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Changes and events in uranium deposit development, exploration, resources, production and the world supply–demand relationship

Proceedings of a Technical Committee meeting jointly organized by the International Atomic Energy Agency and the OECD Nuclear Energy Agency and held in Kiev, 22–26 May 1995

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FOREWORD

This report consists of the proceedings of the Technical Committee Meeting on Recent Changes and Events in Uranium Deposit Development, Exploration, Resources, Production and the World Supply/Demand Relationship, held in co-operation with the OECD Nuclear Energy Agency (OECD/NEA) in Kiev, Ukraine, from 22 to 26 May 1995. It is the latest in a series of meetings organized for the exchange of information on recent developments in uranium related activities. Some of the information from this meeting was also used in preparation of the 1995 edition of "Uranium — Resources, Production and Demand" a joint report by the OECD/NEA and the IAEA.

At the beginning of 1995 there were 432 nuclear power plants in operation with a combined electricity generating capacity of 340 GW(e). This represents nearly a 100% increase over the last decade. In 1995 over 2228 TW·h of electricity were generated, equivalent to about 17% of the world's total electricity. To achieve this, about 61 000 t U were required as nuclear fuel.

For about a decade and a half uranium production and related activities have been decreasing because of declining uranium prices. For many participants in the nuclear industry there has been little interest in uranium supply because of the oversupplied market condition. The declining production led to the development of a supply and demand balance where production is currently meeting a little over 50% of reactor requirements and the excess inventory is being rapidly drawn down. This very unstable relationship has resulted in great uncertainty about the future supply of uranium.

One of the objectives of this Technical Committee meeting was to bring together specialists in the field of uranium supply and demand to collect information on new developments. This helps provide a better understanding of the current situation, as well as providing information to plan for the future.

The IAEA is grateful to the Government of Ukraine, and in particular the State Geological Enterprise "Kirovgeology", for hosting and assisting with organization of the meeting and the field trip. The IAEA is also grateful to "VOSTGOK" (East Mining and Concentrating Complex) for hosting the site visits to the uranium mining and milling facilities at Kirovograd and Zholty Vody. The untiring efforts of A.C. Bakarjiev, Director of Kirovgeology, and the staff of Kirovgeology who contributed to this successful meeting and field trip are very much appreciated.

Special thanks are extended to participants of the Technical Committee meeting who contributed papers and took part in the discussions. Thanks are also extended to: F. Barthel (Bundesanstalt fur Geowissenschaften and Rohstoffe, Germany), G. Érdi-Krausz (Mecsekuran Ltd, Hungary), M.A.G. Hassan (Nuclear Materials Authority, Egypt), M. Matolín (Charles University, Czech Republic) and A. Palfi (Ministry of Mines and Energy, Namibia), the Session Chairmen.

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

EDITORIAL NOTE

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SUMMARY

The Technical Committee Meeting on Recent Changes and Events in Uranium Deposit Development, Exploration, Resources, Production and the World Supply/Demand Relationship was held in co-operation with the OECD Nuclear Energy Agency in Kiev, Ukraine, from 22 to 26 May 1995. It was attended by 68 participants from 20 countries and two international organizations. A total of 36 technical papers covering uranium resources and supply related activities in 14 countries were presented.

This was the first ever Technical Committee meeting dealing with uranium resources, production, supply and demand held in the Commonwealth of Independent States (CIS). The location provided an exceptional opportunity for exchange of ideas and discussion between specialists from the CIS and their colleagues from other parts of the world.

This meeting was particularly instructive in addressing several of the current issues related to the uncertainty of future uranium supply and demand. Two concerns of great importance are: the very large imbalance between world uranium production and requirements and the resulting inventory drawdown; and the integration of the nuclear industries of eastern Europe and the Commonwealth of Independent States into the emerging worldwide uranium market. An additional important issue is the increasing concern for radiation safety and environmental concerns related to uranium production activities.

Of particular note are the early indications of uranium market price increases and increasing interest in production activity reported at this meeting. Most significant among these is the description of the status of the McClean Lake uranium production project by Giroux. This new mine/mill project is the first project developed in Canada since the late 1970s when the Key Lake project was initiated. Other developing projects are reported in Argentina (Navarra & Benitez), India (Bhasin) and Spain (Gonzalez Granda, Sanchez-Porro and Arnaiz de Guezala). Information on the future Inkai ISL Project in Kazakstan is given in the paper by Abakumov and Zhelnov.

Although there are early signs of increases in the level of some uranium related activities, the low priced uranium market has continued to force the closing of mines and mills and the resulting production cuts. This is noted in the Czech Republic (Beneš & Slezák), Hungary (Érdi-Krausz), Kazakstan (Fyodorov, Bayadilov, Zhelnov, Akhmetov, Abakumov) and Uzbekistan (Kuchersky).

Uranium exploration activities have continued to experience cutbacks in most countries of the world. Activities are primarily restricted to countries with uranium deposits with known potential for low cost production such as high grade unconformity and sandstone-type deposits. New insights into geological models for unconformity type (Wheatley, Murphy, Leppin, Cutts and Climie), iron oxide breccia complex type (Dwivedy and Sinha), vein and metasomatic type (Zavarzin, Milovanov, Pigulsky and Tarkhanov), uranium-vanadium Padma-type (Boitsov) and volcanic type (Ischukova) uranium deposits are provided in this report. The paper by Ischukova, "The Streltsovskoye Uranium District" is the first detailed description in English of the geology of the Russian Federation's only operating uranium production centre.

Many considerations related to uranium producing activities including radiation safety, socio-economic impacts and protection of the natural environment have an increasing influence on the planning, development, operation and closure of uranium mining and processing facilities. In his paper "The impact of Canada's Environmental Review Process on New

Uranium Mine Developments" Whillans reports: .."In Canada, the impact of the EA (Environmental Assessment) process on new uranium mining developments has been profound. It has changed the way projects are designed and will change the way they are brought on stream. The process has been time consuming and often difficult, but it has revealed that these new uranium mining proposals are environmentally sound and can remain so over their life-span."

Additional views on the subject are discussed in papers from the Czech Republic (Beneš and Slezák), Germany (Barthel and Mager), Kazakstan (Fyodorov, Bayadilov, Zhelnov, Akhmetov, Abakumov) and Uzbekistan (Kuchersky). The influence of socio-economic and environmental considerations are stated by Whillans.

The paper entitled "CIS Thorium Deposits in the Commonwealth of Independent States and Their Prospective Characteristics" by Kotova and Skorovarov, is a useful companion paper to "Thorium Deposits and Their Availability" by F.H. Barthel and F.J. Dahlkamp, which appeared in IAEA-TECDOC-650, "New Developments in Uranium Exploration, Resources, Production and Demand" (1992), and provides information on thorium resources for former non-WOCA countries.

The paper "Radiometric Map of the Czech Republic and Uranium Mineralization" (Matolín) provides a clear example of radiometric data collected to explore for uranium was used to prepare a map of the natural radioactivity of the Czech Republic.

Several papers describing various aspects of uranium in Ukraine provide a broad insight into the uranium geology and resources of the country: Anysimov; Bakarjiev, Makivchuk, Popov; Lovyunikov, Shumlyanskiy; and others. One paper provides the first report of the use of in situ leach uranium mining in Ukraine (Bakarjiev and Makarenko).

This report provides an update of information from the TCM on Recent Developments in Uranium Resources and Supply, held in Vienna, 24-28 May 1993, the proceedings of which were published as IAEA-TECDOC-823 (1995). One of the principal results of these reports is to provide information on the world's uranium resources and production facilities that will be necessary to fill the increasing uranium fuel requirements for the rest of the century and beyond.

PRODUCTION, INVENTORIES AND HEU IN THE WORLD URANIUM MARKET: PRODUCTION'S VITAL ROLE

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Abstract

This paper analyses recent uranium supply and demand relationships and projects supply through 2010. It discusses how the extremely depressed record low market prices have led to the ongoing annual inventory drawdown of over 25 000 t U resulting from the current 45% world production shortfall. It describes how the policy of the European Union and anti-dumping related activities in the USA are restricting imports of uranium from CIS producers to a majority of the world's nuclear utilities. These factors are reducing low priced uranium supply and forcing buyers to again obtain more of their requirements from producers. It discuses how the sale of Low Enriched Uranium (LEU) produced from of 550 t High Enriched Uranium (HEU) from Russia and Ukraine could potentially supply about 15% of world requirements through 2010. However, legislation currently being developed by the US Congress may ration the sale of this material, extending the LEU supply well into the next century. While the low cost supply is decreasing, nuclear generation capacity and its uranium requirements are projected to grow at about 1.5% through 2010. Demand for new uranium purchases is however, increasing at the much higher rate of 25-30% over the next 10-15 years, because of the increasingly large amount of unfilled demand of reactor operators. This increasing demand in the face of decreasing supply is resulting in a market recovery in which the spot price for non-CIS produced uranium has risen over 25% since October 1994. Prices will continue to increase as the market equilibrium shifts from a balance with alternative excess low priced supply to an equilibrium between production and demand. This change is taking place as the inventory is further depleted, CIS import restrictions are becoming more fully enforced and the rate at which LEU from HEU will enter the market is expected to become more clearly defined. It is anticipated that production must increase from current levels of about 32 000 t U/year, supplying 55% of requirements, to about 60 000 t U/year or greater to meet 80 to 90% of worldwide reactor requirements through 2010 (and beyond). The necessary production increase will occur *only after* market prices have risen to cover full production costs plus a profit. Higher prices are absolutely essential to assure production's vital role in supplying the future fuel supply of the world's nuclear reactors.

WORLD URANIUM MARKET OVERVIEW

During 1994 the average annual spot uranium price again fell to an all-time low, as the worldwide uranium industry continued to produce at far below world reactor requirements. Both uranium producers and buyers continued to have great difficulty in planning for the future because of uncertainty introduced by political decisions that will, in part, define the fundamental nature of the future uranium market. The political decisions relate to the demilitarization of high enriched uranium (HEU) from warheads for use in civilian fuel and the changing restrictions on the sale of uranium produced in the Commonwealth of Independent States (CIS).

Over the last 6 years there have been severe reductions in nearly all phases of the world uranium industry, caused by a massive oversupply that led to the lowest market prices ever recorded. The crisis has been complicated by the merger of the uranium markets of the previously mutually exclusive areas, formerly known as WOCA (the world outside centrally planned economies area) and non-WOCA[1]. This led to the sale on the world market of uranium produced by the CIS, followed by legal and political initiatives in the European Union and the United States of America designed to stabilize the market and protect WOCA producers.

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1 While the WOCA and non-WOCA designations are no longer applicable, these terms are nevertheless still useful for describing the present transition to a fully integrated world market.

The rapid drawdown from the WOCA uranium inventory has brought the inventory to a level where market analysts conclude there is little excess material available for sale. The approaching exhaustion of the excess WOCA inventory and the restrictions on the purchase of CIS produced uranium are respectively, eliminating and controlling, these alternative supply sources. This is happening when the demand for uranium not under contract is projected to increase at a high rate.

Many market participants perceive that the oversupplied condition that has existed for over 15 years will continue because the introduction of low enriched uranium (LEU) derived from HEU warheads will provide an additional low priced supply. Results of analysis indicate, however, that the fundamental supply and demand balance is changing to a balance between production and demand. The near exhaustion of excess WOCA inventory and restrictions on CIS produced uranium substantially reduces the low priced supply. It is expected in the near term that insufficient LEU produced from HEU will be offered for sale to offset this reduction in supply. This will result in a relative shortage causing market prices to continue their increase. This reduction of supply alternatives occurs at a time when demand for uranium is sharply rising. Analysis shows unfilled requirements are increasing at a compounded rate of 25 to 30% per year.

In the longer term the majority of the supply will have to come from new production. The LEU from the 550 t of warhead HEU purchased by the United States of America from Russia (500 t) and Ukraine (50 t) and other surplus supplies from the USA will probably meet between 5 and 17% of WOCA requirements through 2010. Maintaining production at 1994 levels would meet only about 47% of world requirements through 2010. Therefore production will have to increase substantially to meet the requirements not met by other supply sources. New production will only be available, however, if market prices rise sufficiently to pay production costs and provide for a return on investment. It appears that the current market price may continue to rise to price levels that stimulate the increased production that is essential for meeting future reactor requirements.

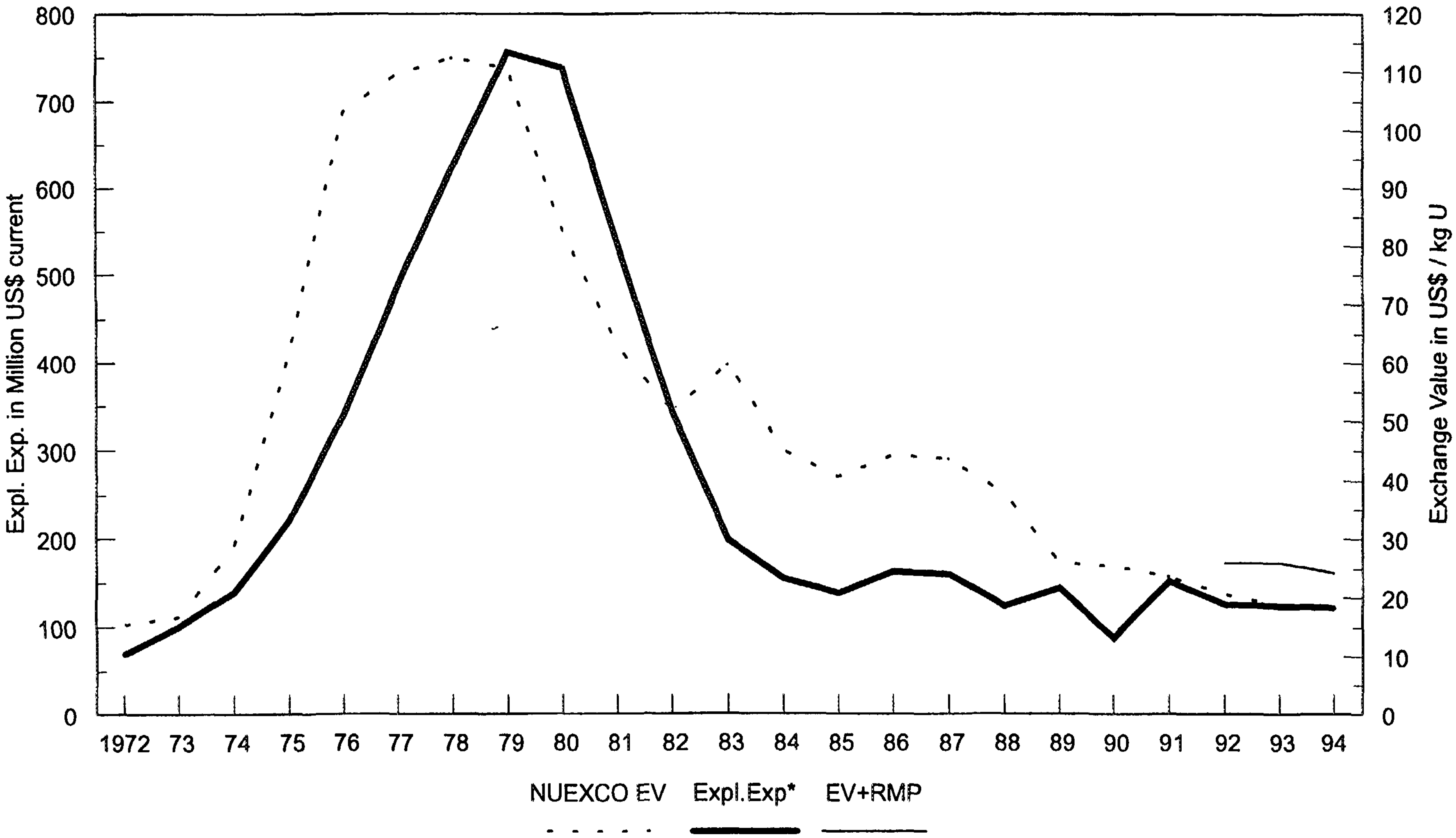
Uranium market prices

Sales on the world uranium market consist of two types: immediate or near term delivery, referred to as spot sales, and longer term multi-annual sales made under contract. The most commonly quoted market indicator for the spot price is the NUEXCO exchange value (or NEV)[2]. Similar indicators are also published by NUKEM (price range) and others. In this publication, reference is made to the NUEXCO exchange value. As was reported in previous years, the annual average spot price peaked in mid-1978 at US \$112.85/kg U (\$43.40/lb U_3O_8)[3]. By 1990 the average price had fallen to \$25.40/kg U (\$9.75/lb U_3O_8) and continued its decline in 1991 and 1992, with a yearly average of \$20.67/kg U (\$7.95/lb U_3O_8) in 1992. This price range represented a historical low (Fig. 1).

Restrictions on imports into the USA resulting from settlement agreements between the US Government and governments within the CIS, as well as actions by the European Union, led to the development of a two price system for spot sales made after October 1992. For countries with no import restrictions, the 1993 price averaged \$18.57/kg U (\$7.13/lb U_3O_8), while for those countries with restrictions the price averaged \$26.00/kg U (\$10.00/lb U_3O_8). The unrestricted price started 1994 at \$18.20/kg U (\$7.00/lb U_3O_8), remained relatively constant, but increased modestly to \$18.72/kg U (\$7.20/lb U_3O_8) in December. The annual average for 1994 was an all time low of \$18.24/kg U (\$7.05/lb U_3O_8). For those countries with restrictions on imports the price averaged \$24.35/kg U (\$9.31/lb U_3O_8). Following the increase started in November 1994, the restricted spot price continued to climb in 1995, reaching \$31.20/kg U (\$12.00/lb U_3O_8) during early May. (Fig. 2). This 30%

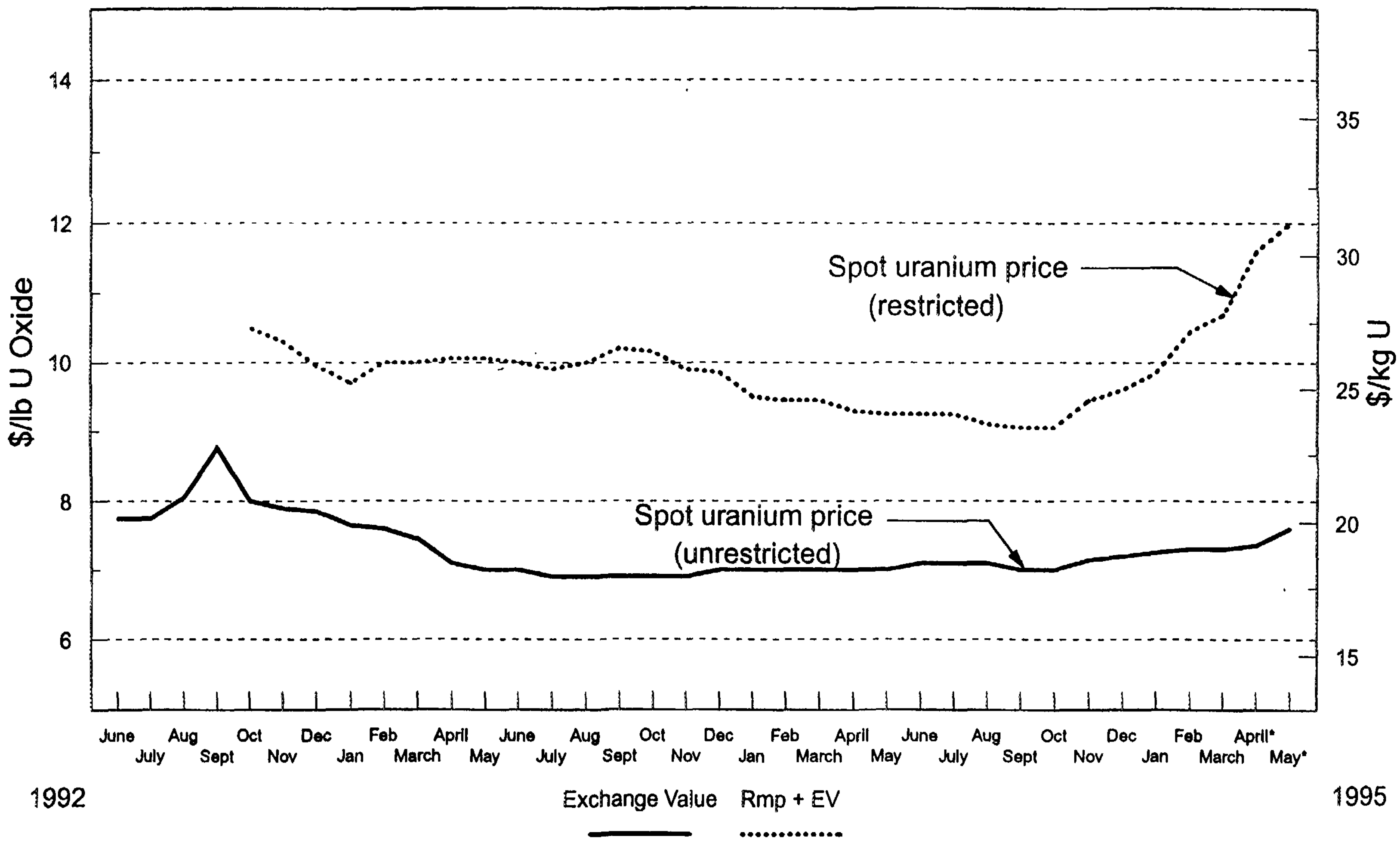
[2] Published by NUEXCO until December 1994, and TradeTech after this date.

[3] All prices are reported in current US dollars.



* Exploration Expenditures from 1993 Red Book

FIG. 1. WOCA uranium exploration expenditures vs average NUEXCO exchange values.



From NUEXCO

* from TRADETEC

Rmp = Restricted Market Penalty

FIG. 2. Recent spot market prices.

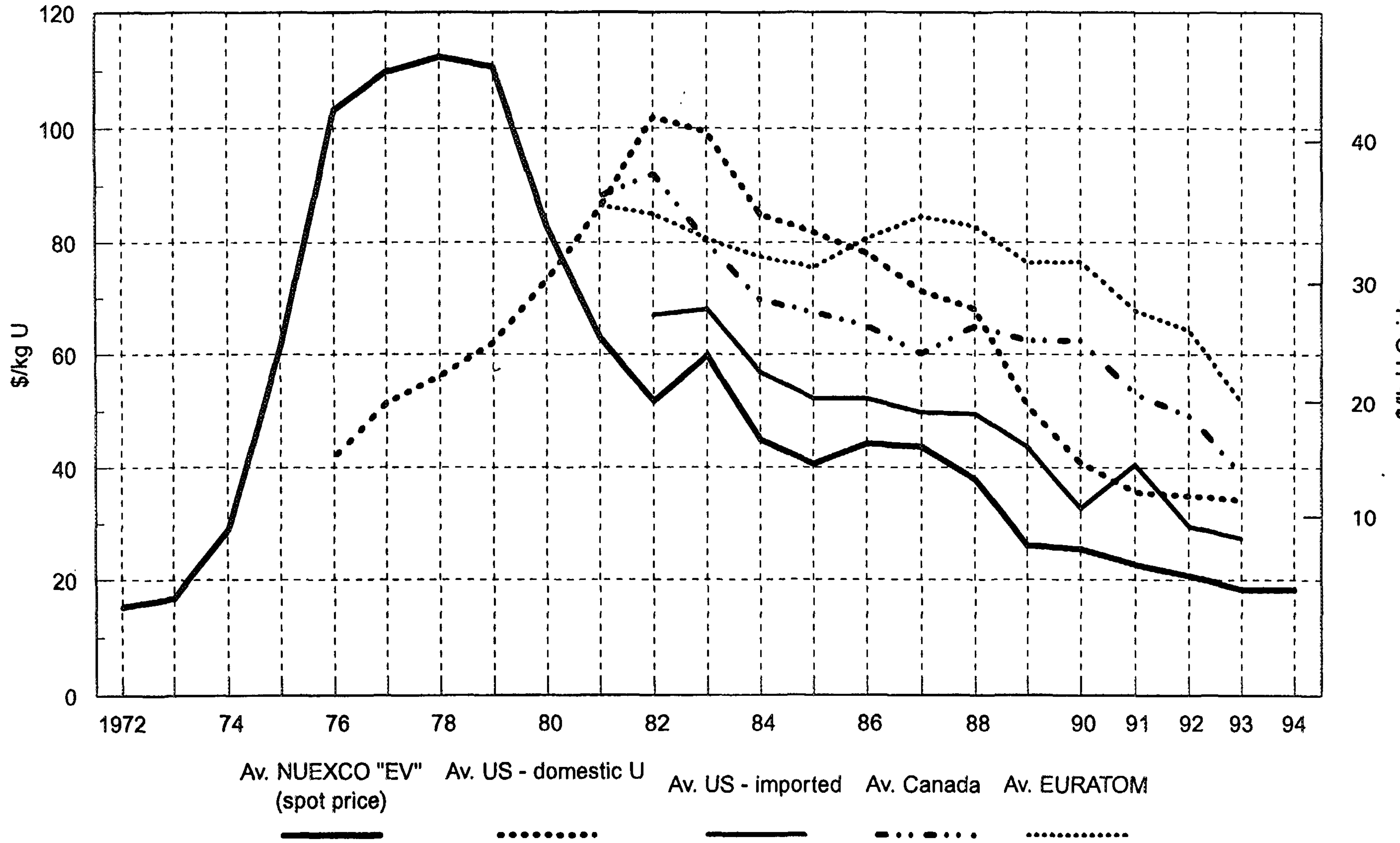


FIG.3. Development of selected uranium prices.

increase over 6 months brought the spot price to its highest value since November 1988. The unrestricted price also recorded an 8% increase since October 1994.

Limited data on long term contract prices are available. Fig. 3 shows a comparison of the average delivered prices for Australia, Canada, the USA and Euratom. With the exception of Euratom which reports both spot and multi-annual prices, these prices are based on variable amounts of both spot and long term sales. All average delivered uranium prices were lower in 1993, the most recent year for which data is available. This continued a general decline in all uranium prices that started in the early 1980s.

MAJOR MARKET EVENTS

Three major events have taken place in the last few years that significantly impact the future uranium supply through the end of the century and beyond. These events are: 1) anti-dumping related activities in the United States, 2) restrictions on the sales of CIS produced uranium in the European Community and 3) plans for Russia, Ukraine and USA to demilitarize HEU weapons material. The first step in weapons conversion involved the signing of a purchase agreement by the United States for 500 t HEU warhead material from the Russian Federation. Ukraine has also agreed to give up 50 t HEU warhead material. The US is currently evaluating both their natural and enriched uranium inventory and have announced preliminary plans to sell surplus material as reactor fuel.

Anti-dumping settlement agreements and amendments

One of the greatest influences on uranium trade resulted from the Anti-dumping Petition in the USA. In October 1992, DOC announced that final suspension agreements were signed with the Republics of Russia, Kazakhstan, Ukraine, Kyrgyzstan, Uzbekistan and Tajikistan. The suspension agreements established quotas on the importation of all uranium products from all of the CIS Republics except Kyrgyzstan and Tajikistan.

The suspension agreements prohibit any CIS uranium imports to the USA until the market price reaches $13 per pound U_3O_8 ($33.80/kg U). The market price is determined by the DOC and some CIS uranium is still allowed to be imported (irrespective of the DOC market price) under grandfathered contracts (subject to DOC approval) entered into with US utilities before March 5, 1992. At this price ($13 per pound U_3O_8), the total amount of nuclear material allowed to be imported into the USA is 2.9 million pounds U_3O_8 (1115 t U) equivalent. Larger amounts are allowed to be imported as the price increases. A total of 15.8 million pounds U_3O_8 (6077 t U) equivalent would be permitted above $20 per pound U_3O_8 ($52/kg U) equivalent. Above $21 per pound ($54.6/kg U), no limits exist except for a ceiling on Russian material of 5.5 million pounds U_3O_8 (2115 t U) equivalent. As a result of termination of the settlement agreements by Tajikistan and Ukraine, these two countries can import uranium (excluding HEU from Ukraine) to the US provided they pay anti-dumping duties [1].

The DOC marked price has remained below $13 per pound U_3O_8 since the settlement agreements were signed with the CIS countries and therefore no uranium subject to the settlement agreements has been purchased by US utilities. As of 1 April 1995 the DOC-determined price was $12.06/lb U_3O_8 ($31.36/kg U). Continued upward movement in the market could soon bring the DOC-determined price above $13.00/lb U_3O_8 thereby allowing the sale in the USA of uranium produced by Kazakhstan and Uzbekistan.

Agreement with Russian Federation renegotiated

As part of the consideration for the 500 t HEU purchase, Russia and the USA renegotiated the settlement agreements between the two countries relating to the US anti-dumping proceedings. The amended agreements, signed on 12 March 1994, will give Russian uranium more access to the US market. Under this amendment, which defers the settlement agreement until 2003, slightly over 2500 t U equivalent of Russian origin can be imported to the US in 1994 and 1995, if that material is matched with "newly produced" US natural uranium. This amendment also authorizes additional matching deliveries of natural uranium up to, but not exceeding, specified levels set for each of the years 1996 through 2003. This level starts from about 740 t U in 1996 increasing to around 1650 t U by 2003 [2].

