. Botusana

Occurrences
19. Bicazul Ardelean
20. Piriul Lesu
21. Holdita
22. Hojda

Uranium provinces
(I) Western Carpathians
(II) Banat Mountains
(III) Eastern Carpathians

Large deposits: > 20 000 t metal
Medium deposits: 5 000–20 000 t metal
Small deposits: < 5 000 t metal
Feldiora plant

Ore deposits depleted
Ore deposits in exploitation
Ore deposits in exploration
Mineralisation in exploration

FIG. 1. Uranium in Romania.

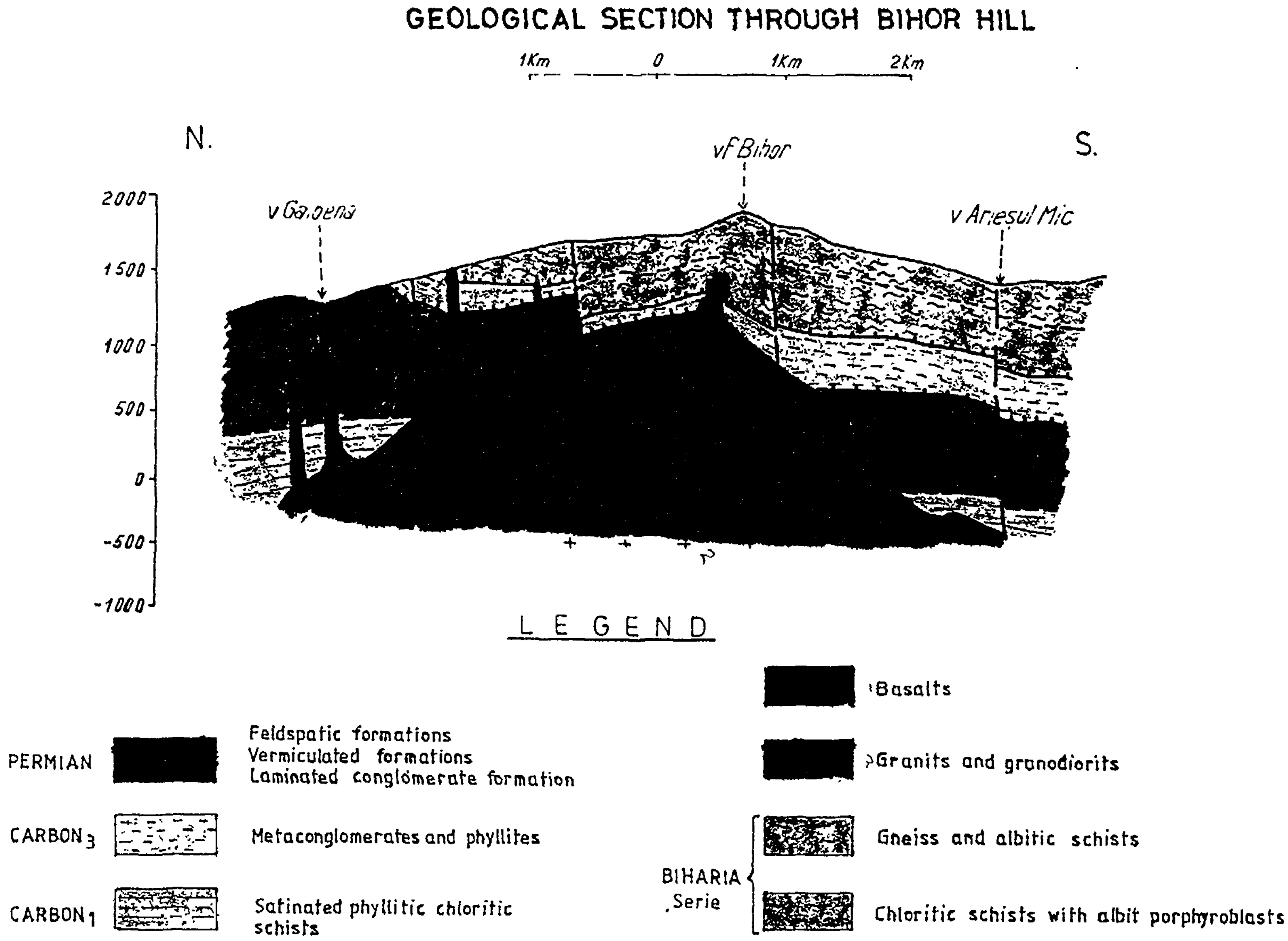


FIG. 2. Geological section through Bihor Hill.

The Baita-Bihor is a representative type as a uranium deposit in Permian sandstone. It is located in the hydrographic basin of Crisu Mic river, 5 km North-West of the Bihor Mountains peak (1851 m). The mineralization of this deposit, represented by pitchblende is in the grey striped sandstone with bands of black sandstone belonging to the Permian age (Fig. 3). Inside the productive layer, known as the "flyschoid horizon", with thickness between 40 and 150 m, ample processes of epidote and albite formation, generated by the hydrothermal solutions, has been noticed. The access ways in their upward movement, were the fault systems oriented north-west to southeast and north-east to south-west. The location of the mineralization at this lithologic level could be determined by the change in the geochemical balance of the bearing solutions. Within this productive area ores are lens shaped with different sizes (Fig. 4). Pitchblende, the main uranium mineral, forms accumulations more or less compact in sandstone cement. The hypergene minerals of uranium are represented by silicates, carbonates, phosphates and arsines which compared with pitchblende do not have industrial importance. Sometimes the uranium mineralization is accompanied by: pyrite, chalcopyrite, blende, galena but, excepting chalcopyrite, in no significant quantity.

Considering the strategic importance of uranium in the 1950-1960 decade, the exploitation of this deposit took place almost at the same time with geological exploration. Thus if until January 1958 16,000 t of metal were outlined with an average grade of 1.13% U at the same time 14,500 t with an average grade of 1.26 % U were already exploited. More than 90% of these reserves were exploited by open pit. (Fig. 3). The extracted ore was later sorted to reduce the crushing expenses and also the transport expenses to the processing plant "Narva" located at the Baltic Sea shore.

During the same period, another deposit Avram Iancu in the Apuseni Mountains was discovered. This deposit appears in similar genetic conditions but it is located in the carbonates area of the Biharia metamorphic rocks.

In the second stage of the exploration for uranium in the metallogenetic province from the Apuseni Mountains, in the Permian formations, the deposits from Ranusa, Rachitele and Budureasa were discovered. The Paiuseni deposit was also outlined in the Biharia metamorphic rocks. The radiometric anomalies and mineralizations encountered at Arieseni, Milova and Conop will confirm the value of this type of deposit, as geological criteria, for the research activity in present.

Exploration conducted in the Banat Mountains also obtained exceptional results. In this area are discovered and later explored mineralizations hosted in sedimentary rocks: micro conglomerates, sandstones and shales of upper Permian age. For uranium of particular importance is the fine granulation facies within the Ciudanovita sedimentation series (Fig. 5). The most complete development of this series is in the eastern part of the Natra-Girliste anticline. In this area five sedimentation rhythms are recognized within a 350-400 m thickness. Starting with the bottom they are named: Dobrei, the Mezorythm of the conglomerates, Lisava, Natra, Ciudanovita.

The Ciudanovita deposit, a representative type for this metallogenetic province, is situated 18 km north-east from Oravita town. The Ciudanovita sedimentation rhythm has generally, fine grain sizes and an average thickness of 30-40 m. From the lithological point of view this sedimentation rhythm has basically grey and red sandstone shaped lenses over which other fine, grey-greenish carbonate sandstone is located. Going upwards the sandstone becomes medium sized. At the upper part of this level the uranium mineralization, formed by pitchblende and antraxolite is encountered. The main mineralization which formed the Ciudanovita deposit is 1500 m long and about 700 m thick. In the North and South extremities the mineralization becomes richer making up two columns with depth development within the limits, of this richer parts, comprised between 0.4 and 2 m and the metal content between 0.1-0.8% U. The uranium mineralization of the Ciudanovita deposit is characteristic for all the deposits in the West Banat. It is represented by pitchblende finely dispersed in solid bitumen, coals, bitumen or coal shale and rarely without bitumen forming layers and small veins along the faults system. Grains of pyrite, chalcopyrite, blende and galena are rarely encountered with bitumen.

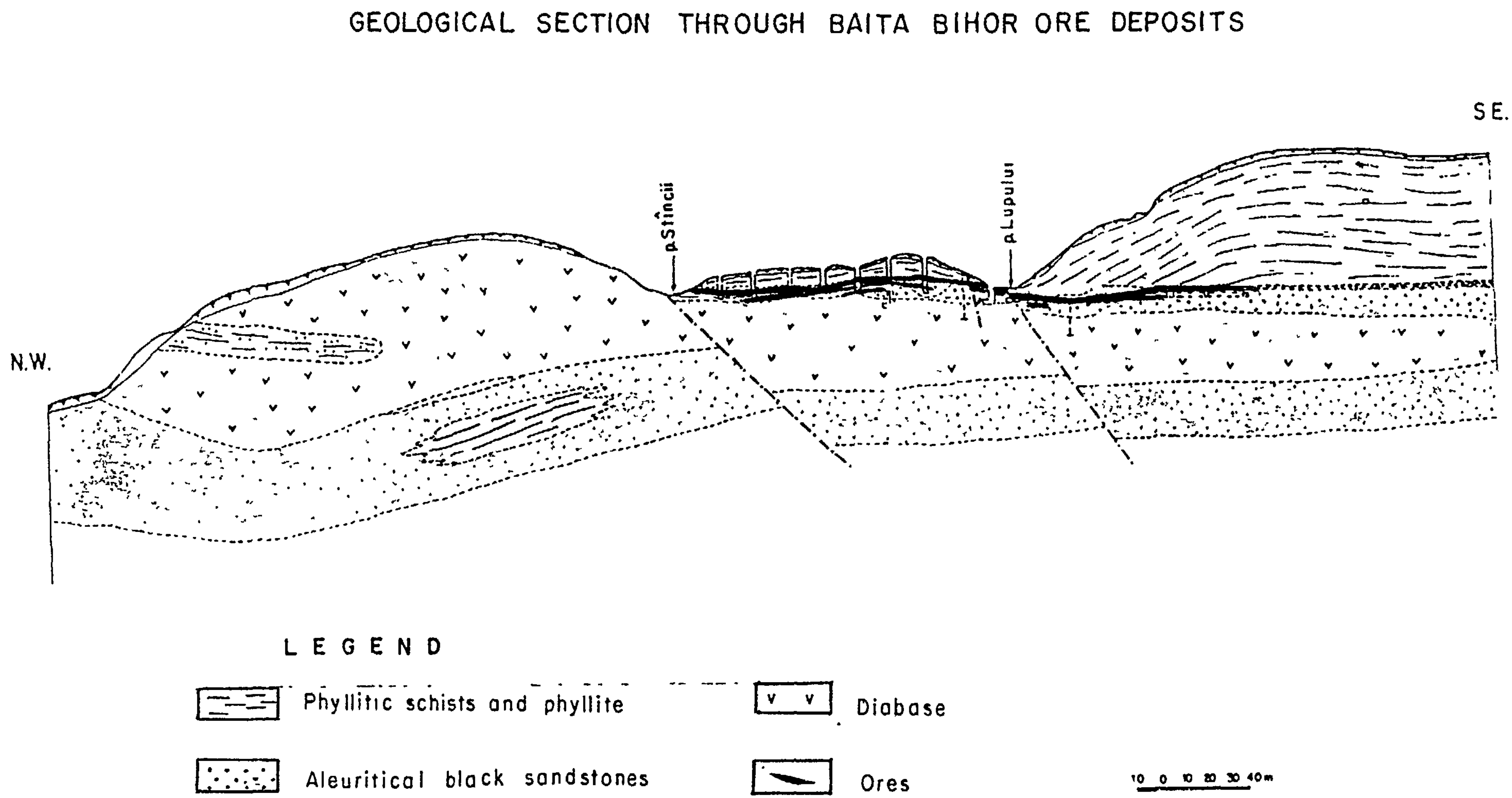


FIG. 3. Geological section through Baita Bihor deposits.

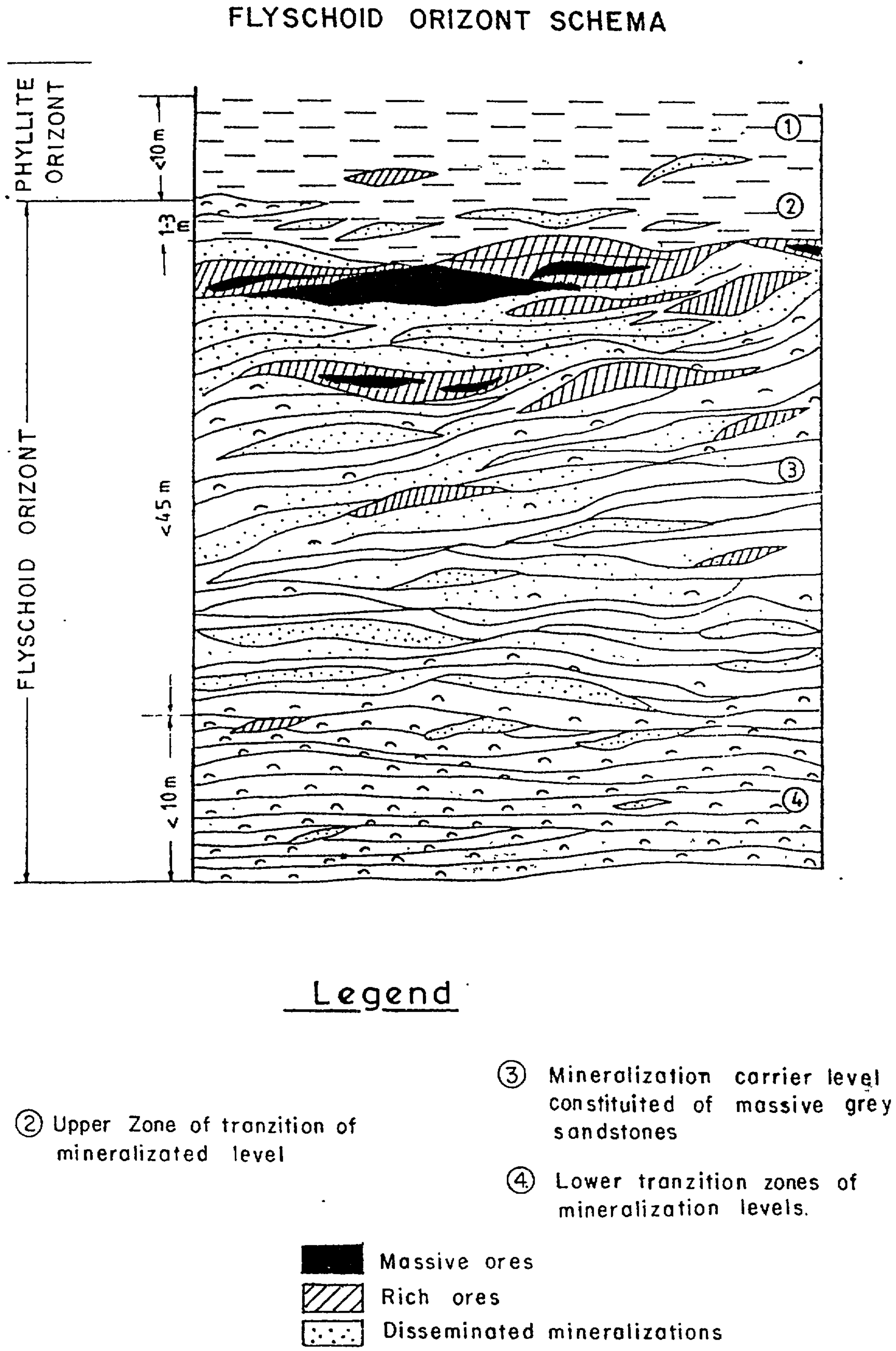


FIG. 4. Flyschoid horizon scheme.

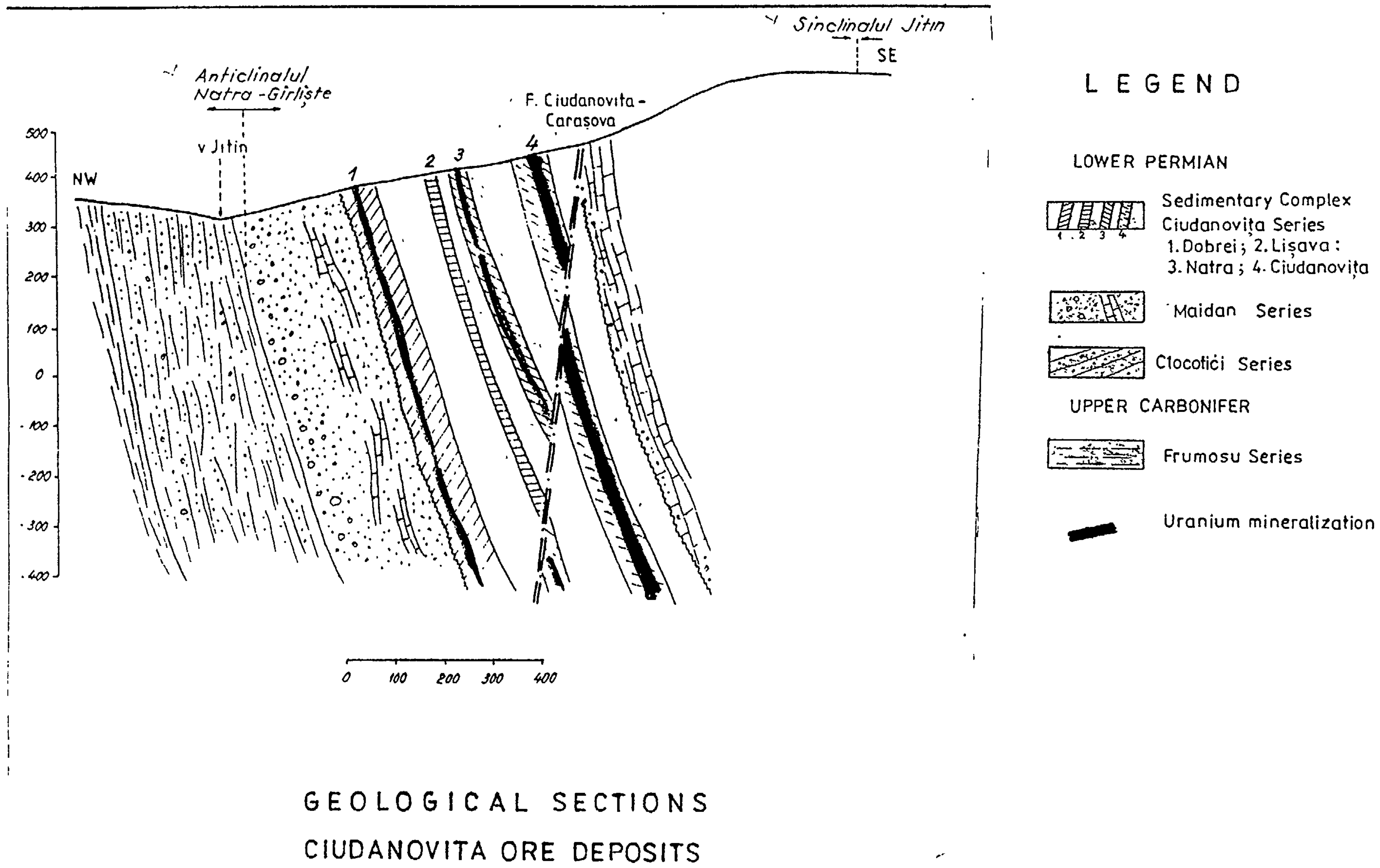


FIG. 5. Geological sections: Ciudanovita ore deposits.

In the upper part of the deposit, on a 30-35 m thickness, the mineralization is oxidized and sometimes partly washed. Within this interval, uranium minerals specific for the hypergenesis area are: autunite, torbernite and black of uranium. The absolute age determinations of the mineralizations in the Ciudanovita deposit, using the U/Pb method indicated two sedimentation periods at 230 and 111 million years.

The exploitation of the Ciudanovita deposit before present was by underground methods. Mining started in 1957 and in January 1993 the ore was nearly exhausted.

The prospect of discovering new deposits within this metallogenetic province is represented by the research works extended on the geological structure already known by drillings. In the Eastern Banat the recent surveys outline a new uranium metallogenetic sub province characterized by mineralization without bitumen support, formed probably due to the hydrothermal implications.

The results of the investigations developed in the second stage (1961-1989), comprises new deposits in the known provinces and a new prospect area. In the new area in short time three important uranium deposits have been discovered (Tulghes, Crucea, Botusana) and also many mineralizations with similar characteristics which all form a metalogenetic province in Oriental Carpatians.

The first characteristic of the mineralization is its location along the main fracture of NNW-SSE orientation which is along the border of the metamorphic rocks of the Oriental Carpatians. The vein ore accumulations have different shapes depending of the opening of the fractures.

In the Tulghes deposit, a typical deposit for this area in a geological section, four mineralized zones can be distinguished, all having almost the same direction NNW-SSE (Fig. 6). In the first zone situated in the West of the deposit, the mineralization occurs about 2 km along the main fracture oriented NNW-SSE, with an estern dip of 60-70 degree. The opening of this fracture, along which the mineralized solutions circulated, varies between 2 and 12 m.

The ore body located on the main fracture, and also on the adjacent faults, is vein shaped and varies from a few meter to 300 hundred meter long. In the clay and carbonate masses which fill the faults, the mineralization is present in different forms: veins, impregnations, nests and lenses of variable sizes (Fig. 7).

The principal uranium mineral pitchblende, is associated with bitumen and sporadic occurrences of pyrite, blende, and chalcopyrite, etc. In the hyper genesis area the secondary uranium minerals form fine crusts or irregular aggregates around the primary minerals. Among these are kasolite, clarkeite, curite and others.

The second zone situated about five hundred meters to the east occurs over a length of about 6 km. Characteristic of the central segment of this deposit is the massif deposition of carbonates (ankerite and siderite), which forms the gangue of the uranium mineralization.

The third zone has the same orientation (NNW-SSE). It is located east from the second zone and has a five km length. The dip of the main fracture is 60-70 degree to the west. This little studied area is similar to the second zone.

The fourth zone is situated six hundred meters east from zone three and extends along 3 km. This is the least studied area .

Determinations of the absolute age of the mineralization at Tulghes indicate the precipitation of pitchblende at occurred 280 million years (C3-P1) before present during the Hercynic orogeny.

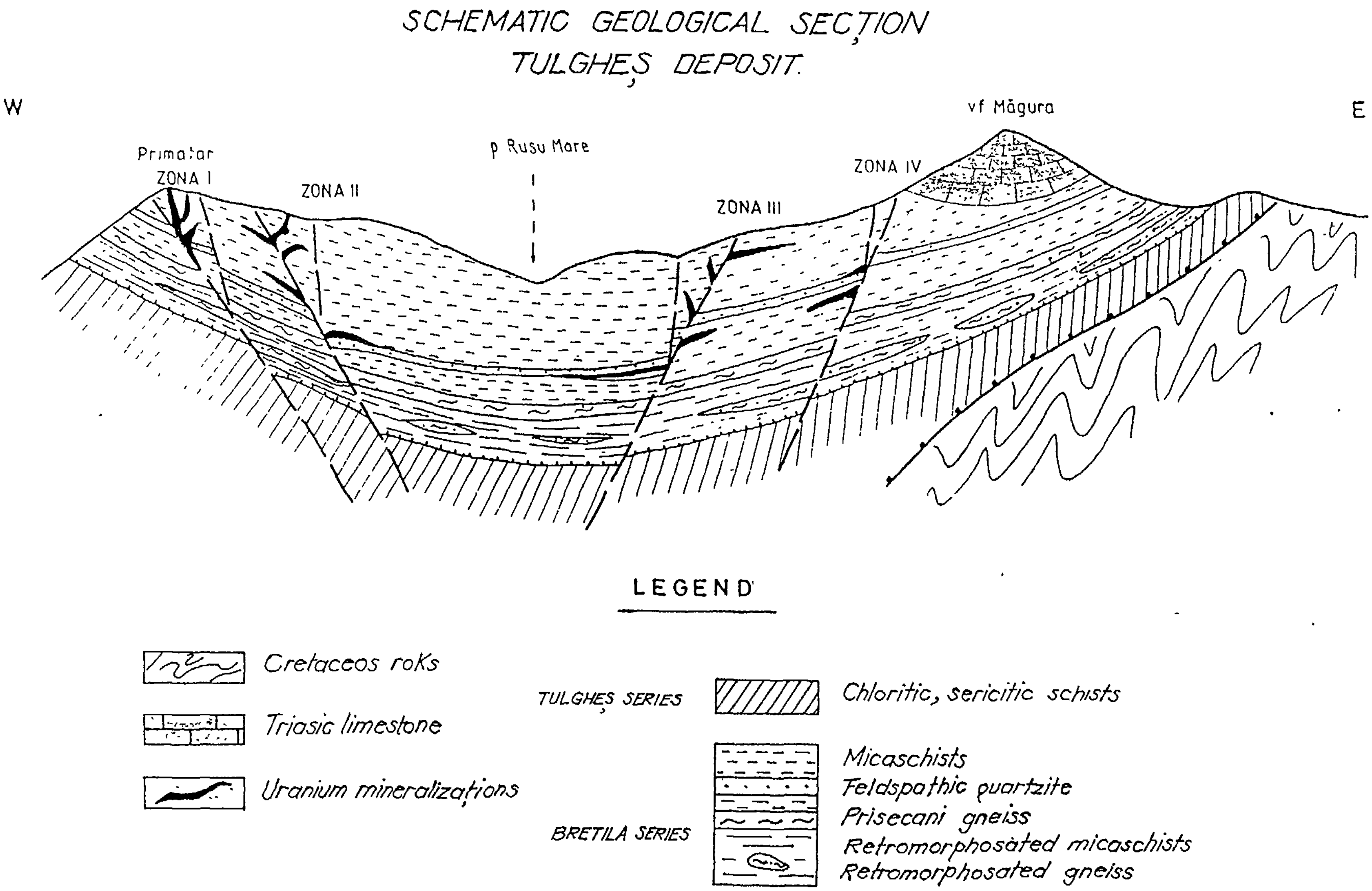


FIG. 6. Schematic geological section: Tulghes deposit.