By 1 April 1995 approved matched uranium sales under the amended settlement agreement with Russia had reached 1850 t U or 74% of the first year quota. This involved fourteen uranium sales and 1 enrichment contract [3].

Agreement with Kazakhstan renegotiated

On 27 March 1995 the Republic of Kazakhstan and DOC signed an amendment to the Kazakhstan Suspension Agreement. The Amendment lasts for 2 years and allows the import to the US of 385 t U (1 million pounds U_3O_8) after the DOC-determined price reaches \$12/lb U_3O_8 (\$31.20/kg U). In exchange, Kazakhstan agreed to stop the use of its uranium in "by-pass" uranium enrichment sales. The DOC-determined price for 1 April 1995 was \$12.06/lb U_3O_8 (\$31.36/kg U). Under the amendment Kazakhstan was permitted to import 195 kg U (500 000 lbs U_3O_8) until October 1995, the date the next DOC price determination is made [3].

The DOC and Uzbekistan are also negotiating an amendment to their suspension agreement. At the time of the preparation of this paper the amendment had not yet been signed.

European Community policy regarding CIS uranium imports

Because of concerns for the potential market destabilizing effects of large imports of CIS origin uranium that were being offered on the European Community market at prices judged to bear no relation to cost of production in Western terms, corrective measures were established by the European Commission and Euratom Supply Agency. The measures are essentially based on the Agency's exclusive right to conclude contracts as provided for in Article 52 of the Euratom Treaty. In response to a question put to the European Parliament during the November 1992 session the Commission provided the following response:

"By virtue of Article 2 (d) and (c) of the Euratom Treaty, the Community must ensure that all users in the Community receive a regular and equitable supply of ores and nuclear fuels and ensure the establishment of the basic installations necessary for the development of nuclear energy. For this purpose, the Euratom Supply Agency was established which, under the provisions of Chapter VI of the Euratom Treaty - and more particularly its Article 52, 2 (b) - has inter alia an exclusive right to conclude contracts for the supply of nuclear materials. Massive imports at extremely low prices, coming from the CIS republics risk endangering the diversification of the Community's supply sources and hence its long-term security of supply and the viability of its production industries. That is why the Supply Agency, in exercising its right to conclude contracts is ensuring the Community does not become over-dependent on any single source of supply beyond reasonable limits and that the acquisition of nuclear materials from CIS republics takes place at prices related to those on the market; that is to say prices which reflect cost of production and are compatible with prices of producers in market economy countries." [4].

According to the Euratom Supply Agency: "In practice, the approach of the Euratom Supply Agency was pragmatic and flexible and took into account the different aspects of the specific situations of the utilities concerned and any divergences of opinions expressed. Reaction to the Agency's approach have been generally positive. Transacting parties have increasingly informed the Supply Agency of their intentions in advance of the finalization of contractual terms. This in turn has meant that in only a very few cases was it necessary to introduce modifications to any contracts or not to proceed with their conclusion."[4]

Prior to 1994 Euratom acted to limit the amount of EC purchases of CIS uranium to about 3000 t U per year. In 1994 the CIS uranium imports to the EC increased to a little over 4000 t U [3]. Euratom also indicated that they continue to monitor the policy and maintain the option of eventually changing the policy.

New supply — US purchase of warhead high enriched uranium from the Russian Federation and Ukraine

Significant amounts of uranium from demilitarized nuclear weapons are expected to enter the civilian market after 2000 as the result of purchase agreements between the Russian Federation, Ukraine and USA. Worldwide efforts to reduce nuclear weapons led to the June 1994 agreement between the Russian Federation and the USA for the transfer to the United States Enrichment Corporation (USEC) of LEU blended from HEU from dismantled Russian nuclear weapons in exchange for cash payments by the USEC. Under the 20 year agreement the USA will pay about $11.9 thousand million (in 1993 dollars) in exchange for 500 t HEU having an assay of 90% or more of ^{235}U. This will be blended down, prior to shipment to the USA, to 15.3 million kg U containing 4.4% ^{235}U, equivalent to 153 000 t U (natural). The USEC will purchase 10 t HEU per year for the first 5 years and 30 t HEU per year over the next 15 years.

In a parallel tripartite agreement of the same date between Russian Federation, Ukraine and USA, an additional 50 t HEU in Ukrainian nuclear weapons is to be part of the purchase agreement. Under agreement of 6 June 1994 the Russian Federation proposed to ship 30 t HEU as UF_6 or UO_2 to the US; this HEU was derived from dismantled Ukraine weapons. The material would be blended down to LEU in the US under the direction of Matek, a joint venture planned to help implement the US-Russian HEU sales. Matek consists of 2 US firms with a 20% interest and 6 Russian firms with a 80% interest. The 550 t HEU under these agreements is equivalent to about 168 400 t U (natural). [2].

The first shipment of LEU blended from HEU under the Russian/US agreement, scheduled for June 1994, was delayed due to difficulties in resolving the transparency issue (i.e. assurance that the LEU is warhead derived material). The first shipment of about 30 t LEU, equivalent to about 1 t HEU, is expected in the spring of 1995. There has been speculation that this LEU could enter the market at the annual rate of up to 17 500 t U, starting as early as 2003. The settlement agreements between the Russian Federation and the USA preclude large quantities of this material from being sold prior to 2003 as it may only be sold in "market-neutral" transactions during this period.

URANIUM PRODUCTION, SUPPLY AND DEMAND

Production

The 1994 world uranium production is estimated to be 31 300 t U (Fig. 4). This is about 5% less than the estimated 1993 production of 32 200 t U and 48% less than the 1988 level [1]. Estimated 1994 production in the former WOCA was 22 000 t U. In general, 1994 uranium production in most countries remained the same or decreased from the previous year. Canada was a major exception where production increased by about 380 t U or 5%, while there were smaller increases in Namibia,

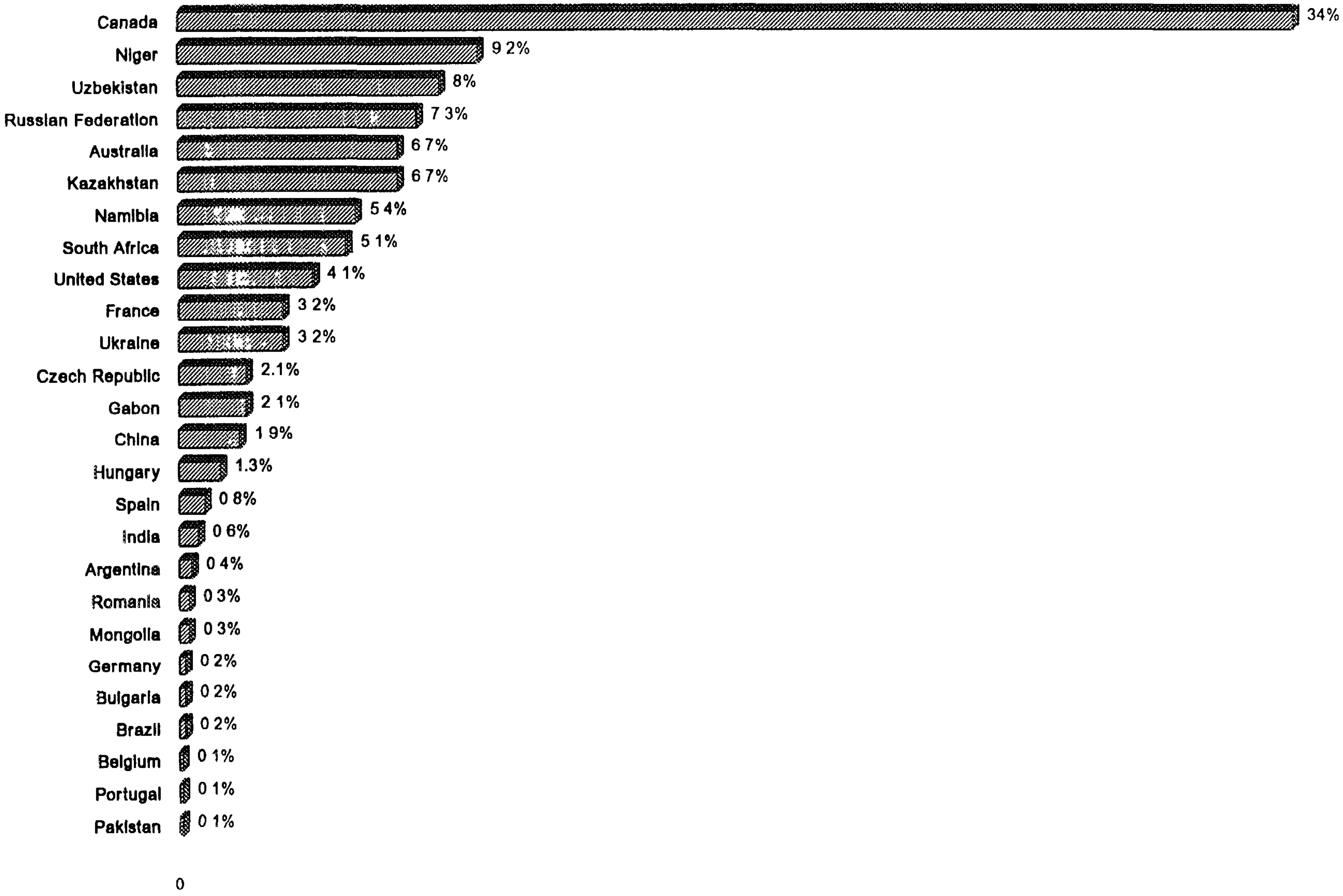


FIG. 4 Estimated 1994 world uranium production and rank (total 31 400 t U)

Spain and the US. The largest decrease was in France, where production fell by 40% to about 1000 t U. In 1994, production took place in 26 countries. Recovery of uranium was stopped in Germany bringing to an end production in what was the world's third largest producing industry. However, nearly 90% of the 1994 world uranium production occurred in 11 countries that each produced 1000 t U or more. They are: Australia, Canada, France, Kazakhstan, Namibia, Niger, the Russian Federation, South Africa, Ukraine, the USA and Uzbekistan. Most of the remainder was produced in China, the Czech Republic, Gabon and Hungary. Canada continued its position as the world's largest producer, increasing its share to over 30% of the total.

Supply and demand

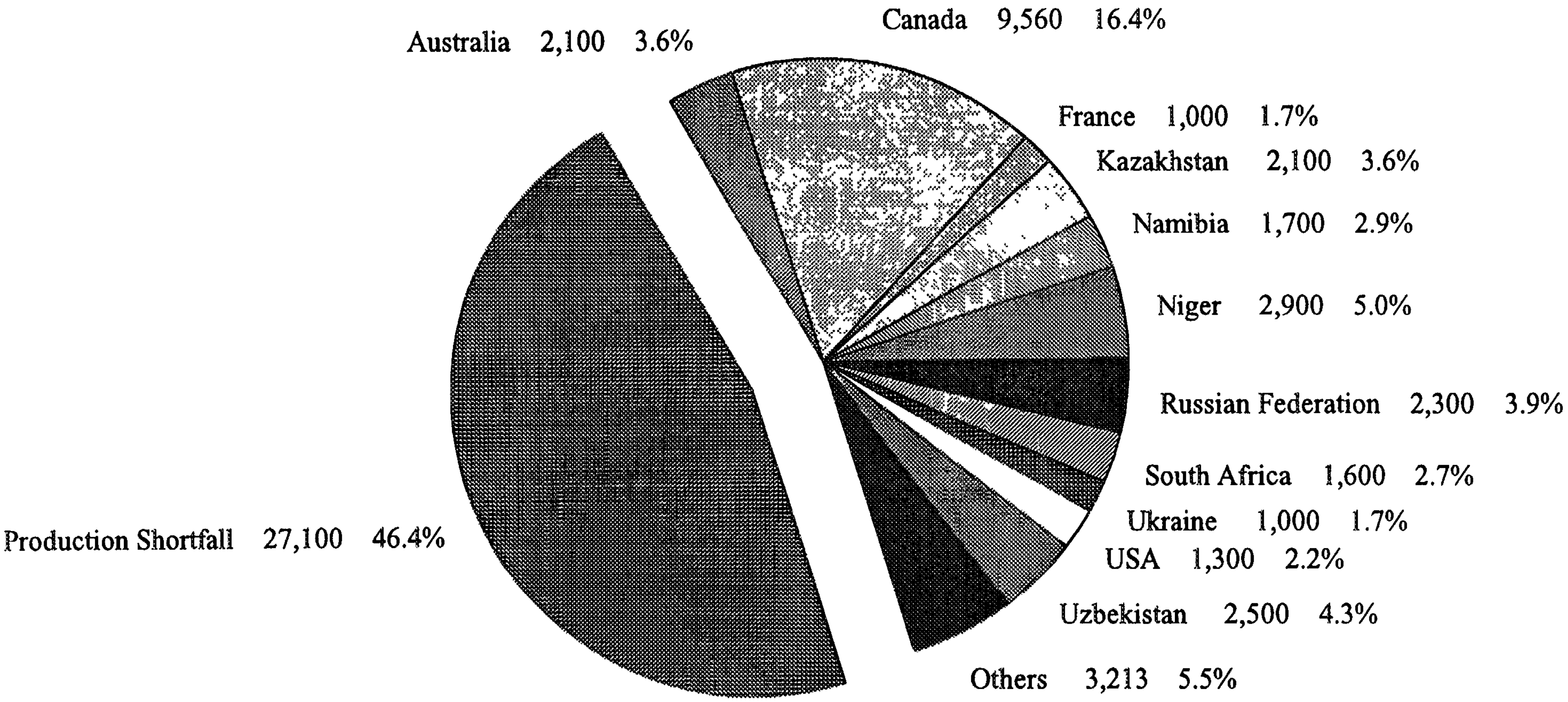
In 1994 the estimated world production of 31 300 t U met only 54% of the world reactor requirements of 58 400 t U (Fig. 5). World uranium production has been below world requirements since about 1990 (Fig. 6). Non-WOCA production, estimated at 9500 t U was about equal to non-WOCA requirements in 1994. It had exceeded non-WOCA demand since 1988, the first year that production estimates are available for the country group (Fig. 7). In 1994, estimated WOCA production of 21 900 t U met only 44% of WOCA requirements of about 49 200 t U (Fig. 8). There was a resulting worldwide shortfall of about 27 100 t U and a WOCA shortfall of about 27 300 t U. Today the uranium market no longer conforms to the traditional supply and demand model of producers selling only to utilities. Secondary market transactions have also been important in recent years. Such transactions include sales, loans and exchanges of natural and enriched uranium by utilities and brokers, including all transactions except the direct purchase by a utility of uranium from a domestic or foreign producer.

WOCA supply and inventory

In the former WOCA, uranium production has been below reactor requirements since 1987. The gap between production and requirements grew from about 4000 t U in 1988 to about 27 700 t U in 1993 and remained nearly the same at 27 200 in 1994 (Table I). The cumulative production shortfall over this period was about 124 000 t U. For the same period uranium imports to the USA and the European Community from the former USSR and its successor States increased from 105 t in 1988 to about 5600 t U in 1991 and then decreased and stabilized in the 4000 to 5000 t U range in 1992 and in 1993 [4, 5, 6]. In 1994 these imports are estimated to be 9450 t U. This included 4000 t U and 2000 t U, respectively for the EU and US. An additional 3450 t U of CIS produced uranium was enriched in Europe and then imported to the US (i.e. the "by-pass" option discussed below) [7]. The imports for the period totalled nearly 24 000 t U. This left an accumulated shortfall of nearly 95 000 t U (or about 250 million pounds U_3O_8). A small part of this shortfall was met by imports from China and through imports of CIS and other non-WOCA produced uranium to countries other than those of the European Union and the USA.

Starting in 1994 a portion of the US supply was also met through the so-called "by-pass option". Under this acquisition strategy US nuclear utilities elected to buy CIS produced uranium that was then enriched in Europe before its import to the US. Nukem reported that in 1994 US utilities bought nearly 3450 t of CIS uranium that was enriched in Europe [7]. Under the Settlement Agreements between the US and CIS countries this was viewed as a substantial transformation of the CIS produced uranium, thereby making it exempt from import restrictions. When this practice rapidly increased in 1994, the parties to the US anti-dumping litigation concluded this was a circumvention of the agreements and asked the US Department of Commerce to disallow the practice in the future.

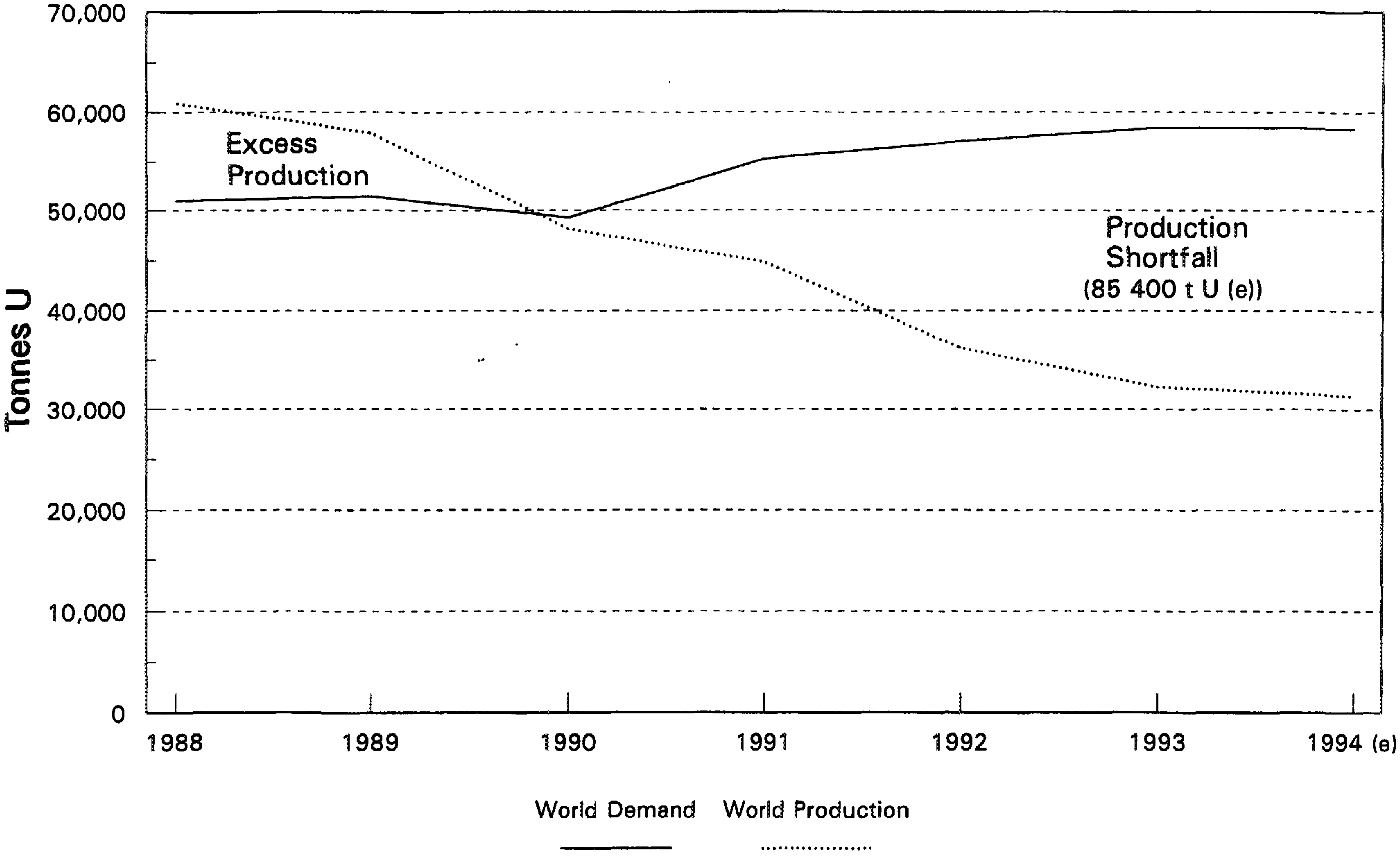
Based on this analysis, it is estimated that a cumulative WOCA supply shortfall of about 85 000 t U occurred during the period 1988–1994. This shortfall was met by drawdown of WOCA inventories. Drawdown is estimated to be continuing in 1995 at a rate of 15 000 to 20 000 t U/annum.



World Demand: 58,400 t U / World Production: 31,300 t U

Others Argentina, Belgium, Brazil, Bulgaria, China, Czech Republic, Gabon, Germany, Hungary, India, Mongolia, Pakistan, Portugal, Romania and Spain

FIG. 5. Estimated 1994 world uranium production vs. reactor related demand



(e) estimate

FIG. 6. World uranium production and demand.

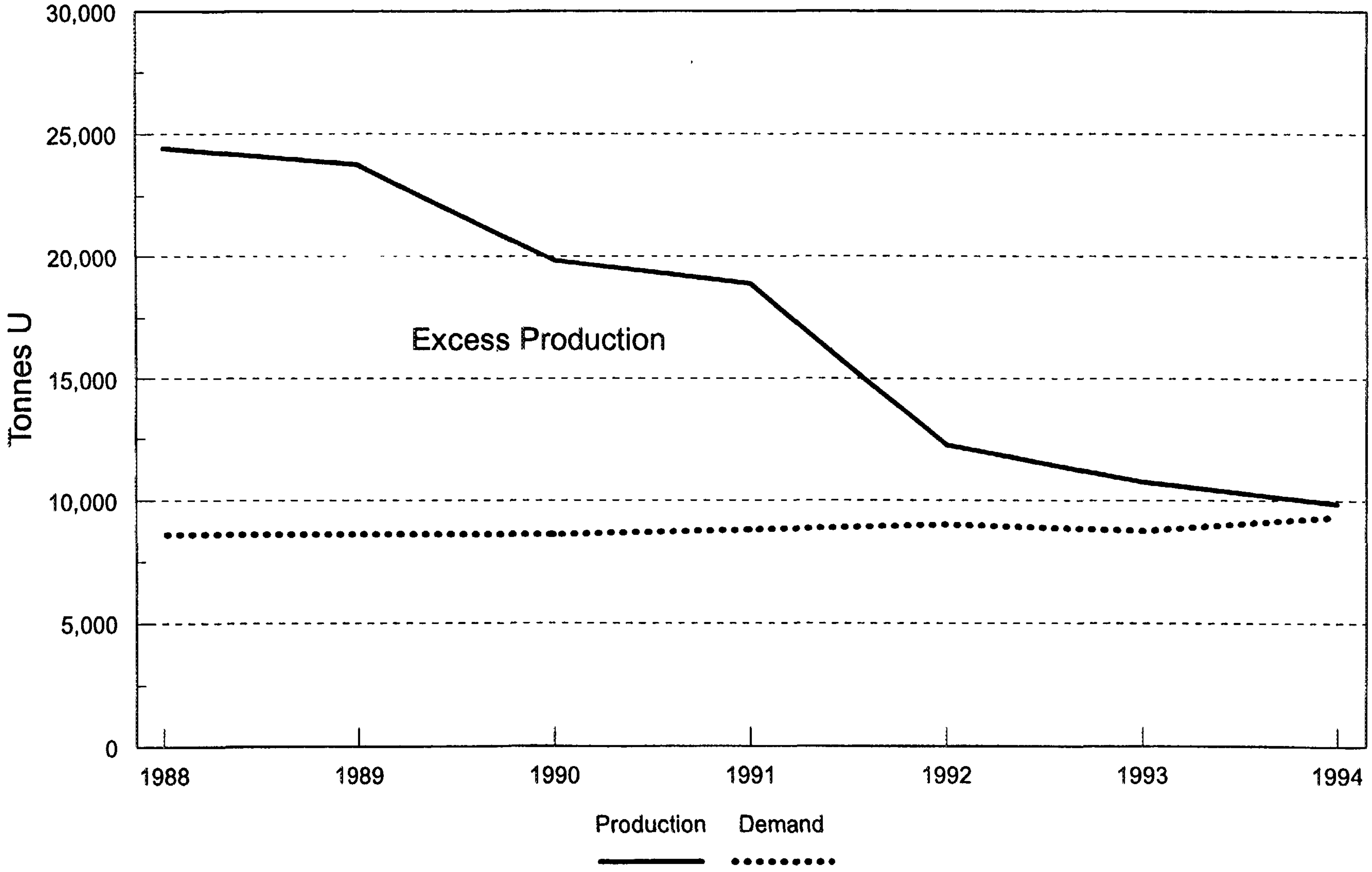


FIG. 7. Non-WOCA production and demand.

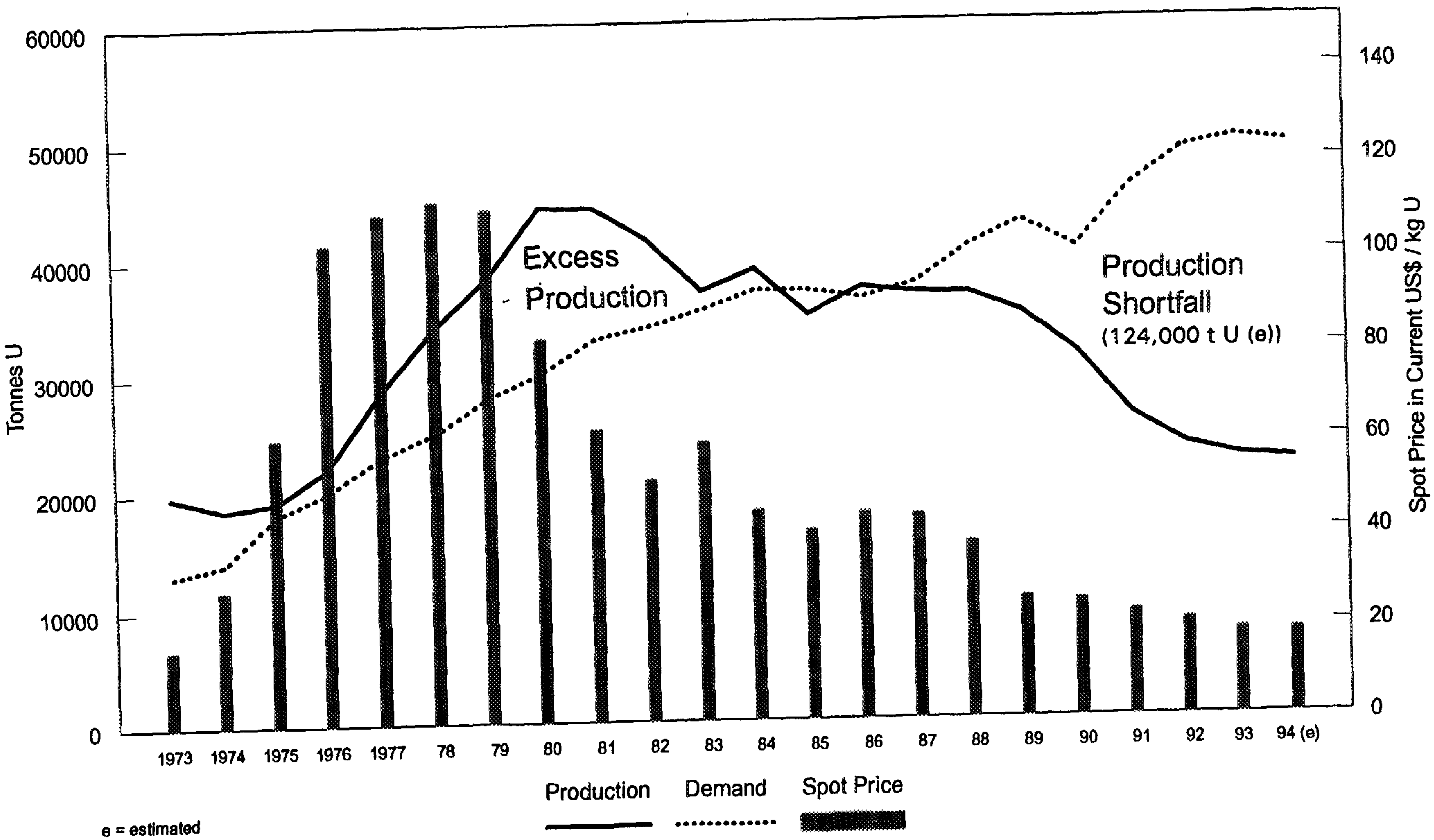
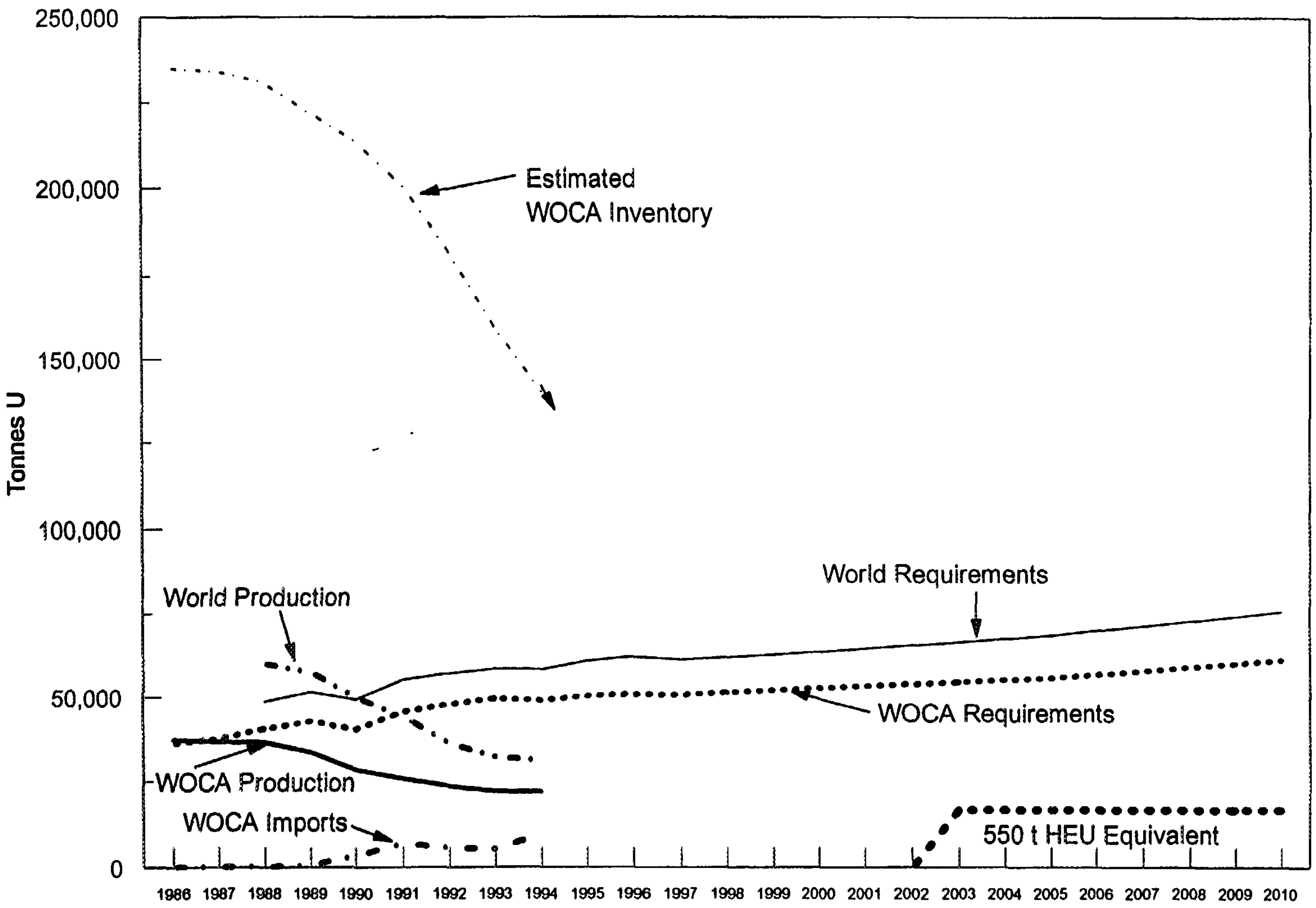


FIG. 8. WOCA uranium production and demand vs. NUEXCO spot price.



Not accounting for: CIS civilian stockpiles; U.S. and CIS HEU other than 550 t HEU from Russian Federation and Ukraine

FIG. 9. Historical development of uranium supply and demand.

The inventories being used to fill the production gap consist of material in the civilian sector (utilities, governments, producers, traders and others). The civilian stocks include strategic stocks, pipeline inventory and excess stocks available on the market. Based on analysis of published reports, the total former WOCA non-military inventory was estimated to be between 130 000 to 150 000 t U as of 1 January 1995 [8, 9, 10, 11]. Of this amount WOCA utilities are estimated to hold about 115 000 t. This is about 2.3 times annual WOCA utility requirements. Although an estimated 15% of the utility inventory is excess and could readily be offered for sale, a major portion comprises strategic stock mandated by law or company policy and will not be offered for sale. Fig. 9 summarizes these supply and demand relationships.

HEU inventory

There is little information regarding uranium inventory held by the Russian Federation. Their civilian stocks could easily surpass the 130 000 to 150 000 t U held in WOCA civilian stockpiles. It was reported by V.N. Mikhailov, Russian Minister for Nuclear Industry, that the Russian Federation's HEU inventory is 1200 t, plus or minus 15% (i.e. 1020 to 1380 t) [12]. The total military stocks held by the nuclear weapon States, consisting of fissile material in a variety of forms, may be several times greater than the civilian portion.

In June 1994, the DOE released information on its highly enriched uranium program in its Interim Uranium Inventory Report [13]. Between 1945 and 1992, when HEU production ceased, cumulative HEU production in the United States was 994 t. About 259 t is currently in DOE inventories, excluding HEU stored at the Pantex site, Texas. Of this amount 50 to 120 t was identified as potential excess. Proposals have been made in conjunction with the US fiscal 1996 budget to sell some portion of the material. Under the Energy Policy Act of 1992, USEC is to be the exclusive marketing agent for US enriched uranium.

Potential schedule for sale of 550 t HEU from Russia and Ukraine

Once it was announced that the 550 t HEU warhead material from the Russian Federation and Ukraine would be blended to LEU and sold for use as reactor fuel it became clear that the sales could have a major impact on the uranium market. The greatest uncertainty impacting the market has been the schedule of deliveries for this material; both the timing and amounts.

It is now probable the schedule for delivery of the 550 t HEU, as well as both US surplus HEU and other uranium, will be set by the US Congress. Legislation related to privatization of the USEC was introduced by Senator Pete Domenici (Republican, New Mexico) in Senate Bill 755. This bill includes a schedule to ration the flow of uranium and separative work units (SWU) drawn from the former US, as well as Russian and Ukraine weapons, until well into the next century. The bill was sponsored by Senator Domenici, Chairman of the Senate Subcommittee on Energy Research & Development of the Energy and Natural Resources Committee and was co-sponsored by other Senators with an interest in the bill [14]. It is anticipated this legislation will not be passed until the second half 1995.

In addition to setting a schedule for sale of HEU derived LEU, the proposed legislation attempts to help the Russian Federation by providing access to cash from the sale of the components of LEU drawn from military HEU. It is also intended to help the US uranium mining companies by delaying and restricting the flow of the material into the market, where its sale could depress the market.

Under the proposal, natural uranium from the DOE stockpile could be sold starting 1 January 1998. The maximum amount that could be sold in one year would be 4 million pounds UF_6, equivalent to 1040 t U natural. Annual sales could not however, exceed 10% of the UF_6 equivalent content of the total amount of natural uranium transferred from the DOE to USEC. The sale of LEU transferred from DOE to USEC could also not exceed 800 000 SWU in any calendar year. This is equivalent to about 1100 t U natural.

In summary, the proposed legislation would provide for sale of a maximum of about 1100 t U/year natural equivalent following passage of the bill. This could continue until 1 January 1998 when an additional 1040 t U, or 2140 t U/year could be sold to 1 January 2002. From 2002 through 2011 about 4740 t U natural equivalent/year could be sold, increasing to about 7340 t U natural equivalent/year after 1 January 2012. This schedule would supply about 6% of the WOCA requirements of 877 000 t U through 2010. It includes management of the 550 t Russian and Ukraine HEU, as well as the surplus USDOE HEU, LEU and natural uranium stockpiles.

The first uranium sold under this framework could result from a 15 December 1994 agreement between DOE and USEC where about thirteen tonnes HEU would be transferred to USEC and blended to LEU. This would yield about 3075 t U natural equivalent being sold over 3 to 5 years starting in 1995 [15].

The other uncertainties regarding future WOCA supply are related to: the full impact of the settlement agreements and their amendments; and the disposition of the potential for additional HEU entering the market from both the USA and the Russian Federation; the remaining Russian stockpile of natural or low enriched uranium (LEU). The disposition of the worldwide weapons plutonium stockpile is expected to have only a minor impact on the supply and demand balance for nuclear fuel.

Early indications of a recovering uranium market

In 1994 the world uranium production industry continued in a very depressed state. As in 1993, the market is highly dependent on political decisions that are subject to change. Any analysis of the uranium market must take this uncertainty into account. There were, however, some indications in 1994 and early 1995 that the sixteen year trend of falling uranium prices and decreasing production related activity may be ending and the market may be in an early stage of recovery.

They include: excess WOCA inventory is rapidly being drawn down and is nearing exhaustion; the decrease in 1994 uranium production relative to the previous year was the smallest since 1989; and Cameco, the world's largest producer, increased its production. In Canada the amount of uranium specified in new export contracts signed by Canadian producers and approved by the Canadian government increased from 4330 t U in 1993 to 15 200 t U in 1994. The completion of fourteen matched uranium sales under the amended US-Russia suspension agreement is expected to stimulate production in these 2 countries. The rapid rise in spot price starting in November 1994 suggests the sixteen year market decline may be at an end. The bankruptcy of a major uranium trading organization early in 1995 may be contributing to market instability placing additional upward pressure on market prices. While these events may be early indications of a market recovery, uncertainty may continue until a sustained recovery is underway and political intervention is further reduced.

FUTURE TRENDS IN SUPPLY AND DEMAND

World reactor requirements and unfilled demand

All projections of future uranium related activities depend on the uranium market. There will be little or no increase in any activities, including exploration, project development and/or production, unless uranium market prices increase. Making projections regarding market trends is fraught with difficulties, primarily because of the uncertainty regarding the availability of future supplies. Future demand is well known through to the year 2000 and can be reasonably estimated through to 2010.

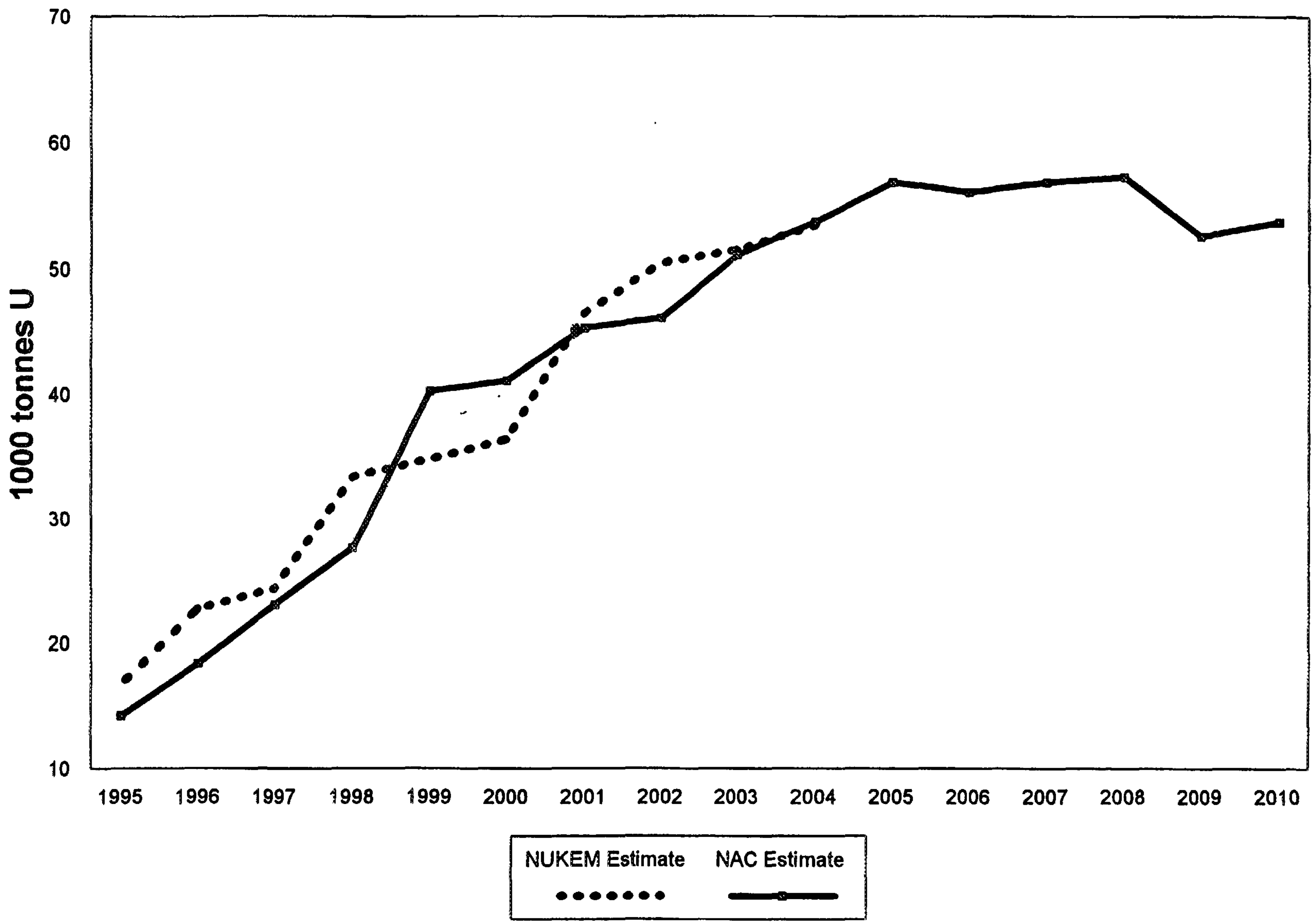


FIG. 10. Worldwide buyer unfilled needs.

The projected annual reactor requirements for both WOCA and non-WOCA up to 2010 are summarized in Table II [1].

On the basis of existing trade agreements and considerations of technology, it is expected that much of the non-WOCA demand will be met by non-WOCA supply over the next 10-15 years. The primary uncertainties related to meeting WOCA demand include the access of CIS produced uranium to the WOCA market and the amount and schedule for sales of HEU derived material. However, the existing US anti-dumping settlement agreements and the policy of the European Union regarding CIS uranium imports have helped reduce uncertainty in these market parameters. This situation could change if there are further substantial amendments to the US-CIS settlement agreements or Euratom policy.

Based on the analysis of WOCA inventory drawdown and the current restrictions on CIS uranium imports it is possible to make projections regarding a likely market price recovery. Whereas the available excess WOCA inventory is rapidly being depleted, the need for new uranium production contracts is expected to rise sharply over the next 15 years [10,16]. Projections of worldwide uranium requirements not covered by contracts indicate that demand for new production contracts will increase from about 16 000 t U in 1995 to about 50 000 t U in 2002. This is a compounded annual growth rate of nearly 30%. After 2002 the requirements will continue to increase, reaching around 55 000 t U in 2005 (Fig. 10). This rapid growth rate, equalling new annual uranium sales of about 5000 t U, or nearly equivalent to the annual production of Canada's Key Lake project, should put substantial upward pressure on uranium prices. This imbalance between demand for new production and available production capacity should be increased by the low level of project development in recent years.

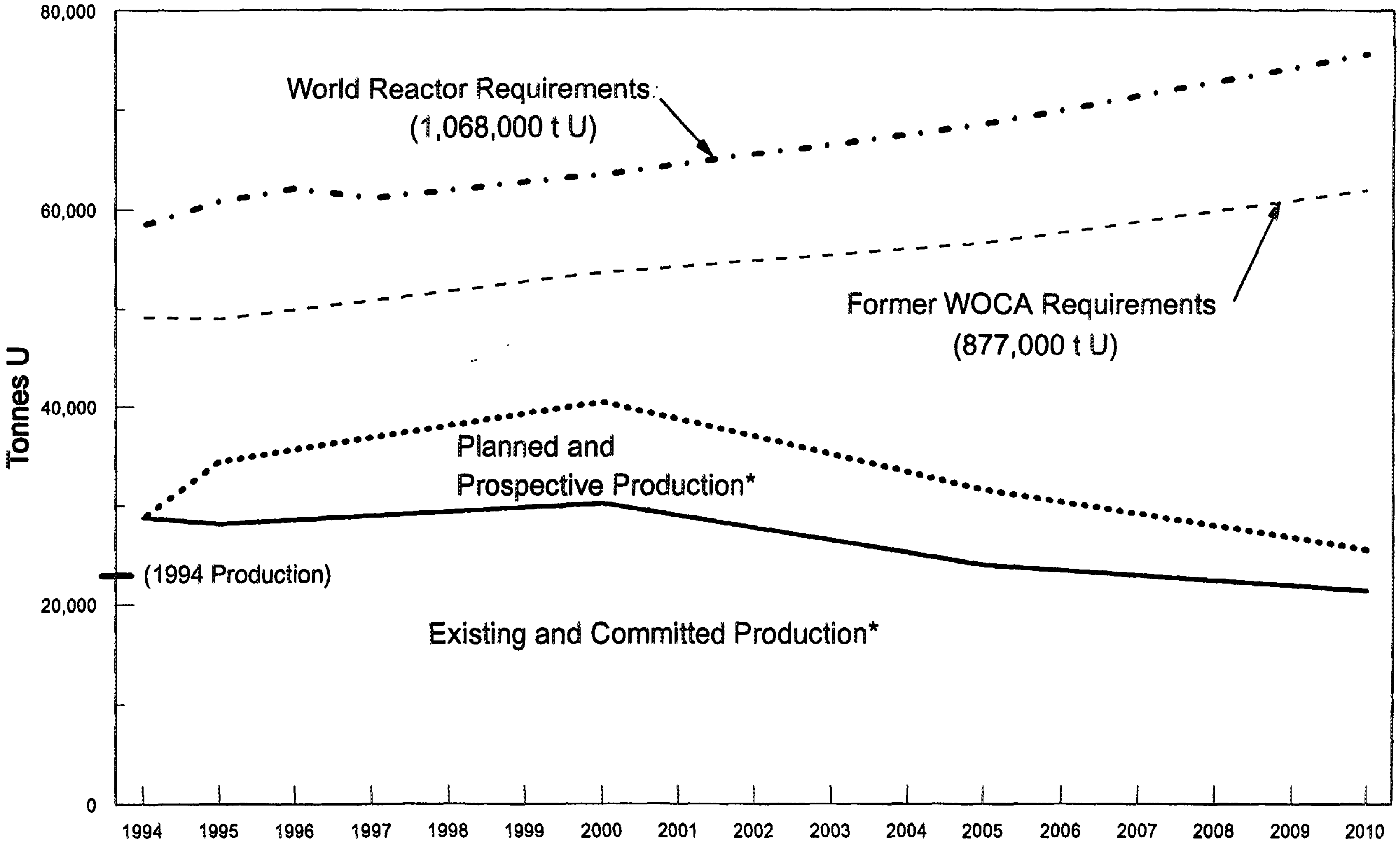
Supply projection

Two projections of the known and anticipated uranium supply sources are made to consider how the future supply may develop. The projections include a high case supply with LEU from HEU entering the market at an annual rate of 17 000 t U natural equivalent and a low case supply with LEU entering at an annual rate not exceeding 4740 t U natural equivalent. All other supply contributions remain the same. The projections take into consideration existing and committed, as well as planned and prospective WOCA production centres, supply from western reprocessing, and LEU from 550 t HEU warhead material plus surplus HEU, LEU and U natural from the USA. It is assumed that the requirements of former non-WOCA will be met from non-WOCA supplies, and that at least 5000 t per year of CIS produced uranium will continue to be sold in the WOCA market. The projections assume that the available WOCA excess inventory will be exhausted within one to two years.

The projections do not take into account potential increased CIS sales allowed with rising market prices under terms of the CIS/US settlement agreements. Nor are matched sales that are taking place under the amended settlement agreement with Russia included. There is a practical limit to CIS sales based on production capability and a cap on Russian import until at least 2003.

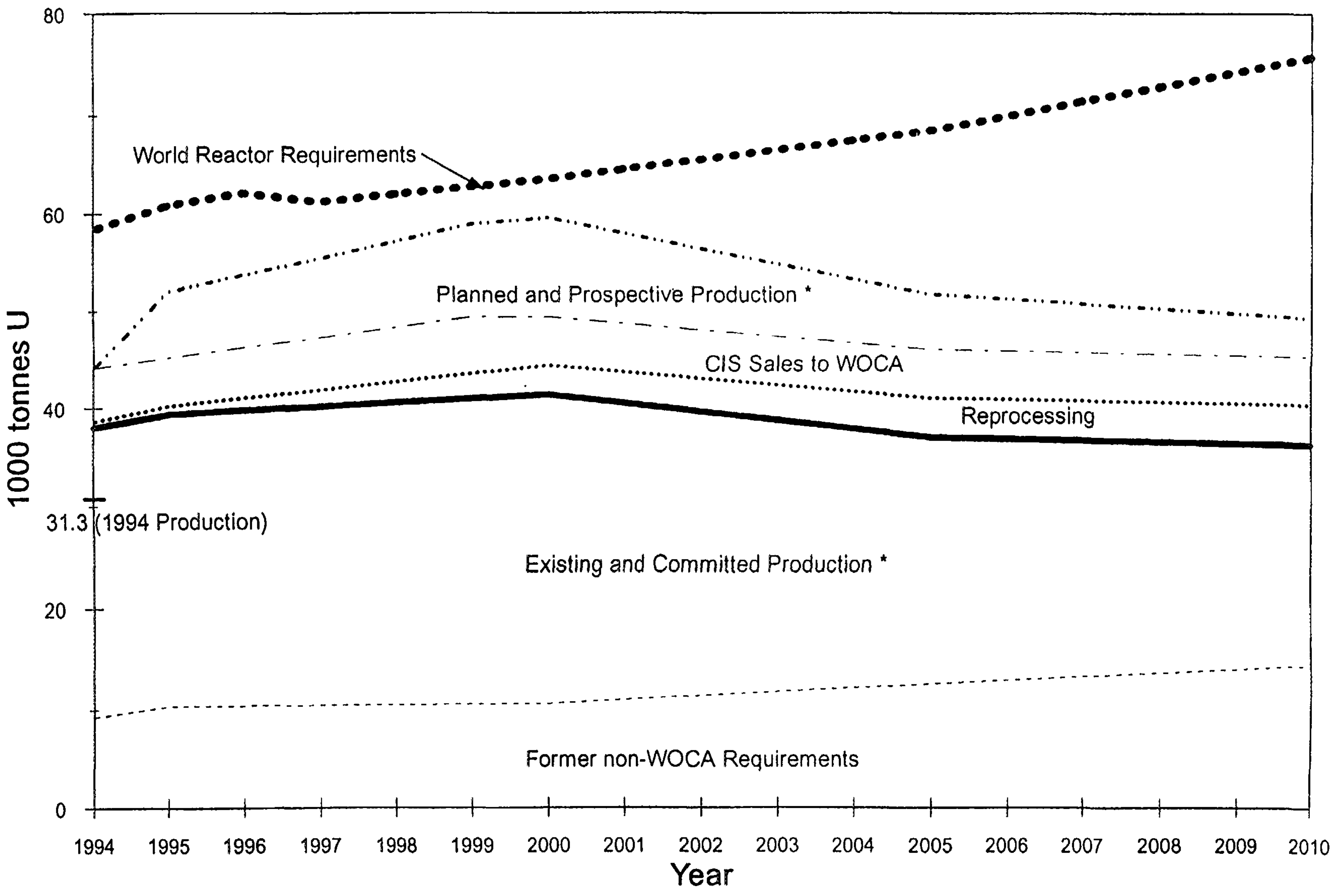
The projections use a WOCA production capability based on an 85% capacity utilization of the 1993 Red Book data [1]. This consists of about 29 000 t U/year of Existing and Committed capacity and a potential of up to about 10 000 t U/year of Planned and Prospective annual capability by 2000. This is shown in Fig. 11.

Production from reprocessing is based on the projection of WOCA mixed oxide (MOX) fuel fabrication capacities from the 1994 IAEA Year Book [17]. This supply source is projected to be 850, 3000, 4000 and 4000 t U (natural equivalent), respectively in 1995, 2000, 2005 and 2010. It totals about 46 000 t U equivalent and is estimated to meet about 5% of WOCA requirements through 2010.



* at 85% capacity utilization

FIG. 11. WOCA short term annual uranium production capability.



* at 85% capacity utilization

FIG. 12. Projected supplies through 2010.

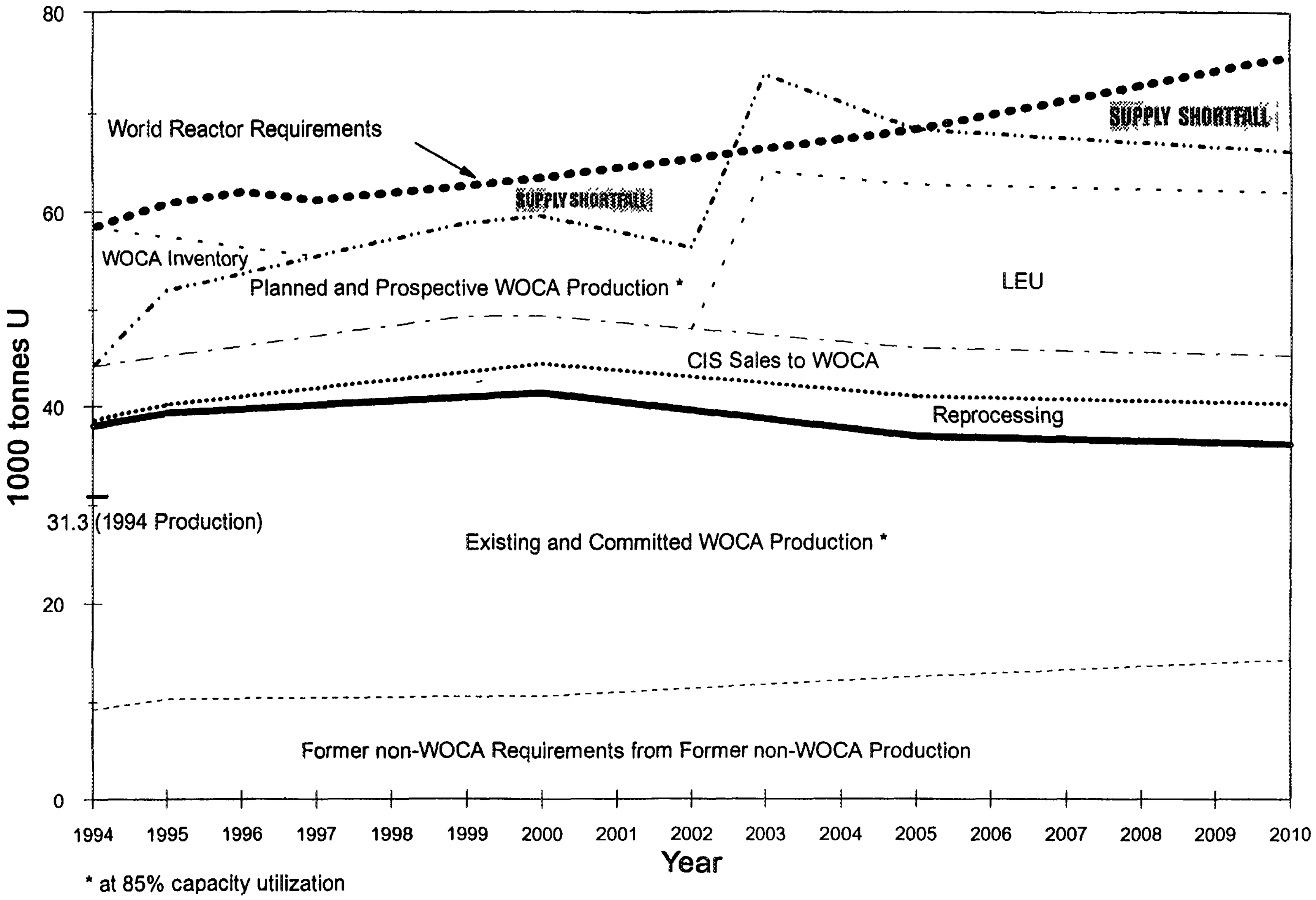
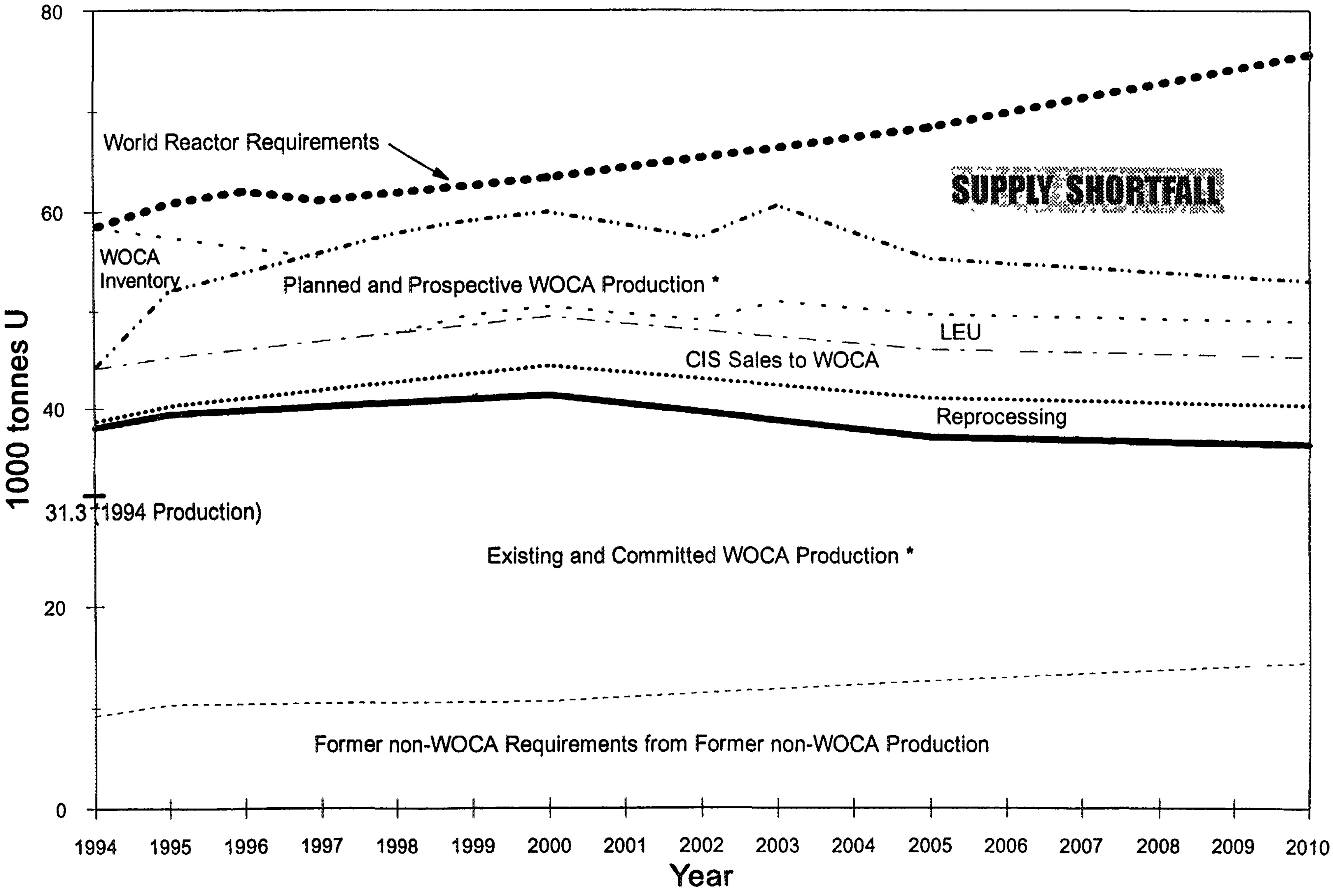


FIG. 13. Projected uranium supplies through 2010 (high LEU case).