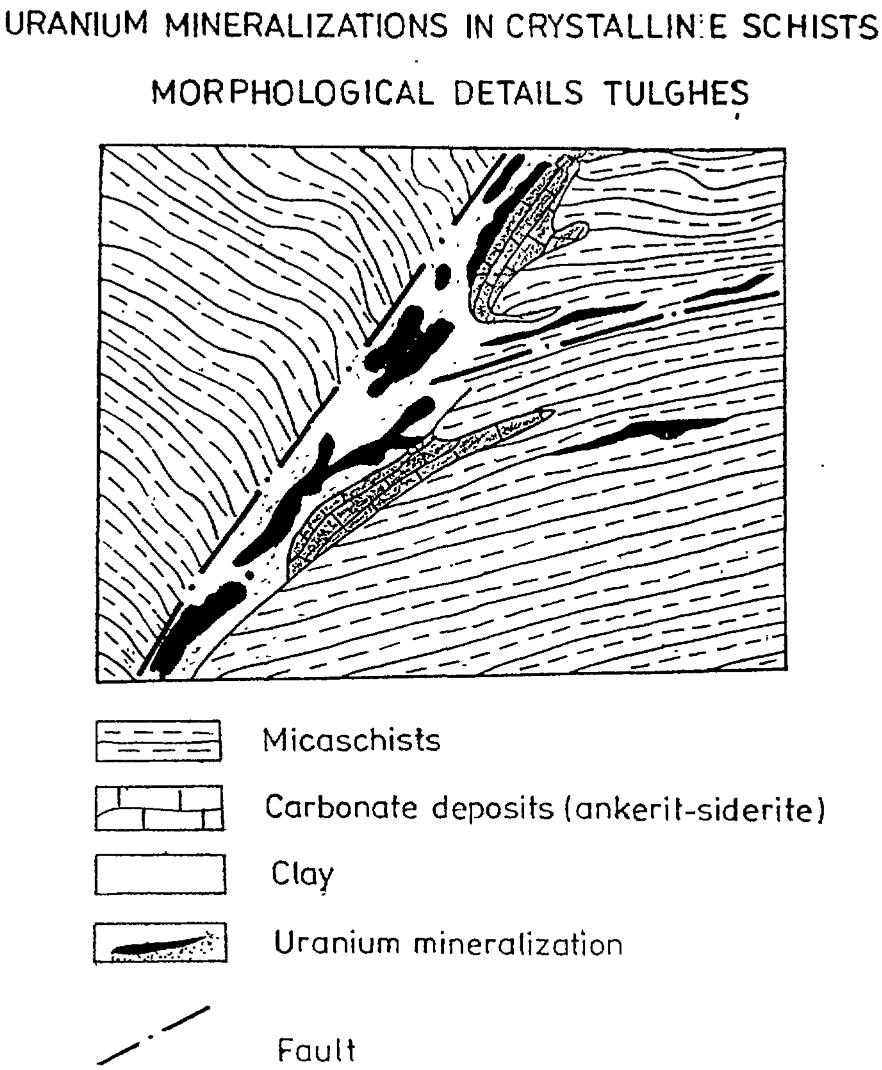


FIG. 7. Uranium mineralization in crystalline schists: Morphological details of Tulghes deposit.

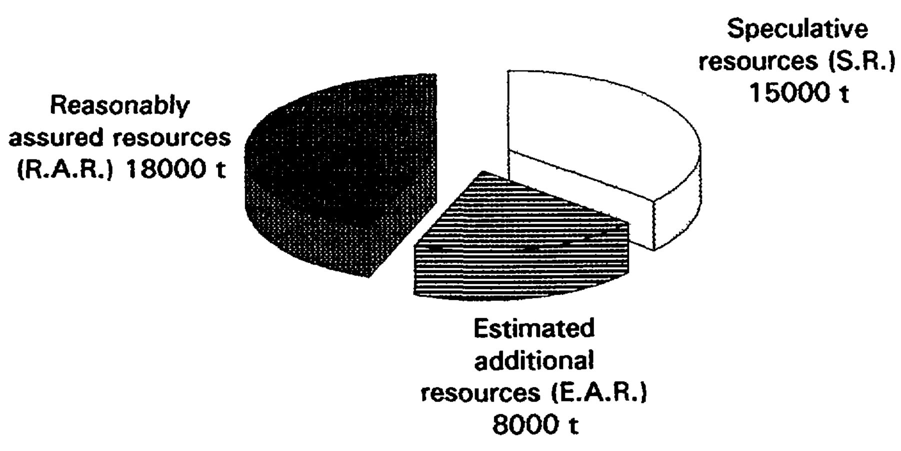


FIG. 8. Uranium ore resources in Romania.

The phases of the Alpine orogeny are well marked. Some specialists believe this had an important role in forming the mineralization.

In the second period of research in the Oriental Carpatian metallogenetic province mineralizations at Bicazu Ardelean, Piriul Lesu, Holdita and Hojda have been distinguished. Additional exploration is required to establish the economic potential of these uranium occurrences.

The immediate prospect of the activity in the uranium field with the purpose of increasing the volume of the geological reserves is subordinated to the research works, drillings and mining works adequate to the productive structures in all the three metalogenetic provinces. For the future, the specific works on the Cretaceous sedimentary structures and younger mountains area have potential of discovering new sedimentary deposits.

2. URANIUM PRODUCTION

Uranium production in Romania is the sole responsibility of the Rare Metals Autonomous Regie (RMAR) .

Exploitation first started in 1952 with one exceptional high grade deposit in the Apuseni Mountains. Exploitation of the deposits from the Banat area began in 1956. Mining began at one deposit in Oriental Carpatians in 1980.

The uranium ore production reached a peak in 1952-1961 when ore produced was exported. The state then decided that the ore export should be stopped. The exploitation re-started in 1978 when the new processing plant at Feldioara began operation. This plant produces technical concentrate as U in DUNA.

A processing department for the production of sintered UO_2 was commisssioned in 1985. This product represents the raw material for nuclear fuel production for the NPP Cernavoda.

The evolution of the production of raw ore and technical concentrates of U in the 1980-1982 period is shown in Fig. 9.

Taking into account that out of five units of 700 MW only unit 1 and 2 will be commissioned in the first stage the existed quality of uranium in UO_2 from the existent stocking delivery for NPP ensures the necessary for 1 unit an entire functioning period of 25 years and 5 years for unit 2 respectively. Under these circumstances a supplementary extraction capacity is necessary and for these purpose we have in view the Tulghes deposit.

To improve the technical and technological parameters in the extraction and processing activities, RMAR plans a programme for modernization and rehabilitation including the following main measures :

- increasing the production capability of the exploited deposits and the Feldioara plant capacity;
- experimenting and achieving the recovery of U through unconventional methods in the areas with lower grades using bulk leaching or in situ leaching;
- the acquisition and introduction in the underground mines of high performance equipment adapted to the specific conditions of the deposits, thus increasing the mechanization degree at the underground works and the new exploitation methods;
- introduction of new technology at the processing plant and achievement of new technological indicators similar to those at other advanced plants;

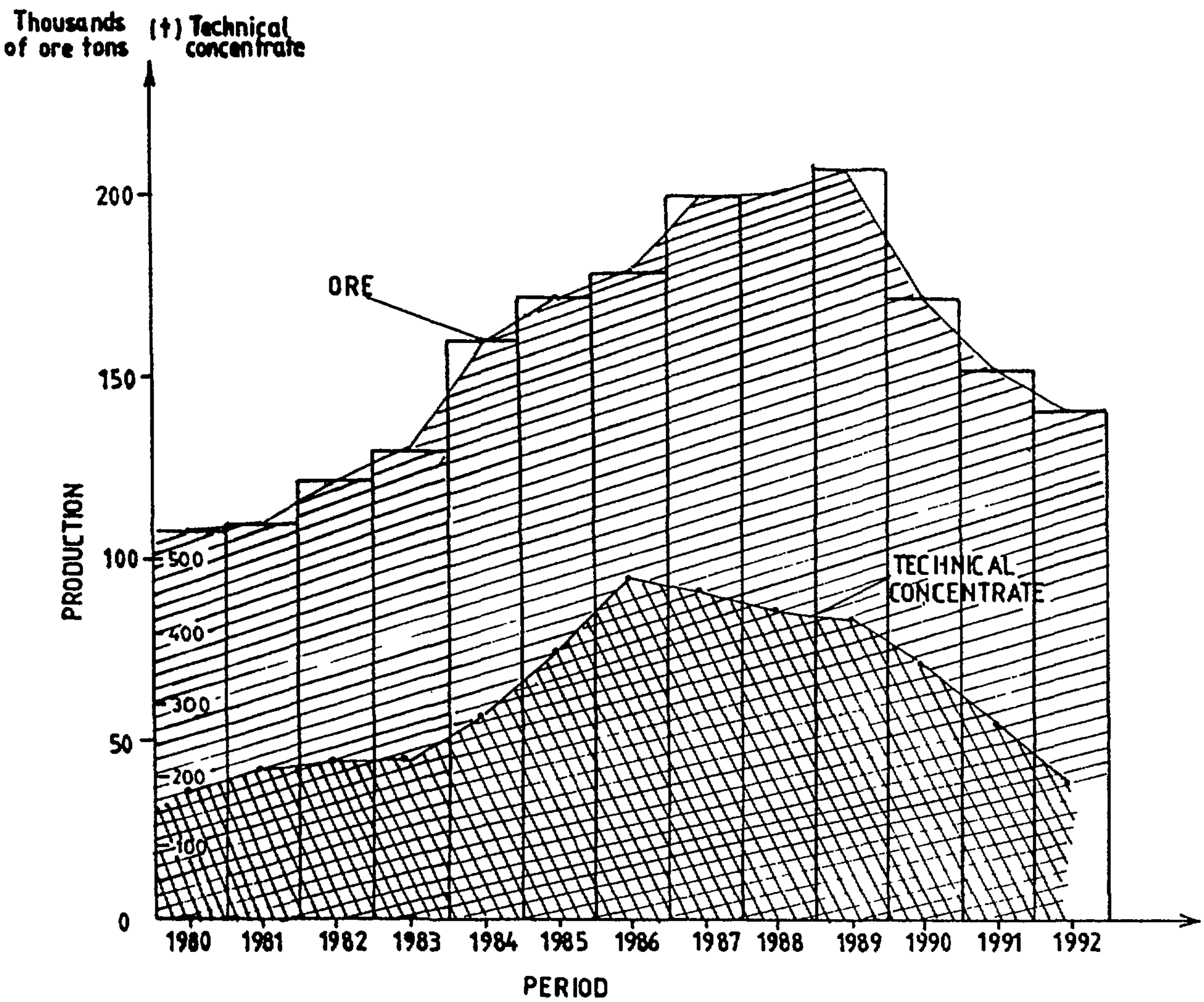


FIG. 9. Ore production evolutions and technical concentrate of uranium in the 1980-1992 period.

- adapting the treatment technology from the U plant to the conditions of building new plants within the mining companies for reducing transport expenses.

It is considered that by adopting these new measures lower production costs will be possible. As a consequence the resulting prices will be similar to those on the international uranium market. Also we have to mention that the extraction and processing activities for uranium are conducted according to international rules regarding environmental protection.

We are now expecting to be helped by the German Government to assist us in increasing the recovery of uranium at the mill at Feldioara from 78-80% up to 90%. This will change the economical results of the plant.

The projected production costs for uranium as raw material to the feed of the NPP Cernavoda for 1 kWh determined by RENEL and shown in the IAEA study from March 1993, is lower than the price at the thermal electric power stations which are fed with conventional domestic fuels.

3. CONCLUSIONS

To increase the production of ore and concentrate, taking into consideration the increasing need outlined in all prognoses by the IAEA papers, it is necessary to find to develop opening and exploitation works of the Tulghes and Ranusa deposits. It is also necessary to increase the efficiency of uranium recovery at the Feldioara processing plant.

BIBLIOGRAPHY

BACIU, F., Uranium deposits in the Oriental Carpathians, MMPG-IMR, ODPT Bucharest (1973).

BEJENARU, C., BOBE, M., Prospects for the uranium sector in Romania, IAEA (1991)

GOGA, I., The metallogenetic province of the West Banat (manuscript).

HADAREANU, R., Uranium deposits in Banat, ODPT Bucharest (1973).

NITU, Ghe., The tectonic-magmatic conditions of formation of the uranium deposits in Romania.

PANICAN, A., The geology of the Bihor Mountains and valuable mineral deposits.

XXX, Geological yearly reports from RAMR archives.

URANIUM RECOVERY FROM PHOSPHATES IN ROMANIA

F. BUNUS, I. MIU
Chimenerg, Craiova, Romania

Abstract

The history of laboratory and pilot-scale research work carried out in Romania is reviewed. Based on this work, three industrial-scale uranium recovery units have been built adjacent to the existing plants that produce phosphoric acid for fertilizer production. The process described uses solvent extraction for recovering uranium from phosphoric acid (sulfuric acid attack) and from phosphonitric acid (nitric acid attack). The extractant used is either a DEPA-TOPO mixture or a mixture of DEPA-TBP. The method selected for the industrial-scale units is a "one-cycle, extraction-stripping process" that differs from the "two-cycle, extraction stripping process" developed by the Oak Ridge National Laboratory (ORNL). In the "one-cycle method" both uranium and the rare earths are co-extracted and then selectively stripped by techniques that simultaneously produce precipitates. The first stripping operation selectively recovers a rare earth precipitate. Uranium is obtained from the second-stage stripping operation as "green cake" (a fluoride of U^{4+}), which can be readily transformed to high purity UFO_6. The treated phosphoric acid produces a triple superphosphate (TSP) of low radioactivity and a diammonium phosphate (DAP) of no radioactivity. Three uranium recovery plants have been built adjacent to the existing phosphoric acid plants and are to be put into operation soon. Each plant can produce approximately 30 tonnes per year of uranium. The technology for conversion of the "green cake" to nuclear grade diuranate has also been finalized. Estimates indicate that the "one-cycle extraction-stripping process" has a lower capital investment cost than the "two-cycle extraction-stripping process", and the projected operating costs are 25-30 US$/kg of U.

1. INTRODUCTION

A history of research work carried out in Romania at laboratory and pilot plant is given. Based on this work, three industrial units have been built adjacent to phosphoric acid plants for fertilizer production. The process described for uranium recovery uses the solvent extraction method from phosphoric acid (sulfuric acid attack) and from phosphonitric acid (nitric acid attack). The extractant is a mixture of DEPA+TBP or DEPA+TOPO. The method selected is "one-cycle extraction-stripping process" and is different of "two cycle extraction-stripping process" of ORNL.

In "one-cycle method" both uranium and rare earths are extracted and then stripped selectively and simultaneously precipitated. Uranium is obtained directly from stripping process as "green cake" a fluoride of U (IV) which can be easily transformed into UF_6 of high purity. Rare earths are also stripped and precipitated at the same time, representing the yttrium group. The fertilizers obtained are non radioactive, the environmental problems are eliminated. Three uranium recovery plants have been built situated near phosphoric acid plants, and are to be put into operation soon. Each recovery plant can process approximately 30 t/year uranium element, i.e. a total of 90 -100 t/year uranium element.

The technology for "green cake" conversion to nuclear grade diuranate as that required for separation of rare earth elements was also finalized. Comparable with "dual process", the "one-cycle extraction-stripping process" has lower investment cost and operation costs are 25 -30 US$/kg U element.

2. URANIUM RECOVERY FROM PHOSPHATES IN ROMANIA

Romania is an important producer of fertilizers in general and of phosphate fertilizers in particular. There are 8 plants with each processing 330 000 t/year phosphates. In four plants, the reagent of attack is sulfuric acid. The resulting phosphoric acid is used to produce triple superphosphate (TSP) and diammonium phosphate (DAP). In the remaining four plants, the phosphate rock is attacked by nitric acid and the resulting phosphonitric acid is used to produce a complex fertilizer of NP or NPK type.

Starting with 1970, intensive work was carried out in Romania [1, 2, 3] in view of recovering uranium from sedimentary phosphates, improving at the same time the quality of phosphoric acid. The research was finalized on solvent extraction method, other processes were eliminated as non-suitable for the phosphoric or phosphonitric media. Therefore, the method must be efficient in both cases including phosphoric acid and phosphonitric acid.

Various extractants have been screened but only acidic organo -phosphorous esters were efficient. Within this class, octyl or nonyl phenylphosphoric acid and alkyl pyrophosphoric acids were efficient but unstable versus hydrolysis as IR spectra, chromatographic and pHmetric determinations have shown. At the same time it is difficult to strip of elements extracted as: U(IV), Y(III), Fe(III), as our extensive work by IR spectrophotocolorimetry, mass spark spectrometry, neutron activation analysis etc, have shown.

The only efficient and stable extractant, described by Hurst et al. [4, 5, 6] di (2ethylhexyl) phosphate (DEPA) is appropriate for both phosphoric and phosphonitric media. This extractant was studied as such or in synergic mixture with TBP or TOPO. The synergic mixture with TOPO is more efficient in both phosphoric acid [2] and phosphonitric media [7].

The extensive work carried out at laboratory scale in this country is given in papers [1, 2, 3, 7] only partially.

The stripping process is different than that used in "two-cycle process"; even the reagents are different. Taking into account the advantages of an acidic strip reagent and the simplicity of a "one-cycle extraction-stripping process" this method was selected.

In cases, extractant DEPA+TBP or DEPA+TOPO, the yttric group of rare earths (REs) are extracted from phosphoric medium [8] a the same time as hexavalent uranium.

One-cycle extraction-stripping process established in Romania at laboratory scale was later applied in a semi -industrial plant. An exhaustive work was carried out to find the most efficient way of acid clarification and organic matter elimination from brown acids (optical density higher than 0.4).

The pilot plant was designed and did process 5 m^3/h phosphoric acid (sulfuric attack). Phosphoric acid was cooled at 35°C and clarified (0.1-0.2 g solids/l). Green phosphoric acid need no further treatment (optical density below 0.3).

Extraction process takes place in an horizontal multi-stage mixer-settler extractor. After the separation of the two phases, the extractant was stripped in one step mixer where rare earths are removed. Rare earths elements are transferred to aqueous phase and in contact with this medium are precipitated and settled. The strip reagent does not affect uranium. The three phases are separated in a separator, the precipitate removed and the reagent is recirculated. The extractant leaving the separator is stripped in one step mixer with a reducing acid media with a lower redox potential than that obtained with H_3PO^4+Fe(II). Uranium as U (IV) is transferred to aqueous phase where it instantly precipitates. Separation of the three phases takes place in a separator. Stripping reagent and the extractant are recirculated. Uranium precipitate is removed and filtered as "green cake". This compound is a fluoride of U(IV) as determined by X-ray diffraction and thermodifferential analysis. This last product can be easily transformed into UF_4 and by fluorination into UF_6 of high purity. Rare earths are also obtained as a cake of 20-40%. The flowsheet of the process is given in Fig. 1.

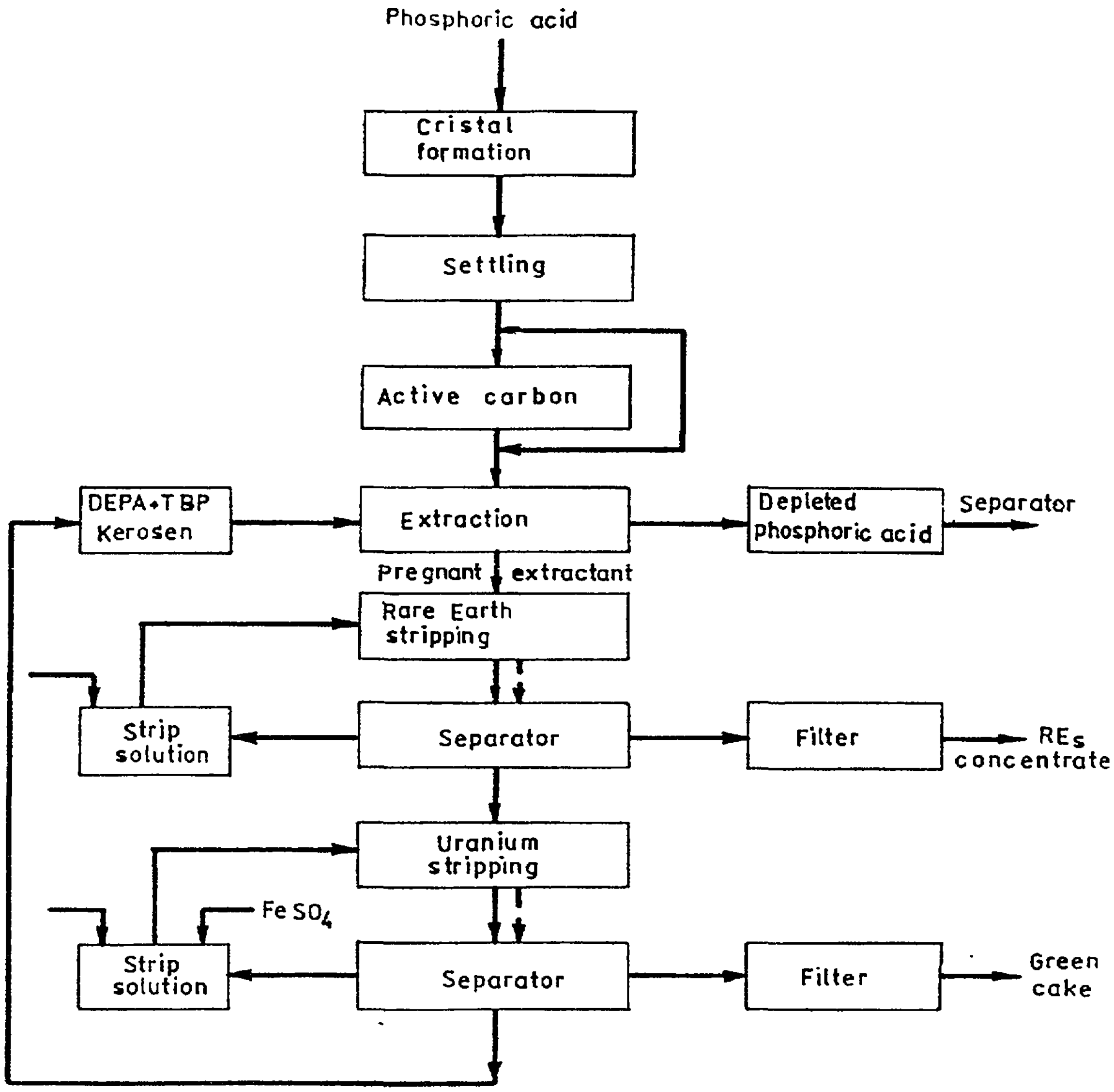


FIG. 1. One-cycle extraction-stripping process flowsheet.

The pilot plant was so built to permit the gravity flow for the process, the number of pumps was minimal (recirculation of reagents). This is the simplest and most economic way to process phosphoric acid for uranium recovery. Based on data obtained the operation costs were estimated at 25-30 US$/kg U. The operation of the pilot plant was very successful and easy to control as all the system was self-controlled by gravity flow. The next step was the industrial plant.

A project for three industrial plants was carried out and three industrial plants adjacent to three phosphoric acid plants were built capable of processing the whole amount of phosphoric acid from sulfuric acid attack. The capacity of such a plant is dependent on parameters from Fig. 2.

The average production of such a plant is 30 t/year uranium, therefore the three existing plants for uranium recovery will produce 90-100 t/year uranium as element. This production could feed a CANDU nuclear reactor of 660 MW(e) which is to be completed at Cernavoda in Romania next year.

The three plants mentioned will also produce a rare earths concentrate. The three plants will soon become operational.

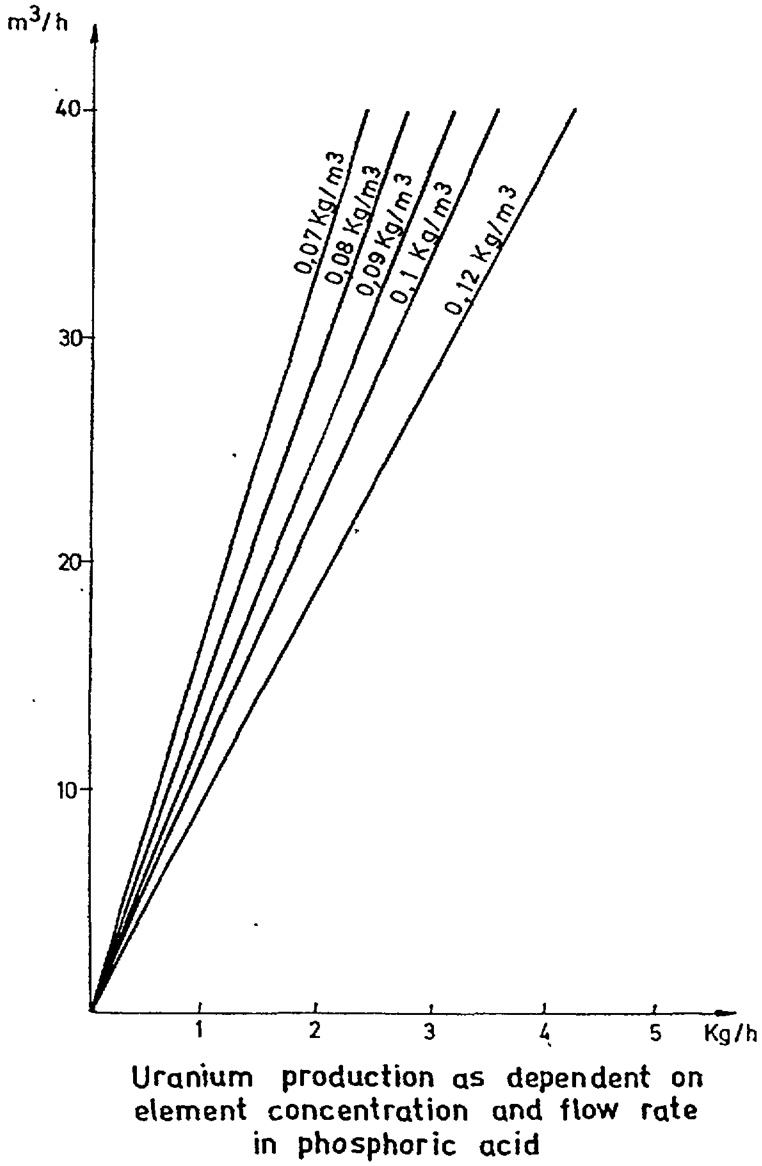


FIG. 2. Uranium production as dependent on the flowrate and the element concentration in the phosphoric acid.

A technology to separate rare earths and uranium in a wet process was also finalized, i.e. to eliminate impurities from rare earths or to obtain a diuranate with nuclear properties. Simultaneous separation of yttrium of high purity was carried out.

The "one-cycle extraction-stripping process" involves lower investment costs and operation costs are almost half of that from the dual system. This is an important advantage at the present in the declining uranium world market.

Uranium obtained in this country from classic ores is much more expensive comparable with that from phosphoric acid.

The "one-cycle process" described here has the following advantages:

- Uranium is recovered as a valuable product easy to transform in UF_6 of high purity or in a wet process to a diuranate of nuclear properties.

- An important source of energy is recovered which otherwise is lost and carried by fertilizers contaminating the agricultural lands.

- From this process a TSP of low radioactivity and a DAP of no radioactivity are obtained. Radium is also eliminated.

- A rare earths concentrate is also obtained (only in this process).

- Phosphoric acid has improved qualities.

REFERENCES

[1] BUNUS, F.T., Talanta 24 (1977)117.

[2] BUNUS F.T., DOMOCOS, V., BULACEANU, DUMITRESCU, P., POPESCU, G., J., Radioanal. Chem. 33 (1976) 251.

[3] BUNUS, F.T., DOMOCOS, V., DUMITRESCU, P., J., Inorg. Nucl. Chem. 40 (1978) 117.

[4] HURST, F.J., CROUSE, D.J., BROWN, K.B., Ind. Eng. Chem. Process Des. Dev. 11 (1972) 122.

[5] HURST, F.J., CROUSE, D.J., Ind. Eng. Chem. Process Des. Dev. 3 (1974) 286.

[6] HURST F.J., The Recovery of Uranium from Phosphoric Acid, IAEA-TECDOC-533, IAEA, Vienna (1989) 9 pp.

[7] BUNUS, F., DUMITRESCU P., Hydrometallurgy 16 (1986) 167.

[8] BUNUS, F., DUMITRESCU P., Hydrometallurgy 28 (1992) 331.

APPLICATION OF MINERALOGICAL-TECHNOLOGICAL MAPPING FOR ORES: QUALITATIVE EVALUATION OF ENDOGENIC URANIUM DEPOSITS OF STRELTSOVSK AND KOKCHETAVSK URANIUM ORE REGIONS

A.V. BOITSOV, G.I. BIRKA, A.L. NICOLSKY, A.S. SHULGIN
All-Russian Institute of Chemical Technology, Moscow, Russian Federation

Abstract

The Mineralogical-Technological Mapping Method (MTM) is used for determining mineral and technological types of ores and for studying the influence of ore composition on their technological qualities. The uranium deposits of Kokchetavsk region are found in various rocks. The Apatite-Coffinite and Coffinite ores occur itites and Pitchblende-Brannerite ores are mapped as deposits of the basement. They correspond to two technological types: the Uranium Carbonaceous and the Complex Rare-Earth-Phosphorus-Uranium Silicate type. The Pitchblende, Pitchblende-Brannerite and Molybdenite-Coffinite-Pitchblende ore types occur as deposits in depressions and close to the surfaces of unconformity. The first type corresponds to the Uranium Silicate technological type, the second and the third to the Uranium moderate Carbonaceous type. The uranium deposits of Streltsovsky region are situated in volcanic-sedimentary rocks and in granites of the basement with the xenoliths of limestones. The main reserves of the deposits are connected with the Silicate Uranium and Molybdenum-Uranium ores which are processed at the plant by sulphuric acid leaching. Considerable reserves of one of the biggest deposits in the limestones are classified as high carbonaceous. The principally new technology of pressure soda leaching is necessary for processing these ores. Some low carbonaceous ores are mapped among Silicate ores at many deposits. They are recommended for selective mining and for blending with the Silicate or high carbonaceous ores. MTM made it also possible to distinguish Pitchblende, Molybdenite-Pitchblende, Coffinite and Brannerite mineral types of ores, which differ in the leaching due to their different refractory properties. The obtained data make it possible to control and operate the quality of ores supplied to processing.

1. INTRODUCTION

Evaluation of minerals quality is very important for the maximal and integral recovery of valuable components from ores and for the development of effective mining and processing methods.

The endogenic uranium deposits ores are notable for their complex mineral composition and for an uneven distribution of both valuable components and various minerals affecting the technological characteristics. The quality of uranium ores was commonly evaluated by studying the averaged single technological sample's composition. Still, this method could not supply sufficient information on the variability of the material composition and technological properties of the naturally deposited ores. Therefore, since the 1960s the method of mineralogical-technological mapping (MTM) has been implemented at uranium deposits. A significant contribution to the development of methodological principles for technological assessing of uranium ores was made by Mr. P.V. Pribytkov. He has developed the principles classifying uranium ores by technological indications [1, 2, 3], which the authors used for conducting MTM. The presented report summarizes the scientists of the All-Russian Research Institute of Chemical Technology experience concerning MTM of uranium endogenic deposits [4, 5].

2. METHOD OF MINERALOGICAL-TECHNOLOGICAL MAPPING (MTM)

The mineralogical-technological mapping presents staged complex activities including testing of ores, studies of their interrelated mineral composition and technological characteristics, determining the mineral and technological ore types and characteristics of their spatial location. The mineral (natural) type presents spatially isolated ores with typical mineral composition and technological properties. The technological type is presented by the ores which can be separately mined and processed according to a special technology principally devised for them. The technological types are subdivided into technological ores grades. They are to be treated in uniform circuits but differ in technological indications.

MTM is to be carried out at all stages of exploration and working of the deposits and is an integral part of geological survey activities. At the stage of prospecting and prospecting-evaluation work the main task would be the evaluation of the mineral products' technological type in principle, based on the testing of mineralogical and small single technological samples.

The systematic application of MTM is worthwhile at the stages of preliminary and detailed exploration of deposits. Usually it starts with a detailed mineralogical mapping, aimed at classification of ores into types according to the material composition. Then technological tests would follow using ore samples of various mineral types. On the basis of the obtained results the relation of technological characteristics and ores composition is determined and technological types of ores are singled out. The data on various ores' types distribution would be decisive for the taking of representative samples necessary for the development of the most favourable technological process.

At the stage of deposits exploitation, MTM should be carried out if it was not used during the exploration, in the case of newly discovered ore bodies, and also in the blocks prepared for the working.

The sampling methods are to be chosen in each separate case depending on the geological structure complexity and the deposit exploration degree, and should correspond to certain regulations. [6, 7].

The MTM experience on endogenic uranium deposits has shown that the main geological-mineralogical factors determining technological properties of uranium ores are the following:

- Content of uranium in the ores;
- Presence of associated useful components in the ores;
- Mineral and chemical composition of rock mass and its physical condition;
- Mineral forms of uranium, chemical composition and physical properties of uranium and uranium-bearing minerals;
- Textures and structures of the uranium ores.

The above factors, pertaining to uranium deposits of various genetic types, are of unequal significance. The MTM task would be then to determine which factors of the deposit influence the choice of a viable technological scheme and to map them as types and grades of ores.

The data on the various ore types distribution is used by mining facilities for the controlling of the ores' quality, delivered to the plant, due to their more rational mining, blending and improving the technological processing scheme.

The MTM application is demonstrated by the examples of two large uranium ore regions: the Streltsovsk and the Kokchetavsk ones which play a significant role in the Commonwealth uranium resources balance. The uranium reserves of the Streltsovsk region deposits (the East Transbaikal) comprise 14%, and those of the Kokchetavsk region (North Kazakhstan) – 10.4% of the entire reserves of uranium in the Commonwealth. These regions predominantly possess reasonable assured resources priced to US $80/kg, comprising 25.6% (the Streltsovsk region) and 15.5% (the Kokchetavsk region) of this category reserves in the Commonwealth [8].

3. MINERAL AND TECHNOLOGICAL ORE TYPES OF KOKCHETAVSK REGION

Within the Kokchetavsk ore region limits, the systematic MTM was for the first time applied at the Manybai deposit. This happened 10 years after its discovery and was caused by the fact that the ores of one of the ore bodies appeared to have been composed of more refractory zirconium-molybdenum-uranium ores. This case showed the necessity of getting the most complete information on technological properties of the ores at the early stages of geological exploration works.

The MTM of the Grachevsk and the Ishim ore knots deposits has shown a great variety of the uranium ores composition, requiring principally different technological processing schemes.

The deposits of these ore bodies can be divided into three groups, according to their geological position (Table I). The first group consists of the deposits localized in the Pre-Cambrian crystalline rocks and in the intrusive granites (Grachevsk and Kosachin deposits). The second group includes the deposits in the folding rocks of the geosyncline stage (the Ishim deposit). The deposits of the third group are directly confined to the surface of the Silurian-Devonian regional unconformity in the basement of the orogenic stage rocks (the Kamyshovoe and Shokpak deposits).

The Ishim deposit ores are presented by a complex uranium-molybdenum carbonate technological type. By the beginning of the work the deposit was in operation, and the ores were treated at the plant by the pressure soda leaching scheme. Therefore, the MTM was not conducted there.

MTM of various deposits in the region made it possible to determine the dependance of the ores' mineral composition and the zonality of the deposits on their geological position. The latter is explained by the fact that the deposited ores represent a series of paragenesises, composing a basically single entity as a continuous series of sequentially formed mineral associations. Their formation took place at various stages of uniform paleohydrothermal systems of open or closed types.

The earliest paragenesises have been mapped in the ores of the Grachevsk deposit. They are presented by the apatite-coffinite ores, composing the main part of the reserves (Table I). The ore bodies are located in the central parts of albitised granites or quartzite-like sandstones of vend. The Gratchevsk deposit ores are of complex rare earths-phosphorus-uranium types. Their uranium percentage varies, reaching 1% and over, P205 - from 0.3 to 10%, rare earths 0.1-0.2%. Some admixtures of rare earth are observed in association with apatite, these of yttrium and thorium - in coffinite.

The technological tests have shown that any concurrent recovery of phosphorus and rare earths could be provided with an acid flow sheet processing only. The current soda pressure leaching scheme, used at the plant, had been designed to recover only uranium from the ores.

The Kosachin deposit ores are localized in the zone of a large fault in the layer of carbonaceous shales and in diabases removed from granites. The early apatite-coffinite paragenesis is absent in the ores. The central and lower parts of the ore bodies are presented by chlorite-coffinite paragenesis in albitites (Fig.1). On their background in the upper parts of the ore bodies there are quartz-goethite and chlorite-carbonate metasomatites developed with some brannerite and pitchblende. The zonality of the ore bodies is complicated by manifestations of some posterior dolomitization. In its juxtaposition zones over earlier uranium ores formations a pyrite-coffinite mineral association has been formed.

The above processes had resulted in the formation of three mineral ores types at the Kosachin deposit: the coffinite type in albitites; the brannerite and pitchblende-brannerite types in quartz-goethite-carbonate metasomatites; the coffinite type in dolomite metasomatites.

TABLE I. MINERAL AND TECHNOLOGICAL ORE TYPES OF ISHIMSK AND GRATCHEVSK ORE KNOTS (KOKCHETAVSK REGION)

Geological position of deposits	Deposits	Mineral ore types	Technological ore types
In the rocks of crystalline and basement and in granites (Pt3)	Grachevskoe	apatite-coffinite in albitite	phosphorous-rare-earth-uranium silicate
	Kosachinoe	coffinite in albitite; brannerite and pitchblende -brannerite in quartz-goethite-carbonate metasomatites; coffinite in dolomite metasomites	uranium carbonaceous
In the rocks of geosyncline stage ($\in$-O)	Ishimskoe	iordizite-coffinite and molybdenite-pitchblende in hydromica metasomatites	uranium-molybdenum carbonaceous
Close to the surface of S-D unconformity	Kamyshovoe	brannerite and brannerite-pitchblende in quartz-carbonate metasomatites	uranium carbonaceous
	Shokpak	pitchblende in hematitizated quartz rocks	uranium silicate

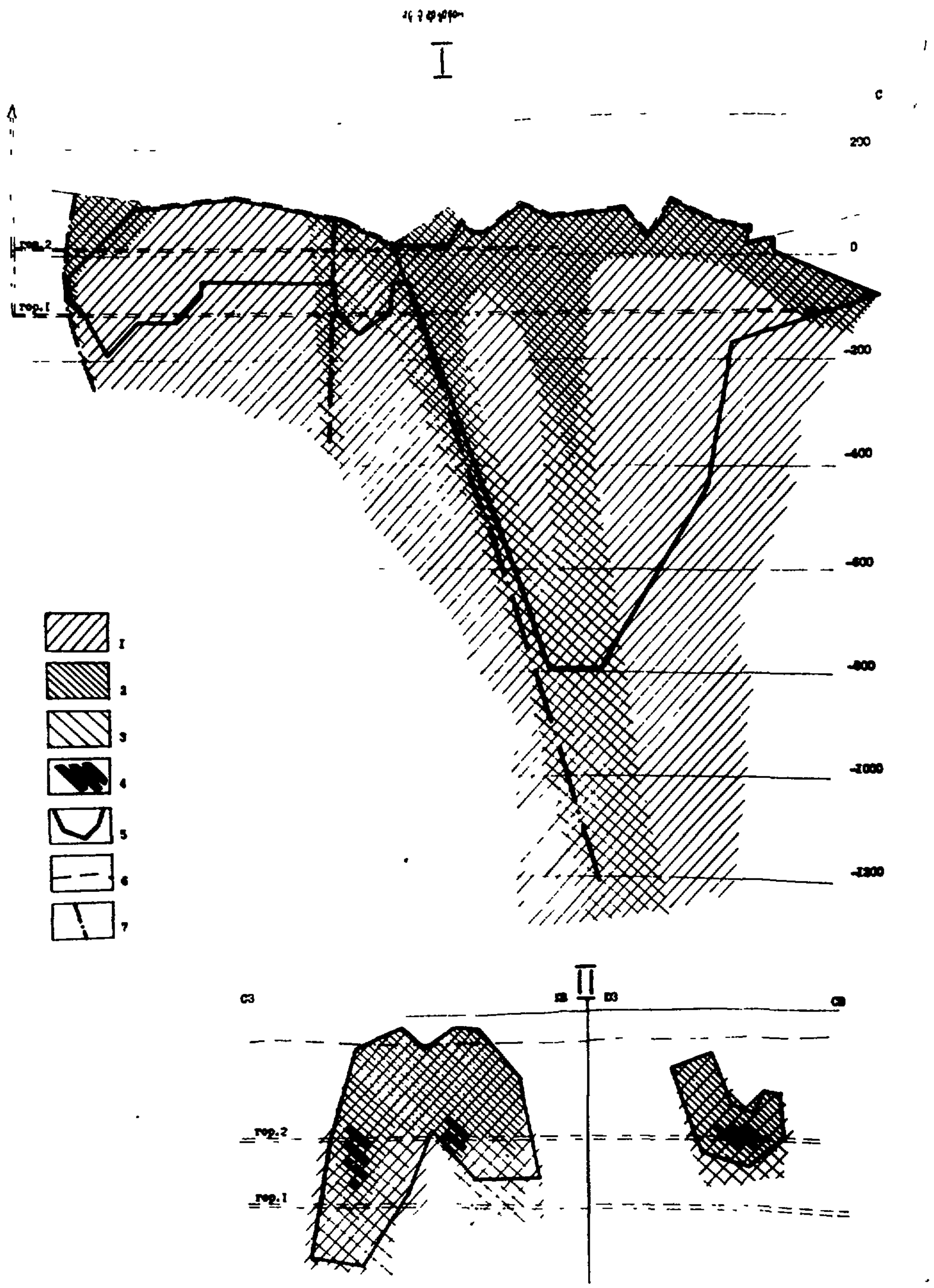
The results of the technological tests made it possible to unite them into one technological type — the proper uranium carbonaceous ores. Considering the uranium content they are predominantly low-grade. The presence of carbonates (over 6%) makes it viable to break them down with soda pressure leaching.

The deposits of the third group — Shokpak and Kamyshovoe — are localized in the contact zones of Cambrian-Ordovician layers and Devonian red-beds of a superimposed basin, presenting in fact an entity. The first one is located in its upper horizons, the second's manifestation is dipping up to one kilometer. The deposit's ores are presented by three mineral types (Table I).

The Kamyshovoe deposit ore bodies, removed from the contact zone, are filled with brannerite ore in quartz-goethite-carbonate formations over the albitites (Fig. 2.) similar to the ores of the upper horizons of Kosachin deposit. Directly in the contact zone these ores are superpositioned by the chlorite-pitchblende paragenesis. Its development at the lower horizons in the bodies of transformed albitites had resulted in the formation of brannerite-pitchblende ore types. Both mineral types belong to the uranium carbonaceous technological type.

Unlike Kamyshovoe deposit, the Shokpak site chlorite-pitchblende paragenesis was developing in the rocks unaffected by albitization. Correspondingly, these ores were classified as proper uranium silicate ones. Their processing in the acid leaching circuit is more rational than the soda pressure leaching treatment.

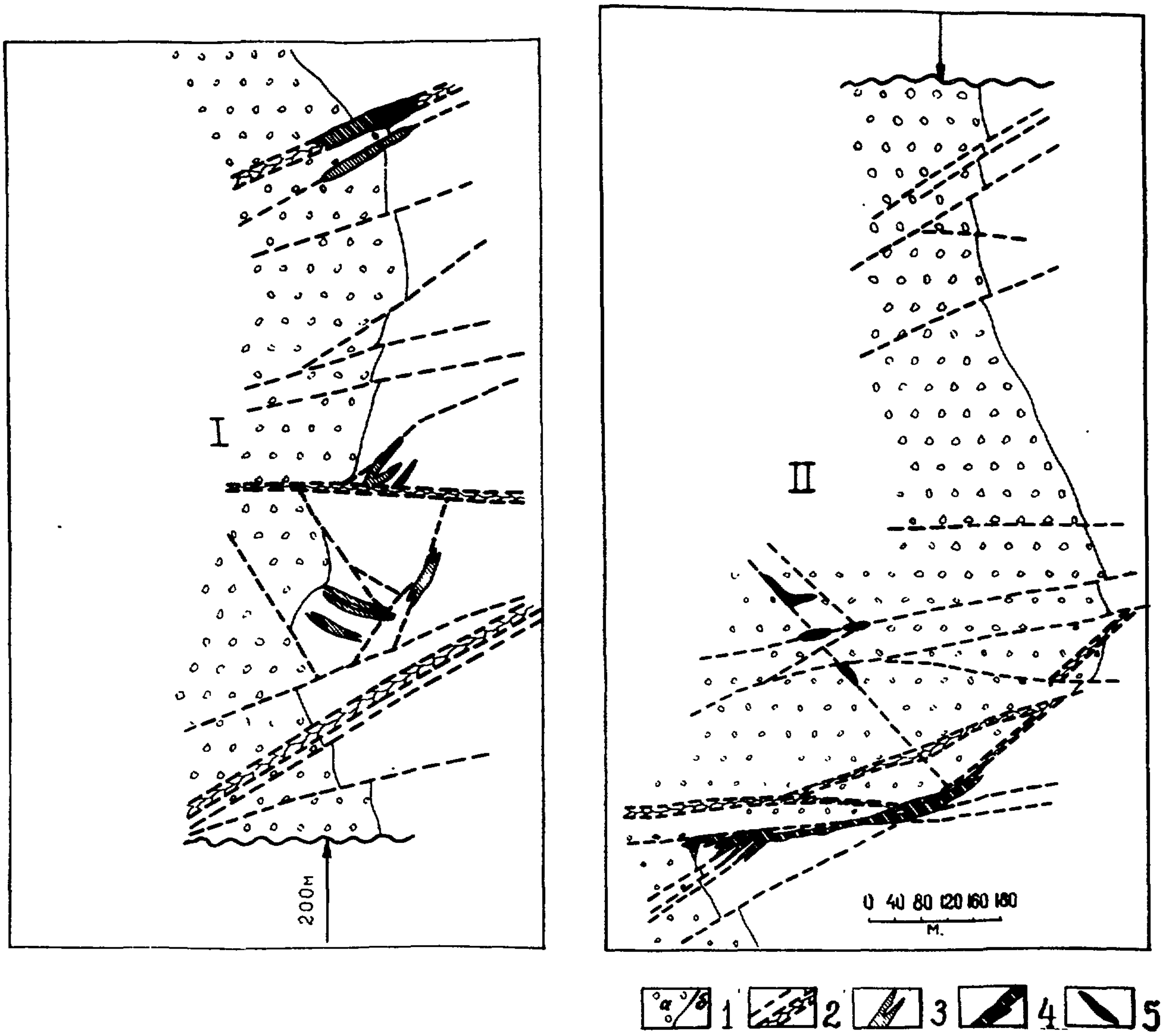
Thus, the MTM procedure has made it possible to elucidate some general relations of the material composition of the ores and the geological position of deposits (Table I). The crystalline basement blocks are the localization space for complex phosphorus-rareearths-uranium and proper uranium carbonaceous ores in abilites. The layers of geosyncline stages house complex U-Mo ores in hydromicaceous metasomatites. At the surface of the regional unconformity the upper parts of the deposits are presented by proper uranium (uraninite) silicate ores downwardly replaced by uranium carbonaceous ores in albitites. The former, in their material composition, are similar to the ores of known deposits of "unconformity type".



EXPLANATION:

1 - albitites with coffinite ores; 2 - quartz-hematite metasomatites; 3 - chlorite-carbonate metasomatites; 4 - pitchblende mineralization; 5 - contour of ore bodies; 6 - boundary of weathering crust; 7 - fractures.

FIG. 1. The distribution of mineral types in the ore bodies of deposit Kosachinoe (Vertical projection of ore bodies).



EXPLANATION:
1 - contact of conglomerates and sandstones (a) with rocks of basement (б);
2 -fractures; 3 - pitchblende ores; 4 - pitchblende-brannerite ores; 5 - brannerite ores.

FIG. 2. The distribution of mineral types in the ore bodies of Shokpak (1) and Kamyshovoe (2) [Map of level +80 m].

4. MINERAL AND TECHNOLOGICAL ORE TYPES OF STRELTSOVSK REGION

Presently the region encompasses 16 uranium deposits belonging to the uranium-molybdenum formation. The majority of them are localized in the depression sedimentative-volcanogenic rocks, formed in the period of Mesozoic tectono-magmatic previous activization. Some deposits in the Paleozoic basement granites and in xenoliths of dolomitized limestones are also known there.