* at 85% capacity utilization

FIG. 14. Projected uranium supplies through 2010 (low LEU case).

Fig. 12 is a projection of all indicated supply sources excluding HEU and other US government surplus uranium.

The high supply LEU projection (Fig. 13) is based on the 550 t HEU under the sales agreement(s) between the Russian Federation, Ukraine and the USA. This represents nearly 168 000 t U natural equivalent. It is projected to enter the market starting in 2003 at the rate of about 17 000 t U per year and continue through 2012. In this scenario the LEU equals over 15% of the WOCA requirements from 1995 to 2010. Additional surplus US HEU, LEU and U natural would probably not enter the market until 2012.

Based on the assumptions above, a supply shortfall will continue throughout the projection period except for years 2002 to 2005. With the exception of this short period when world requirements are exceeded, all of the supply sources are insufficient to meet world requirements between 1995 and 2010.

The low supply LEU case (Fig. 14) is based on the proposal in Senator Dominici's Bill 755 introduced to the US Congress and discussed above. In this case the identified supply sources always fall below world requirements. The shortfall varies from a minimum of about 3000 t U in 2000, increasing to a maximum of nearly 25 000 t U by 2010. For world requirements to be met, world production will have to increase by about 80% within a few years and then continue to increase over the next 15 years. This would require a rapid buildup of planned and prospective production facilities, as well as additional new projects that are not presently defined.

The short term instability is increased by the low level of world production which is currently meeting only about 55% of world demand.

CONCLUSIONS

The uranium supply is evolving under a restricted worldwide market. The vastly oversupplied condition that existed for about 16 years drove spot prices to all time lows in 1994.

The excess low-priced supply that drove down the prices was comprised of excess WOCA civilian inventories and production from CIS countries. The low market prices, together with the curtailment of government purchases under the centrally planned economies of the former COMECOM, forced production cutbacks and the closure of production facilities worldwide. As a result, production met only about 55% of world reactor requirements in 1994.

The low production levels caused the drawdown of inventories worldwide. This impact was greatest in WOCA where stockpiles have been drawn down annually at the rate of about 15 000 to 20 000 t U since 1991. It appears the excess WOCA inventory is now essentially exhausted. Political and legal restrictions on the sales of CIS produced uranium to the USA and the European Union also limit this supply. The changes in two low cost supply sources have greatly reduced their market influence.

A steady market price increase starting in November 1994 has, over 6 months, resulted in the restricted spot price rising by 30% to \$12/pound U_3O_8 (\$31.20//kg U). The price of unrestricted uranium has also increased 8% to about \$7.60/pound U_3O_8 (\$19.76/kg U) over this period.

The purchase by the US of 550 t HEU warhead material from the Russian Federation and Ukraine is expected to provide a new uranium supply equivalent of about 168 400 t U natural, that may enter the market after 2002. Additional supply is expected from the release of excess US government stockpiles of natural uranium, LEU and HEU. Some analysts have projected that this government controlled material could enter the market at rates as high as about 17 000 t U natural equivalent per year. There are now indications that the US Congress will pass legislation rationing the flow to the market of both the CIS and US uranium (and SWU) until well into the next century. Draft legislation before Congress would limit the cumulative amount of this uranium supply to not more than 6% of WOCA reactor requirements through 2010.

Based on analysis in this report, it is concluded that substantial additional uranium production is required to meet reactor requirements under both the low and high sale scenarios for military derived material. It is projected that world uranium production will have to increase within a very few years by at least 60 to 80% over 1994 levels to meet world reactor requirements.

The recent spot market price increase may indicate that the worldwide supply and demand relation is already undergoing the necessary change that will result in increased uranium production. For this to happen prices will have to continue their increase to a level where producers can pay all their costs of production and make a profit on their investment. This must occur before production can play its vital role in meeting 80 to 90% or more of the world reactor requirements through 2010 and beyond.

TABLE I. CIS URANIUM IMPORTS TO THE US AND EC AND WOCA INVENTORY DRAWDOWN

Year	WOCA Demand	WOCA Production[a]	Shortfall	CIS Imports[b]	Inventory Drawdown[c]
1988	40 564[d]	36 500	4 064	105	3 959
1989	42 694[e]	33 580	9 114	534	8 580
1990	40 342[e]	28 562	11 780	3 427	8 353
1991	45 596[e]	25 779	19 817	5 625	14 192
1992	47 921[a]	23 651	24 270	5 243	19 027
1993	49 688[a]	22 000[g]	27 688	4 216	23 472
1994[f]	49 165[a]	21 900[g]	27 265	9 450[g]	17 815
Total	**315 970**	**191 972**	**123 998**	**28 600**	**95 398**

a. Source: Ref. [1].
b. Data for 1988–1993 are from the US Department of Energy (Energy Information Administration) [6] and the Euratom Supply Agency [4, 5].
c. Drawdown does not account for CIS Imports to WOCA countries other than the USA and European Community, nor for Chinese imports to WOCA.
d. Source: Ref. [5].
e. Source: Ref. [6].
f. Estimated data including production and CIS imports to the European Community of 3000 t U.
g. IAEA estimate, includes 2000 US, 4000 Euratom and 3450 from CIS uranium enriched in Europe and imported to the USA.

TABLE II. PROJECTED ANNUAL REACTOR URANIUM REQUIREMENTS TO 2010 [1]

	1995	2000	2005	2010	Aggregate 1995-2010 (%)
World Total	60 800	63 500	68 400	75 700	1 068 000 (100)
Former Non-WOCA	10 300	10 600	12 600	14 400	191 000 (17.9)
Former WOCA	50 500	52 900	55 800	61 300	877 000 (82.1)

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THE INDUSTRIAL TYPES OF URANIUM DEPOSITS OF UKRAINE AND THEIR RESOURCES

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Abstract

Industrial uranium deposits of Ukraine are represented by two types. Their origin is related to the processes of alkali metasomatism in areas of proto-activization that took place at the late orogenic stage of the formation of the Ukrainian shield. Deposits are located in large cataclatic zones that are formed at the intersection of deep fractures.

1. INTRODUCTION

The industrial uranium deposits of Ukraine are represented by endogenic deposits in albitites and by exogenic epigenetic deposits in sediments of platform cover of the Ukrainian shield. At present the main suppliers of uranium ores are deposits in albitites of the Kirovograd ore region. Two deposits of this genetic type of the Krivoi Rog ore region (Zheltorechenskoye and Pervomayskoye) have mined out Albitite-type deposits and are not considered in the present report.

The Kirovograd ore region is located in the Kirovograd district of Ukraine. Uranium deposits of this region are represented by the Michurinskoye, Severinskoye and Vatutinskoye deposits. The Michurinskoye and Vatutinskoye deposits are exploited by VostGOK combine. The Severinskoye deposit is prepared for operation but is not yet in production. The uranium mining complex of the region includes two uranium mines (Ingulskoye and Smolinskoye). They are located in the towns of Kirovograd and Smolino, 80 km from each other. The recovered uranium ores are processed at the hydrometallurgical plant located in Zhelty Vody. Mining ores is done underground. The final product is uranium oxide-protoxide.

The formation of deposits of the Kirovograd region is connected with processes of sodium metasomatism, juxtaposed on granite-metamorphic substratum in fault zones during Early Proterozoic activization. This took place at the end of the orogenic stage of the Ukrainian shield formation. Uranium ore formation (1.7–1.8 Ga) follows the stage of regional granitization (about 2 Ga).

The Kirovograd region is also in the limits of the same geoblock of the Ukrainian shield. The structure of this region is defined by a large Korsun-Novomirgorodsky geoanticlinorium. The axis lift of the structure consits of two granitoid complexes various age and nature. The southern part of the axial zone is formed by the Novoukrainsky massif of anatectic potassium granites (the age is about 2 Ga). The northern part is formed by the Korsun-Novomirgorodsky pluton of rapakivi-granites and anorthosites (1.7–1.8 Ga). The limbs of anticlinorium consist of Early Proterozoic gneisses and migmatites and small-sized granite bodies. The Korsun-Novomirgorodsky anticlinorum is limited by the Kirovogradsky regional fault in the east and by the Zvenigorodsko-Annovsky regional fault in the west (Fig. 1). Seismic investigations indicacte that the Kirovograd region corresponds to a block of earth's crust with the greatest depth (20 km) of occurrence of anatectic granitoids in the Ukrainian shield.

The basement rocks within deposits are predominantly biotite gneisses, migmatites and granite-gneisses. These rocks have been transformed under conditions of amphibolite facies, and folded in system of steep and relatively simple folds with submeridional direction. They are non-conformly granitized and intruded by subconcordant bodies of granites and pegmatoids.

On the whole, the positions of the Michurinskoye and Severinskoye deposits are controlled by the Kirovogradsky fault and the Vatutinskoye deposit — by the Zvenigorodsko-Annovsky fault (Fig. 1). Within regional faults the structural position of the deposits is defined by their localization to sites of complications of local faults by system of cross cutting disturbances. Thus the Severisnkoye and Michurinskoye deposits are located at sites of complication of the main submeridional faults by cross cutting north-west disturbances. The Vatutinskoye deposit is located where the main north-west fault is intersected by cross cutting structures.

Faults have complex internal structures and include structural elements of two of different age groups. The structural elements of the first group developed during formation in the making of the crystalline basement. They are presented by consistently formed small-sized granite bodies, zones of folding, boudinage and pegmatoid veins, as well as zones of blastomylonites. The folded zones and seams of blastomylonites developed in conditions of almandine-amphibolite facies of metamorphism during plastic deformation.

The structural elements of the second, later group were formed under conditions of relatively near surface, brittle deformation. They are represented by mylonites and zones of cataclasis accompanying wide zones of greenschist (chlorite-epidote) metamorphism, as well as later cataclasites where the bodies of uranium-bearing albitites are located.

Sodium metasomatism forms the large bodies of albitites. They extend from a few hundred metres to 2 km deep and have a thickness from tens to one hundred metres. The depth of occurrence of albitites is comparable with their lateral extent (Figs 2, 4). Albitites are developed from granites, migmatites and gneisses. The textural-structural peculiarities of the replaced rocks are preserved. Such minerals as chlorite-epidote, riebeckiteaegirine, aegirine, phlogopite and carbonate-hematite-chlorite are represented.

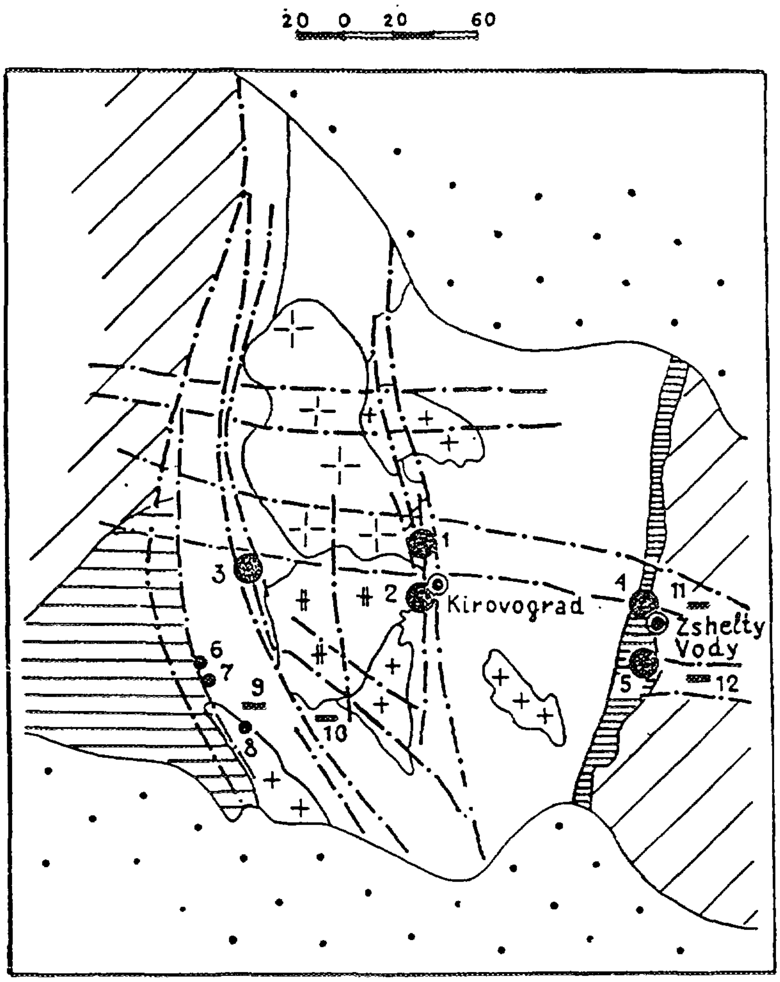
There is a time interval indicated between the time of albitite formation and of uranium ore formation that is indicated by the cataclasis of albitites before ore formation. Uranium mineralization occurs in cataclas the albitites and formes fine impregnation and microveins. This mineralization together with late albitite, rhodusite, phlogopite, chlorite, carbonate and hematite, fills the systems of small-sized intergrain faults and forms the cement of cataclic albitites.

The position of orebodies is controlled by main and cross cutting faults, and the changes in attitude of faults in horizontal and vertical directions. In addition to the structural control in all deposits, the lithological control is expressed by the primary localization of albitites and orebodies within granitoids. It is controlled by favourable physico-chemical properties of granitoids. Orebodies occur within the internal zones of albitite bodies, taking subconcordant position with them. They occur as blankets, lens and columnar stockwork. The thickness ranges from a few metres to ten metres, and the horizontal extent from the tens to one hundred metres (Figs 3, 4). The vertical extent frequently exceeds the horizontal, and reaches 1.5 km (Severinskoye deposit).

Uranium minerals present in the ores include uranitite, nasturan, brannerite, coffinite, hydroxides, uranium silicates and uranium black. According to conditions of formation, uranium minerals are divided into primary: (uraninite, nasturan, brannerite, coffinite); and secondary: (hydroxides, uranophane, boltwoodite, beta-uranotile and uranium blacks). Zoning of uranium minerals within the deposits is absent. Primary and secondary minerals are developed at the same depth levels. Secondary minerals occur at depths of 1000 m and more.

Known resources (RAR & EAR-I) uranium resources of the Kirovograd ore region are 102 000 t U including 52 000 t U with a production cost of $80/kg U. Prognostic (EAR-II) uranium resources are estimated at 136 000 t U.

Some of the exogenic type uranium deposits in the sedimentary cover of the Ukrainian shield, are suitable for exploitation by in situ leach mining technology (ISL). These deposits are located



platform complex (K-P)

metamorphic complexes (AR-PR)

protogeosynclinical complex (PR)

granite-gneiss complex of Early Archean stabilization

gneiss complex of Upper Archean stabilization

granulite complex (AR)

proto-orogenic granitoids (PR)

rapakivi granites

granites

subalkalic granites

faults

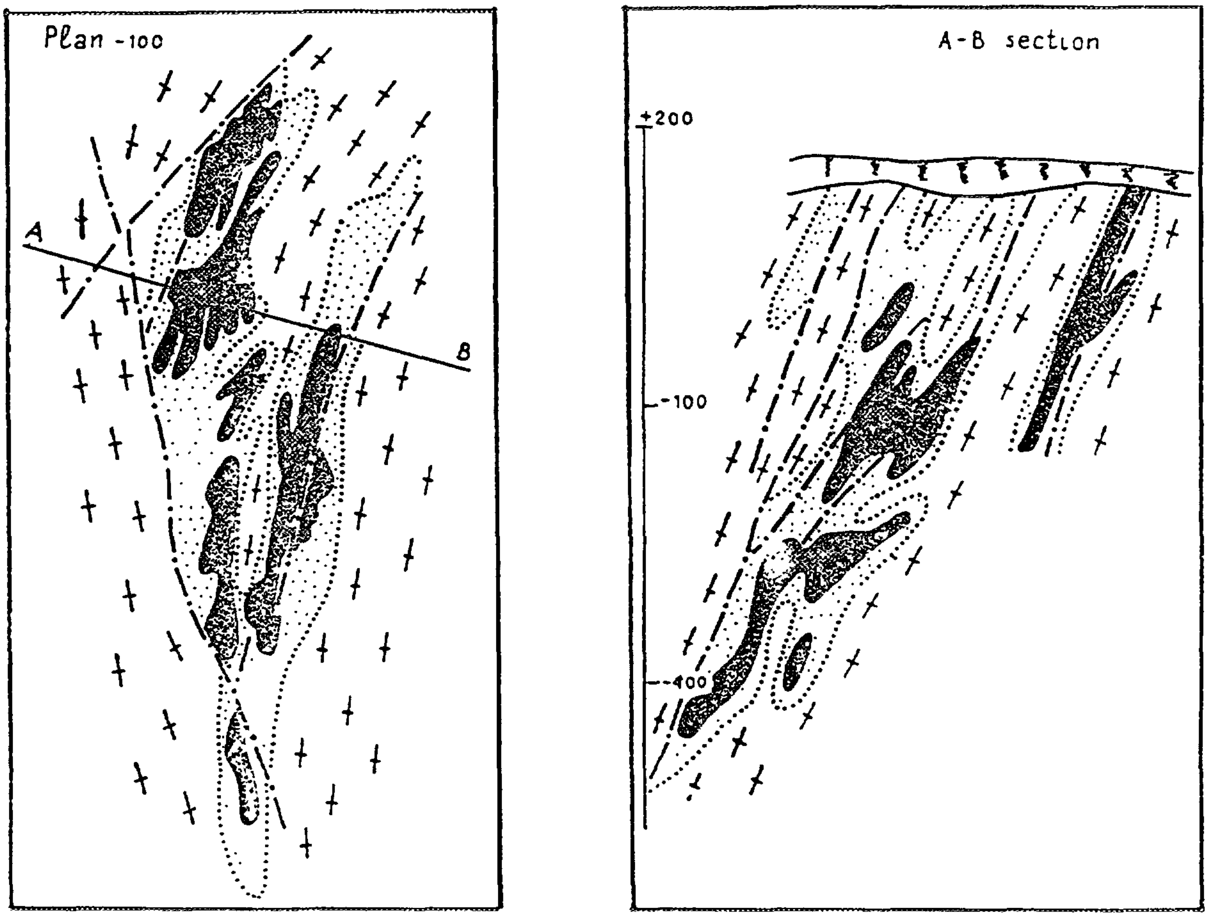
endogenic uranium deposits:

in sodium metasomatites-albitites (1-Severinskoye, 2-Michurinskoye, 3-Vatutinskoye, 4-Zheltorechenskoye, 5-Pervomayskoye)

in potassium metatomatites (6-Kalinovskoye, 7-Lozovatskoye, 8-Yuzhnoye)

exogenic uranium deposits (9-Sadovoye, 1-Bratskoye, 11-Novogutyevskoye, 12-Devladovskoye)

FIG. 1. Krivoi Rog and Kirovograd uranium-ore regions. Geological map without cover of Neogene and Quarternary sediments.



Plan of the horizon -100 m (left) and gross section along A-B (right)

- gneisses, granites, migmatites
- albitites
- uranium ores
- faults, blastomylonites seams, zones of brecciation

FIG. 2. Vatutinskoye deposit.

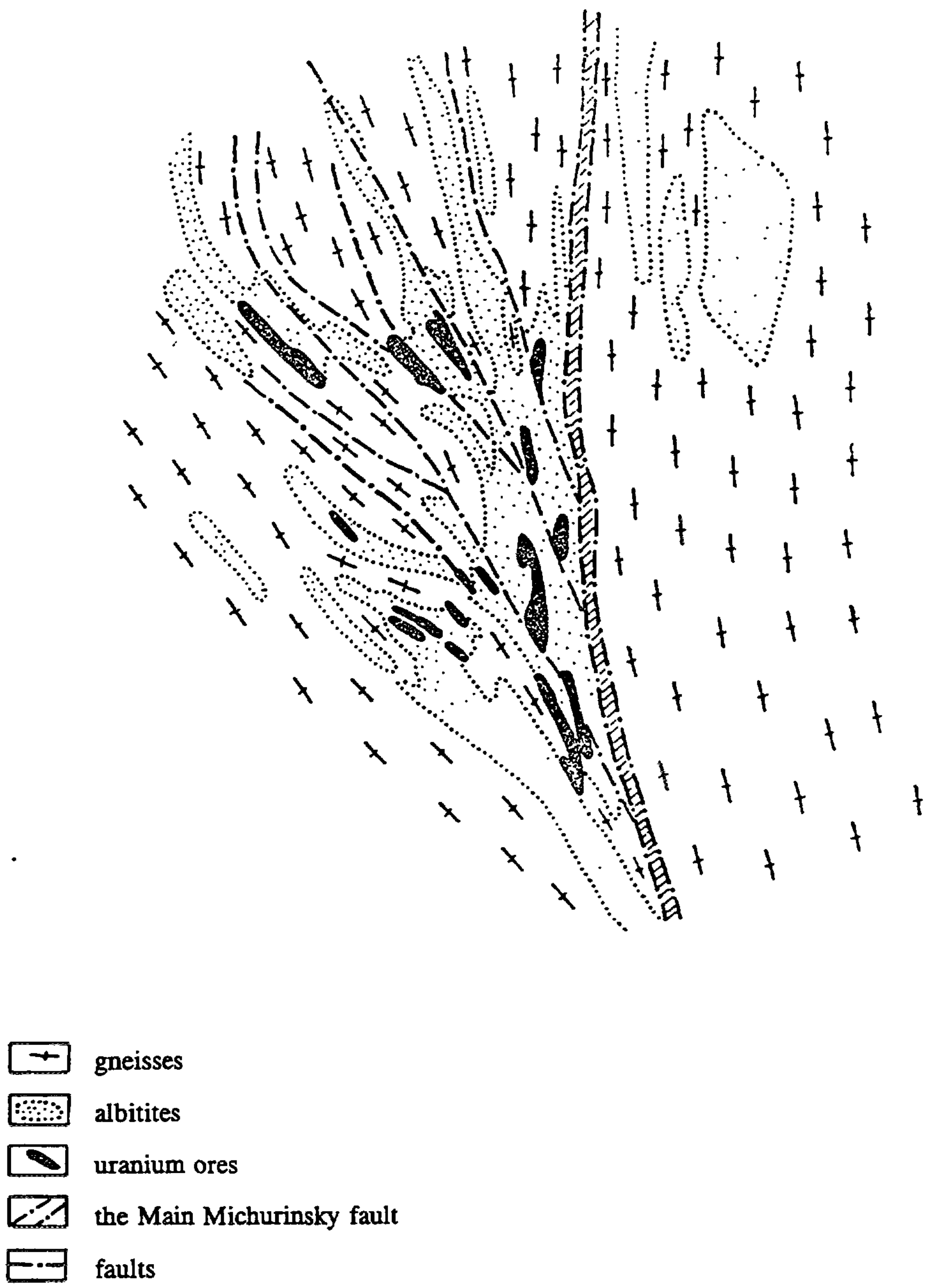
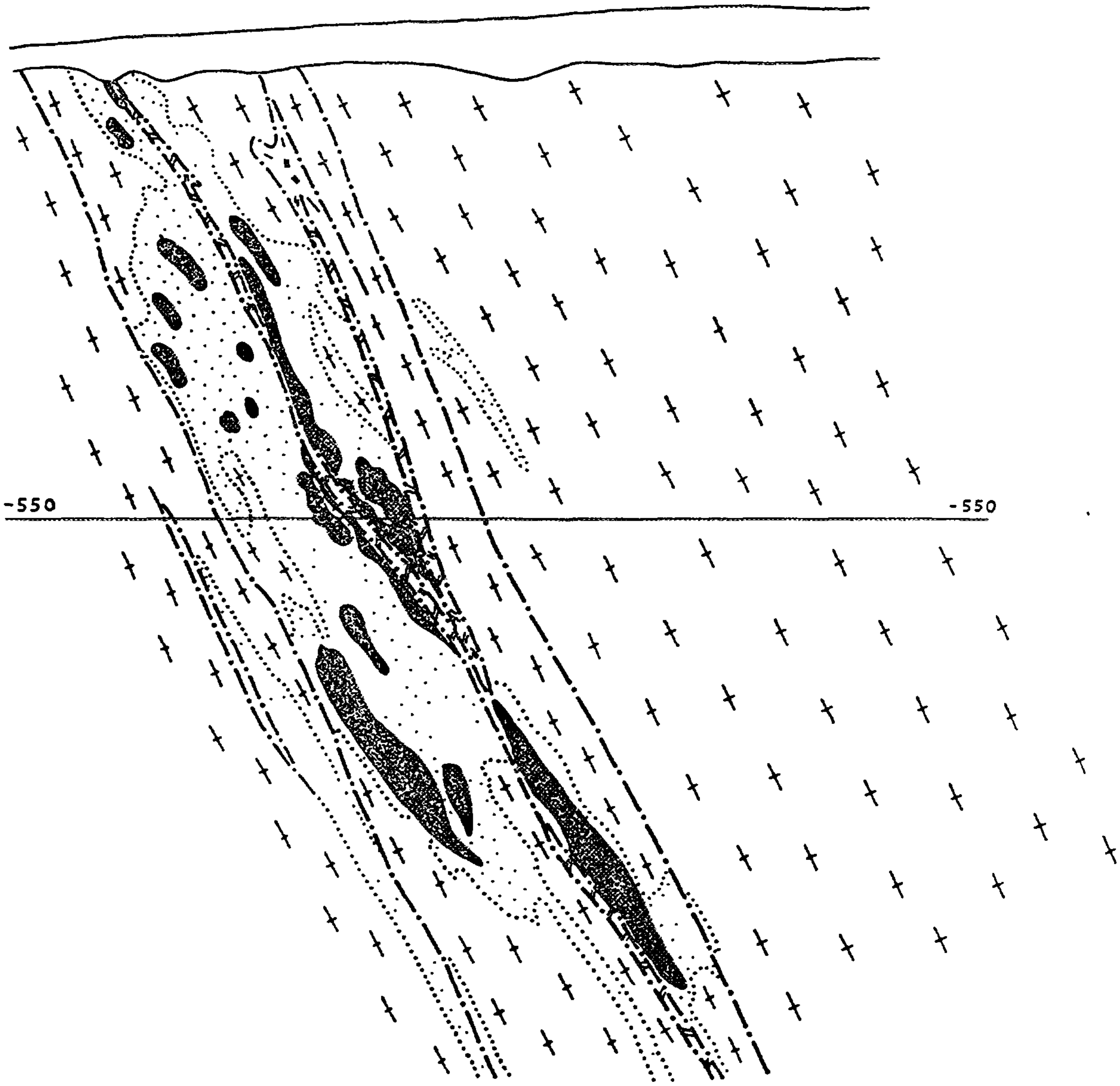


FIG. 3. Michurinskoye deposit.



gneisses, granites, migmatites

albitites

zones of cataclasites and milonites

uranium ores

FIG. 4. Cross section along profile. Scale 1:10 000.