According to the mineralogical studies results, the ores are composed by three consequently formed uranium mineral associations: the albite-coffinite-brannerite, the quartzmolybdenite-pitchblende and chlorite-carbonate-pitchblende. The formation of the mineral association differed in the country rock alteration, composition, deposition condition and distribution sites, characteristic for each association. More than often they telescoped. The MTM procedure of the deposits has shown that a complex and changeable composition of ores and heterogeneous composition of the enclosing rocks considerably affect the technological properties of ores. It has been found out that the major factors determining the efficiency of the processing technology are:

- the composition of the ore-bearing rocks;
- the molybdenum content in uranium ores;
- the mineral form of the ore component and its aggregate state.

The major reserves of the deposits relate to two technological types of ores: the silicate uranium type and the silicate uranium-molybdenum type (Table II). The proper uranium ores are treated at the plant, extracting uranium by leaching with sulphuric acid. There is a stronger treatment of sulphuric acid leaching for a concomitant recovery of molybdenum from complex uranium-molybdenum ores.

Substantial reserves of uranium and uranium-molybdenum ores of one of the deposits are localized in the basement dolomitized limestones. In their composition they belong to the high-carbonaceous technological grade. The high dolomite content (from 25 to 96%, on average 70%) make them useless for the current processing scheme of the sulphuric acid leaching. They are recommended for treatment in the soda pressure leaching regime.

The MTM procedure, conducted at many deposits of volcanogenic-sedimentation beds has also allowed to map in andesites, basalts and conglomerates among silicate ores, the sites of the carbonate ores development, containing from 6 to 25% of dolomite. They are to be singled out into an independent technological grade. Their processing in the sulphuric acid leaching circuit would be unprofitable, requiring a considerable amount of sulphuric acid (from 180 to 300 kg/t). Therefore they are recommended to be worked selectively and blended with the silicate or highly carbonaceous ores.

The mineral form of the ore component is an important factor determining the complete break-down of the ore at leaching. As the result of the MTM procedure four mineral ore types were

TABLE II. TECHNOLOGICAL ORE TYPES AND GRADES OF STRELTSOVSK REGION

Technological ore types	Technolgical ore grades	Percentage of carbonates	Processing of ores	Distribution throughout deposits
uranium silicate ores	pitchblende and coffinite ores	below 6	sulphuric acid leaching regime for uranium ores	main reserves of deposits in the rocks of depressions and in granites
	refractory brannerite ores		sulphuric acid leaching regime for uranium-molybdenum ores	ores on deep levels in granites and in lower sheet of trachydacites
uranium-molybdenum silicate ores				upper and central parts of deposits in the rocks of depressions
uranium and uranium-molybdenum-molybdenum carbonaceous ores	high-carbonaceous ores	over 25	pressure soda leaching	ores deposited in the limestones of the basement
	low-carbonaceous ores	6-25	blending with silicate or high cabonaceous ores	ores in andesites, basalts and conglomerates among silicate ores

determined at the deposits. Namely: the molybdenite-pitchblende, the pitchblende, the coffinite and brannerite types (Table III).

TABLE III. MINERAL ORE TYPES OF STRELTSOVSK REGION

Mineral ore types	Industrial impor-tance	Mo percentage	Ore quality	Ore texture	Main minerals or uranium (molybdenum)
molybdenite-pitchblende	main	over 0.03	average-grade and rich	streaky, brecciated, cocarde, mottled, cemented, massive	pitchblende, uranophane, hydrous-pitchblende (molybdenite) (femolite) (ilsemanite) (iriginite)
pitchblende		0.01-0.03	avergage grade, lean	streaky, mottled-disseminated	
coffinite	secondary	below 0.015	lean	disseminated	coffinite
brannerite					brannerite

The pitchblende ores compose the major reserves of the deposits. They are rich and average uranium-bearing ores with textures filling open cavities and fissures. The predominating ore minerals are pitchblende of quartz-molybdenite-pitchblende mineral association. The quantity of coffinite and brannerite usually does not exceed 20% of the uranium minerals total.

The complex molybdenite-pitchblende ores differ from the pitchblende ones in higher content of molybdenum (over 0.03%). The major molybdenum minerals are molybdenite and femolite. The coffinite ores are average-grade and lean. The quartz-molybdenite-pitchblende association also predominates there. The ores' textures are disseminated and streaky-disseminated. The brannerite ores are lean with disseminated textures. The portion of the reserves associated with them is not great.

In the oxidation zone the hypogenic uranium minerals are mainly transformed into uranyl silicates (uranophane-uranotil) and the molybdenum - into ilsemanite and uranium-molybdates iriginite, umohoite, maurite).

General localization regularities for ores of various mineral types have been found. Molybdenite-pitchblende and pitchblende ores are mainly confined to the upper and central parts of deposits, with complex ores predominating in the upper regions of a volcanogenic-sedimentation beds. The coffinite ores generally develop along the wings of deposits. The brannerite ores are mapped in deep horizons of a deposit in the basement granites and in trachydacites in the lower part of a volcanogenic-sedimentation bed.

The tests on the sulphuric acid leaching of useful components on a production scale have shown the most complete uranium recovery to be from pitchblende and molybdenite-pitchblende ores, at that, the oxidized ores be the most leachable. The brannerite ores are hardly leached at all (Table II).

The best demonstration of this dependence can be seen with the ore samples from the deposits in granites (Fig. 3). The uranium recovered from the brannerite ores comprises less than 80% with its residual in the cake over 0.008%. A special study on the products of technological treatment has testified that the main reason for the incomplete uranium recovery was brannerite presence in the ores. The secondary factors were the finely disseminated inclusions of uranium minerals in the unsoluble rock- and oreforming minerals.

Therefore brannerite ores are to be classified as a special technological grade of "refractory" ores. It would be sensible to work them selectively and process in a more rigid regime than the uranium-molybdenum ores leaching.

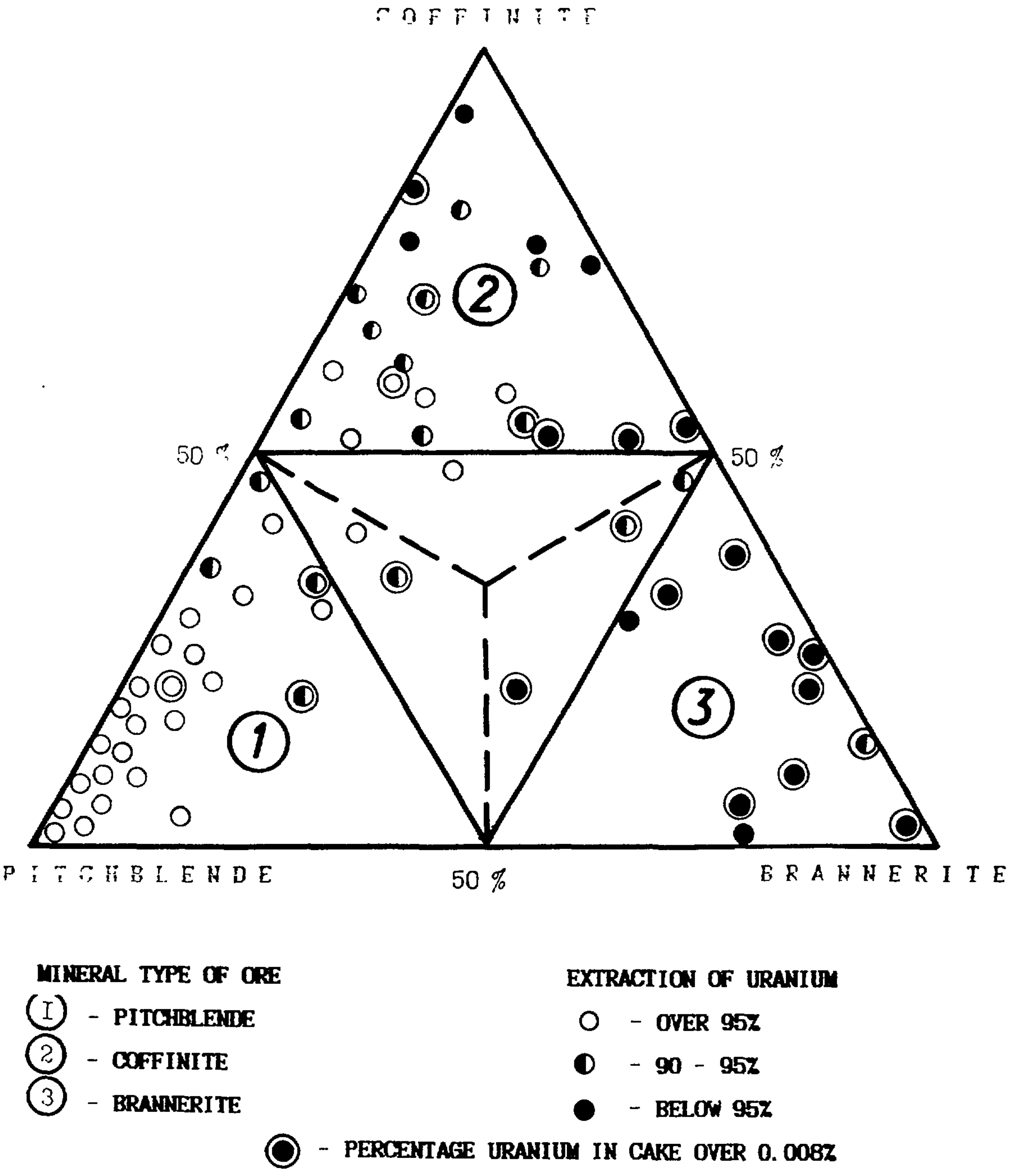


FIG. 3. Technological characteristics of mineral types of ores.

The molybdenum recovery from complex ores usually varies within 30-70% for hypogenic ores and 50-90% for oxidized. The most refractory molybdenum mineral is finely disseminated molybdenite.

The statistical evaluation of the MTM data on the basic of the correlation and regression analyses has allowed determination of the relationship of technological parameters and the mineral composition as twin coefficients of a correlation and regression equation. The quantitative correlations of the acid inventory and the content of FeO and CaCO in the ores (Fig. 4) have been obtained for a deposit in granites which has been tested in detail. These components testify to the presence of brown spar. The uranium content in the cake is the most tightly connected with the brannerite content (c.c. = 0.76), and the recoverability index positively correlates with the uranium content, and negatively with that of brannerite. The analyses of the regression correlation models has made it possible to describe the technological and mineralogical characteristics relationship in terms of regression equations with minimal prognostication errors and high coefficients of multiple correlation. The regression equations might be useful in the prognostication of the technological properties of ores in natural occurrence.

TWIN COEFFICIENTS OF CORRELATION:

	U	FeO,	CaCO3	hydro mica	pitch blend	coffi nite	brann erite
acid inventory	0.59	0.70	0.82	-0.01	-0.10	-0.10	0.11
U content in cake	0.12	-0.10	0.09	0.63	-0.52	0.15	0.76
uranium extraction	0.62	0.17	-0.04	-0.50	0.75	0.10	-0.80

REGRESSION EQUATIONS:

Acid inventory = 12.47 CaCO3 + 17.25 FeO + 32.42 CaF2 + 41.02

⋆ R = 0.81 O = 1-19 %

U content in cake = 0.0014 cont.brannerite + 0.004

⋆ R = 0.76 O = 0-48 %

U extraction = 14.40 U - 0.15 relat.brannerite + 94.01

⋆ R = 0.83 O = 0-9 %

⋆ R - coefficient of multiple correlation,

⋆ O - prognostication error.

FIG. 4. The dependence of technological features on ore composition (Deposits in granites, Strelsovsk region).

5. CONCLUSION

The presented examples show the significance of the MTM results for the technological evaluation of uranium ores occurring in endogenic deposits with a complex material composition. The data obtained on the distribution of various mineral and technological ores types are used at the stage of a deposit exploration in order to create an optimal program for its development and for designing mining and processing facilities, and at the working stage – for an operational control of the ore quality delivered to the processing circuits.

REFERENCES

[1] BRODIN, B.V., PRIBYTKOV, P.V.,Tasks of Applied Mineralogy, Sovetskaja Geologija, 10 (1980).

[2] PRIBYTKOV, P.V., General Principles for Classification of Commercial Uranium Ores, Atomnaja Energija, v. 9, issue 3 (1960).

[3] PRIBYTKOV, P.V., Classification of Commercial Uranium Ores on Technological Indications and Evaluation of Textures and Structures Impact on Processing Methods. In 'Textures and Structures of Endogenic Deposits Uranium Ores', Moscow, ATOMIZDAT (1977).

[4] PRIBYTKOV, P.V., KONONOVA, T.G., BOITSOV, A.V., ORLOVA, L.A., ADERJAGIN, A.A., Mineralogical-Technological Mapping of Deposits for Evaluating Quality of Commercial Ores Types and Prognostication of Their Composition Change in Space, abstracts of reports to the III All-Union Mineralogical Seminar, Miass (1983).

[5] BOITSOV, A.V., EGOROV, I.N., LARINA, M.G., PRIBYTKOV, P.V., Mineralogical-Technological Mapping of Uranium-Molybdenum Formation Deposits, abstract of reports to VMO Session, Leningrad (1983).

[6] Manual, Small-Scale Technological Testing and Mapping of Ore Deposits at Exploration, VIMS, Moscow (1983).

[7] Technological Evaluation of Minerals, Testing of Deposits, Characteristics of Minerals, Manual reference book, Moscow, NEDRA (1990).

[8] LAVEROV, N.P., VELICHKIN, V.L., VETROV V.L. et al., Uranium Resources of the USSR, Report on Technical Committee IAEA, Vienna (1991).

[9] DERJAGIN, A.A., DROBYSHEVA, N.A., NIKOLSKI, A.A., PRYBYTKOV, P.A., ORLOVA, L.A., Prognostication on Technological Properties of Uranium Ores in Natural Occurrence Based on Regression Model, Atomnaja Energija, v. 49 (1980).

Next page(s) left blank

GEOLOGICAL MODELS OF URANIUM DEPOSITS APPLIED TO PROGNOSTICATION, CLASSIFICATION AND EVALUATION OF RESOURCES

A.A. DERJAGIN
All-Russian Institute of Chemical Technology, Moscow, Russian Federation
[Presented by A. Boitsov]

Abstract

The processes of exploration and evaluation of mineral resources may be optimized by application of geostatistical or mathematical models, and geological models of a deposit. It is common to describe two types of geological models: dynamic and static. This paper discusses application of models to several stages of geological exploration including regional mapping, evaluation of reserves, and working of identified deposits.

The present evaluation of mineral resources of deposits, including the uranium ones, is based on geometrization of ore bodies (accounting for conditional indications), requiring a lot of expensive mining drilling operations. Therefore the importance of a speedier exploration of deposits and a reliable evaluation of the resources with fewer mining-drilling operations can hardly be exaggerated. There are two possible ways to optimize the processes of exploration and evaluation of the resources. The first is based on the applied geostatistical methods used for the construction and investigation of the mathematical models of the valuable component distribution throughout the ore body and its boundaries. The second — involving in addition to the trial data, a large quantity of geological-structural, mineralogical-geochemical and geophysical characteristics, qualitatively determining the localization conditions and variability of a mineralization, in other words "geological models of a deposit".

The problem of applying uranium deposits geological models in prognostication and evaluation of indicated uranium mineralizations reserves concerns the following questions:

1. What is the prognostication and evaluation subject at various stages of geological survey;

2. What is a "geological model of a uranium deposit";

3. What is the structure (classification) of the reserves undergoing prognostication and evaluation;

4. What are the principles and approaches for a qualitative prognostication and evaluation of indicated reserves.

Uranium ore entities are complex geological formations. They can be organized and classified within a two-coordinate system — according to the substance organization level and to ore concentration in one volume unit of the geological space.

In accordance with the systematical concept of the levels hierarchy of the natural matter organization [1], developed in Russia, "ore" as a geological formation is considered by the author to relate to one and only level — the geopetrean one[1]. On the whole, the ore zone and the adjacent proximity, being the result of ore formation throughout time and enclosing medium, is adequate in its outline to the region of the altering constitutional properties (material, structural, morphological) pertaining to the enclosing m0eium for an epigenetic (including a polygenic) and the facies boundaries — for a syngenetic mineralization. The same idea is applicable to uranium ore formation processes.

Presently the generally adopted classification subdivided the ore entities, accordingly to the ore quantities concentrated in one volume unit of geological space (accounting for the present technical-economic criteria), into the following hierarchic series: . . .. ore body, deposit, ore field, ore node, ore region, ore province, . . ., which was denoted as "ore system" [1].

It has to be noted, that the theory and practice of geological survey consider the boundaries, outlined between the ore entities of certain ranks throughout the hierarchic series, as rather vague.

It is obvious, that from the standpoint of the systematic approach, the hierarchy of ore (uranium ore) entities should correspond to the hierarchy of the properties and factors of the enclosing medium ("frame", according to A.A. Poljakov), which determine the conditions of localization and the type of ore-controlling mineralization. The manifestation scale of these factors and properties is determined by the rank of an ore entity, and the combination specifics — by the commercial-genetic type of mineralization.

The author's perceptions are grounded on the basic principles of materialistic unity of universe, determining the global interrelations of natural (geological) entities, their properties (morphology, composition, structure and genesis), which allow us to consider the ore entities, the enclosing medium, as well as their properties and characteristics as their reciprocal information source. In some cases the relationships between the entities and their properties are direct and easily detectable, in others — they can be determined only after a thorough study of their correlation structure through time and space.

Proceeding from the above premises, the reserves (inferred resources) of a valuable component could be considered as one of a multitude of causatively interrelated properties pertaining to certain ore entity of certain rank), which formation had been determined by physical-chemical and thermodynamic parameters of the ore-forming process and specifics of geologic situation during the ore-formation period.

It is natural, that every genetic type of mineralization has its own specific minerals distribution function. It obviously follows that all aspects of the problem concerning formation, exploration and evaluation of the so called "unique deposits" are similar.

From this point of view it would be generally correct, substantially and formally, to apply the "geological model of an ore entity" to the solving of the problems, pertaining to the reserves evaluation and the assessment of inferred resources of valuable components.

The description of the composition, structure, morphology of any ranked ore entity and the enclosing medium ("frame"), organized in accordance with the idea of their genetic nature, presents in fact a geological model of these entities. Adequacy of such models to natural entities will depend on the extent of our knowledge of the entities and their interrelations character through time and space.

---

[1] The ore-forming process here is regarded as a partial realization of the global geological process of rock formation (sediments, magmatic and metamorphous rocks, soils, weathering crusts, hydrothermalyths, etc.) (Consultants' Meeting on Uranium Deposits Classification and Recognition Criteria, Vienna, March 1988)

It is common to single out two types of ore deposits geological models - dynamical and statical. The geological models of the first type relate to the perceptions of the parameters pertaining to the temporal evolution of the ore-forming process, to the character and dynamics of the development of the enclosing rocks — the "frame". These models are based on genetic hypotheses and reconstructions. The present level of the ore-formation theory advancement is not sufficiently high to use genetic criteria and conditions for any quantitative evaluation of reserves. In any case, there are no updates published with reliable and trustworthy results on any successful application of dynamic geological models of ore deposits formation to the quantitative evaluation of reserves.

The author understands the statical geological model of an ore entity as a description summarizing the material, morphological and structural properties and characteristics of an ore- and ore-proximal zone (spatial variation of mineralization, mineralogical composition of the ores and their texture-structural peculiarities, character of the ore-enclosing cavities and their shape, variations in the type of enclosing rocks and many others) and of geological-structural elements, determining the structural peculiarities of the "frame" enclosing the ore entity[2].

Considering substantiality, any statical geological model of an ore entity could be described in the terms of elemental (geochemical), minerals and rocks (geological-structural) analyses. In the terms of formal logic — as a multidimensional space of characteristics (material, morphological and structural), organized determinantly or probabilistically, when every characteristic of that multi-dimensional space will correspond to a statical field in a three-dimensional co-ordinates system. The statical form reflecting the geological model of an ore entity is the basis for genetic reconstruction (restoration of the ore formation dynamics).

Further on we will consider only approaches related to the use of statical geological models of uranium ore deposits for the evaluation of reserves.

The statistical scheme used in Russia for geological exploration [2] regulates the sequence, contents, functional orientation and scale of geological, geophysical, geochemical and other types of activities and research, aimed at the recognition and evaluation of all entities ranked in the hierarchy series. Any stage of geological exploration concerns both the entities to be studied and the entities to be evaluated, as well as the requirements to the trustworthiness of their evaluation (Table I)[3].

The classification and structure of resources and reserves in the Russian Federation considerably different from those adopted in other countries, regarding trustworthiness of evaluation [3]. Table II presents their comparison.

The general geological exploration plan includes four sequent stages:

- geological-geophysical studying and mapping of the territory (scaled 1:1 000 000-1:50 000 (1:25 000));
- surveying-evaluation (scaled 1:50 000 - 1:2 000 (1:1 000));
- prospecting of deposits;
- working.

---

[2] IAEA Technical Committee's approved classification of uranium deposits is based on similar principles (1988).

[3] considering the author's concepts.

TABLE I. SEQUENCE CHART FOR CONDUCTING EXPLORATION WORK (EW) USED IN RUSSIAN MINERAL DEPOSITS (MD)

EW stage	EW steps	EW sub-steps	Scale	Aim of the work	Study entity	Results of work	Evaluation level
1 Geological-geophysical study and mapping	1 Regional geological-geophysical study and mapping	1 1 Geological-geophysical studies	1 1 000 000 1 500 000	Creating geological-geophy-sical basis, determining the most important properties of geol structure of region and general rules for MD localization	Large regions / ore provinces	Geol , geophys and prognostic maps, guide abyssal sections	
		1 2 Geophysical and geological surveying	1 200 000 1 100 000	Study of geol regional structure and determining of MD search criteria and indications for choosing promising geological structures		Geol and geogr maps and MD maps with determining geol structures	Prognosticated resource
	2 Geological abyssal mapping	2 1 Advance geophysical work 2 2 Geological mapping, accompanying geophysical, geochemical and other work	1 50 000 1 25 000	Planned large-scale mapping, search geological conditions favourable for MD localization, prognostication-evaluationof promising sites	Part of ore regions	Geological map with prognosticated ore fields for survey, detailed survey and survey-evaluation work	Prognosticated resource P_2
2 Survey-evaluation	3 Surveying	3 1 General surveying / including abyssal[4]					Prognosticated resources P_2 / P_1
		3 2 Detailed surveying / specialized, including abyssal	1 10 000	Identifying promising geological structures and sites with mineralization indications	Ore field	Singling out MD	Prognosticated resource P_1
	4 Surveying-evaluation		1 5 000 - 1 2 000 1 1 000	Pre-evaluation of identified MD and choosing subjects for detailed surveying	Deposit or a group of deposits	Determination of probable commercial potential	Prognosticated resource P_1 Reserves C_2 →

4 Sub-steps 2 2 and 3 1 are often implemented simultaneously

TABLE I. SEQUENCE CHART FOR CONDUCTING EXPLORATION WORK (EW) USED IN RUSSIAN MINERAL DEPOSITS (MD) cont.

EW stage	EW steps	EW sub-steps	Scale	Aim of the work	Study entity	Results of work	Evaluation level
3 Prospecting	5 Preliminary prospecting		Density of prospecting network is determined by mineralization variation and geolog conditions	Commercial evaluation of MD	Deposit / group of ore dep or bodies	Feasibility study of detailed prospecting	Reserves C_1 - C_2
	6 Detailed prospecting			Preparing MD / or a part of it / for commercial working	Ore mineralizations or ore bodies	Calculation of reserves	Reserves $A+B+C_1$
	7 Complimentary prospecting of maiden and mines deposits			Commercial re-evaluation of MD, evaluation of flanks and deep horizons	Ore deposits, ore bodies	Calculation of reserves	
	8 Working prospecting			Preparing data for working of ore bodies	Operations blocks / parts of ore deposits and ore bodies	Operational calculation of reserves in the operation blocks	
4 Working	9 Geological mining surveying at cleaning operations		1 500 1 100	Preparation of clean area for working the ore entity	Operation block	Calculation of changing reserves	Evaluation of losses and dilution level

TABLE II. COMPARISON OF RESERVES AND RESOURCES CLASSIFICATIONS ADOPTED IN RUSSIA AND ABROAD

RUSSIA	Reserves			Resources	
	$A + B + C_1$	$C_1 + C_2$	P_1	P_2	P_3
ABROAD	Identified			Undiscovered	
	Demonstrated		Inferred	Hypothetical	Speculative
	Measured	Indicated	Possible		

The first stage implements the description procedure pertaining to the regional geological structure and prognostication of potentially ore-bearing areas and geological situations; the second - search for the direct indications of the ore process manifestation, revealing and evaluation of the practical significance of the ore manifestations; the third surveying of deposits and calculation of the reserves; the fourth working of the ore zone.

According to the singled out stages, the prognosticated resources and reserves evaluation task, in its structure and composition, can be divided into three types (Table III):

1) evaluation of the prognosticated resources of potentially ore-bearing areas and geological structures without any geometrization of the ore area on the basis of indirect characteristics complex (prognostication task);

2) determining of the found ore entities scale, using the single nodes, which are insufficient for the ore zones geometrization according to the direct and indirect characteristics complex (the evaluation task);

3) reserves calculation within the variously determined limits according to the direct indication - trial results (the calculation task).