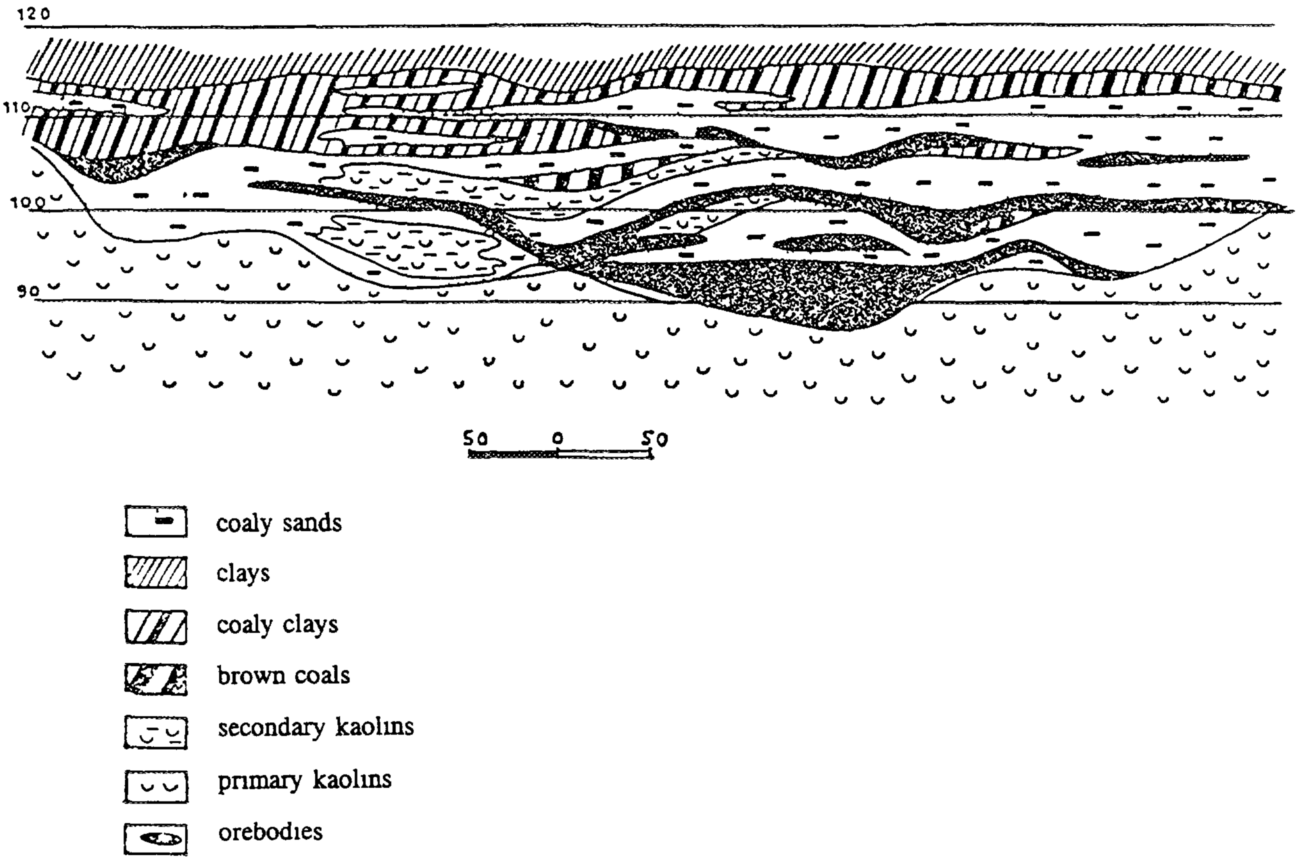


FIG. 5. Bratskoye deposit. Cross section

within the Dnieper brown coal basin (Devladovskoye, Bratskoye, Surskoye, Safonovskoye etc.). Some of the (Devladovskoye, Bratskoye, Safonovskoye) have been exploited. The first two are completely mined out and the resource have been deducted "cancelled" from the national uranium resource inventory.

The deposits are located in erosional-tectonic paleovalleys, filled by Paleogene-Neogene coal bearing sediments. They controlled by zones of ground or ground-bed oxidation. The uranium ores are located in alluvial sediments in the lower part of coal bearing formations, where coal sands, seldom coaly clays and brown coals are present. The depth of the mineralization ranges from tens of metres to 70-80 metres.

The deposits have different shapes and extend along paleochannels and/or along paleovalleys. The width of orebodies ranges from 50–80 meters to several hundred metres. The length is 2–4 km, the thickness is 3–10 m. In section, the uranium deposits consist of numerous horizontal orebodies with complicated contacts (Fig. 5). The uranium contents in ores are low — the first hundredth of percent. The uranium is concentrated in coaly and clayed material. Uranium blacks, uranium-bearing leucoxene and iron hydroxides are present in small quantity. The Uranium reserves of these deposits are not large and range from 1000 to 3000 t U.

The prospected and previously appreciated (RAR & EAR-I) resources of these deposits are 10 000 t U with a production cost of less than $80/kg U. Prognostic (EAR-II) resources are estimated to the 20 000 t U.

2. SUMMARY

The whole prospected and previously appreciated (RAR & EAR-I) uranium resources of industrial deposits of Ukraine are 112 000 t U including 62 000 t U with a production cost of $80/kg U. Prognostic (EAR-II) resources are estimated to be 156 000 t U.

IMPROVEMENT OF URANIUM PRODUCTION EFFICIENCY TO MEET CHINA'S NUCLEAR POWER REQUIREMENTS

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Abstract

Recently China put the Qinshan Nuclear Power Plant, with an installed capacity of 300 MW, in the province of Zhejiang and the Daya Bay Nuclear Power Plant, with a total installed capacity of 2 × 900 MW, in commercial operation. China plans a rapid growth in nuclear power from 1995 to 2010. China's uranium production will therefore also enter a new period with nuclear power increasing. In order to meet the demand of nuclear power for uranium, special attention has been paid to both technical progress improvement using management with the aim of reducing the cost of uranium production. The application of the trackless mining technique has enhanced the uranium mining productivity significantly. China has produced a radiometric sorter, model 5421-2 for pre-concentrating uranium run-of-mine ore. This effectively increases the uranium content in mill feed and decreases the operating cost of hydrometallurgical treatment. The in situ leach technique after blasting is applied underground in the Lantian Mine, in addition to the surface heap leaching, and has obtained a perfect result. The concentrated acid-curing, and ferric sulphate trickle leaching process, will soon be used in commercial operation for treating uranium ore grading −5 to −7 mm in size. The annual production capability of the Yining Mine will be extended to 100 tonnes U using improving in situ leaching technology. For the purpose of improving the uranium production efficiency much work has been done optimizing the distribution of production centres. China plans to expand its uranium production to meet the uranium requirements of the developing nuclear power plants.

1. INTRODUCTION

Recently the nuclear power of the mainland of China put the first self-designed and self-constructed Qinshan Nuclear Power Plant in Zhejiang province with 300 MW(e) and the largest joint venture project, Daya Bay Nuclear Power Plant, in province Guangdong, with 2 × 900 MW(e), in commercial operation. China plans a fast growth of nuclear power in the period from 1995 to 2010. New power reactors totalling 10 GW(e) will be under construction in 2000. The key nuclear power plants will be concentrated in the coastal areas, where the economy develops faster, and there is a lack of primary energy resources. The construction of the second Qinshan NPP project with 2 × 600 MW(e) has been started. The second Daya Bay NPP with 4 × 1 GW(e) located in Ling'ao near Daya Bay will be constructed in two phases. The active preparation work for construction of the first phase project with 2 × 1 GW(e) sets is under way. For the third NPP of Guangdong province, the site has been basically planned in Yangjiang. The site selection for NPP with 4 × 1 GW(e) in Liaoning province has been approved. It will be located in Wafandian. Its feasibility study is carried out by both China and Russia. The Sanmen NPP with 4 × 1 GW(e) will be constructed in two phases Sanmen county, Zhejiang province. In addition, the earlier stage work on construction of nuclear power plants will be developed for Shandong, Jiangsu, Fujian, Hunan, Jiangxi and Jilin provinces.

Specialists believe that the rapid period of development China's nuclear power will be round the year 2010. The installed nuclear generating capacity will reach 20 to 30 GW(e) by 2010.

China follows the policy of "self-sufficiency of uranium" for nuclear power plants. China's uranium production will therefore also enter a new historical period with rapid development of nuclear power. In order to meet the demands of uranium for nuclear power, China's uranium industry must provide at least 3500 tonnes uranium each year before 2010. This is a promising future for China's uranium industry. In recent years, special attention has been paid to technical progresses, and the management has been improved, with the aim of reducing the uranium production cost and increasing the competitive ability of China's uranium production industry.

2. TRACKLESS MINING

The application of trackless mining has had a great effect on simplifying the mining process, resulting in higher efficiency. In China's uranium mining the trackless mining technique was started in the 1980s. It has industrial application at Quzhou Uranium Mine. Several years practice at Quzhou Uranium Mine demonstrated its advantages over the traditional mining system.

TABLE I. COMPARISON OF TRACKLESS MINING WITH TRADITIONAL MINING METHOD IN QUZHOU URANIUM MINE

Items	Traditional	Trackless
Height of mining level	25 m	50 m
Stope area	300–500 m^2	500–1000 m^2
Annual output each stope	8000 t	15 000–35 000 t
Operating staff	100%	40–60%
Ore loss and dilution	100%	70–90%
Operating cost	100%	85.5–60%

The trackless mining technique has been planned to be adopted for the existing Renhua Uranium Mine and the new Benxi Mine.

3. RADIOMETRIC SORTING

The new radiometric sorter has also produced good results.

The radiometric sorters have been adopted in uranium production since first China's uranium mine was constructed. By eliminating waste rock and below grade ores the consumption of chemicals and energy has been considerably reduced in uranium extraction process. To increase the sorting efficiency, the 5421 model radiometric sorter was developed and went to commercial operation in the 1980s. On this basis, the more advanced 5421-2 model radiometric sorter was developed in the 1990s. The 5421-2 sorter is a sorting system, consisting of one 4 channel unit processing 25–60 mm ore and one 2 channel unit processing 60–150 mm ore. The capacity of both units used together in a complete set can meet the demands of a uranium mine's sorting plant with a capacity of 150 000 t per year. The main technical specifications are shown in Table II.

TABLE II. TECHNICAL SPECIFICATIONS OF 5421-2 MODEL SORTER

Size, range, mm	60–150	25–60
Capacity, t/h	26-31	14–17
Sorting efficiency, %	>90	>80
Sorting sensitivity, mg (U)	<55	<15

The 5421-2 model radiometric sorter employs a computer for the controlling process. Multiple scintillometers are used to detect ore by relay mode. Other advanced techniques, such as mathematical statistics and digital computation are also adopted in the sorter. This sorter has the advantages of higher sorting sensitivity and efficiency, higher capacity and better automation. The sensitivity range of uranium grade can reach ± 10 ppm at a certain cut-off grade.

The use of two 5421-2 model sorters in the sorting plant of Fuzhou Uranium Mine simplifies the process flowsheet. The 11 old sorters were replaced, and operating personnel was decreased. The operating cost was reduced by 10%.

4. IN-PLACE LEACHING AFTER BLASTING

In-place leaching after blasting was first applied at the Lantian Uranium Mine. Heap leaching is a comparatively low cost processing method and has wide industrial application at China's uranium mines. In-place leaching after blasting has been successfully put into operation at Lantian since 1990. In place leaching after blasting is a mining system consisting of the underground blasting of hard and compact orebody, reducing the ore to the desired size and permeability. The leaching agent, is then added selectively recovering useful metal from the ore. Compared with the traditional mining and metallurgical technology, this method has advantages of higher efficiency, lower cost of production, safe operation and environmental benefits. It is applicable to orebodies with easily leached property of the desired metals.

In-place leaching after blasting was carried out at orebody No.30. It occurred in a tectonoclastic zone of fractured granite, with a density of 2.48 t/m^3, and the average thickness of 6.59 m. The top of the body was close to the surface, and the hydrogeological condition was simple. The geological reserve was 7160 t of ore with a uranium content of 0.171%.

The sublevel caving and shrinkage system was adopted. At the bottom of the body liquor collecting tunnel was developed. In the entire mining area, four blasting sublevels with the height of 10–16 m for downward blasting were arranged. The barrage-type distribution was adopted as the main mode, and the trickling distribution and injection through wells as a subsidiary one. Usually the liquor is well distributed and the leaching was relatively complete. An average uranium content of 0.014% was obtained in residue, with the uranium recovery 88.98% and the utilization coefficient of mineral resources of 83.43%. This method will be applied to other orebodies.

5. CONCENTRATED ACID CURING AND FERRIC SULPHATE TRICKLE LEACHING

The method of uranium recovery using concentrated acid curing and ferric sulphate trickle leaching uranium process is adopted in production. Grinding is an indispensable operation in the traditional hydrometallurgical processing of uranium ore. Its proportion of cost in ore processing is great. The energy consumption of grinding usually accounts for 30% to 50% of the total. In the late 1980s, we started investigation on concentrated acid curing and ferric sulphate trickle leaching process (NGJ process, N, G and J — the first letters of concentrated, ferric and leaching in the Chinese alphabetic system of writing respectively. The process includes ore crushing (up to 5–7 mm), concentrated acid curing, ferric sulphate leaching, tertiary amine solvent extraction, product precipitation and residue disposal with the process effluent in a closed circuit. Four of China's typical uranium ores were studied using the NGJ process and compared with the traditional agitation leaching (AL) process (see Table III). Either for soft sedimentary type uranium ore or for hard and tight volcanic type ones, leaching results indicate that the NGJ process has advantages over AL process.

TABLE III. COMPARISON OF LEACHING RESULTS BETWEEN NGJ AND AL PROCESSES

Ore		NGJ process			AL process		
Ore	U grade	Operation condition		Recovery %	Operation condition		Recovery %
		Size mm	H_2SO_4 %		Size mm	H_2SO_4 %	
Sedimentary	0.126	-5.0	9-10	90.5	-0.5	13-14	90.0
Volcanic (rhyolite)	0.0815	-5.0	1.5-2	88.1	-0.25	5-6	90.5
Granite	0.56	-5.0	5.6	98.0	-0.5	6-9	98.2
Quarzite	0.10	-5.0	5	91.0	-1.0	7	93
	0.43	-3.0	5	97.0	-0.32	5.6	96.5

In 1993, an industrial experiment was carried out for the sedimentary type uranium ore. It was steadily operated for 92 days with 726 tonnes ore treated and 500 kg sodium diuranate produced. The extraction rate reached the level of the AL process, when the ore size was less than 7 mm, and the trickle leaching cycle was 10 to 45 days. The NGJ process is simple and its operation is stable. Compared with the AL process (see Table IV), the process effluent discharge is eliminated and most of the residue can be used for backfill in mine.

TABLE IV. SOME ECONOMIC COMPARISON BETWEEN NGJ AND AL PROCESSES

Items	AL process	NGJ process
Power	1	1/3
Water	1	1/20-1/10
Operating costs	1	0.4-0.55

It can be concluded that the NGJ process is an intensified heap leaching operation. The practice shows that the NGJ process is a very effective extraction method for some of China's uranium ores. The method if of important significance in China's uranium ore processing.

6. IN SITU LEACH MINES

The Yining Uranium Mine is reaching one hundred tonnes annual production capability using in situ leach technology. A small scale production of in situ leaching is being successfully carried out at Deposit No. 512, Yining Uranium Mine, Xinjiang Uygur Autonomous Region, and useful experience has been obtained. Now the larger project is being developed.

7. REORGANIZATION AND MANAGEMENT OF URANIUM PRODUCTION

Beside the technical progresses obtained in uranium mining and metallurgy, a series of adjustments and reformation measures have been adopted over the last decade to conform to the requirements of a market economy. The first adjustment was cutting back uranium production and the closure of uranium mines and mills that had comparatively high production costs. The remaining operating uranium production enterprises must, according to the product price, define proper cut-off grade of uranium ore and decrease ore dilution. They must reduce also the workforce, and reduce material and energy consumption.

Another important adjustment is to pursue diversified economy while maintaining uranium industry as the main objective. All the enterprises and institutions of the uranium industry have been energetically developing non-uranium products and techniques. Significant results have already been achieved. To date, the equivalent of about 200 millon US Dollars has been invested and the non-uranium development has started producing the following main products: titanium pigment, magnesium metal, rare earths, ordinary phosphorus, etc. A total of 25 000 employees from uranium production have been transferred to diversified projects. It is evident that under the China's specific economy system non-uranium production improves uranium production efficiency.

We believe that in the coming 15 years China will have a stable and rapid development in the uranium industry to meet the requirements of nuclear power for uranium.

THE URANIUM RESOURCES AND PRODUCTION OF NAMIBIA

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Abstract

The promulgation of the Minerals (Prospecting and Mining) Act, 1992, on 1 April 1994 and the simultaneous repeal of restrictive South African legislation on reporting uranium exploration and production results, allowed the Namibian Government for the first time to present information for publication of the report "Uranium 1995 — Resources, Production and Demand", by the OECD Nuclear Energy Agency and the IAEA. Namibia, one of the youngest independent nations in Africa, has a large number of uranium occurrences and deposits in several geological environments. The total estimated uranium resource amounts to about 299 thousand tonnes recoverable uranium at a cost of less than US$ 130/kg U, within the known conventional resources category. The most prominent geological type of these is the unique, granite-related uranium occurrences located in the central part of the Namib Desert. A number of large tonnage but low-grade deposits suitable for open-cast mining, were identified between 1960 and 1980, the peak period for uranium exploration. At one of these deposits, Rössing, mining operations started in 1976 and will continue into the first quarter of the next century. The presence of other, so far undiscovered deposits are suspected under thin Tertiary cover within this uranium province. Calcrete-hosted uranium occurrences and deposits are of secondary importance, due to a lower recoverable tonnage of uranium and complications with metallurgical processes. At times of better uranium markets however, at least one of these deposits will receive serious attention. Permo-Triassic age Karoo sandstone-hosted uranium deposits were subject to only limited exploration due to the down-turn of uranium prices in the latter part of 1980s, despite the very encouraging exploration results. As only limited Karoo sandstone-covered areas were tested there is still great potential for further discoveries. The planned output of Rössing Uranium Mine at 40 000 tonnes of ore per day which results in an annual production of 4536 tonnes of uranium oxide, was achieved in 1979. Due however, to the subsequent slump in uranium prices and demand the annual production was reduced by about 50% to the present 1911 tonnes of contained uranium (in 1994). Full production capacity, depending on world markets, can be achieved within a short period of time. In case of improved uranium market conditions, Namibia is in a strong position to increase uranium production and open up new production centrès to strengthen the country's position as an important uranium producer in the world.

1. INTRODUCTION

The promulgation of the Minerals (Prospecting and Mining) Act, 1992, on 1 April 1994 and the simultaneous repeal of restrictive South African legislation on reporting uranium exploration and production results, allowed the Namibian Government for the first time to present information for the publication of the Red Book, a report compiled by the OECD Nuclear Energy Agency and the IAEA.

As the purpose of this paper is provide an overall review of the uranium deposits/occurrences, no great details are given of the geological description of the more than 50 known occurrences nor of the results of reserve calculations or feasibility studies, most of which are in any case, out-dated by at least twenty years. For the location of the most important uranium deposits of Namibia the reader is referred to Fig. 1. In case of further interest the reader is referred to articles in various geological publications, the open file reports of the Geological Survey of Namibia and the soon to be published Uranium Chapter of the Mineral Resources of Namibia

2. URANIUM EXPLORATION

The first significant discovery of radioactive mineralization within Namibia was made in 1928 in the Rössing region by autoradiograph tests on a supposed sample of pitchblende.

As a result of an upswing in uranium market demand and prices, extensive uranium exploration started in Namibia in the late 1960s. Several airborne radiometric surveys were conducted

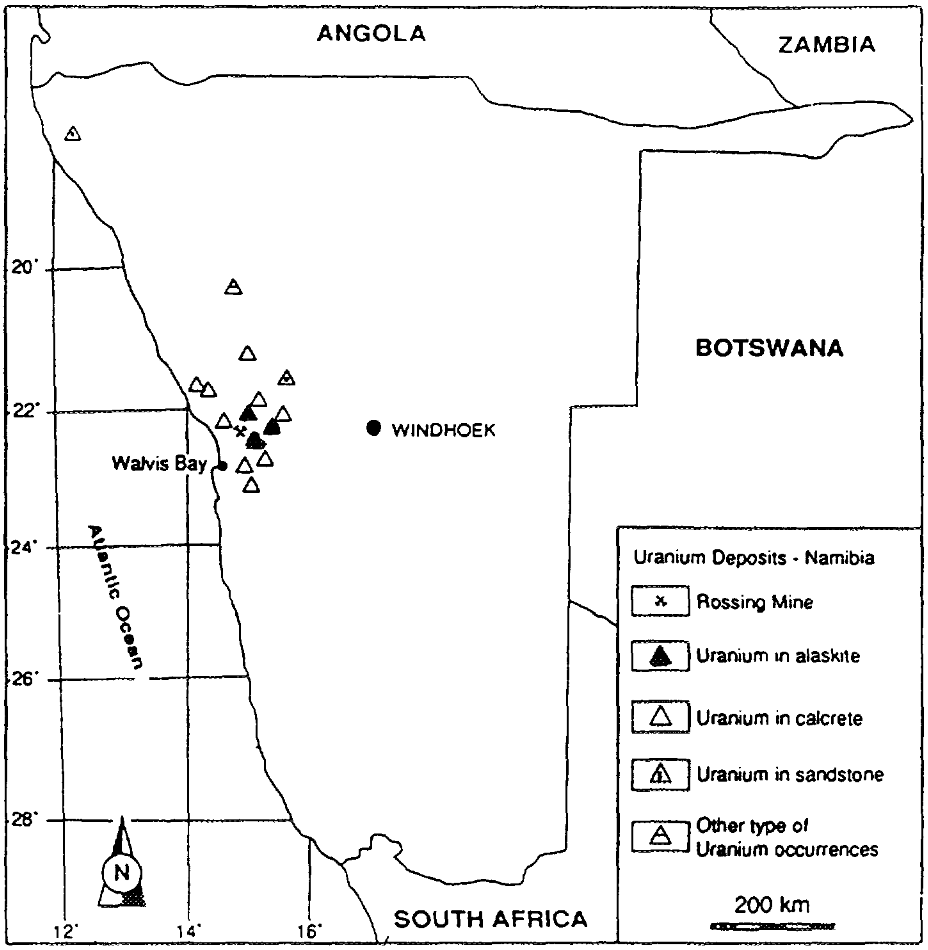

FIG. 1. Uranium deposits of Namibia.

by the Geological Survey during this period and numerous uranium anomalies were identified. Of these, the Rössing deposit where Rio Tinto Zinc obtained exploration rights in 1966, developed into a large scale open-cast mine which started production in 1976.

Development of Rössing combined with a sharp upward trend in uranium prices, stimulated extensive exploration activity, mainly in the Namib Desert. Two major types of deposits were located i.e. mineralization associated with intrusive granitic rocks ("alaskite") and mineralization associated with recent calcrete formations. Of the granitic type deposits, beside Rössing Mine, the Trekkopje deposit has significant reserves. Langer Heinrich, a calcrete hosted uranium deposit is the most promising occurrence within the second category. The combined effect of political uncertainty and the decline in uranium prices caused the rapid curtailment of exploration and development work by the early 1980s. This was indeed unfortunate as the refinement of exploration techniques on this unusual area were poised to locate a number of new deposits.

Since the 1980s, the continued weakness of the uranium market discouraged further exploration activities, except in the immediate vicinity of Rössing Uranium Mine. While uranium exploration in a limited extent continued near Rössing until 1992, exploration for uranium ceased in Namibia since that date. In 1992 uranium exploration expenditure amounted to just over 1 million Namibian Dollars (at par with South African Rand).

However, should a sustained upturn in demand for uranium occur, which may be the case by the end of the 1990s, it remains possible that mining of one of the mentioned deposits will prove commercially viable, with Langer Heinrich generally regarded as having the best potential.

3. URANIUM RESOURCES

Costs were calculated by using data provided by US Bureau of Mines 1993, updated to 1st January 1995. Descriptions, including reserve calculations are available for most uranium deposits of the country excluding some, often larger deposits where mining companies are still the holder of the mineral rights or information is not available.

While the cost of acid leaching uranium recovery is relatively well known, costs are not available for the alkaline leaching technique, which recovery method is essential for the calcrete hosted uranium deposits. In the latter case recovery costs were increased by an additional 50% to take into account the envisaged higher costs.

In view of limited information available for the Estimated Additional Resources Category II and the Speculative Resources Category no estimation for these resource categories were attempted.

3.1. Known Conventional Resources (Reasonably Assured Resources and Estimated Additional Resources Category 1)

The total resource in this category amounts to about 299 thousand tonnes of uranium at a cost of less than US$ 130/kg U, see Table I.

TABLE I. NAMIBIA — KNOWN CONVENTIONAL URANIUM RESOURCES (IN TONNES OF URANIUM)

IAEA Resource Class	Cumulative Cost Ranges		
	< US$40/kg U	< US$80/kg U	< US$130/kg U
Reasonably Assured	78 552	160 587	191 822
Estimated Additional Category I	70 546	90 815	107 513
TOTAL	149 098	251 402	299 335

The bulk of this resource is associated with intrusive granites — locally termed "alaskite" (alkaline leucogranite) in the vicinity of Rössing Uranium Mine, in the proximity of Walvis Bay, the main harbour town of Namibia. See Figs 2, 3 and 4. The total resource excludes few deposits where reserve estimations and therefore cost estimations have not as yet been assessed by the Mining Directorate.

The granite-associated uranium province is restricted to the axial structural zone of the Precambrian Damara Orogenic Belt and is approximately 100 kilometres long and 50 kilometres wide.

A large number of calcrete hosted deposits have been identified and intensively explored, however their total combined uranium content is less than 10% of the total resource of this category. The calcrete hosted uranium deposits are broadly associated with the uraniferous alaskite and were derived by decomposition of the alaskite and the subsequent migration of secondary uranium mineralization to a favourable depositional environment.

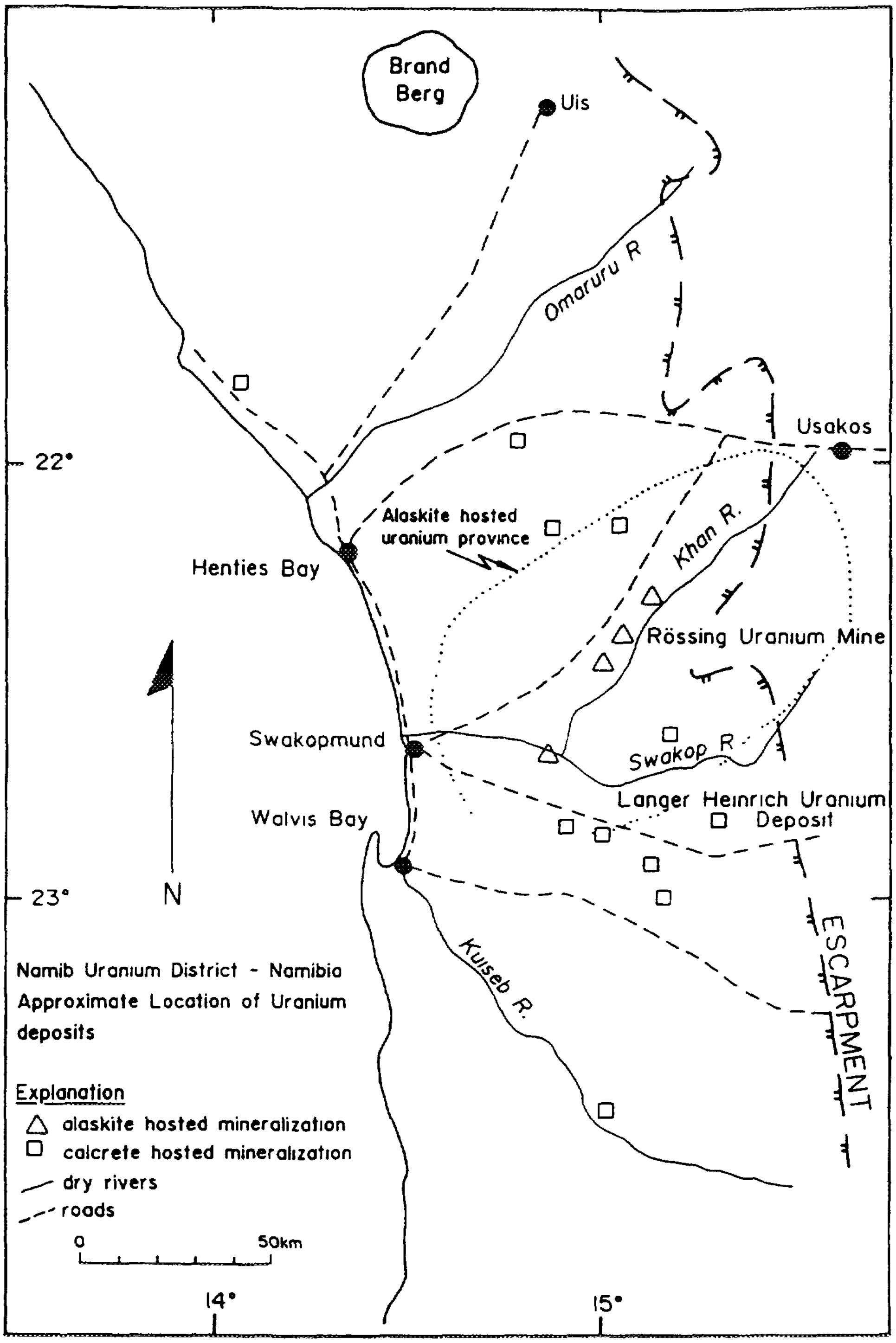

FIG. 2. Location of uranium deposits in the Namib uranium district.

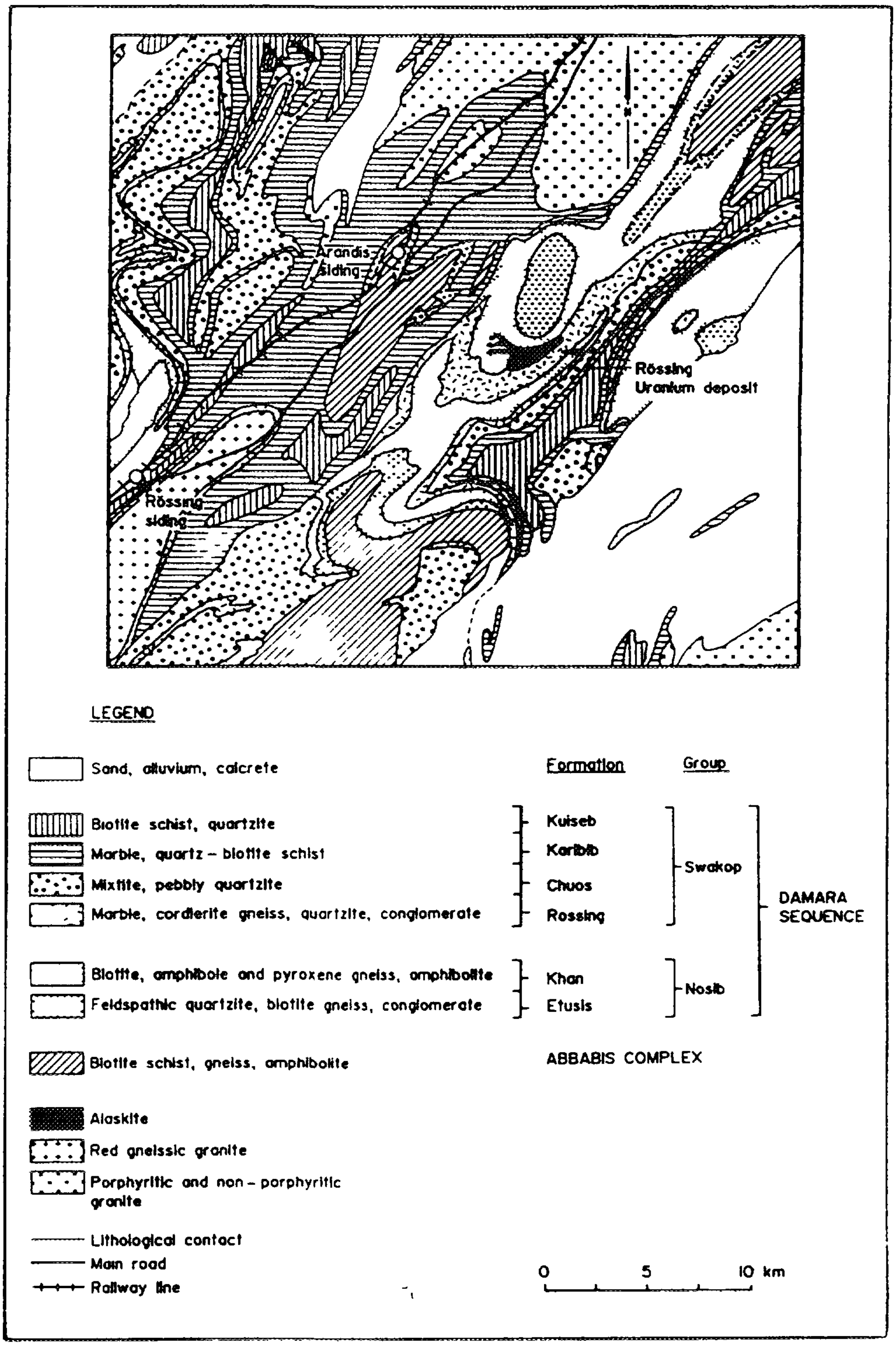

FIG. 3. Geological map of Rössing uranium mine and vicinity.

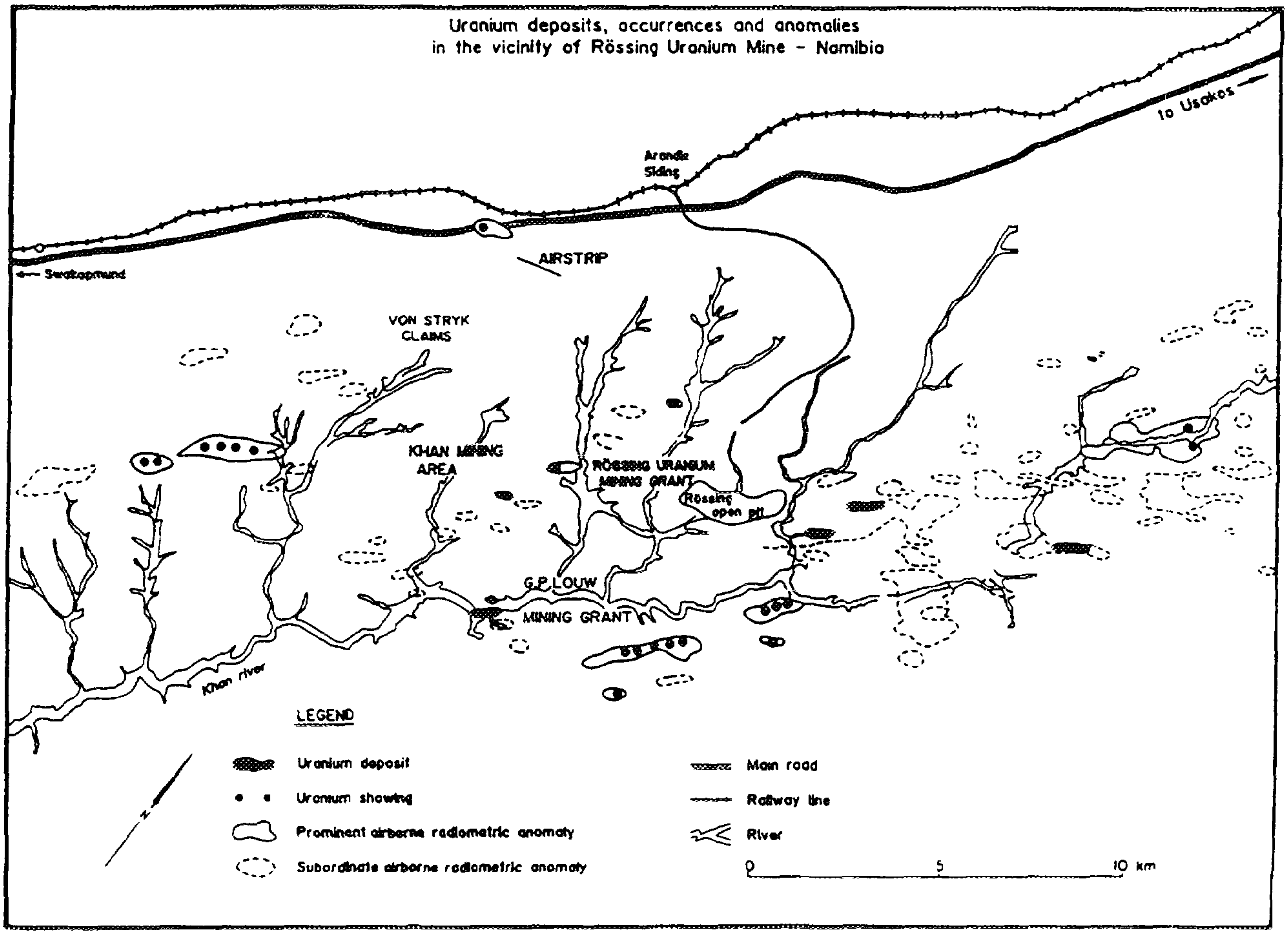

FIG. 4. Uranium deposits, occurrences and anomalies in the vicinity of Rössing uranium mine.

3.2. Undiscovered Conventional Resources (Estimated Additional Resources Category II and Speculative Resources)

Although speculative figures are not provided within the Undiscovered Conventional Resources Category, substantial resources are expected in the following geological types.

3.2.1. Intrusive deposits (IAEA type 6)

The granite-associated uranium province covers approximately 5000 km² of an area which is largely covered by calcrete and or wind-blown semi-consolidated sand. As past investigation concentrated on follow-up of airborne radiometric anomalies, substantial additional reserves, maybe of the size of Rössing, are suspected under the superficial cover.

3.2.2. Calcrete-hosted deposits (IAEA type 10)

Within the calcrete covered terrain, of the 38 major regional airborne radiometric anomalies, eleven anomalies were successfully investigated by intensive drilling, providing proven resources included under the proven resource category. In most cases the generally low grade mineralization is associated with calcrete-filled paleo-river channels. Whilst the existence of additional resources within Tertiary sediments is not discounted, the presence of a large undiscovered resource is unlikely. See also Fig. 2.

3.2.3. Sandstone-hosted deposits (IAEA type 2)

The Permo-Triassic age Karoo sediments were intensively investigated in neighbouring countries in the early 1970s and to a limited extent in Namibia as well. As these sediments are extensively dissected by river systems in the north-western part of Namibia, airborne radiometric anomalies are more pronounced. Ground follow-up and extensive drilling delineated nearly 6 million tonnes of low grade uranium mineralization, which was excluded from the proven resource category due to high cost of recovery. The mineralization is associated with coarse clastic sediments, carbonaceous sulphidic shale and limestone. Additional economically recoverable resources may be present within similar age sediment in other, so far unexplored parts of Namibia.

4. URANIUM PRODUCTION — RöSSING URANIUM MINE

4.1. Historical Review — Rössing Uranium Mine

In 1928, Captain G. Peter Louw prospected and found uranium mineralization in the vicinity of Rössing Mountains within the Namib Desert. Over many years he tried to promote the prospect, but only in the late 1950's, a major mining company, Anglo American Corporation of South Africa, prospected the area by drilling and some underground exploration. Due to erratic uranium values and poor economic prospects for uranium, Anglo American abandoned the search.

In August 1966, Rio Tinto Zinc acquired the exploration rights and conducted an intensive exploration programme till March 1973. Surveying, mapping, drilling, bulk sampling and metallurgical testing in a 100 tonnes/day pilot plant indicated the feasibility of establishing a mine.

Rössing Uranium Limited was formed in 1970 to develop the deposit. RTZ was the leading shareholder with 51.3 % (at the time of the formation of the company) of the equity.

In 1972, Rössing awarded a management contract for the design, engineering, procurement and construction of the project to a joint venture of Arthur G. McKee, Western Knapp Engineering Division and Davy Powergas. Mine development commenced in 1974 and the commissioning of the plant and the initial production commenced in July 1976 with the objective of reaching full design capacity of 5000 short tonnes (4536 metric tonnes) per year of uranium oxide during 1977. Due to the highly abrasive nature of the ore, which was not identified during pilot plant testing stage, after some major plant design changes, the target capacity was only reached in 1979.

4.2. Status of Production Capability — Rössing Uranium Mine

At full production the plant's full throughput rate at Rössing Uranium Mine is 40 000 tonnes of ore per day which would provide 4536 tonnes of uranium oxide annually. However, due to weakness in the current market the Rössing operation has been restructured, downsized and is now operating at 50% of capacity. Full production capacity could be achieved within a short period of time, should market conditions warrant.

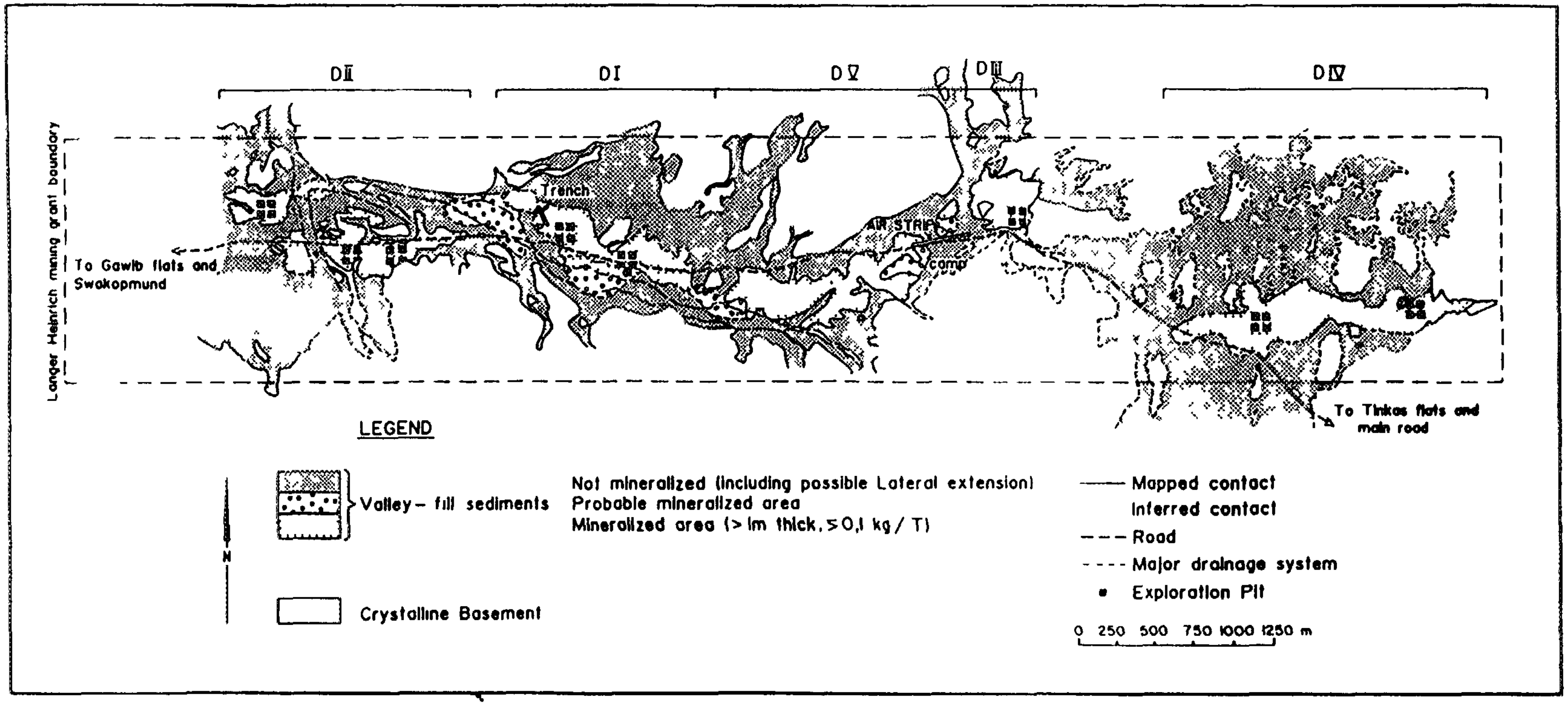

FIG. 5. Simplified geological map of Langer Heinrich uranium deposit.

TABLE II. HISTORICAL URANIUM PRODUCTION — RÖSSING URANIUM MINE (TONNES URANIUM CONTAINED IN CONCENTRATE)

	Pre 1992	1992	1993	1994	Total to 1994	Expected 1995
Conventional Open Pit Mining	51 360	1673	1668	1911	56 612	1962

4.3. Ownership structure and employment in the uranium industry — Rössing Uranium Mine

The present ownership structure of Rössing uranium mine is:

RTZ Corporation	56.3%	IDC South Africa	10.0%
Namibian Government	3.5%	Others	20.2%
Rio Algom Limited	10.0%		

There have been no significant changes in the employment in the uranium industry within the last two years. Employment at Rössing Uranium Limited, the sole producer, is currently 1250.

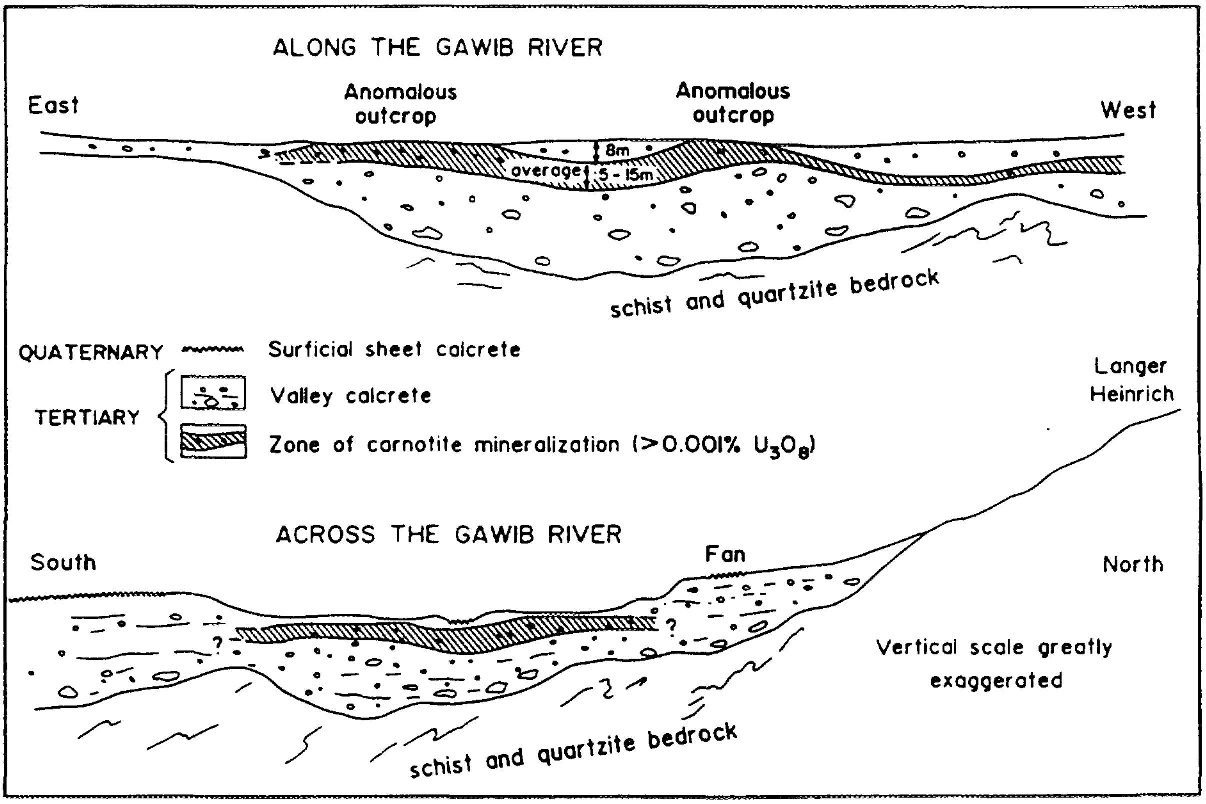

FIG. 6. Simplified sections across the Langer Heinrich uranium deposit.

4.4. Future production centres

Beside the Rössing operation no new production centre is planned for the next five years, even if the uranium market dramatically improves. However, after the five year period, under a favourable market conditions, the planning of at least one additional production centre is envisaged, maybe at Langer Heinrich, where large proven resources are available. See Fig. 5 for the Simplified Geological Map and Fig. 6 for Simplified Sections across the Langer Heinrich Deposit.

4.5. Uranium production, long term capability

Under favourable market conditions Rössing Uranium Limited, the sole uranium producer in Namibia, could return to full production capacity of close to 4000 t U per annum. The existing reserves would be expected to enable production from this source to continue until at least 2017.

Favourable market conditions would also allow the exploitation of at least one additional mine at a rate of about 1000 t U per year.

4.6. Factors influencing long term uranium production capability of Namibia

A number of proven uranium deposits have been discovered in Namibia and there is great potential for the discovery of additional deposits under the Tertiary sand and calcrete cover.

The most important criteria to extend production or opening new production centres is the price and demand for uranium in the world markets. Under favourable conditions some of the already proven deposits could be brought into a production stage. An additional and also important factor is the availability of water for the possible new production centres.

5. ENVIRONMENTAL CONSIDERATIONS

Namibia's constitution requires that the state actively promote and maintain the welfare of the people by adopting policies aimed at ensuring that ecosystems, essential ecological processes and the biological diversity of Namibia are maintained. However, environmental legislation that stems from this provision still remains a draft (soon to be finalized) as the country addresses more pertinent issues of education and development of its people.

Under the provisions of the Minerals (Prospecting and Mining) Act 1992, an applicant for a mineral licence, including the mining licence, has to complete an environmental assessment study and to prevent any damage to the environment from exploration and mining activities. In case of mining, the rights holder is obliged to rehabilitate land disturbed by mining.

Whilst the Namibian environmental legislation and standards remain to be established, the management of Rössing Uranium has adopted standards and performance criteria used by other developed countries. Presently a comprehensive review of environmental standards and performance criteria is being carried out by the Rössing Uranium Mine to develop site specific, risk based environmental objectives and thresholds.

As Namibia's only producing uranium mine and a substantial percentage of the country's uranium resources are located within the Namib Desert, the principal environmental consideration is the management of available water resources.

Potable water for the Rössing Uranium Mine as well as for the coastal towns of Walvis Bay and Swakopmund is supplied from aquifers at the Kuiseb and Omaruru river deltas. To save those limited water resources and to save the cost of pumping over long distances, the management of Rössing undertaken an integrated water management programme, which has resulted not only in the reduction of water consumption of the mine but also substantially reduced environmental impacts. A new tailings deposition method was developed by the operator to minimize the amount of water which is lost on the tailings impoundment due to the high evaporation rates experienced in this area. Addition of carbonate rich tailings also neutralizes the acid mine drainage, a large percentage of which is returned to the mine.

Radiological concerns are catered for, and the recommendations included in the International Commission on Radiological Protection's Publication 60 of 1990 have been implemented at Rössing Mine. The challenge of radiological exposure is thus not with achieving compliance with dose limits, but in the application of the principle of ALARA (As Low as Reasonably Achievable) to reduce radiological exposure. There have been concerns about the potential for the incidence of excess cancers, which are thought to be related to occupational radiation exposure. These can, however, only be addressed in comparison with national cancer statistics, which do not exist in Namibia at the present time.

6. NATIONAL POLICIES RELATING TO URANIUM

Namibia achieved independence on 21 March 1990 and the Minerals (Prospecting and Mining) Act, 1992 was promulgated on 1 April 1994. With the introduction of the Act, a number of South African laws were repealed or amended, including all laws relating to the uranium industry, such as the Atomic Energy Act, 1967, the Nuclear Installations (Licensing and Security) Act, 1963 and all their amendments.

The provisions of Part XIII of the Act relate to source materials as specified by Schedule 1 of the Act. Source material is defined as:

a) uranium, expressed as uranium oxide, of more than 0.006 per cent;

b) thorium, expressed as thorium oxide, of more than 0.5 per cent, and of which the mass is more than half a kilogram.

Section 102 of the Act relates to the possession, disposal, enrichment, re-processing and export of source material, while section 103 specifies penalties for the contravention or a failure to comply with the provisions of section 102.

While the repeal of the South African uranium-related legislations was justified, due to its complexity and reference to enrichment and the use of enriched material in nuclear reactors, which are not relevant to Namibia, the provisions of the Act are not detailed enough to control the safety or the environmental aspects of the uranium industry. The introduction of a new Act or amendments to existing legislation are presently being considered.

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A REVIEW OF SPANISH URANIUM RESOURCES AND RECENT DEVELOPMENTS IN THE PROVINCE OF SALAMANCA

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Abstract

Uranium exploration activities in Spain carried out during the 1950–1992 period, led to the discovery of a number of deposits in different geological environments. Presently there is only activity at the FE area in Salamanca province, where the only remaining mining centre is located. A new dynamic leaching processing plant with a capacity of up to 950 t U_3O_8 t/year began operation in 1993, at FE mine. The development and planning of the mining in the open pits of ENUSA (province of Salamanca, Spain) under the present low market prices, has led to the implementation of a working scheme, based on the following concepts: Detailed knowledge of the distribution and quality of the mineralization by sufficiently close spaced drilling, with 3D positioning and grade estimation by deviation and gamma ray probing. Use of either geostatistical or arithmetical grade interpolation techniques, properly validated with production, adapted to the density of the information available. Economic optimization of the open pit, by means of the 3D Lerchs-Grossmann technique, as a guide for the final pit design. Calculation of the optimal pit shapes and recoverable resources under different price conditions. These techniques implemented by means of computerized data acquisition and processing systems, are used to face with versatility, the present economic conditions. A full review of the uranium deposits in the province of Salamanca is being carried out with these means.

1. URANIUM DEPOSITS AND EXPLORATION IN SPAIN

1.1. Historical exploration in Spain

Uranium exploration in Spain was carried out, from 1950 to 1981 by the Junta de Energía Nuclear (J.E.N.), a public organism that depends on the Industry Ministry.

The Empresa Nacional del Uranio S.A.(ENUSA) created in 1972, is a company owned by the J.E.N. and the National Industry Institute (I.N.I.) (Fig. 1). ENUSA has carried out uranium exploration in Spain and overseas, directly, since 1974 until 1992, when all exploration activities were stopped and all the investigation effort was concentrated on the development and feasibility studies of the FE area deposits.

From 1989 to 1994 a Joint Venture, ENUSA/CISA (COGEMA), has done some exploration in the province of Cáceres (precambrian/cambrian schists and hercynian granites), without outstanding results.

1.2. Uranium deposits

During this time, most of the favourable geological units of Spain have been covered with airborne and ground exploration methods (Fig. 2).

EMPRESA NACIONAL DEL URANIO, S.A.

INCORPORATED IN 1972

ACTIVITIES

-PROCUREMENT OF ENRICHED URANIUM
-PRODUCTION & EXPLORATION OF URANIUM CONCENTRATES
-DESIGN & FABRICATION OF FUEL BUNDLES

PRODUCTS

-ENRICHED UF6 FOR SPANISH REACTORS
-DESIGN & FABRICATION OF FUEL BUNDLES FOR SPANISH AND EUROPEAN REACTORS

SHARE CAPITAL: 10.000 MILLION PTAS

SHAREHOLDERS

TENEO: 60% CIEMAT: 40%

TOTAL WORK FORCE : 703 EMPLOYEES

CORPORATION'S INTEREST IN EURODIF (11,11 %)
CORPORATION'S INTEREST IN COMINAK (10 %)

FIG. 1. ENUSA.