The analysis of the geological preconditions for the solving of the prognostication task shows, that by their nature they belong to the class of both structured and weakly structured tasks (Table III).

The procedure of solving prognostication tasks, as it is, presents a process of the unique choice of substantiality concept, determining favourable conditions for localization and formation of a mineralization, among a multitute of alternatives, suggested by specialists. In their essence they come to the problems of multi-aspect comparison on multiple geological models, constructed on a complex of various geological factors regarded by specialists as of dissimilar significance, considering their influence on the mineralization control.

The procedure of prognostic resources evaluation can be divided into three main elements:

1. Determination and selection of the method for constructing prognostic alternatives.

2. Formation of indicating area or selection of geologic-structural, mineralogic-geochemical and geophysical factors, bearing necessary and sufficient information for the solution of the set task — in other words, construction of a geological model.

3. Selection and implementation of criteria for a comparative evaluation of prognosticated alternatives.

Analysis of published sources on the quantitative evaluation of prognosticated resources has shown that all methods practically utilized could be divided into two groups:

- subjective methods based on intuitive evaluation of the perspectivity level of a potentially ore-bearing area or structure, and

- objective methods making the prognostic evaluation of resources based on geological models, constructed on the indices characterizing properties and manifestations of the entities under study, as well as on the more or less strict functional relations, reflecting their interdependencies.

The subjective methods are the methods of individual or team expertise, based on genetic-statistical ideas of the experts.

TABLE III. TASKS FOR EVALUATION OF PROGNOSTIC RESOURCES AND RESERVES

No.	Structural type according to Simond and E. Newell	Character of descriptions and relations between task elements	Logic processes for tasks solution	Principles of analysis and methods for tasks solution	Solution algorithm	Examples of geological prospecting tasks
1.	Unstructured or weakly structured tasks	There is a description of task elements the interrelations of which are generally unknown	Unknown	Heuristic approaches	Intuitional algorithms	Geological expertise, expert's evaluation, genetic constructions evaluation of prognostic reserves
2.	Weakly structured tasks	Qualifative relations among elements predominate, only single elements have quantitative relations	*Inadequately manifested*	System analysis, operations studies, classification studies, etc.	Solution based on task decomposition and using both numerical and intuitional algorithms	Determining scale revealing ore entities by single nodes. Evaluation of reserves C_2, prognostication resources P_1, P_2 (partially)
3.	Well structured tasks	Task elements are described and quantitatively related	Known	Analytical (calculation) methods	Numercial (calculation) solution algorithms	Clculation of reserves (categories $A+B+C_1$; rarely C_2)

Experts' methods can be generally used in the cases of insufficient trustworthiness of initial information, without clearly defined algorithms for the task solution. The main principle forming the basis for the experts' evaluation of quantitative prognostication and resources assessment, e.g. of some indicated by nodes mineralization of a promising area, is the assumption that the unknown quantitative characteristics of the entity under study could be regarded as a random variable which distribution law is sufficiently proximal to the experts' distribution law of their individual evaluation. When the evaluation results are obtained from many experts, one could reliably assume that the value of the prognostic characteristics (prognosticated resources) would be within the evaluations range, and the summarized collective judgement passed would be the most probable value of it [4].

The group of objective methods might include the methods of constructing geological models of ore entities with the most frequently used:

- direct analogy;
- singling out non-typical geological situations characterized by utmost complicity of geological structure and by an anomalous significance of the factors, indirectly related to the mineralization;
- denoting as promising the areas similar in peculiar geological structure, where the already known ore entities are located, or partial analogy;
- heuristic modelling;
- Clarke's model;
- probabilistic methods for evaluation of large regions' prognostic resources;
- reconstruction methods of geological (geochemical) processes.

The evaluation tasks determining the ore entities scale are largely also of the weakly-structured tasks class (Table III).

The first attempts to establish relationship between the minerals resources and the indirect indications of various rank ore entities, in particular the ores chemical composition, were made by Mitch and Shoemaker. Those researchers, using the methods of regressive analysis, had shown that the concentration of uranium, yttrium, sodium, iron, zirconium, manganese, calcium and nickel in ore pulp samples taken from 75 uranium deposits occurring in the Jurassic sands of Salt Uoi, Morrison Formation (Colorado Plateau), statistically related to the deposits' locations and could be used for a tentative evaluation of similar types uranium deposits according to single nodes.

The author, using the methods of images identification, has determined a significant relationship among the size of uranium deposits of organogenic-phosphate type, the ore material composition and some geological-structural elements forming productive deposits.

The attempts to statistically relate the uranium reserves in single ore bodies and geochemical ore spectrum, made by the author at a number of deposits, confined to the uranium-molybdenum formation, were unsuccessful .

It has to be noted that in the practice of large-scale surveying-evaluation assessing the sizes of uranium mineralization, determined after single nodes, the use of a geological model of the enclosing medium ("frame") is quite common. Such models are to be compared with the geological models of the enclosing medium of the similar type uranium deposits known within the region limits, using the methods of classification [5, 6, 7].

Analysis of extensive experience, accumulated in the long period of exploration and working of the large uranium veined Prshibram deposit, and application of regression-correlation analysing and classification methods have allowed establishment of a close relationship between geological characteristics of variously ranked hierarchic ore entities — ore nodes, ore veins, ore bodies and blocks under development, (such as complicacy of the ore outline, thickness, ore concentration coefficient, capacity, spatial situation within the main ore-controlling elements, structural order of the ore-containing rock failures, material composition of ore, etc.) and the parameters of the reserves [8,9].

The number of examples is far too small to exhaust the practice of using geological models for evaluation of uranium deposit extent. Finally, certain questions on using geological models for evaluation of reserves and working of a uranium deposit — the tasks of the third class (Table III) are addressed.

The processes for exploration and working of mineral deposits are in principle implemented on the basis of two interrelating procedures for the tests data treatment — the geometrization of ore entities (of various hierarchy level) and the assessment of the parameters pertaining to the mineralization distributed within the determined outlines. Both procedures are to be carried out using certain methods of interpolation-extrapolation and averaging of the tests results for the ore and ore-proximal space with an account for geological-structural factors, controlling the localized mineralization.

The automated data processing systems, lately widely used for information service of geological exploration and development tasks, formally realize the procedures of geometrization and parameters assessment by averaging "window", and the geological conditions are taken into account by the controlling of the window's parameters (size, configuration, structure) and by orientation according to the leading elements of ore control.

REFERENCES

[1] Geological Bodies (Terminology), Moscow, NEDRA (1986).

[2] Methodology for Conducting Geological Prospecting Stage-wise (solid minerals), Moscow, VIEMS (1984).

[3] Classification of Solid Mineral Reserves and Prognostical Resources, Moscow, USSR GKS (1982).

[4] KHARCHENKOV, A.G., Principles and Methods of Mineral Resources Prognostication, Moscow, NEDRA (1987).

[5] KONSTANTINOV, R.M., Mathematical Methods of Quantitative Prognosis for Mineralization, Moscow, NEDRA (1979).

[6] MARCHENKO, V.V. Men-Hour Methods of Geological Prognostication, Moscow, NEDRA, (1988).

[7] Logical-Information Methods for Evaluation of Ore Deposits, Moscow, NAUKA, (1977).

[8] Uranium Deposits of Czechoslovakia, Moscow, NEDRA (1984).

[9] Hornickà Přibram ve vědě a technice, Matematicke metody v geologii (1977) 491-507, 508-539.

Next page(s) left blank

VALLEY-TYPE URANIUM DEPOSITS IN RUSSIA

I.L. LOUTCHININ
Zelenogradskoje Geological Enterprise of Concern Geologorazvedka,
Moscow, Russian Federation
[Presented by A. Boitsov]

Abstract

Since the destruction of the Soviet Union uranium exploration geologists in the Russian Federation have placed emphasis on evaluation of valley-type uranium deposits in order to increase the resource base. The estimated potential of this deposit type is near 500 000 t U. Nearly 25% of this resource is classified as "identified". Valley-type uranium deposits are of the "basal-type" and are epigenetic-infiltrated concentration of uranium in river depressions within the crystalline rocks of the basement complex. These deposits are known in two areas: Northern Transbaikal and Western Siberia. This paper describes these deposits including the host lithology and ore mineralogy. It provides a description of the required geochemical and hydrologic conditions for ore formation. It describes the exploration methods used to discover and delineate these deposits.

Recently after the destruction of the Soviet Union valley-type uranium deposits (according to Mr. N. Katajama's term "basal-type") have been important in Russia.

Valley-types uranium deposits are epigenetic-infiltrated concentrations of uranium in river depressions within the crystalline rocks of the basement complex.

Ore-forming process is determined by the role of the valleys as a paleodrainage system, it directs the groundwater current. Those water permeable alluvial sediments concentrated that current having been enriched by oxygen and uranium. The degree of the uranium concentrations in rocks is proportional to the infiltration time, often some short time. The concentration of the organic material is the reductive potential index. Sometimes the rocks rich in uranium which are considered the valley-floor basin are of no importance.

In Russia there are two grand groups of deposits differ in their ages and positions. The former includes the ore occurrences in Hiagda uranium ore district (Northern Zhabaikalye). The latter unites deposits in tremendous West Siberian uranium ore belt.

Hiagda ore district occupies the Vitim highlands in Northern Zhabaikalie, localizes into Hamalat plateau outlines. The deposits occur in those tributary valleys of two rivers, which streamed along Buysiuchan valleys (Fig. 1). The valleys contain colluvial sediments mainly and alluvial ones along the thalweg. These sediments are overlain by tuffaceous beds which are covered by a basalt mantle (Fig. 2). This Miocene rock mass has thickness from 50 to 250 m. Primary grey rocks contain high plant carbon concentrations, maximal medium one 0.8%.

Those valley-heads and valley-slopes ore forming currents of oxygen carrying water gather a reach the valley-line. Oxidized multicoloured rocks contain iron hydroxides replace pyrite, siderite and plant detritus. The dynamic oxidizing-reductive process along the boundary between grey and multicoloured rocks determines the secondary white-coloured zone. The ore is the result of infiltration of uranium-bearing vadose water into collector-layers with precipitation of uranium on the geochemical barriers.

In plan, ore bodies have some ribbon form revising the form of the valleys. In section ore bodies have roll and lens forms. Those ore bodies are some kilometers long, from 150 to 4 000 m wide and the maximum thickness is 23 m. The uranium content varies from 0.01 to 0.5%.

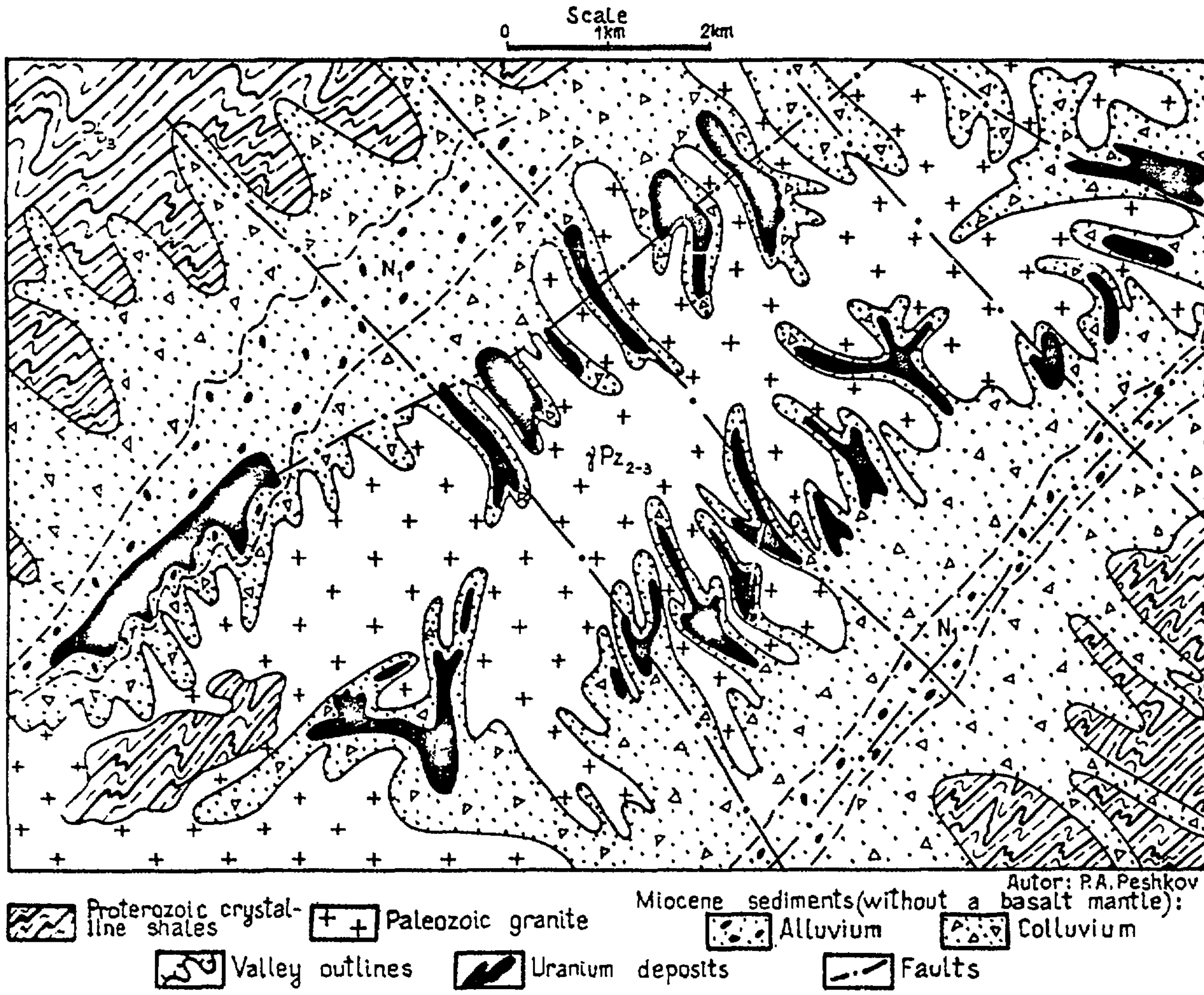


FIG. 1. Geological map of Haigda ore district.

Uranium mineralization represents dispersed uranium oxides and coffinite. The smaller part of uranium is sorbed.

Ore bodies contain molybdenum, zinc, cobalt, zirconium, arsenic, thorium, copper, yttrium, scandium and lanthanoides 5-400 clarke of concentration. The concentration of scandium, yttrium, molybdenum and lanthanoides may be of a commercial value.

The isotopic age of ores is continued from 25 million years to recent.

Uranium ore-bearing valleys are within Paleozoic granites only. The valleys within gneiss masses contains only gold.

The West Siberian uranium ore belt occupies the outlines of a coastal alluvial plain of the late Jurassic sea (Fig. 3). Alluvium is concentrated only in narrow 1-5 km wide valley-structures on the denudation surface. Those thin stripes are observed from the valley-head in upper blocks to the sea coast (Fig. 4).

The Bathian-Kimmerigian alluvium is divided into three sedimentary cycles (Fig. 5) which reflect attenuating movements of the last folding and uplift phase in the Ural region. After the movements stopped, the river valleys degraded in chains of drainage lakes that filled with proluvial

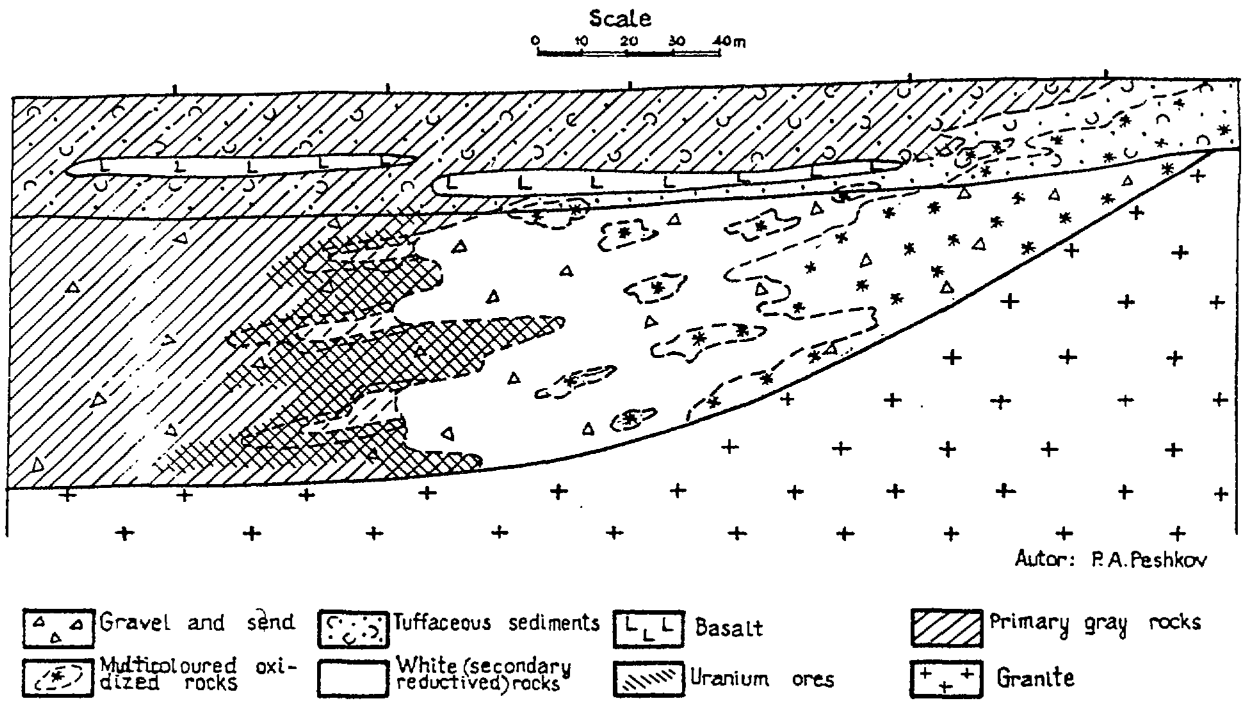


FIG. 2. Geological cross section of Haigda ore district (without a basalt mantle).

and limnic sediments. These sediments consist of red aleurites, clays, as well as sands. Red rocks are of the Volga-Stage-Berryacian Age. The thickness of alluvium is from 30 to 120 m, proluvium and limnic thickness is 30 to 150 m. Generally valley rocks masses are overlain by cover of Cretaceous-Quaternary sediments from 300 to 1 500 m thick.

The embedding valleys of primary rocks have uranium clarke of concentration no more than one. At the same time the upper redstones contain the dispersed particles of plant detritus, which carries syngenetic uranium concentrations from 0.01 to 0.03%.

There are marine sediments in the neighboring area, which contain near 1.5 billion tons of uranium, transported by the true solutions from the continental areas around the sea.

Uranium and oxygen-bearing surface waters partly flowed into the valley-head under the impermeable red stones and in the subjacent water-permeable alluvial beds. The sub-surface stream formed an epigenetic oxidized rock zone. In front of the zone the geochemical barrier is localized where geochemical conditions changed generally. Uranium precipited on the barrier, among grey rocks.

The ore-generating solutions entered the alluvial underground stream from the valley-heads and only the valley heads. Therefore the source of uranium for the described deposits is the adjacent weathering peneplained surface. In this case the lithologic composition and uranium content in the valley-floor basement is not important.

There is also an interesting and new fact. The early weathering stage of the recently formed peneplain is a main period of uranium mobilization. This period is the least active tectonic stage during the entire Mesozoic era in the Ural region.

The northern limit of the ore belt is the outline of red stones presence. This is equal to the boundary between the Late Jurassic semi-arid and humid climatic zones.

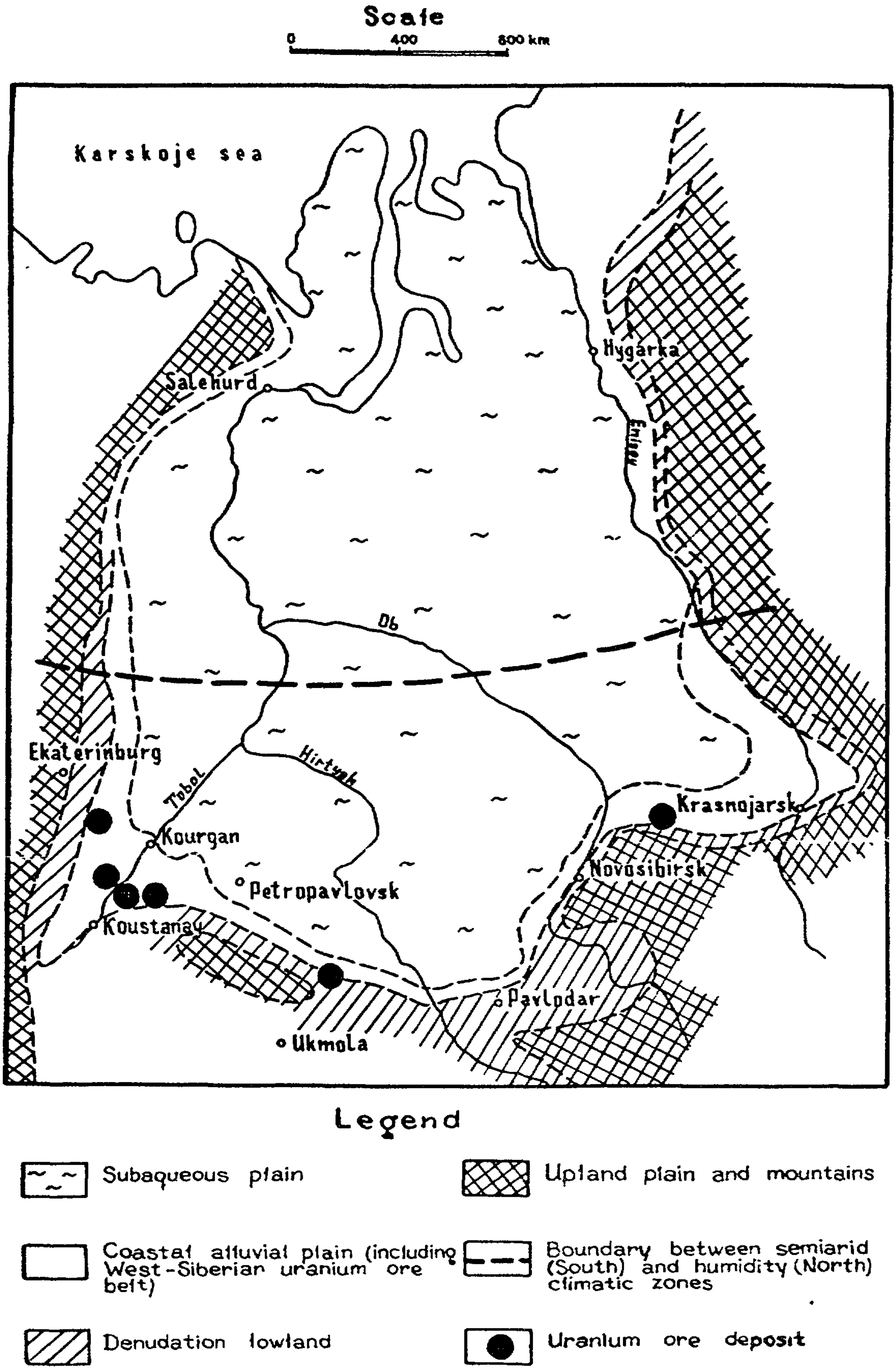


FIG. 3. Landscape map of Middle Jurassic, Early Cretaceous age (West-Siberian region).