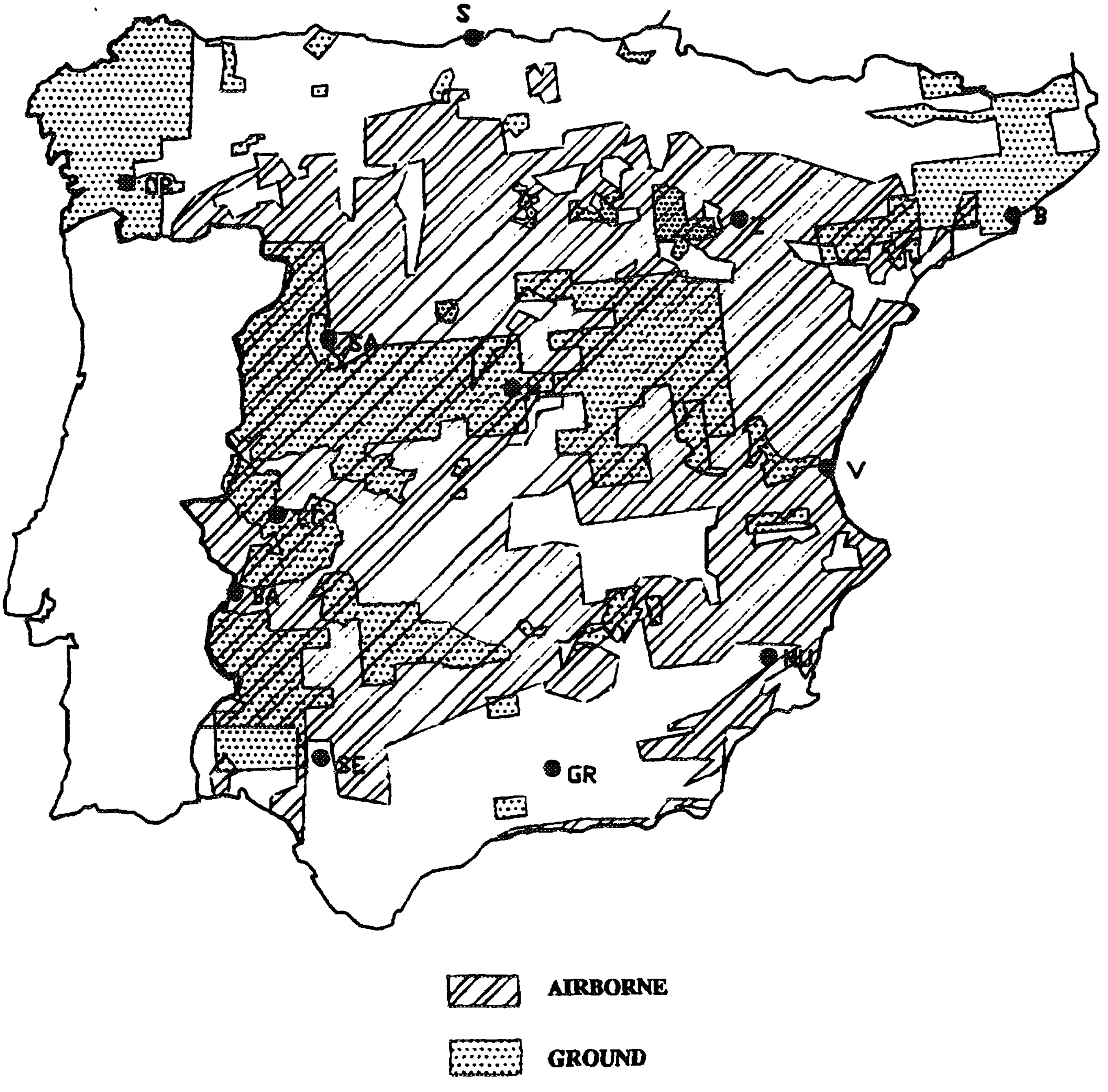
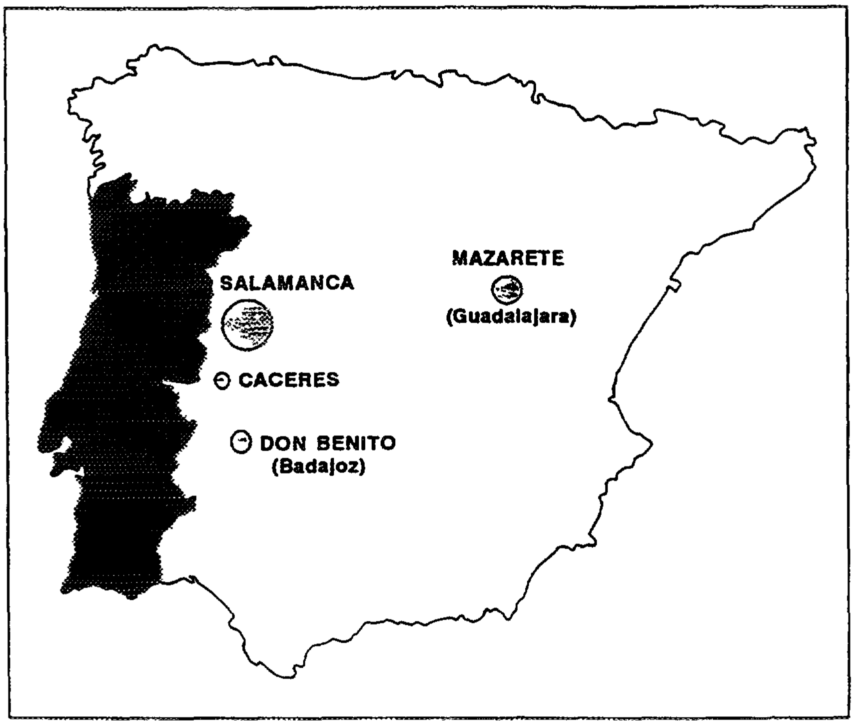


FIG. 2. Areas covered with airborne and ground exploration methods.



AREA	TYPE	IN SITU RESOURCES (t U3O8)	PRESENT SITUATION
CIUDAD RODRIGO (Salamanca Province)	VEIN (IBERIAN TYPE)	36.391	MINING / DEVELOPMENT
CACERES PROVINCE	VEIN (IBERIAN TYPE)	1.082	UNDEVELOPED NOT FEASIBLE PRESENTLY
DON BENITO (Badajoz Province)	VEIN (IBERIAN TYPE)	3.225	UNDEVELOPED NOT FEASIBLE PRESENTLY
MAZARETE (Guadalajara Province)	SANDSTONE	5.666	UNDEVELOPED NOT FEASIBLE PRESENTLY
TOTAL		46.364	

FIG. 3. Uranium in situ resources in Spain.

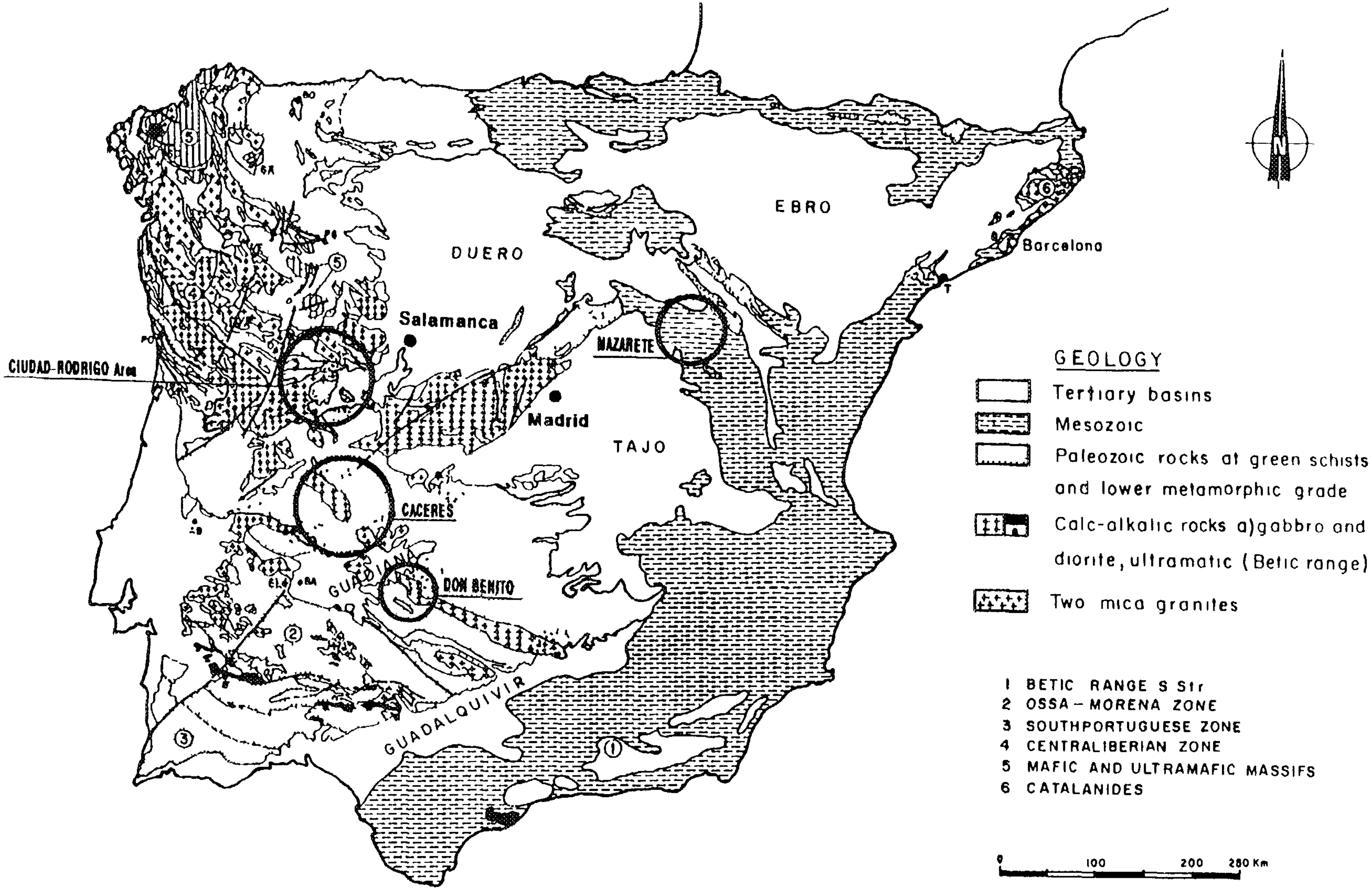


FIG 4 Geological setting of uranium deposits in Spain

Geological setting and in situ resources are given in Figs 3 and 4. Among the great number of occurrences studied, a number of deposits were evaluated, some of them (vein type in granites of Cáceres and Jaen) mined out by J.E.N.. Of remaining deposits the most important are in Salamanca where they are being mined, whereas the rest is not mineable under the present economic conditions.

The main deposits outside the province of Salamanca can be summarized as follows:

PROVINCE	NAME OF DEPOSIT	GEOLOGICAL SETTING	TYPE	IN SITU RESOURCES (t U_3O_8)
GUADALAJARA	MAZARETE	Fluvial sandstone braided channels Triassic (Buntsandstein)	SANDSTONE	5 660
BADAJOZ	DON BENITO AREA	Silurian carbonaceous schists, in contact with granites	VEIN (Iberian) TYPE	3 225
CACERES	ACEHUCHE-CECLAVIN	Precambrian Cambrian schists, in contact with granites	VEIN (Iberian) TYPE	1 082

Most of the in situ resources (78%) and all the presently mineable resources of Spain, are located in the province of Salamanca.

RAR resources amount to 9148 t U, and EAR-I to 10 688 at the < $80/kg U cost range. Average grades range from 0.6 to 2 kg/t, depending on the cut-off grades (from 0.2 to 1.0 kg/t).

The main deposits in Salamanca are of the vein-Iberian type, with mineralization placed in fractured precambrian- cambrian and occasionally silurian schists (map in Fig. 5). The deposits are of a low temperature hydrothermal origin. The main metallogenetic characteristics are summarized in Fig. 6.

The mineralization controls at regional and ore body scale are:

1) Regional fracture zones NE-SW;
2) Ore deposited in associated (Riedel type) fractures, following complex patterns;
3) Ore in a band parallel to the pre-tertiary erosion surface, 5–20 m below and deposited in the reduction zone and lower part of the oxidization zone.
4) Occasional lithological control, when carbonaceous schists and contrasts of competence (hardness) are present.

A block diagram is given in Fig. 7, and a map of mineralized fractures at FE in Fig. 8.

1.3. Historical uranium production

The evolution of the production in Spain, is summarized in Fig. 9.

Production sites at different state of activity are shown in Fig. 10.

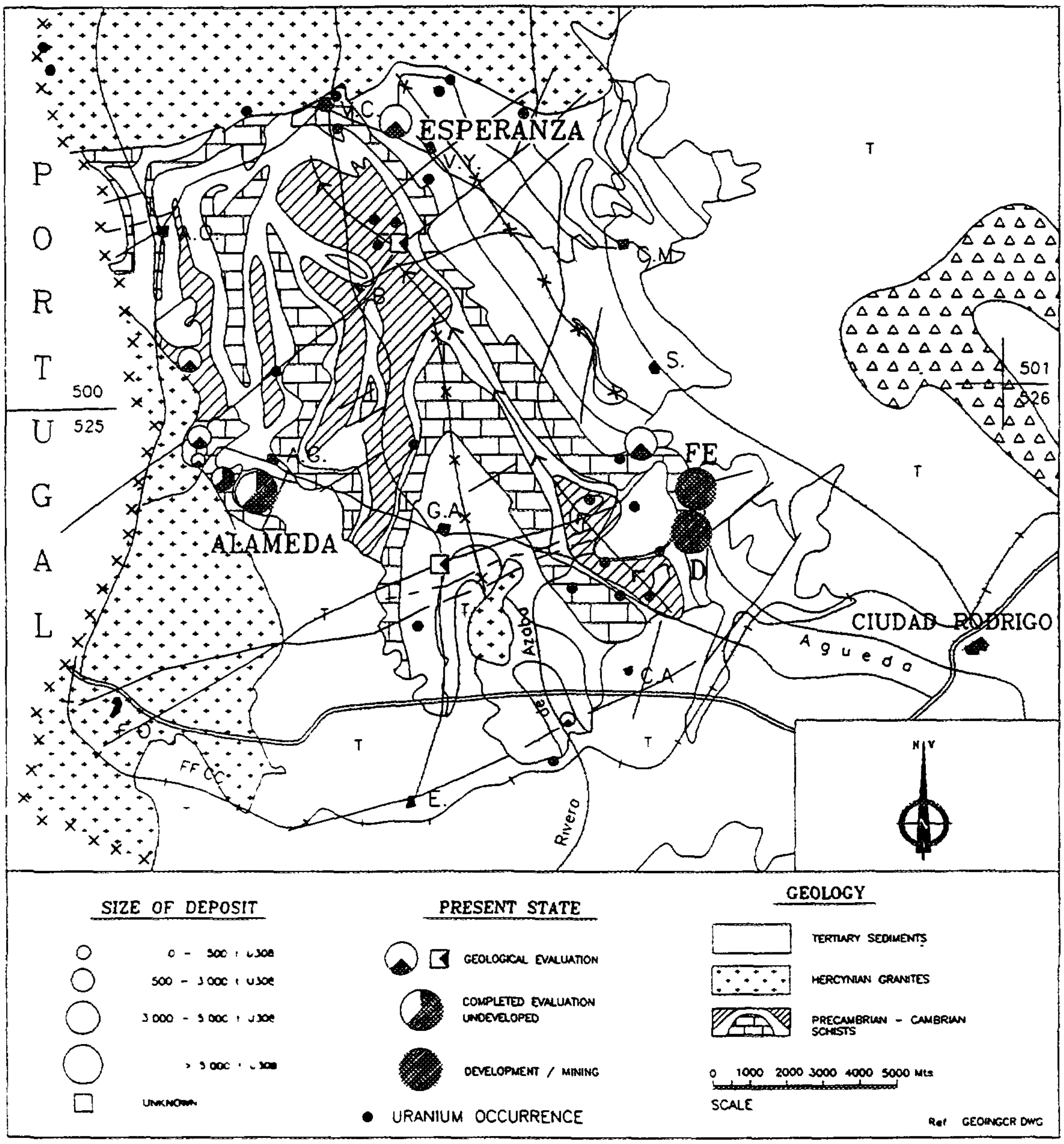


FIG. 5. Geological map with the main uranium deposits in FE area (Salamanca).

1.- **High geochemical U Content** in the carbonaceous schists.

2.- Nature of the alteration processes: **Chloritization** and **hematitization** (intensive but not penetratives).

3.- **Low temperature**, hydrothermal, paragenesis.

4.- Banded, geopetal and varved structures; **Subsurficial environments** and **intermittent character** of the mineralization.

5.- **Radiometric age** of the pitchblende (37 - 57 m.a., lower tertiary).

6.- **Temperature** (70 - 230°C) and salinity (0 - 25% NaCl) deducted from fluid inclusion studies.

7.- Primary ore placed in **fractures** and **breccias**.

8.- **Surficial character** of the tectonic processes.

FIG. 6. Metallogenetic characterization of FE type uranium deposits.

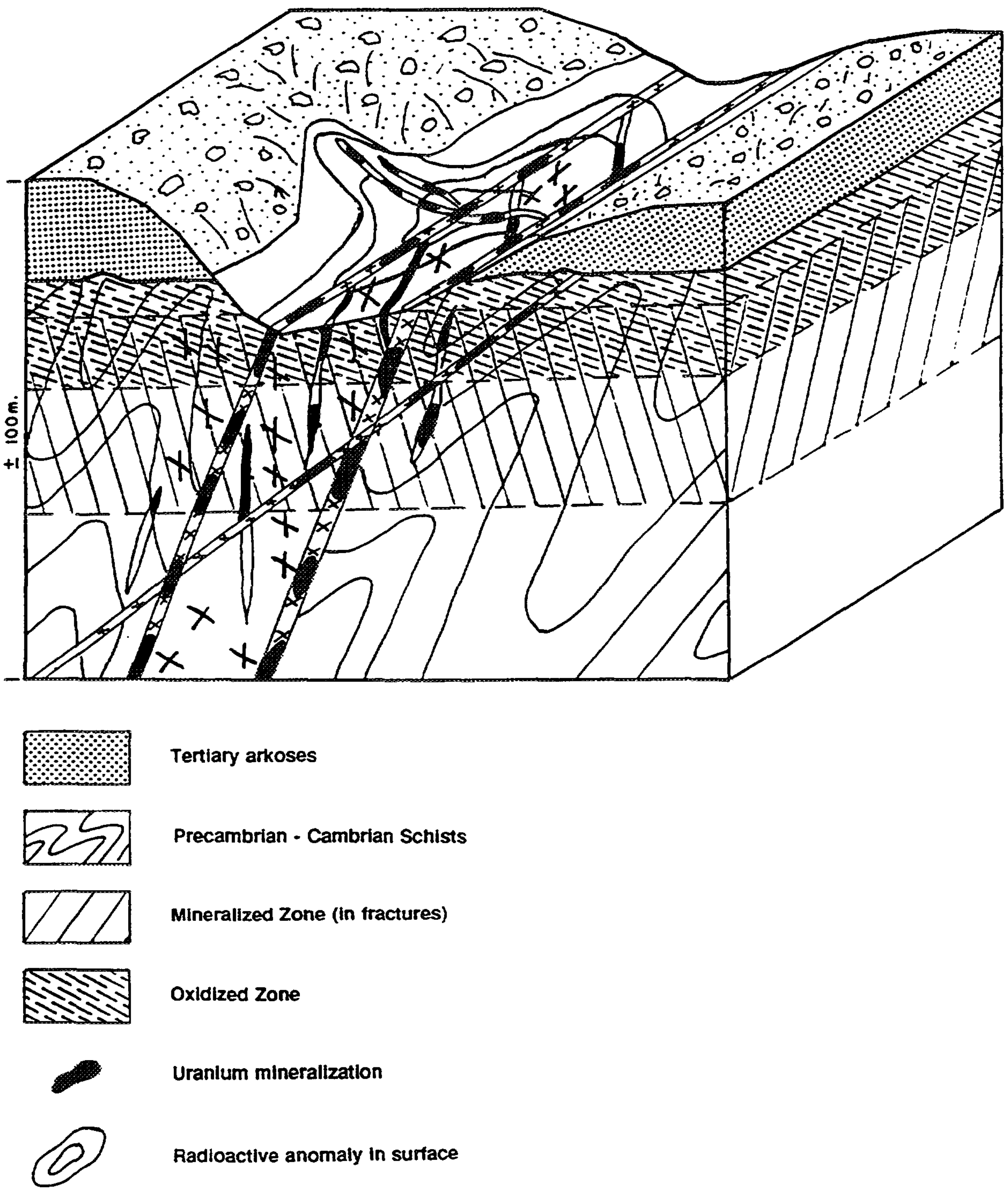


FIG. 7. Uranium ore controls at FE area (diagram).

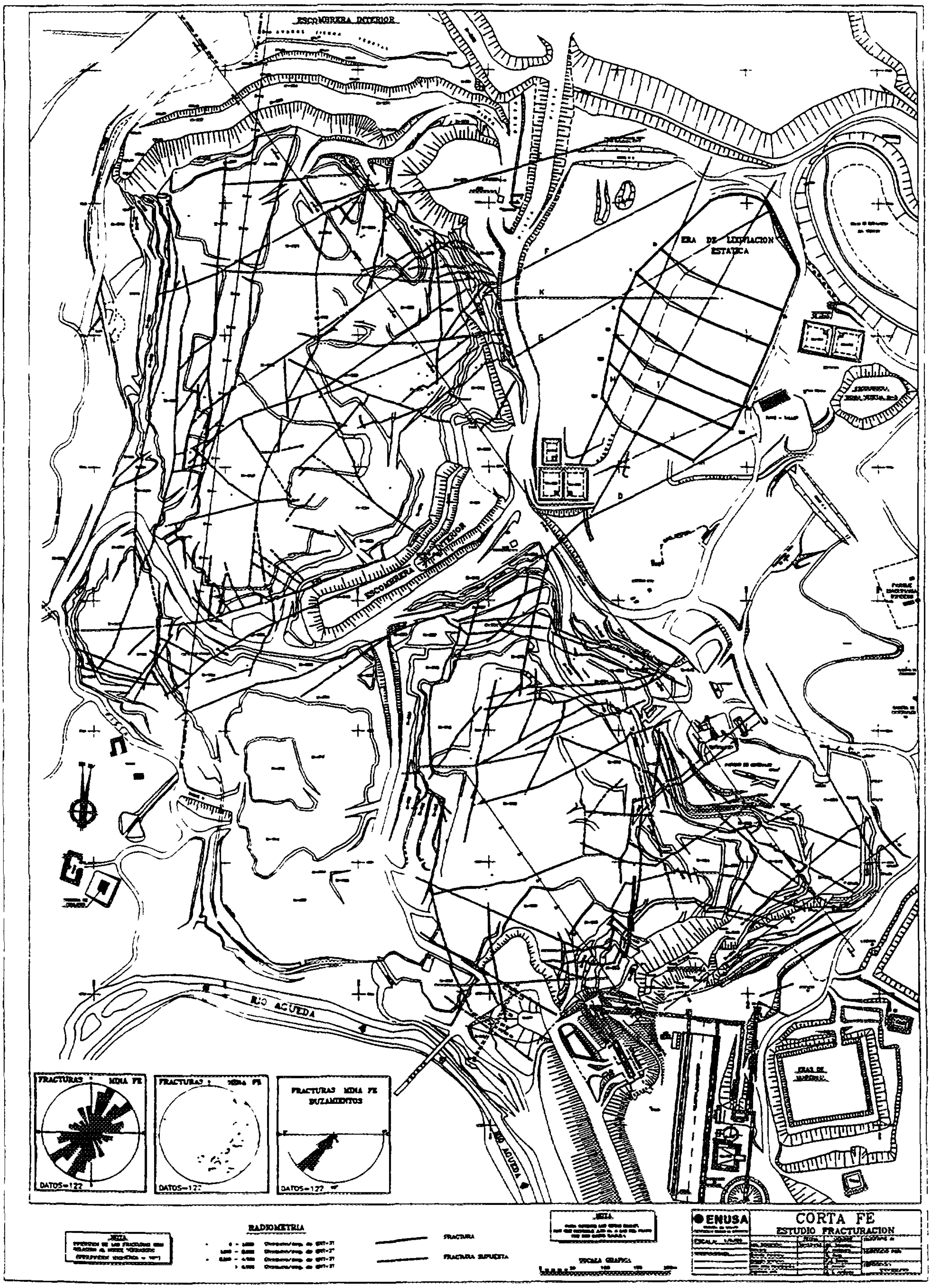


FIG. 8. Mineralized fractures at Fe mine.

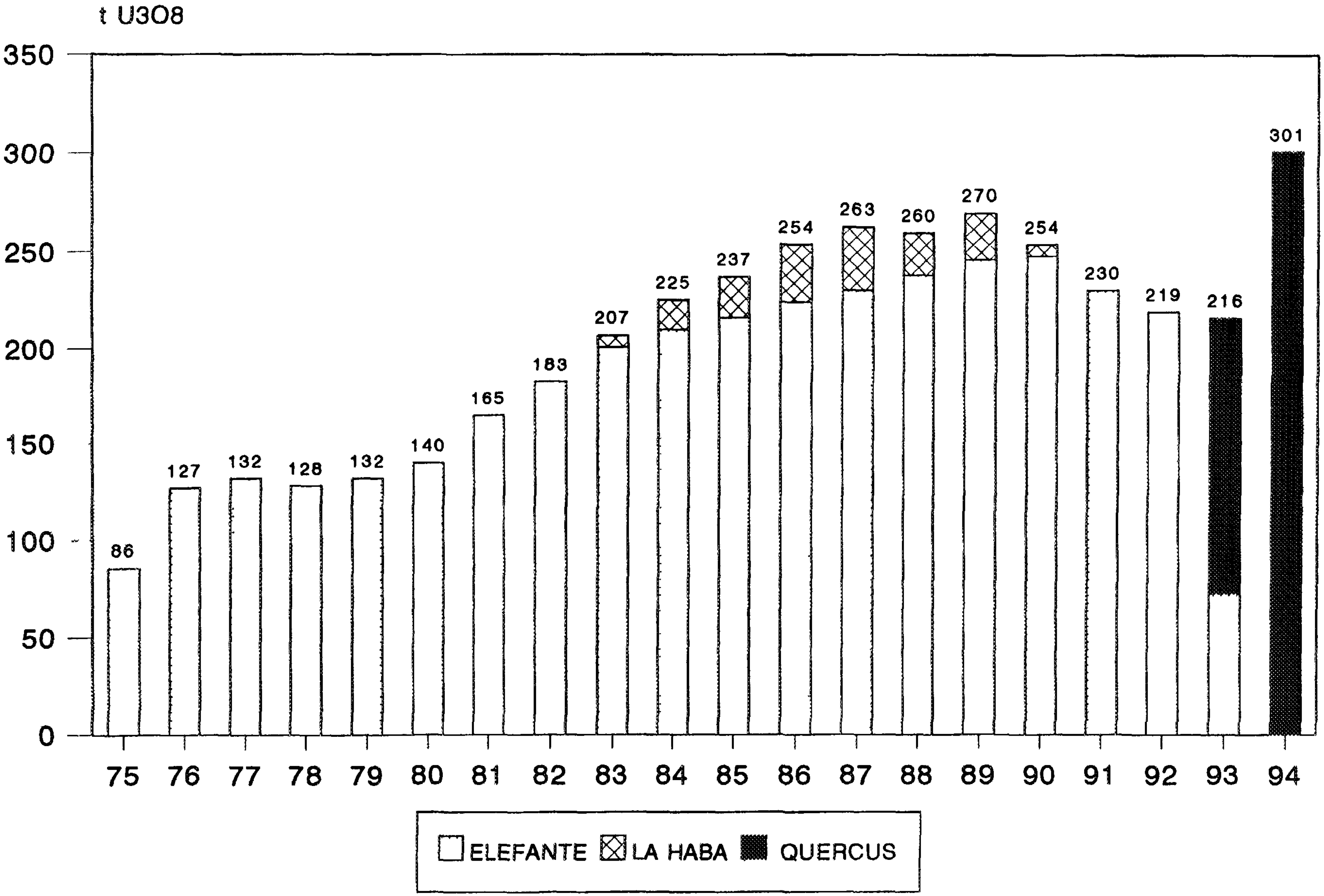


FIG. 9. Historical evolution of uranium production in Spain

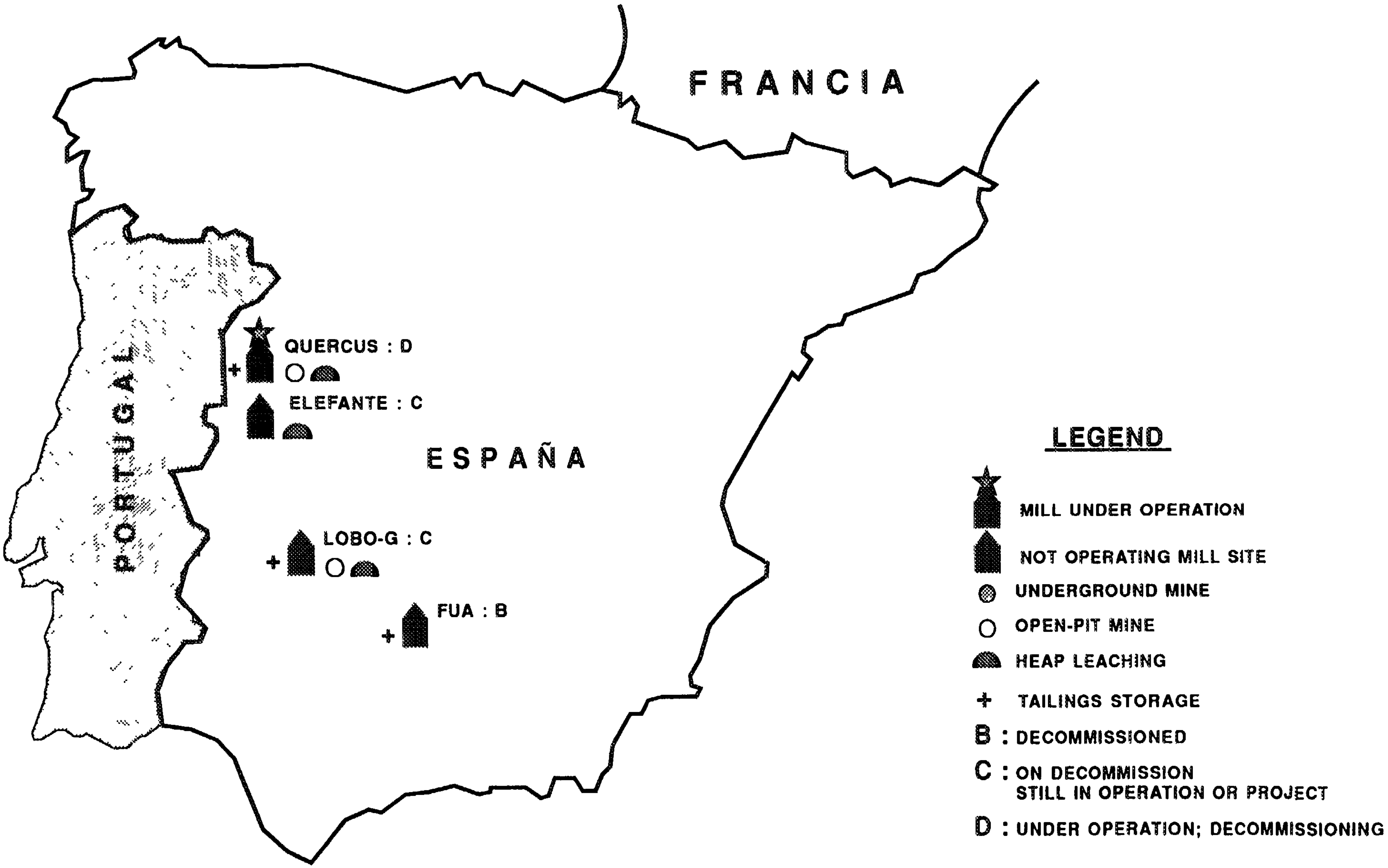


FIG 10 Uranium facilities in Spain

2. PRESENT ACTIVITIES

2.1. Exploration/development

2.1.1. General

Presently, all investigation related activities are concentrated in FE area, province of Salamanca, where development drilling at 10 × 10 m spacing, is being carried out at a rate of 100 000 m of percussion boreholes per year. In Fig. 11 all exploration and development drilling in recent years is shown compared with in situ resources.