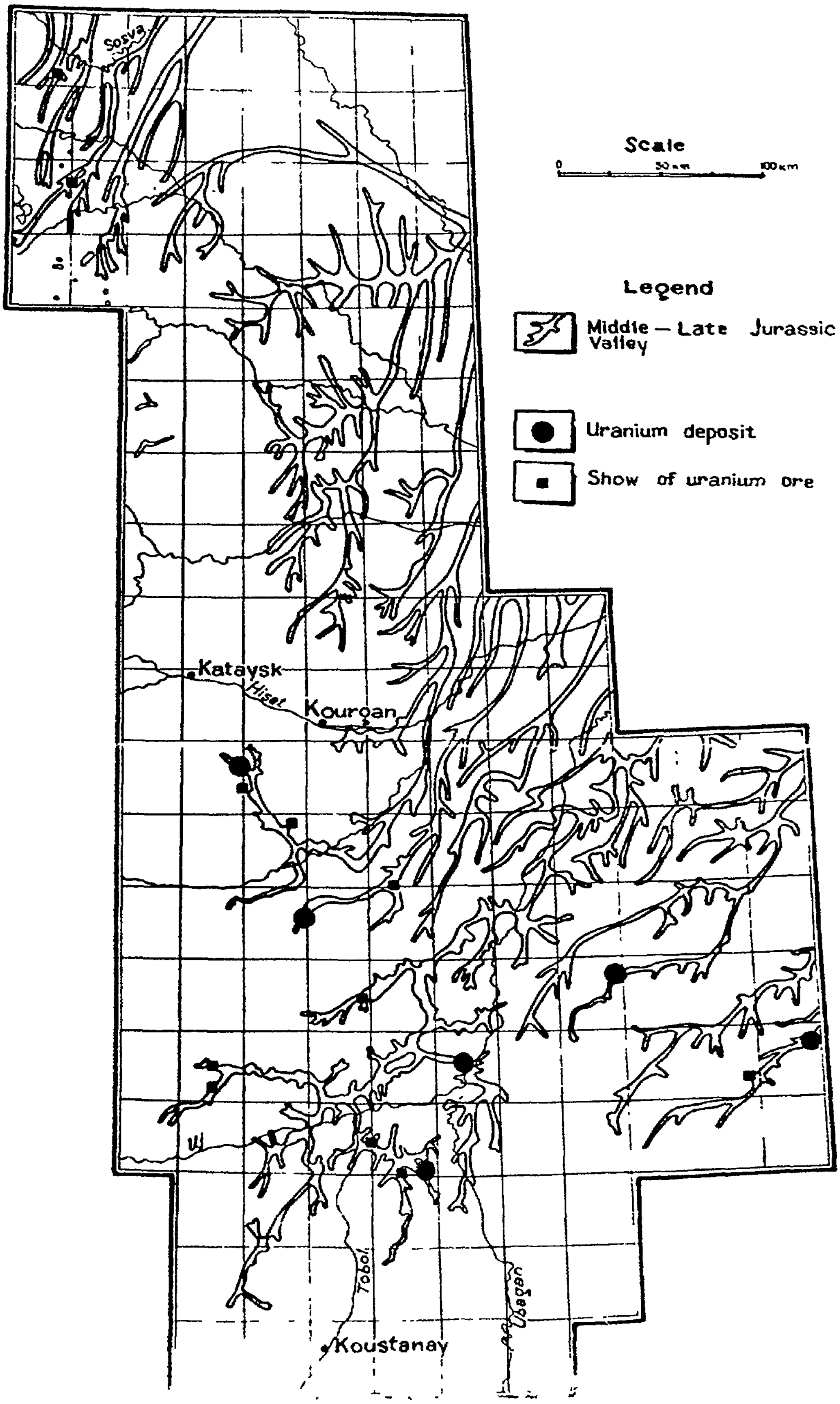


FIG. 4. Chart of Middle-Late Jurassic valleys in Zauraije.

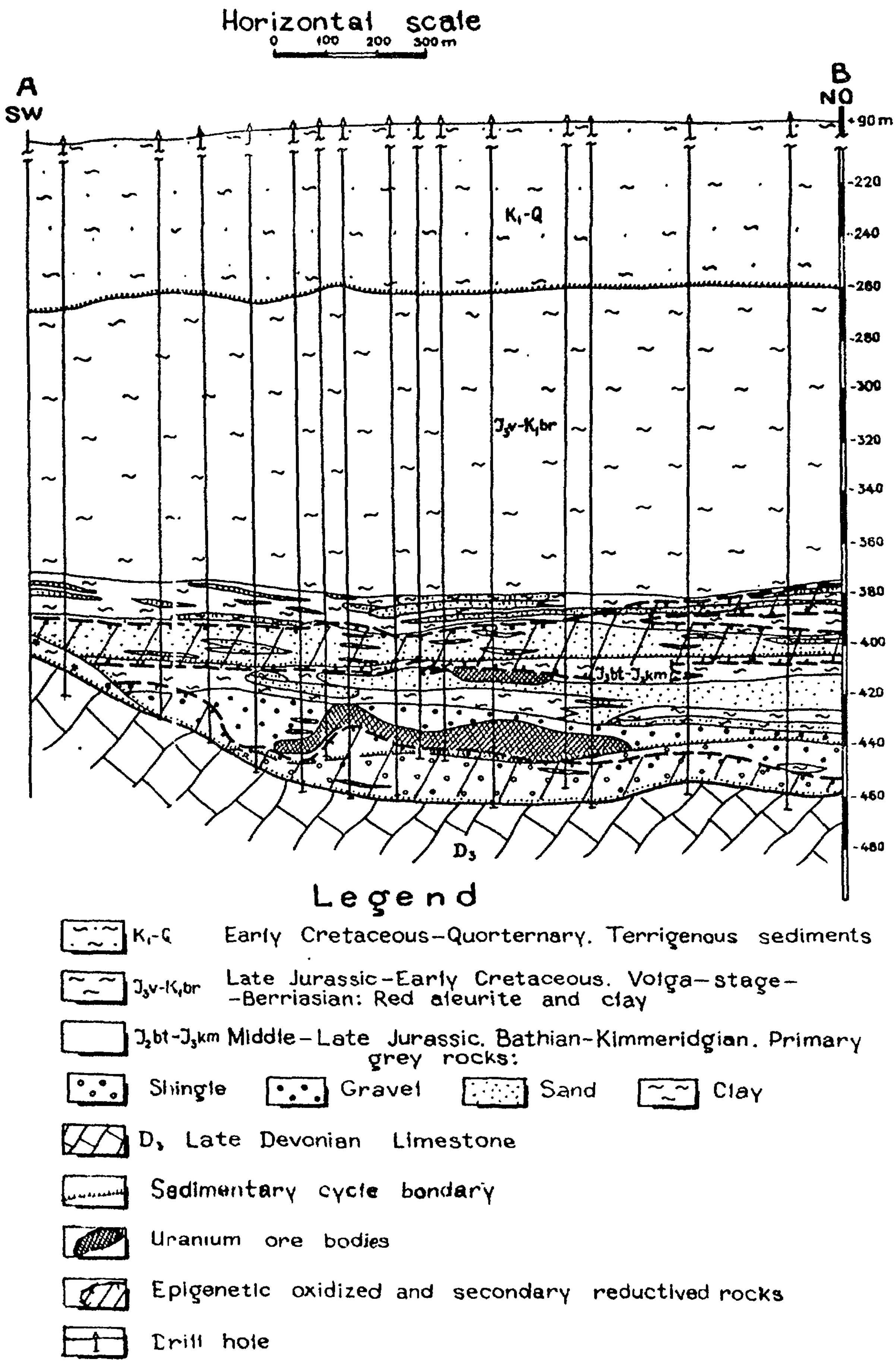


FIG. 5. Dobrovolnoye uranium ore deposit: Geological cross section.

Orebodies of uranium deposits have a ribbon form in plan (Fig. 6). Bodies are from, 1 to 7 km long, from 50 to 700 m wide and from 1.5 to 11 m thick. In section, ore bodies have a roll or lens form. There are three levels of bodies corresponding to three sedimentary cycles. Percentage of uranium in ores is from 0.01 to 3%.

Ore-bearing alluvium was secondary reductive after over-riding by red-stones because the primary concentration of plant carbon in rocks is large (average figure is of medium concentration from 0.5 to 3%).

The epigenetic oxidized and secondary reductive rocks do not contain carbon and iron oxides. There is little concentration of iron in white coloured rocks.

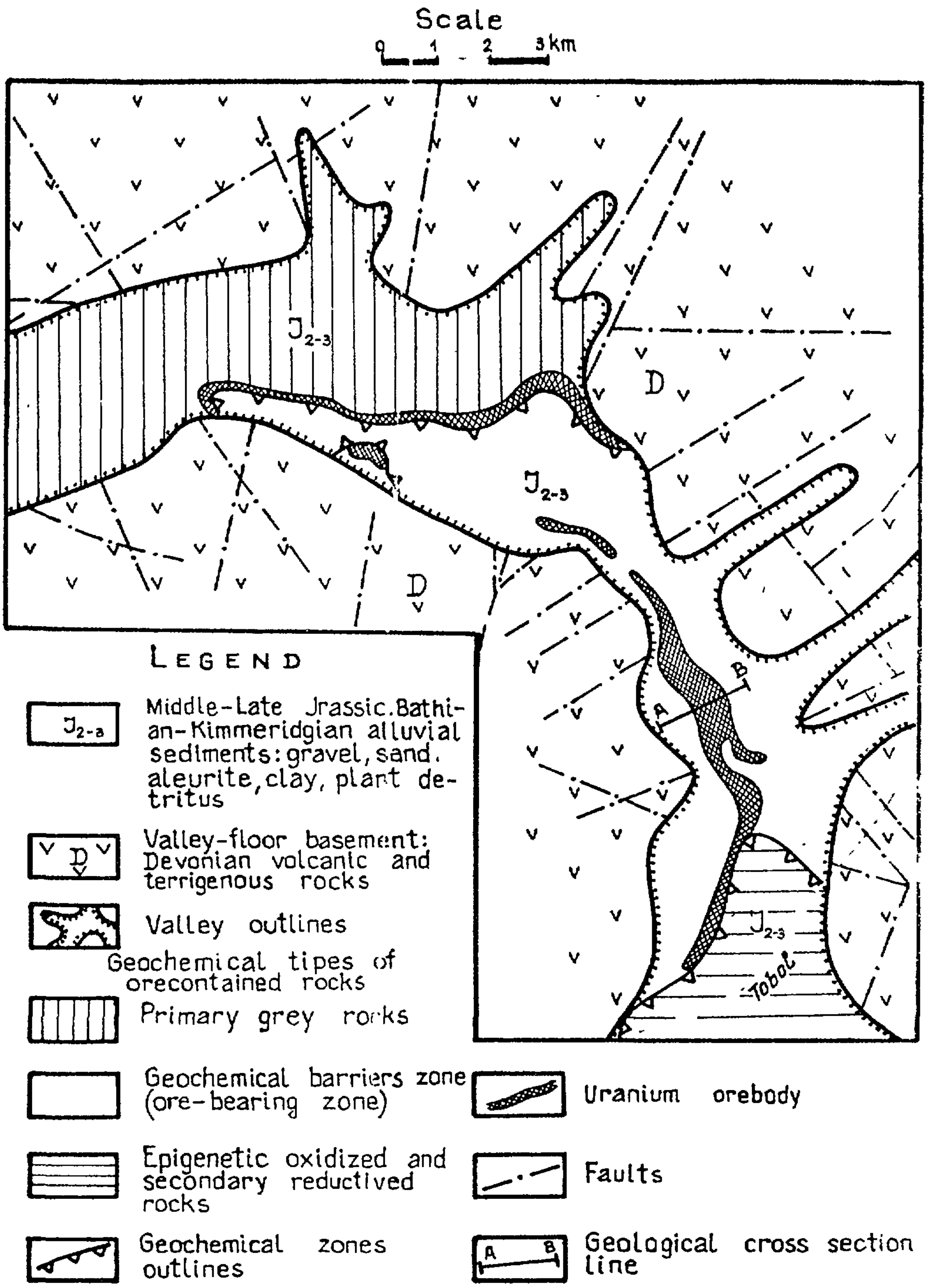


FIG. 6. Geological map of Dobrovolnoye uranium ore deposit (without Cretaceous- Cenozoic sediments).

The well-known chemical composition zoning determines the presence of molybdenum, rhenium, vanadium, selenium in uranium ores and nearby. Scandium, yttrium and lanthanoides in ores are syngenetic concentrated metals.

Uranium minerals in ores are represented by coliform uranium oxides and coffinite. There minerals are accompanied by marcasite, pyrite, jordisite, sphalerite, chalcopyrite, ferriselite, natural selenium, rhenium oxides. The commercial value of ores may be determined now for uranium, scandium, rhenium, yttrium, lanthanoides, possibly vanadium.

Uranium-lead age of these ores is 135 ± 7 million years.

Our real exploration is allowed to recommend a rational complex of methods for development uranium deposits of valley types.

For the West-Siberian ore belt the complex includes seismic and gravity prospecting and electrical prospecting and core-drilling among separated valleys.

For the Hiagda ore district the preparation of magnetic survey and electrical prospecting deciphered valleys cross with core-drilling should be necessary.

SUMMARY

1. Valley-type uranium deposits are the main potential commercial ore source for Russia now. Total resources of uranium for this type of deposit are near 500 000 t, which include nearly 25% of identified resources (reserves).

2. The main groups of these deposits are of Jurassic and Miocene age. Other ages are possible too: there are known as of the Eocene and Quaternary ages.

3. Every deposit includes a complex ore. Uranium, scandium, yttrium, lanthanoides, rhenium play the leading commercial role. Vanadium, molybdenum, selenium may also be commercially valuable.

4. Each deposit of this type may be mined using sub-surface in situ leaching by the sulphuric acid method.

5. Indicators for valley-type uranium ores are:

   - presence of water-permeable sediments in paleodrainage systems, which were formed during the time of uplift where epigenetic alterations formed in early stage crustal weathering conditions of an arid or semi-arid climate;

   - availability of a highly reductive environment. Commercial ores in the Jurassic valleys are not found in sediments which contain less than 0.2% plant carbon;

   - the role of the uranium concentration in the valley-floor basement divides deposits into two groups. The former needs the uranium-rich granites in basement (Hiagde district). For the latter it is important to have a large watershed area (West Siberia belt).

6. There is constructed a rational complex development methods for the described type of the uranium deposits.

GEOLOGICAL PROSPECTING EXPERIENCE RESULTING IN DISCOVERY OF WORKABLE URANIUM DEPOSITS OF VARIOUS GENETIC TYPES IN NORTH KAZAKHSTAN ORE PROVINCE

G.P. POLUARSHINOV
All-Russian Institute of Chemical Technology, Moscow, Russian Federation

V. M. PIGULSKI
Tselinny Chemical Mining Works, Tselinny, Kazakhstan
[Presented by A. Boitsov]

Abstract

The mineral resources of the North Kazakhstan region are represented by uranium deposits of two major types. These are endogenic, occurring in the basement rocks, and epigenetic. Discovery of the Vostok deposit (1964) of endogenic origin, and the hydrogenous Semizbay (1973) are of particular commercial interest. Guidelines for the prognostication, feasibility study and recommended mining methods successfully conducted in North Kazakhstan are presented in this report. Implementation of these methods may prove useful in conducting exploration under similar conditions.

1. INTRODUCTION

By the 1980s North Kazakhstan has become an extensive uranium ore province with over 50 uranium deposits, including some possessing 20-100 thousand tons of metal reserves. Largely the mineral resources of the region are represented by uranium deposits of two genetic types:

- endogenic deposits, without exposure to the surface, occurring in the basement and overlap in a thick layer of loose sediments;
- epigenetic infiltrations, confined to platform deposits and belonging to original old epigenetic hydrogenous formations which have undergone post-orogenic transformation.

The most important events were the discoveries of the endogenic deposit Vostok (1964) and the hydrogenous — Semizbay (1973), presenting much commercial interest, the latter for the in situ leach working.

The discovery of the above type uranium deposits is quite illuminative, since they reflect the successful application of prognostical recommendations and modified methods of detailed plans and commercial assessment for new ore deposits.

The scientific basis for prognostication, feasibility study and recommended mining methods were the predetermined geological features of previously located deposits and ore bodies, similarities in their location and deposition, geological preconditions of their formation, and mineralization control. Other important factors were the modern studies of the special geological development and metallogenesis of the North Kazakhstan province, expected new types of uranium deposits and their prospecting indications and assessment criteria.

The positive results on prognostication, metallogenic and geological exploration studies, conducted in North Kazakhstan in sequence, according to the recommended guidelines and methods, have proven significant. The results have provided high geological and economic efficiency of the works.

Disregarding the long period of time since the deposit's discovery, we believe that the successful realization of prognostication regarding exploration in specific areas of North Kazakhstan, may prove useful in conducting exploration under similar conditions.

We have given a concise description of the methods, used by geologists teams, headed by the authors of this report. The authors express their genuine gratitude to their colleagues, who contributed to the report material.

2. VOSTOK DEPOSIT

The large deposit Vostok is situated in the eastern part of the Ishim-Balkashin metallogenic zone, mapped to the scale 1:200 000 on the basis of previously conducted metallogenic studies. Up to the initiation of detailed works, a Balkashin deposit was known there, as well as a number of small mineralizations (the Dergachev and Akkan-Burluk sites, the Olginsk ore manifestation, etc.), forming the Balkashin ore region.

The Balkashin ore region is situated in the area of two large jointed structural entities, separated by the abyssal zone of fracture (Fig. 1). The first of them - the Kokchetav block (the median mass) presents an ancient anticlinal surface, built up with Pre-Cambrian gneiss formations, amphibolites and crystalline schists, with Ordovic-Silurian and Devonian granitoids. During the Caledonian geosynclinal period, the Kokchetav block has been the region of steady elevation. The second structural entity — the Kalmakkol synclinorium — is a Caledonian depression. It is built up with Cambrian-Ordovician volcanogenic-sedimentary deposits and flysches $O_{2\text{-}3}$, pressed into steep linear folds. During the Caledonian period of development this block was influenced by differentiated movement on the background of general subsidence. The main folding phase took place in the Silurian.

The Pre-Cambrian and Lower Paleozoic folded formations with a sharp angular unconformity have deposits of volcanogenic-sedimentatious rocks of the Middle-Upper Devonic age (red molassa), filling the late orogenic depressions. Some of the depressions are characterized by Devonic volcanogenic formations present there, represented by mantle and extrusive facies of quartz-porphyries. In such cases the depressions are considered as volcano-tectonic depressions.

In most of the area of the Balkashin ore region (up to 80-85%), the folded basement rocks are overlain by a mantle of loose platform deposits 40-60 m thick, reaching over 100 m in some places. Under these conditions, local prognostication and exploration for uranium in the basement rocks is very difficult. The usual surface and airborne gamma survey, completed in 1956-57 resulted in the discovery of the Balkashin and Ishim deposits, several ore bodies and anomalous sites with shallow or outcropping depositions. Upon investigation, these failed to give any positive results, and could not possibly do so. Certain "abyssal" methods of search by secondary dispersion haloes in the ancient weathered crust, using the units SVA-2 and SUGP-10 also proved ineffective. On the one hand, in most areas the weathering crust is buried under 25 m thick Mesozoic-Cenozoic deposits, and on the other, the weathered crusts themselves are developed on 30-35% of the area. The search has been also impaired by the absence of detailed geological maps of the basement or the poor quality of the maps available.

In 1962 the All-Union Institute of Chemical Technology and the Tselinny Chemical Mining Works started research works with the aim to assess the uraniferous potential of the areas adjacent to the Balkashin ore field and to expand methods for detailed prognostication and exploration work to be carried out in the regions overlain with a mantle of loose sediments.

The research carried out in 1962-65 resulted in the development of a method for local prognostication and exploration of uranium deposits, localized in the basement rocks. The method is based on integrated application of geological, geophysical, and geochemical techniques.

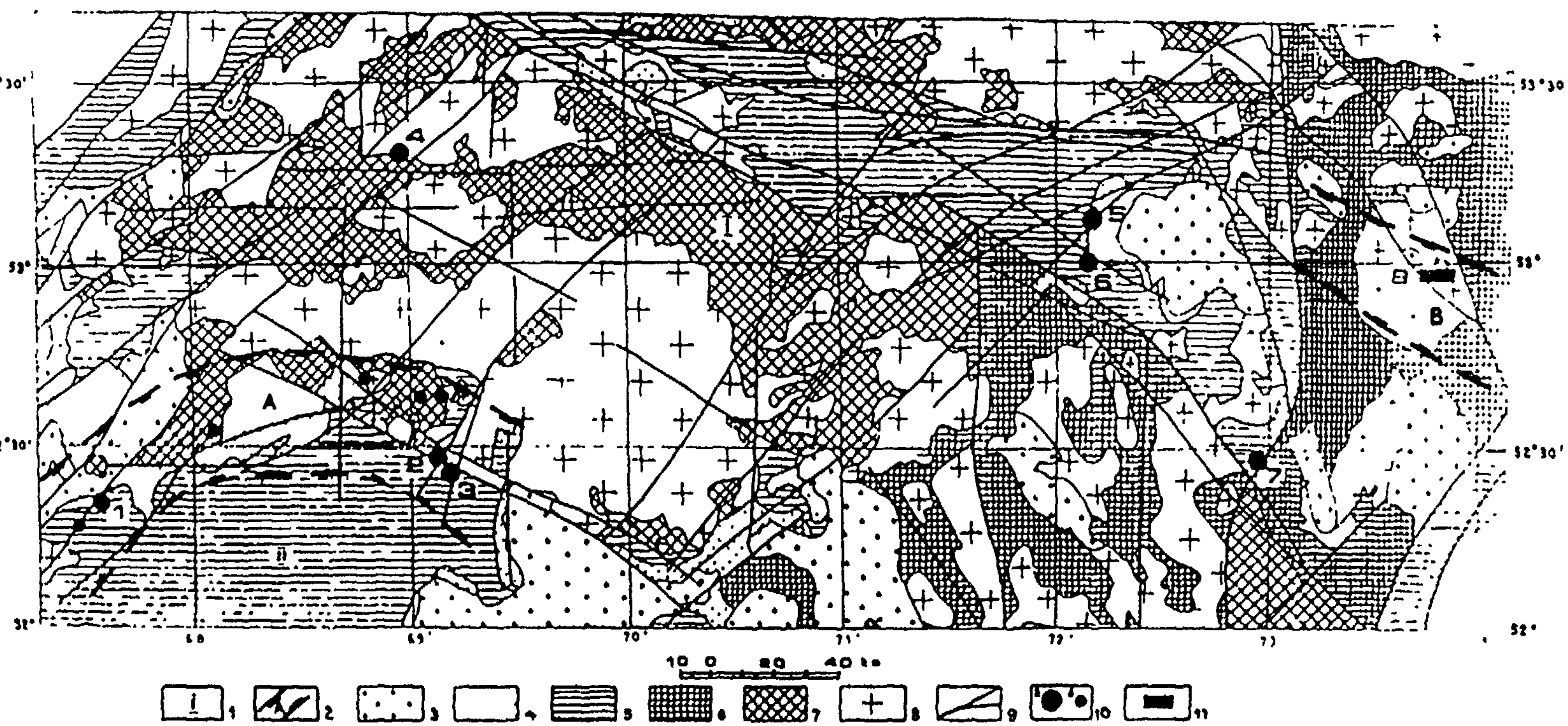


FIG. 1. Explanations:

1 - structural blocks (I - Kokchetau, II - Kalmakkol)
2 - structural-metallogenetic zones (A - Ishim-Balkashino, B - Shokay)
3 - platform complex
4 - orogenic complex
5 - pre-orogenic complex
6 - pre-orogenic complex of reduced capacity on metamorphic basement
7 - metamorphic basement (PR)
8 - granitoids belonging to the pre-orogenic complex
9 - fault
10 - uranium deposits (a) and occurrences (B) of the endogenetic type (1 - Ishimskoye, 2 - Balkashino, 3 - Vostok, 4 - Grachevskoye, 5 - Zaozernoye, 6 - Tastykol, 7 - Manybay)
11 - uranium deposits of the exogenic type (8 - Semizbay)

FIG. 1. Geological map of Kokchetau area.

The method involves four consequent stages: 1) preparation, 2) local prognostication, 3) exploration, 4) evaluation transitional to surveying.

The first stage includes collection, analysis and classification of all present data on geology, geophysics, geochemistry of the minerals pertaining to the region under study (in the case of the Ishim deposit) or to a similar region. The main aim of the first stage — the determining of the leading ore controlling factors and search indications.

By 1962 a number of research and production organization have elaborated the following main criteria and search indications for a deposit:

1. Localization of a deposit group (ore fields) within the range of a 25-30 km wide bend, confined to an abyssal fracture zone, separating the Kokchetav and Kalmakol blocks (the Ishim-Balkash uranium ore metallogenic zone).

2. Confinement of single ore fields to the traverse nodes of the longitudinal and intersecting zones of abyssal fractures or their joints.

3. Localization of the deposits in the sites of intensive post-orogenic Devonian volcanism manifestation.

4. Confinement of the deposits to the II and III order tectonic dislocations or to their intersection nodes at the outer limits of orogenic depressions.

5. Localization of the deposits within the limits of single volcano-tectonic structures.

6. Confinement of the deposits to the beds with favourable chemical (rich carbon contents) and physical-mechanical properties (lithologically heterogenous interlain beds with different mechanical properties.

7. Controlling the ore fields and deposits by dyke belts of various composition.

8. Localization of the deposits within the zones of intensive metasomatic alterations (beresitization, argillization).

9. Some complex-differentiated radioactivity fields and anomalous uranium concentrations and indicator elements (Mo, Pb, As) present in the deposits and ore bodies).

10. Helium anomalies present in the tectonic nodes and zones housing the deposits.

The second stage (exploration-prognostication) includes specialized geological mapping to the scale 1:50 000 and a complex of geological, geophysical and geochemical research. The specialized mapping has to point out and register the main ore controlling factors, search indications (2-10). The aim of the stage is the working out of a geological-prognostic map, pointing out certain promising areas to be assigned for the detailed prospecting for uranium.

In general the methods for the second stage activities are as follows:

Prior to the geological mapping, the reconnaissance geological routes are to be drilled in order to evaluate the exposure degree of the region and choose the representative lines necessary for the construction of the geological-geophysical key sections. The reconnaisance routes construction will determine the trends of main fold-and-break dislocations, the contact character of intrusive rocks, etc. The sites for a detailed geological survey of exposed areas will be determined, as well as the lines of geophysical profiles and mapping drilling.

The key sections are mapped to horizontal scale 1:25 000 to 1:10 000, the vertical scale could be larger. The number and position of the key sections is chosen in such a way, that a most complete idea should be formed considering the geological structure of the area, the rocks composition and main physical properties.

The geophysical survey should be carried out one season ahead of the geological mapping.

The metamorphic, sedimentary and magmatic rocks composing the Balkashin ore region are well differentiated in their physical properties, especially in magnetism and density, which has predetermined magnetometry and gravimetry as being of primary importance. The gravimetric survey was executed to the scale 1:50 000 and the magnetometric 1:25 000.

The geological mapping of the exposed areas was made to the scale 1:25 000-1:10 000 via the common method of geological survey.

The main area mapping was conducted using mapping *drilling after the geophysical surveying*. For the drillings, profiles were used, made for the geophysical survey purposes. The drilling is conducted by drilling rigs ZIV-150 or ZIF-300 mounted on trucks.

In the described region, the specialized mapping required the bore holes be drilled accordingly to the profiles every 1 km, at that the drilling profiles coincided with every fourth profile of the magnetometric survey. The profiled core holes were spaced depending on the geophysical and geological data, with the distance varying from 250-300 m to 1 km and over. The basement rocks were stripped to the depth of 5-10 m. The site of drilling was decided by the geologist or geophysicist for each separate profile following analysis of the physical fields at the site and the geological drilling data on the previous profiles. The drill core samples were taken from the basement rocks and only 10% of the boreholes — beginning from the surface. The latter were made along the profiles, which provided the most complete characteristics of the loose Meso-Cenozoic mantle cross-section. The total thickness of the loose sediments and weathered crust were determined reliably enough in advance,using the data of the resistivity prospecting (vertical electric sounding).

All the bore holes underwent obligatory gamma logging, and in some case gamma-spectral logging and electrical logging. With core-meters and coroscopes available, the measurements of rocks elements deposition, lamination, foliation, etc, could be conducted.

Upon completion of the second stage works, the following graphical materials could be compiled:

1) a specialized geological-structural map with stripped loose sediment mantle, scaled to 1:50 000, with a series of geological sections and a stratigraphic column;
2) an iso-thickness map for loose sediments of the same scale;
3) a set of geophysical maps (maps of isolines, graphs, etc.);
4) a summarized interpretation map of geophysical data:
5) a radioactivity distribution map, compiled from radiometry data;
6) geochemical maps (distribution of uranium and elements-indicators for uranium ore bodies - As, Mo, Pb);
7) a map of hydrothermal-metasomatic alteration of rocks;
8) a map of factual material;
9) tables of the background uranium contents, elements-indicators and accessories in rocks' physical properties, etc.;
10) prognostic maps based on indicators scaled to 1:50 000, pointing out the sites for detailed survey of the first and second priority.

The third stage — exploration. Its main task is to determine the actual potential ore-bearing structures (tectonic zones, the nodes of their intersection, single volcanic structures, "productive" horizons), radioactive anomalies, and, under favourable conditions, uranium deposits, such as the Vostok case, within the areas singled out via specialized mapping, scaled 1: 50 000.

Another task of the stage is typification and preliminary evaluation of the singled out anomalies and anomalous sites. The set tasks can be solved by complex geological, geophysical and geochemical studies combined with drilling. At that, the set of methods remain the same as for the purposes of the specialized mapping, scale 1:50 000, but is directed to more concrete tasks at local sites.

The set of activities include:

1) surveying control,
2) detailed geological-geophysical study of the exposed areas (scale 1:5 000-1:2 000),
3) magnetic and gravimetric survey, scale 1:10 000,
4) prospecting (mapped) drilling with trucked units ZIV-150 or ZIF-300,
5) detailed study of anomalies,
6) mineralogical-petrographic and geochemical study of the drill cores,

The perspective sites are determined by the mapped drilling along the profiles oriented across the strike of the main structures which represent interest, according to the prognosticated evaluation. For the reliable deposits prospecting, the optimal calculated drilling network, depending on the primary aureole of scattering (fields of concentrations), as in the Balkashin ore region, should measure 400 × 100 m.

The distance between the bore holes varied within 50-200 m, depending on the results of mapping drilling along the previous profiles and the data of structural geophysics. Over the most promising sites the bore holes were drilled along the profiles every 200 m. All the bore holes were obligatory logged using the stations PRKS-1 or PRKS-2. The drilling core was registered and tested like the mapping, scale 1:50 000.

In case of the appearance of some anomalies and anomalous zones, their immediate detailed was made using a smaller spaced network — 200 × 50, 100 × 50 and even 50 × 50. An exception was made only for such anomalies which geological position was not clear, and those characterized with a low gamma activity. Such anomalies were surveyed in detail upon conclusion of the prospection of the whole area of the site.

The mineralogical-petrographical and geochemical studies are to be carried out in order to single out sites (zones) with a higher concentration of uranium and indicating elements, as well as for determining the zones of hydrothermally altered rocks.

Empirical data show that the ratio value of indicating elements to uranium (Mo/U, Pb/U, As/U) can determine the value assessing the erosion section of a deposit. Thus, a high value of As/U testifies to the singled out anomaly being over an ore body, much higher than the erosion section level, i.e. in the case of a blind ore body. A high value Mo/U, Pb/U most probable testifies to a large erosion section, therefore we can deal here with the root part of some ore body.

The exploration stage is concluded with compiling graphs and tables, such as:

1) a specialized geological map, scaled 1:10 000,
2) a map for factual materials,
3) a map for radioactivity distribution and maps of gamma fields of anomalous sites (the latter large scaled),
4) geochemical maps of uranium and indicating elements distribution, as superposed maps over a schematized geological base,

5) a map of hydrothermal alterations and regeneration capacity of the rocks (ΔEH),
6) geophysical maps and graphs Δz, Δg, ρk, etc,
7) classification tables of anomalies, denoting the anomalies passes on for evaluation.

The fourth stage of complex research for the means of evaluation. The surveyed anomalies and ore manifestations as well as the structures appearing perspective in accordance with a number of indirect indications.

The survey-evaluation work is conducted by profile drilling of angled boreholes across the strike of the anomalous zones and favourable structures from their hanging block.

The distance between the profiles as well as the drilling locations, their depth, etc. are to be chosen separately in each case, accounting for the character of the anomaly, its form, the gamma field intensity.

It is worthwhile to drill the first hole at the site of the maximal gamma activity, with maximal values of uranium concentration, concentration of indicating elements and other indirect ore manifestation indications. The following boreholes should be drilled using the results on the first hole in order to observe the strike and dip of the anomaly (mineralization).

In case mineralization has been found, the surveying-evaluation stage proceeds to the stage of prospecting.

It has to be pointed out, that the discovery and prospecting of the Vostok deposit has proven that large hydrothermal deposits with characteristic veined-disseminated ores may localize within fracture zones of the "abyssal" type. The largest ore deposits are confined to the sites of the main fracture plane dip angle variation and not to the intersection nodes associated with breaks in continuity in various directions .

The practice has shown the hydrothermal alteration of rocks (beresitization) to be the most sharply defined indication of an uranium mineralization and a reliable prospection criterion.

The total complex of geochemical research methods includes as most efficient the determination of rocks reducing capacity, used for both a local prognostication in the specialized mapping, scaled 1:50 000, and in the detailed surveying in singling out the potential ore-bearing zones. A higher reducing capacity should be considered a most favourable search indicator.

The efficiency of the method has been proven by the operation practice within the limits of the Balkashin ore region in the 1962-68 period. In 1964 the prospection of the promising sites, singled out by the specialized geological mapping, scaled 1:50 000, resulted in the discovery of the large Vostok deposit, overlain with a mantle of loose sediments ca. 70 m thick, and a number of uranium ore manifestations. Some of these later on were transferred into the deposits class.

A specialized mapping, scaled 1:50 000, carried out in the areas adjacent to the Balkashin ore region, has also allowed identification of a number of sites requiring detailed surveying.

It has been shown, that the specialized mapping, scaled 1:50 000 conducted according to the above methods, makes it possible to prognosticate beyond the known molybdenum-uranium deposits. Some other types, for instance, the endogenic deposits in granitoids and the exogenic-in terrigenous deposits of late orogenic molassa and in the loose sediments of the platform mantle may be located with these methods.

An example of the methods application, resulting in the discovery of the exogenic deposit Semizbay, follows.

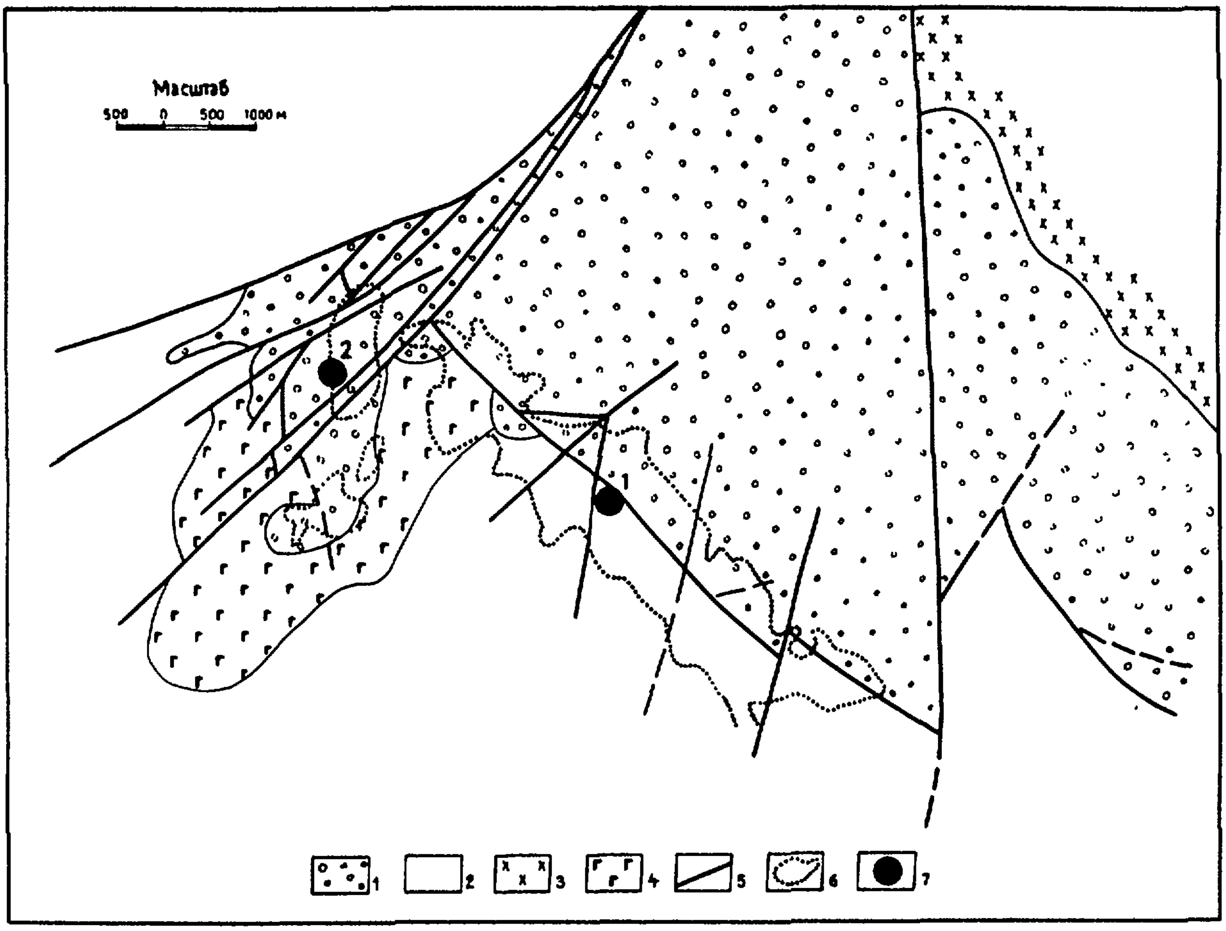


FIG. 2. Explanations:

1 - volcanic-terrigeneous sediments D_2-D_3
2 - intercalate series O_{2-3}
3 - granite, granodiorite O_3
4 - gabbro, gabbrodiorite O_3
5 - faults
6 - summarized contour line of anomalous concentration (10 backgrounds and over) of uranium and elements indicator (Mo, Pb, As) in the basement rocks
7 - uranium deposits: 1 - Vostok, 2 - Balkashino

FIG. 2. Bulkushino ore field.

3. THE SEMIZBAY DEPOSIT

The first search of exogenic uranium deposits in North Kazakhstan was carried out by the Stepnoi expedition of the Ministry of Geology in 1954-62 in regions of their probable occurrence in the Mesozoic-Cenozoic deposits of the marginal southern part of the West Siberian platform. As a result the infiltration-epigenetic Torfjanoe deposit — in the Oligocene lignites — has been discovered, as well as the Koitass, the Pjatigorsk and some other ore manifestations, confined to the carboniferous Jurassic-Cretaceous sediments, and the Aurtav sedimentatious-diagenetic ore manifestation in the Quaternary clays.

The found deposits contained small reserves and were evaluated as non-workable. The ore manifestations were assessed negative. The region potential was declared limited. Thus all the activities along the exogenic direction were stopped in North Kazakhstan in 1963.

The limited potential of the region, if compared with its proximate analog — the Kizil-Kum uranium province, with characteristic large infiltration deposits of the sandstone type, was explained by the formation peculiarities of the platform stage being unfavourable for exogenic ore formation. This was believed to be mainly due to the absence of Neogen-Quaternary tectonic movements of the activation stage and a wide spreading of the regional water confining stratum, built up with the Chagan series clays of the Paleocene age. The ubiquitous development of those clays had resulted in isolation of the subjacent Mesozoic sediments, making the potentially favourable for uranium mineralization permeable sandstone horizons unpassable for descending stratal waters. These had formed the present artesian basins in other provinces, creating, the geochemical zones of stratal oxidation and related uranium mineralizations.

1969-70 the specialists of Geological Department of the Tselinny Chemical Mining Works together with the All-Union Research Institute of Chemical Technology experts, having summarized and analysed the collected data, with the account for general theory and the USSR developed concept on exogenic (hydrogenic) ore formation, radically revised the earlier concepts on the uranium metallogenesis of the region under consideration.

For the first time, the uranium-bearing ability of the post-geosyncline Mesozoic-Cenozoic sediments of North Kazakhstan was considered as positive. Conviction was aired that the region's potential was far from having been exhausted and there were quite possible analogues of the known "Uchkuduk" sandstone type deposits to be found, which were related to the regional zones of stratal oxidation. And more than that, there could occur other, rarely met in natural conditions, epigenetic old infiltrations of presumably Pre-Tertiary (Jurassic-Cretaceous) age.

The most important criteria for the formation of hydrogenous uranium deposits in North Kazakhstan were determined by the following factors:

1. Potential uraniferous formations under favourable lithologic-geochemical conditions, containing organic substances and other reducing agents as the most viable uranium concentrators at the diagenesis stage and following epigenetic processes, present in Mesozoic-Cenozoic depressions in the transitory region of the Kazakh shield towards the West Siberian platform;

2. Manifestations of the main stratigraphical breaks in the dormancy periods of the tectonic activity, which could be considered as probable stages of the epigenetic infiltration uranium ore formation;

3. Favourable geological-structural and paleo-hydrodynamic conditions for the creation of minor artesian basins in various paleo-depressions and the generation of a descending infiltration of oxygenated stratal waters containing uranium.

A favourable condition is also the regional sites of the fully profiled weathering crusts, present in North Kazakhstan; their long-term formation during periods of arid conditions had been accompanied by the uranium liberalization from the rocks of the folded basement, thus creating prerequisites for its later migration into hydrogenous ore formation.

The above considerations on the positive results in prospecting uranium ore mineralizations of hydrogenous type have been taken as the basis in designing geological survey work. As the first and the most promising we have chosen the Olenty-Seletinsk region on the margin of the Pri-Irtysh syncline, in the area of the developed Jurassic-Cretaceous depressions (the Seletinsk, Semizbay, Kiziltuk sites and others), with single branches of them spread for tens kilometers inside the crystalline basement.

The recommended, and finally implemented, set of specialized research methods, resulting in the discovery of the Smizbai deposit, contained the following activities:

1) prognostication-metallogenetic study, summarizing the synthesis and analysis of the accumulated geological, geophysical, geochemical, etc. data all over the territory of North Kazakhstan; validation and assessment of a potential discovery of various types of mineralizations; compilation of corresponding lithologo-facies, geochemical, geologic-prognostication maps for the suggested single stages of the uranium ore formations, scaled 1:200 000;

2) revision-evaluation on the basis of the specialized geological mapping, scaled 1:50 000, in the singled out potential areas, resulting in determining direct indications for conditional uranium mineralizations and localizing sites for detailed surveying;

3) abyssal surveying geophysical and drilling works, resulting in the present discovery of the Semizbay deposit uranium ores, 50-150 m deep;

4) simultaneously conducted preliminary and detailed surveying, field and pilot plant mineralogical-technological tests on the assessing of the potential to work the deposit by the underground leaching methods using drilled boreholes;

5) compiling the summarized report on the detailed geological survey results, calculation and approval of the Semizbay uranium ores deposit; evaluation of the prognosticated reserves and general potential of the deposit and its region; setting up foundations for the directions of the following geological survey work.

During the surveying of the deposit several thousand boreholes were drilled, mainly arranged as a network of 100 × 50 m, adopted for payable category assessment, thinning out at the wings to 400 × 100 m and concentrating at two sites to 12.50 × 6.25 m which had been surveyed in detail. A considerable extent of mineralogical-technological research was carried out, as well as drilling, core tests and chemical analyses assaying the main valuable and associated elements and harmful impurities.

The detailed study had determined that the Semizbay deposit was confined to the grey alluvial sediments of the depression of the same name, presenting the apex of a complicated branched Late Jurassic-Early Cretaceous paleofluvial system, dipping to the east towards the sea basin of the same age, in the ares of the present West Siberian lowland.

The basement and the nearest surroundings of the depression are mainly composed by granitoids of the Zhaman-Kotass massive, and, to a lesser degree, by Paleozoic sand-schistose rocks (Fig. 3).

The ore-bearing fluvial-flood-plain deposits had been ubiquitously overlain with the Lower Cretaceous continental clays of the Kijalin suite (erosion destroyed in most of the area of the region), which presented a secondary regional water confining layer sealing up all subjacent formations.

The uranium mineralization was found at the 25 km length in the marginal part of the paleo-valley. It forms stratified ribbons of ore, practically horizontal, strongly tabular and laterally and vertically discontinuous, as well as oblong lenticular, roll- or pocket-like ore bodies (Fig. 4). Their thickness varies from tens of centimetres to 7.5 m (the average over the 260 surveyed deposits 2.1 m), their extent from hundreds of meters up to 5 km, with the width from 20-80 up t o 200 m.

The mineralization is characterized by a strongly uneven distribution of uranium ores. On the whole, the ores are ordinary, containing on an average 0.1% of uranium, varying throughout an ore body from hundredth parts of one percent up to 0.5% and in some single samples - up to 3-5% and even 8%. As impurities, selenium, germanium and workable quantities of scandium were found, the latter could be recovered simultaneously with uranium by the underground leaching technique via drilled bore holes.

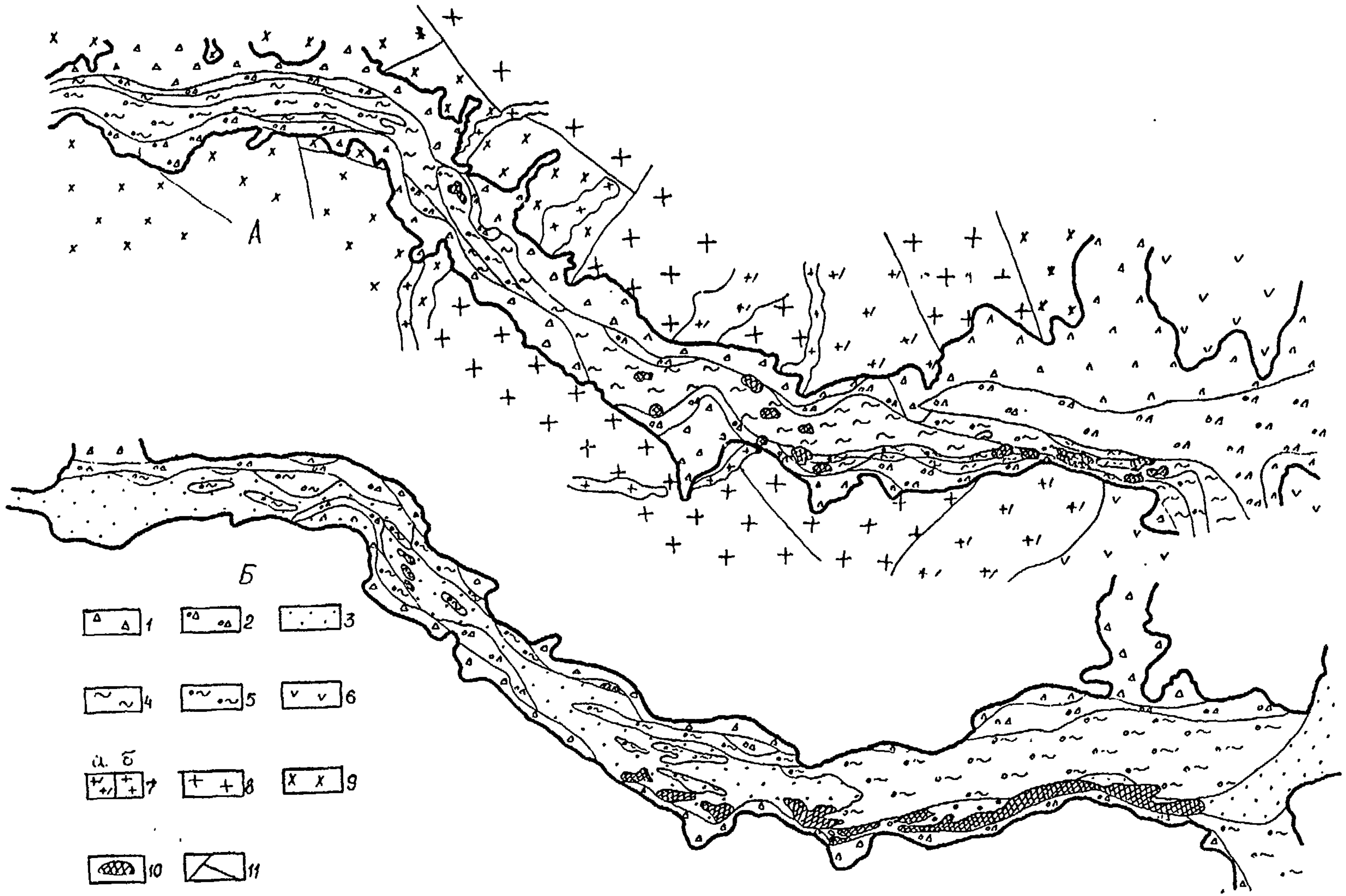


FIG. 3. Explanations:

A - upper ore-bearing horizon
B - lower ore-bearing horizon
1-5 Semizbay suite sediments
(J_3 - K_1SM)
1 -mottled slope gravel-sandy and aleurolite clayish
2 - intercalation of slope and alluvial
3 - 5 grey alluvial with included bed sediments
3 - 90%, 4 - 90-50%, 5 - <50%

6 - andezite - porphyres, andezite basalts and their tulfs
7 - intruzive suites: 7a - alascite granite, 7 - dyke swarm of granite-porphyres (D_{2-3})
8 - biotite granites (S_2-D_1)
9 - diorites, granodiorites (O_3-S_1)
10 - uranium ore
11 - faults

FIG. 3. Geological map of Semizbay deposit.

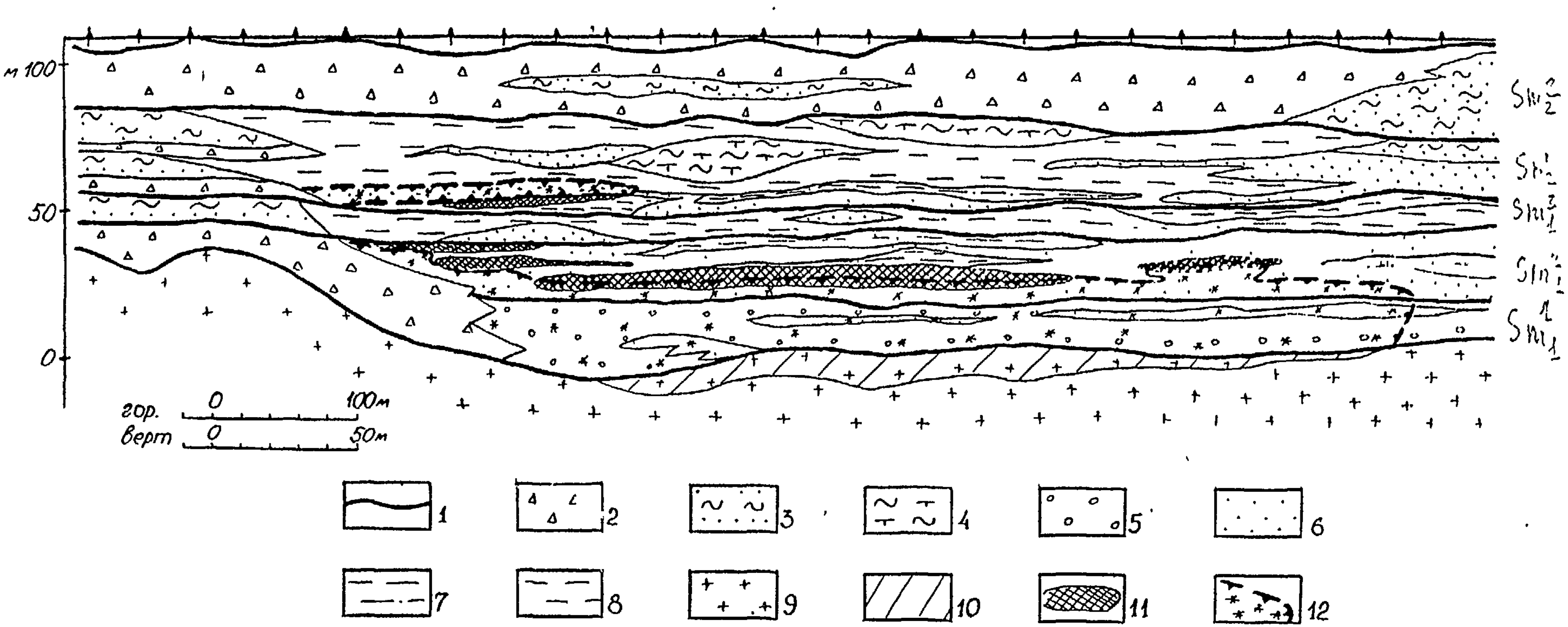


FIG 4. Explanations

1 - conoures of the Semizbay suite and stratigraphic -lithological horizons
2 - 4 slope sediments·
2 - intercalation of gravelite clayish sandstones, assorted rock of temporary currents
3 - intercalation sandstone and clay deltaic cones
4 - lumped clays of drying reservoirs
5 - 8 alluvial sediments
5 - bed gravel-pebbles
6 - sandy bedded
7 - clay-alevrite-sandy stagnant bedded
8 - alevrite-clay of flood plans and flood-plain lakes
9 - granodiorites
10 - weathering crast
11 - uranium ore
12 - old zone oxidation

FIG. 4. Geological section of the Semizbay deposit.

The carried out revision-survey works, resulted in the discovery of the Semizbay deposit, and ore-geological characteristics obtained in its detailed surveying clearly proved the earlier prognostications and geological preconditions.

It has been found due to the Late Mesozoic tectonic activation and periods of arid conditions of the platformic sedimentation mantle in the North Kazakhstan province, manifested in Pre-Cretaceous, some infiltration-epigenetic processes had taken place, resulting in the formation of "ancient" zones of stratiformed oxidation, and their geochemical contrast barriers - a workable coffinite-black uranium mineralization of the Samizbai deposit. It has been determined that later on the uranium deposits underwent reduction and a high-temperature (150-200°C) carbonation.

The discovery of the Semizbay deposit had given impetus to the arranging survey for such mineralization type in the adjacent region of West Siberia, resulting in the discovery of similar deposits in the Trans-Urals (the Dalmatov deposit, etc.).

STATUS OF THE ŽIROVSKI VRH MINE

Z. LOGAR, B. LIKAR
Rudnik Žirovski, vrh, Gorenja Vas, Slovenia

T. BUDKOVIČ
SP Geološki zavod, Kjubljana, Slovenia

Abstract

Systematical geological investigations on uranium in Slovenia had started in 1969 and practically ended in 1990. Several anomalies had been discovered, particularly in Permian sandstone in vicinity of Skofja Loka. Except Žirovski vrh ore deposit none has economical value and has not been investigated. The government of Republic Slovenia decided in 1978 to construct uranium mine Žirovski vrh to supply fuel for Nuclear power plant Krsko. The uranium concentrate production by acid leach process started in 1985. The capacity of the production equipment was 160 000 tonnes of ore per year and production up to 120 tonnes of uranium concentrate. During the operation of the mine 620 000 tonnes of ore was excavated and 452 ton U_3O_8 were produced. With the uranium world market changes and non economical production the government decided in 1990 to close the uranium mine. After that the exploitation has never started again. The last estimation of geological ore reserves was done in 1990: Reasonably Assured Resources (RAR): 1 350 000 tonnes 0.12% U; Estimated Additional Resources — Category I (EAR-I): 8 640 000 tonnes 0.11% U; Estimated Additional Resources-Category II (EAR-II): 1 160 000 tonnes 0.1% U. Only uranium mine closing and reclamation works are executed by now referring to the Programme, which was elaborated in February 1993 and given to the authorities organizations for approval. The different required studies and design for four basic fields will follow this Programme for safe and permanent closing down of the mine. The programme predicts that the closing down of the mine will last six years.

1. SUMMARY OF HISTORY

Systematical geological investigations on uranium in Republic Slovenia started in 1960. Several areas were discovered, where uranium ore is appeared. The most important are in Skofja Loka vicinity (Žirovski vrh with vicinity, St. Valentin, St. Tomaz, Breznica, Bodovlje, St. Ozbolt, Sopotnica and Polhovec). Uranium enriched are also shales in mercury mine Idrija and coal in mines Kocevje and Kanizarica. Except Žirovski vrh ore deposit none has economical value and has not been investigated. The last estimation of geological ore reserves was done in Žirovski vrh deposit in 1990:

- Reasonably Assured Resources (RAR):	1 350 000 tonnes 0.12% U
- Estimated Additional Resources-Category I (EAR):	8 640 000 tonnes 0.11% U
- Estimated Additional Resources-Category II (EAR-II):	1 160 000 tonnes 0.1% U

Uranium Mine Žirovski vrh (Rudnik urana Žirovski vrh-RUZV) was the only working uranium ore mine in the state. It was constructed to provide uranium concentrate for the nuclear power station in Krsko. Especially due to the uneconomical exploitation of the ore deposit, the government of Republic Slovenia on the 18th of October 1990 issued a decree on temporary shutdown of exploitation and investigations of uranium ore in the Uranium Mine Žirovski vrh along with the immediate stop of production. After that the exploitation was never started again.

The law on definite closing down of the uranium mine exploitation and on rehabilitation of the effects of mining on the environment was issued on the 24th of July 1992. RUŽV became a public owned establishment responsible to carry out complete and permanent closing down of uranium mine.

Some important dates:

1960 Beginning of investigations
1961 Beginning of mining investigations
1968 Construction of tunnel P-10
1971 Feasibility study on possibilities of uranium ore concentrate production
1977 Foundation of the Uranium Mine Žirovski vrh
1978 Decision to construct the mine, elaboration of the programme of investment
1979 Beginning of building works
1982 Beginning of mining
1984 Beginning of the uranium concentrate production
1990 Temporary stop of the exploitation and investigation of uranium ore
1992 The law on definite closing
1993 Programme for complete and permanent closing down of mine

During the mine exploitation 600 000 tonnes of the ore of the average concentration of 840 g U_3O_8/t were processed and 452 000 kg of U_3O_8 were produced. The exploitation was of underground type, mine waste was deposited in three waste disposals. A procedure of the ore processing was acid leach with filtration to separate solid/liquid. Mill tailings were transported by trucks to the dry tailing disposal Boršt, located 120 m above the valley bottom, above the temperature inversion level.

When the decision on the closing down of the mine was passed, 480 employees worked in the mine. Now 150 people are employed. They carry out maintaining, decommissioning and work on projects of restructuring.

The decision of the government was sudden and unexpected. The uranium mine was working to capacity and there were no plans or projects on closing down. This is not practice in mining. Only after the decree on closing down was passed, a elaboration of the project documentation on closing down began.

The implementation of the Programme is advancing slowly mainly because of the lack of exact decisions of the republic government and also for formal reasons of the local community.

2. PRESENT SITUATION

Because of the sudden stop of the exploitation, ore remained at the ore storage of the crushing plant to be processed, in the processing plant processing media and large stocks of processing chemicals remained. In the storehouse a stock of the one-year production of uranium technical concentrate was kept. Stoping areas of rich ore were remained opened in the mine. During 1991 the mine was in a state of standstill. Only upon the internal agreement between the representatives of the government and the representatives of RUZV on the final closing down of the ore deposit exploitation in May 1991, some activities regarding closing down started. In the second half of the 1991 and in 1992, part of the excavated ore (ca. 5 000 tonnes) was taken back to the mine and reservoirs containing processing media were emptied. Acid liquors were neutralized. Organic phase was regenerated and prepared to be burnt and solutions of ammonium sulphate were processed. Transportation of waste from two small temporary waste disposals to the central waste disposal began.

A critical situation arose at the mill tailing disposal "Boršt", where approximately 700 000 tonnes of mill tailing is deposited. An earthslide beneath the deposited mill tailings was established. Speed of sliding of approximately 7.4 million tonnes of material is approx. 1 mm per day. The instability was caused by the extremely high level of the underground water in November, 1990.

Extensive geodethical, geomechanical and hydrogeological ground investigations were carried out, which were required to elaborate projects for permanent rehabilitation of the area and for the protection of surface against precipitation waters. Studies of natural materials to cover tailings disposal areas in order to separate them from precipitation waters and to reduce exhalation of radon, studies of migration of chemical and radioactive substances from the waste disposals and the mine, studies of geomechanical stability of the mine rooms, etc. are in the process of elaboration.

During the standstill the continuous control of liquid and gaseous releases, radiological control and control of the effects of the uranium mine on the environment is performed. Maintenance works in the mine are accompanied by mine water discharge treatment.

The stipulated regular health control is carried out with all employees. Twice a year a control on sputum is performed with those miners who have worked in the mine more than ten years.

3. PLANS AND PROGRAMME OF THE PERMANENT REORGANIZATION OF THE MINE

The Programme of complete and permanent closing down of Uranium Mine Žirovski vrh exploitation and protection the environment from effects of mining was made by Inzenirski biro Elektroprojekt (Engineering Bureau Electroproject). The closing down was considered on technical, economical, and time basis. The following projects are to be made:

a) Project of a permanent closing down of the uranium ore exploitation accompanied by permanent protection of the environment

   Fulfillment should give solutions to: the permanent protection of surface against influences of mining works, the excessive pollution of the air by radon, the excessive pollution of the surface waters by radioactive substances from the mine water and regulated collection and discharge of the mine waters.

b) Project of a permanent closing down of the uranium concentrate extraction with permanent protection of the environment

   Fulfillment should give solutions to: drainage of technological system by neutralization or regeneration of waste liquids and their depositing or use; decontamination of the used processing equipment and buildings, disassembly of the superfluous equipment and rearrangement of premises for new production programmes.

c) Project of a permanent rehabilitation and solution of the problem of mill tailings disposal "Boršt".

   Fulfillment should give solutions to: geomechanical stability of the area of sliding by drainage tunnels and drainage borings, protection of mill tailing disposal against background waters, preventing the solution of the undesired soluble components into the underground waters and into the surface waters, covering the mill tailing disposal by natural materials in order to prevent the excessive exhalation of radon, recultivation of the surface to prevent erosion caused by precipitation waters.

d) Project of a permanent rehabilitation and solution of the problem of the mine waste disposal "Jazbec".

   Fulfillment should give solutions to: geomechanical stability of the area, regulation of background waters and their regulated drainage into surface waters, preventing the solution of the undesired soluble components into the underground waters and into the surface waters, covering the mine waste disposal by natural materials in order to prevent the excessive exhalation of radon, recultivation of the surface to prevent erosion caused by precipitations waters.

e) Project of the long-term control over the effects of mining on the environment after closing down of the mine exploitation.

Fulfillment should give solutions to: location and frequency of sampling, types of samples and contaminants to be controlled. Determination of the emergency measures to be taken in the event the authorized limits should be excessed and determination of inspection, terms carried out in the field. Determination of the systematic health control for the people who have worked in the Uranium Mine Žirovski vrh.

Projects are in preparation. Closing down of the mine exploitation should take seven years according to the plan.

4. CONCLUSION

The exploitation of the Uranium Mine Žirovski vrh was stopped unplanned, therefore the governmental authorities only now prepare the authorized limits which should be taken into consideration in elaborating project documentation for the definite closing down of the Uranium Mine.

BIBLIOGRAPHY

DIMKOVSKI T., Results of the Geological Explorations of the Uranium in SR Slovenia, Proceedings of Conference, Results of Till Now and Future Explorations of Nuclear Raw Minerals, Belgrade (1983).

JERAN M. et al., Action Programme of the Permanent Closing Down of the Uranium Ore Exploitation and Permanent Protection of the Environment in Uranium Mine Žirovski Vrh IBE, Ljubljana (1993).

URSIC M., Red Book Questionnaire (1993) (unpublished data).

APPENDIX

THE ROŽNÁ MINE AND URANIUM PRODUCTION FACILITIES

A. HÁJEK
Geology and Survey Department, DIAMO, Stráž pod Ralskem, Czech Republic

1. KEY FACTS

Location:	Dolní Rožínka, 55 km northwest of Brno, Czech Republic
Deposit:	uranium hydrothermal deposit Rožná in metamorphic rocks
Economic reserves:	3 500 t U
Final product:	$(NH_4)_2\ U_2O_7$ (70% U)
1993 U sales:	300 t (concentrate)
Number of employees:	1 200 (two mines and milling plant)
Total U sales from the start:	approx. 16 500 t

2. SITE DESCRIPTION

O.z. GEAM at Dolní Rožínka is part of the state enterprise DIAMO, Stráž pod Ralskem. The facility primarily conducts uranium mining and milling. The production facility is located in souther Moravia, about 55 km northwest of Brno.

The site of the mined uranium deposit is situated on a slightly undulated plateau where only minor changes of altitude (500–100 m) exist. The average altitude of the site is about 500 m.

The climate of the site is characterized as piedmont. The yearly average temperature is +7°C (July +17°C, January -3°C). Water precipitation about 650–700 mm per year.

3. HISTORY OF OPERATIONS

The Rožná deposit mining was begun in 1957 (this deposit is still under operation). The Olší deposit was mined from 1958 to 1989, the Javornik deposit from 1956 to 1968 and the Slavkovice-Petrovice deposit from 1966 to 1970. The operation of the uranium processing plant began in 1968. The plant processes uranium ore recovered from the mining operation using an alkaline leaching method.

4. ROŽNÁ DEPOSIT — GEOLOGY, MINING AND PROCESSING

The Rožná deposit is situated in a formation of metamorphic sedimentary–effusive rocks of Precambrian age in the Czech massif. This region is part of the eastern Moldanubian branch, the so-called Strážecké moldanubikum.

Deep-fold structures of rocks have been affected in the late tectonic stages by fault tectonics.

The rocks complex of Rožná deposit mainly consists of a multi-coloured Moldanubic rock group represented by plagioklase–biotite–amphibolite gneisses of different stages of migmatization and amphibolites. The other rock forming components are marble, erlan, small bodies of serpentine and pyroxene.

Uranium mineralization is of hydrothermal origin occurring in fissure structures. Longitudinal faults having a strike of 340–350° and dipping 45–70° to the west should be classified according to their origin as tectonic zones and linked veins.

The thickness of zones is mostly several metres, in exceptions up to 25–30 m. In a longitudinal direction they reach up to 10–15 km. Zones fillings consist mainly of broken surrounding rocks together with a small amount of vein minerals (calcity, graphite, pyrite). Uranium mineralization mostly forms big mineralized bodies of dispersed character.

Veins are classified as linked veins of the main zones. In a longitudinal direction they should extend to a maximum of 4–5 km. Their thickness is generally limited to up to 2.5 m. Fillings of the veins are formed up to 50% from vein minerals. Mineralization of veins is mostly of lenticular character with sharp limits.

A metasomatic character of mineralization in the deposit is present in the depth of more than 600 m too. Metasomatic mineralization occurs in nets of local dislocations accompanied by albitization. The thickness of metasomatic ore bodies is up to 10 m. The mineralization has a disseminated character.

The deposit has a hydrothermal character (low-temperature deposit). Uranium mineralization consists of uraninite and coffinite (Variscan age — approx. 250 million years ago). The uranium content in ore is 0.15–0.25 %.

Crushing strength of paragneisses has value of 70–90 MPa, this parameter is for zone and vein fillings about 25–50 MPa.

Overhead stoping with filling was a prevailing excavating method in the early stages of mining of this deposit. From 1970 on, the underhand stoping method (top slicing) has become predominant.

The average stope productivity in the past was about 5.5 t per manshift. At the present time the productivity reaches about 8.5 t per manshift (approx. 4 m^3 per manshift).

The deposit is developed by means of longitudinal crosscuts with short offsets running through zones (the distance between offsets is 50 m — that is the length of stopes). The stopes dimensions are both 50 m on longitudinal and vertical directions. The vertical distance of levels is 50 m.

There is a timber support in stopes. Rotary-percussive drilling machines mounted on special masts are commonly used in combination with blasting at underground mining operations.

Ore transportation in stopes is provided by means of scrapers. Under the stopes the uranium ore is loaded into mine cars, then measured at radiometrical measuring stations on uranium content and sorted accordingly. After transportation to the milling plant, the ore is crushed to a size of 0.01 mm. The crushed uranium ore is then leached and oxidized using sodium carbonate (Na_2Co_3) at atmospheric pressure and temperature of 60–65°C. The final product is uranium concentrate — $(NH_4)_2\ U_2O_7$ (70% U).

Big reclamation operations are carried out following the end of mining in some areas.

LIST OF PARTICIPANTS

Abakumov, A.A.	KATEP, ul. Bogenbai-Batyr 168, 480012 Alma-Ata, Kazakhstan
Al-Dahian, S.K.	Institute of Atomic Energy Research, King Abdulaziz City for Science and Technology (KACST), P.O. Box 6086, Riyadh 11442, Saudi Arabia
Ballery, J.J.	Commissariat à l'Energie Atomique, DCC/MNC Bât 476, C.E. de Saclay, F-91191 Gif-sur-Yvette, France
Barthel, F.	Bundesanstalt für Geowissenschaften und Rohstoffe, Stilleweg 2, D-30655 Hannover 51, Germany
Bashir, S.S.	Jordan Phosphate Mines Co., P.O. Box 30, Amman, Jordan
Bejenaru, C.	Regie Autonom for Rare Metals, 68, Dionisie Lupu Street, Bucharest, Romania
Bhar, R.	The Uranium Institute, Twelfth Floor, Bowater House, 68 Knightsbridge, London SW1X 7LT, United Kingdom
Bhasin, J.K.	Uranium Corporation of India Ltd., Jagigida, Bihar, India
Blaise, J.R.	COGEMA, 2 rue Paul Dautier, BP 4, F-78141 Velizy Cedex, France
Boisson, M.	COGEMA, 2 rue Paul Dautier, BP 4, F-78141 Velizy Cedex, France
Boitsov, A.	All-Russian Institute of Chemical Technology, 33, Kashirskoe Shosse, 115230 Moscow, Russian Federation
Bunus, F.T.	Chimenerg, Drumul E 70 km 6 Craiova, Postal Code 1124, Romania
Cioloboc, D.	Regie Autonom for Rare Metals, 68, Dionisie Lupu Street, Bucharest, Romania
Dahlkamp, F.J.	Ölbergstrasse 10-Liessen, D-53343 Wachtberg/Bonn, Germany
Desderedjian, M.	Electricité de France/DG, 23, bis Avenue de Messine, F-75384 Paris Cedex 08, France
Dwivedy, K.K.	Atomic Minerals Division, Department of Atomic Energy, Government of India, Begumpet, Hyderabat 500016, India

Érdi-Krausz, G.	Mecsekuran LLC, P. O. Box 65, H-7614 Pécs Hungary
Giroux, M.M.	COGEMA, 2 rue Paul Dautier, BP 4, F-78141 Velizy Cedex, France
Graul, H.	Urangesellschaft mbH, Solmsstrasse 2-26, P.O. Box 900 980, D-60486 Frankfurt/Main 90, Germany
Hashimi, J.A.	Attaché, Embassy of Pakistan, Hofzeile 13, A-1190 Vienna, Austria
Hassan, M.A.	Nuclear Materials Authority, P.O. Box 530, El Maadi, Cairo, Egypt
Hrádek, J.	DIAMO, s.p., TUU o.z., 471 27 Stráž pod Ralskem, Czech Republic
Janský, J.	DIAMO, s.p., Liberec, Jáchymovská233, 471 27 Stráž pod Ralskem, Czech Republic
Joosten, J.	OECD/NEA, Le Seine-Saint Germaine, 12 Boulevard des Îles, F-92130 Issy-les Moulineaux, France
Kawamura, K.	Power Reactor and Nuclear Fuel Development Corporation (PNC), 4-8 Rue Sainte-Anne, F-75001 Paris, France
Kelter, D.	Bundesanstalt für Geowissenschaften und Rohstoffe, Stilleweg 2, D- 30655 Hannover 51, Germany
Kidd, A.P.	RTZ Limited, Headquarters Company of the RTZ Corporation PLC 6 St. James Square, London, SW1Y 4LD, United Kingdom
Krische, E.H.	Uranerzbergbau GmbH, Kölner Strasse 38-44, Postfach 1638, D-50398 Wesseling, Germany
Lawrence, M.	Counsellor for Nuclear Policy, Resident Representative of the United States of America in Austria, Obersteinergasse 11/1, A-1190 Vienna, Austria
Likar, B.	RŽV Mine Žirovski VRH, Todraž 1, SLO-64 224 Gorenje Vas, Slovenia
Logar, Z.	RŽV Mine Žirovski VRH, Todraž 1, SLO-64 224 Gorenje Vas, Slovenia

Matolin, M.	Faculty of Science, Charles University, Albertov 6, 128 43 Prague 2, Czech Republic
Miu, I.	Chimenerg, Drumul E 70 km 6 Craiova, Postal Code 1124, Romania
Müller-Kahle, E.	Ferdinandstrasse 61, D-53127 Bonn, Germany
Parslow, G.R.	Geology Department, University of Regina, CW Building, Regina, Saskatchewan S4S 0A2, Canada
Pluskal, O.	Faculty of Science, Charles University, Albertov 6, 128 43 Prague 2, Czech Republic
Pype, J.	Synatom, Fuel Supply Department Avenue Marnix 13, Marnixlaan, B-1050 Brussels, Belgium
Rengifo, D.F.	Empresa Nacional del Uranio, S.A., Santiago Ruisiñol, 12, E-28040 Madrid, Spain
Ruzicka, V.	Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada K1A OE8
Sayyah, J.J.	Nuclear Materials Authority, P.O. Box 530, El Maadi, Cairo, Egypt
Shen, F.	Bureau of Geology, China National Nuclear Corporation, P.O.Box 1436, Beijing 100013, China
Simov, S.V.	Interpreter, Dragan Tsankov Blvd. 36, Interpred, office 402, Sofia 1057, Bulgaria
Slezák, J.	DIAMO, s.p., TUU o.z., 471 27 Stráž pod Ralskem, Czech Republic
Tauzin, M.	Total Campagnie Minière France, BP 1 - Le Cherbois, F-87890 Jouac-F, France
Tsogtsaihan, B.	Research, Production and Trade Geological Company, URAN, Baga toiruu 6, Ulaanbaatar 210646, Mongolia
Underhill, D.H.	Division of Nuclear Fuel and Waste Management, International Atomic Energy Agency, Wagramerstrasse 5, P.O. Box 100, A-1400 Vienna, Austria

Wolkowicz, S. Państwowy Instytut Geologiczny,
ul Rakowiecka 4, 00-975 Warszawa, Poland

Zhang, R. Bureau of Mining and Metallurgy,
China National Nuclear Corporation,
P.O. Box 2102-9, 100822 Beijing, China

Consultants' Meeting

Vienna-Austria, 24-26 May 1993

QUESTIONNAIRE ON IAEA-TECDOCs

It would greatly assist the International Atomic Energy Agency in its analysis of the effectiveness of its Technical Document programme if you could kindly answer the following questions and return the form to the address shown below. Your co-operation is greatly appreciated.

Title: **Recent developments in uranium resources and supply**
Number: **IAEA-TECDOC-823**

1. How did you obtain this TECDOC?

[ ] From the IAEA:
  [ ] At own request
  [ ] Without request
  [ ] As participant at an IAEA meeting
[ ] From a professional colleague
[ ] From library

2. How do you rate the content of the TECDOC?

[ ] Useful, includes information not found elsewhere
[ ] Useful as a survey of the subject area
[ ] Useful for reference
[ ] Useful because of its international character
[ ] Useful for training or study purposes
[ ] Not very useful. If not, why not?

3. How do you become aware of the TECDOCs available from the IAEA?

[ ] From references in:
  [ ] IAEA publications
  [ ] Other publications
[ ] From IAEA meetings
[ ] From IAEA newsletters
[ ] By other means (please specify)
[ ] If you find it difficult to obtain information on TECDOCs please tick this box

4. Do you make use of IAEA-TECDOCs?

[ ] Frequently
[ ] Occasionally
[ ] Rarely

5. Please state the institute (or country) in which you are working:

Please return to: R.F. Kelleher
Head, Publishing Section
International Atomic Energy Agency
P.O. Box 100
Wagramerstrasse 5
A-1400 Vienna, Austria