Great effort is being made to complete the investigation of the D and M-SAGERAS deposits close to FE (Fig. 5), from which all medium to short term production will be obtained, together with FE.

2.1.2. Implementation of new integrated data acquisition and processing techniques to investigation by close spaced drilling, open pit design and mine planning

In the present situation of low market prices for the concentrates, it becomes very important to reduce production costs. The first step is to have the best possible knowledge of the deposits, so to be able to plan accurately the mining operations. This affects the following aspects:

- grade and tonnages forecast,
- localization of ore,
- localization of barren areas in or nearby the deposit, to place waste dumps, in order to reduce transport distances,
- design of haulage roads,
- determine types of ore that need different processing parameters.

The acquisition/processing system at FE is shown in Fig. 12.

To achieve this, ENUSA has upgraded the following phases of the process:

2.1.2.1. Grade estimation by simultaneous gamma ray and deviation logging

In the FE type deposits, due to the foliated and fractured nature of the schists, borehole deviation can be of importance at the 10 × 10 m grid scale (Fig. 13). To correct this, boreholes are logged systematically with simultaneous gamma scintillometric and magnetometric deviation probes. Position and radiometry is recorded every 10 cm.

Great care is taken regarding the regular calibration of probes, correction of background (most due to Rn), and water absorption (see Fig. 14). Grade is estimated through the application of correlation curves, specific for each deposit. The whole process is computerized.

2.1.2.2. Ore body grade modelling by geostatistics and other methods

All borehole data is stored in a workstation with the processing programs. Due to the irregular distribution of the ore, geostatistics are only used in the wide spaced data, whereas average within surface of influence, has proved to be more accurate, with data from the 10 × 10 m grid. This fact can be seen taking the example of an area in FE, comparing data from kriging and average with production (Fig. 15).

2.1.2.3. Economic optimization of open pit design

Economic optimization and analysis is done systematically on all deposits, as a guide for the final pit design. Three dimensional Lerchs-Grossman optimization techniques, implemented through the WHITTLE-4D software, are used.

Bearing in mind the present economic situation, ENUSA tries to mine its deposits as economically as possible and to maintain open the possibility of future exploitation of lower grade ore, not mineable today.

When deciding the optimum pit for the price considered (Fig. 16), the pit with the maximum net present value (N.P.V.), is initially chosen. As the N.P.V. curve is normally quite flat in its maximum, and if the pit permits a convenient scheduling of the mining operation, a bigger pit can be chosen if trying to increase the recoverable resources, or a smaller one if the scheduling is difficult, without much change in its economic value.

In short the priorities for ENUSA are:

- Design a pit that will produce the maximum economic value.
- Design a pit that, once mined out, permits, if economic conditions improve, mine the remaining, lower grade ore (nested optimum pits).
- Schedule the mining operation looking for short distances to dumps but without dumping waste over lower grade ore zones, mineable at reasonably higher prices.

2.1.2.4. Estimation of recoverable resources at different economic conditions

Using the same techniques, a range of optimum pits for different prices can be obtained (Fig. 17). This curve is valid as far as the level and distribution of costs does not change significantly, that is, the mining and treatment methods do not change.

2.2. Production

In 1994 production was started at D mine, simultaneously with FE. Treatment of the ore is done at the Quercus Plant (Fig. 18), that was commissioned in 1993. The plant uses a mixed dynamic-heap leaching process. One characteristic of the FE ore is that uranium gets concentrated in the fine grained material. The ore is sorted at the following sizes:

	> 10 mm	Waste	(67% tonnes; 15% U_3O_8)
1 mm	$< x < 10$ mm	Heap leaching	(22% tonnes; 20% U_3O_8)
	< 1 mm	Dynamic leaching	(11% tonnes; 65% U_3O_8)

The treatment is acid leaching, with solvent extraction and precipitation with ammonia. The capacity of the plant is 950 t/year, being the present production level of 300 t/year.

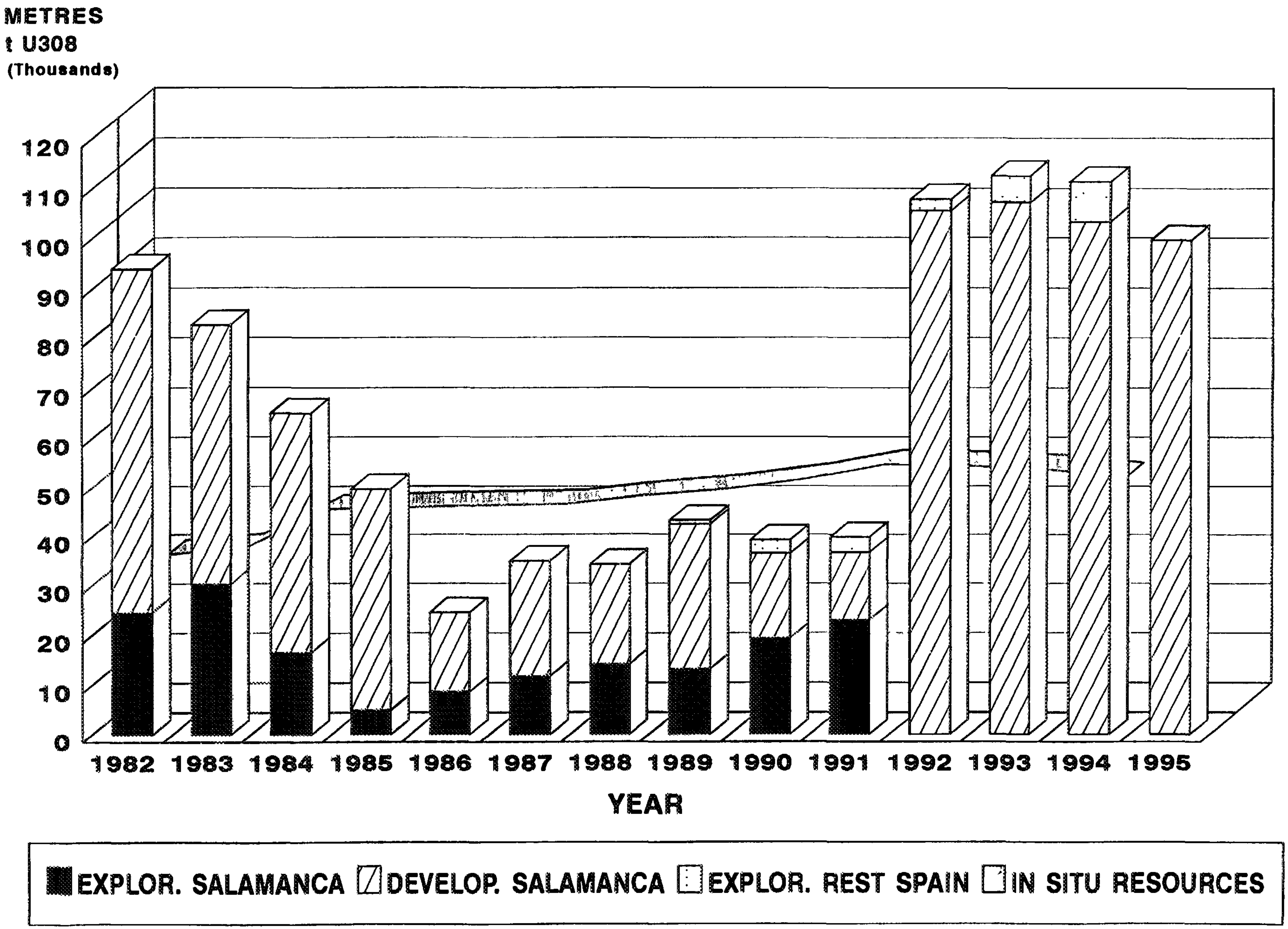


FIG. 11. Exploration and development drilling.

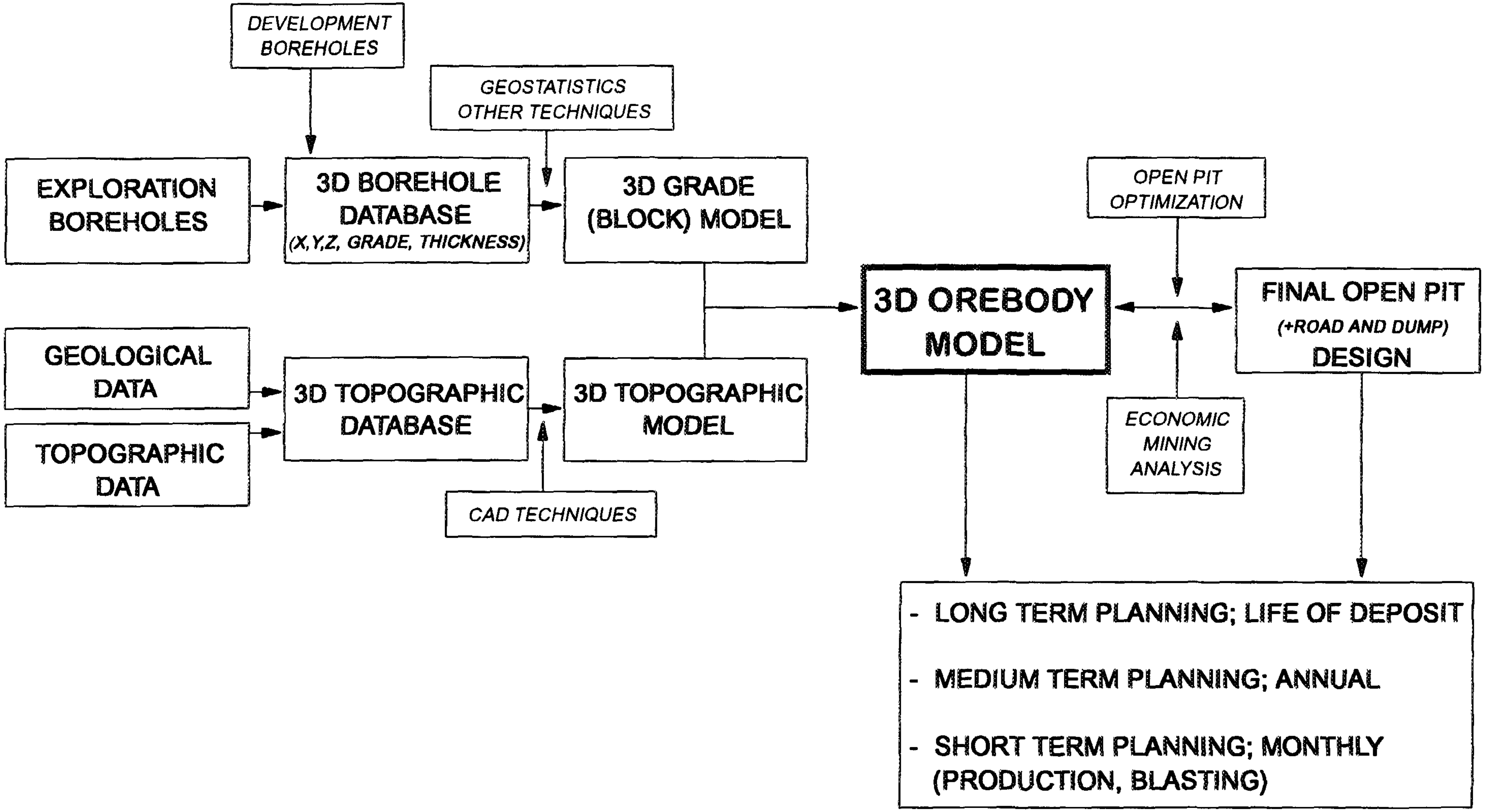


FIG. 12. Diagram of borehole data acquisition/processing at FE.

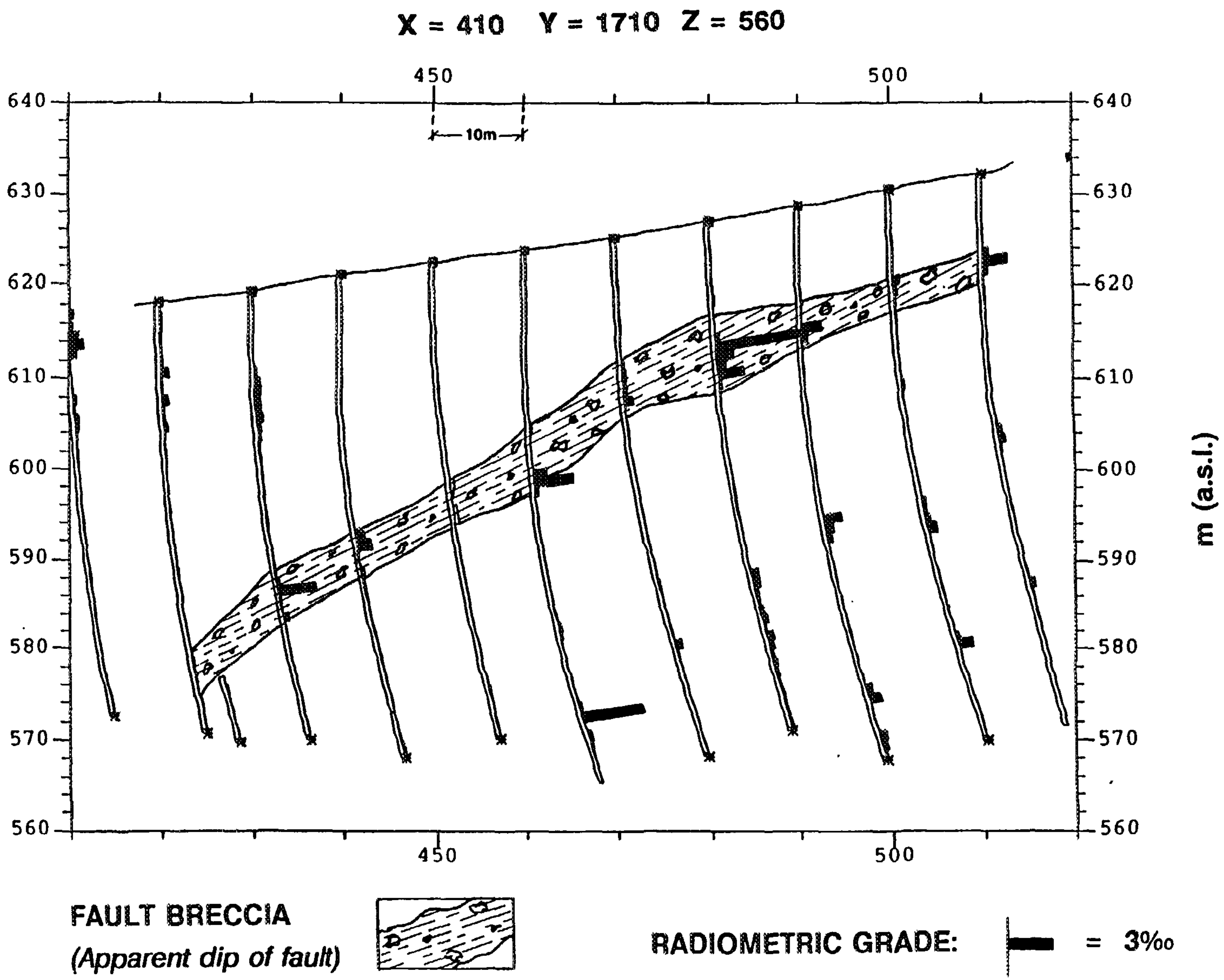


FIG. 13. Borehole profile from D Mine.

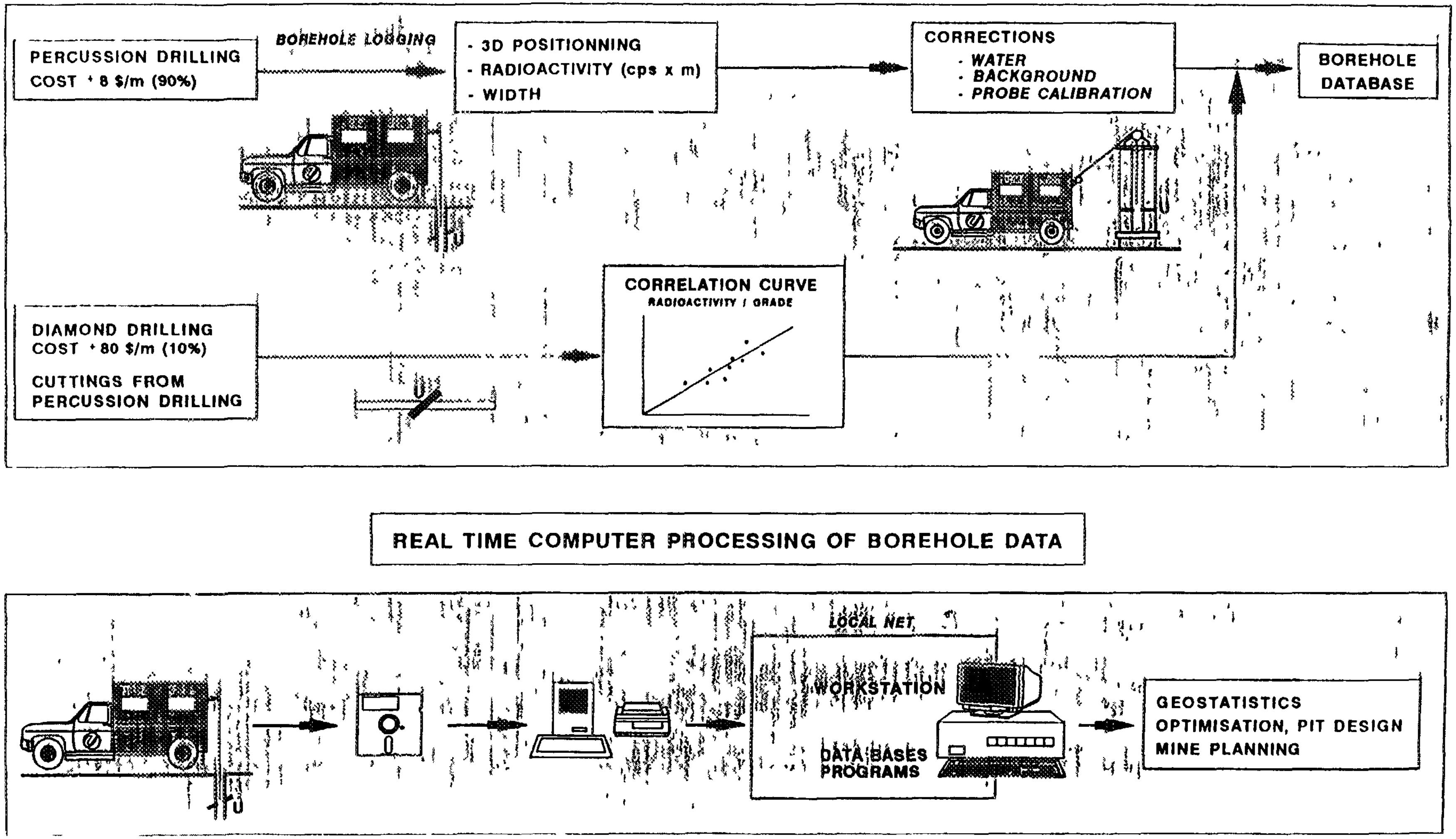


FIG. 14. Grade estimation by gamma ray logging

EXPLORATION GRIDS / INVESTIGATION	(50 x 50 m) (20 x 20 m)	METHOD: KRIGING
DEVELOPMENT / GRIDS PRODUCTION	(10 x 10 m)	METHOD: AVERAGE IN SUFACE OF INFLUENCE

COMPARISON PRODUCTION BENCH 618-624 (FE)			
	ORE (t)	GRADE (Kg/t)	U308
PRODUCTION	77.247	0,480	37.046
AVERAGE	83.267	0,453	37.696
KRIGING	60.639	0,391	23.688

FIG. 15. Comparison of kriging with average at FE.

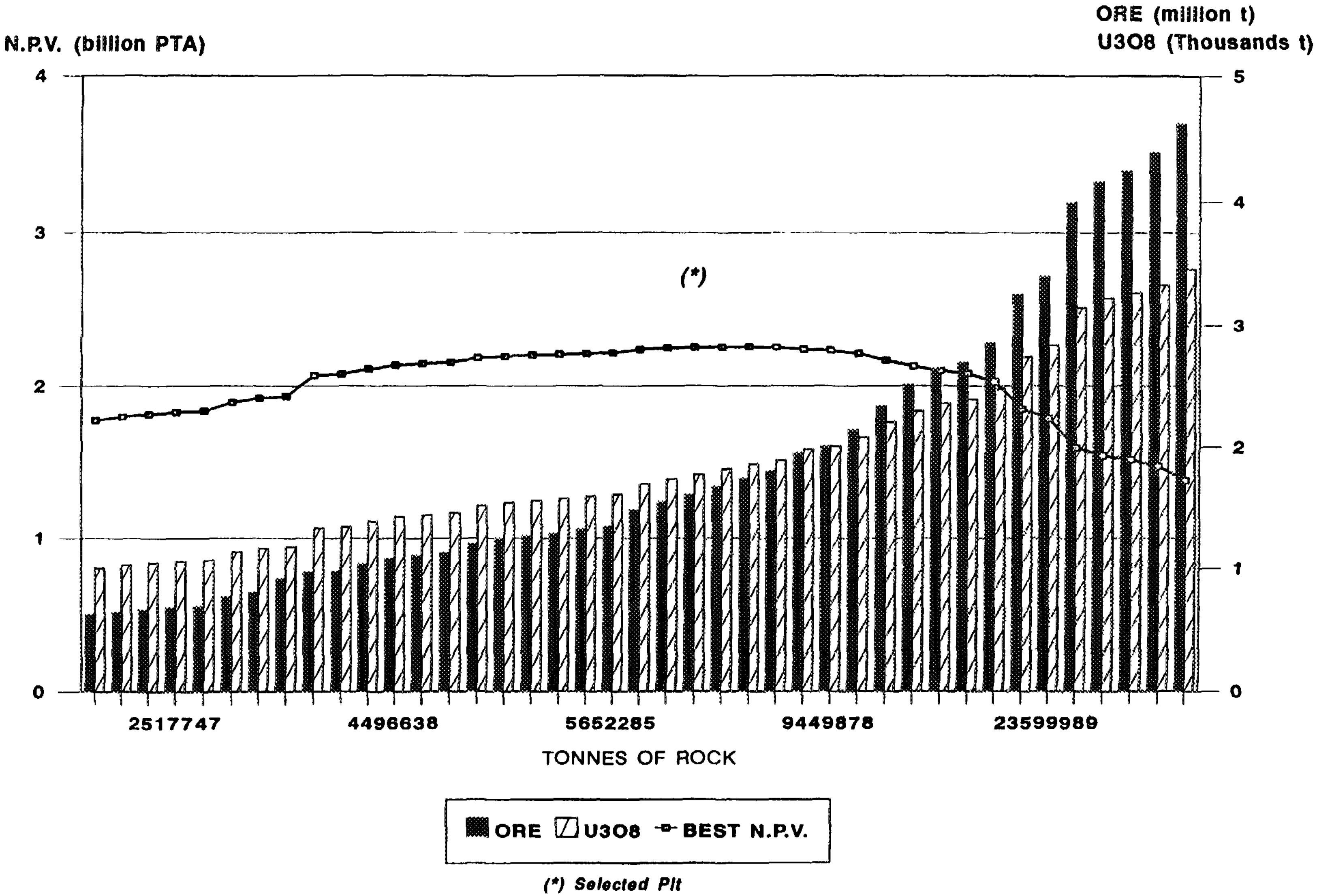


FIG. 16. Optimum pit for current price.

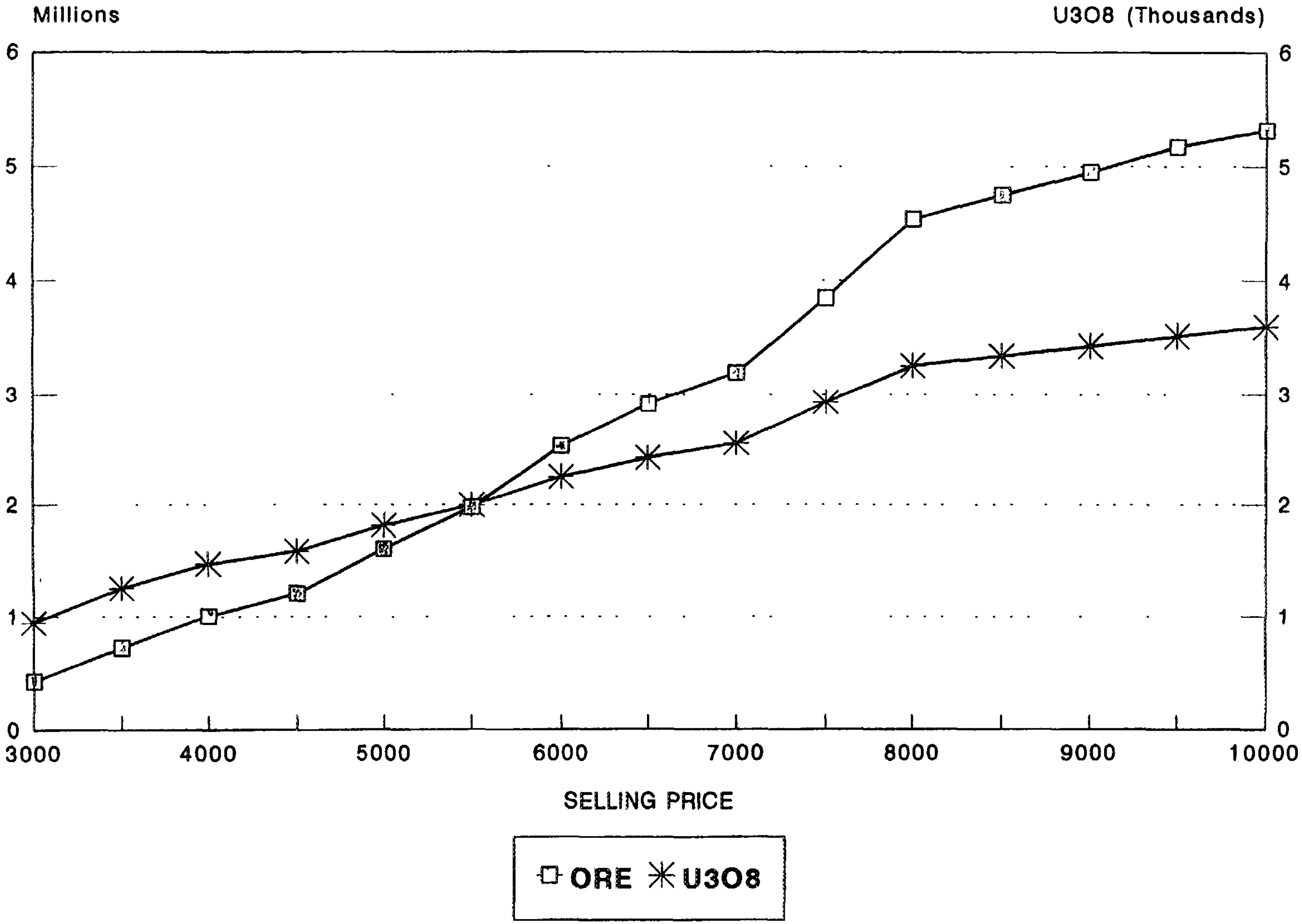


FIG. 17. Recoverable resources versus price curve.

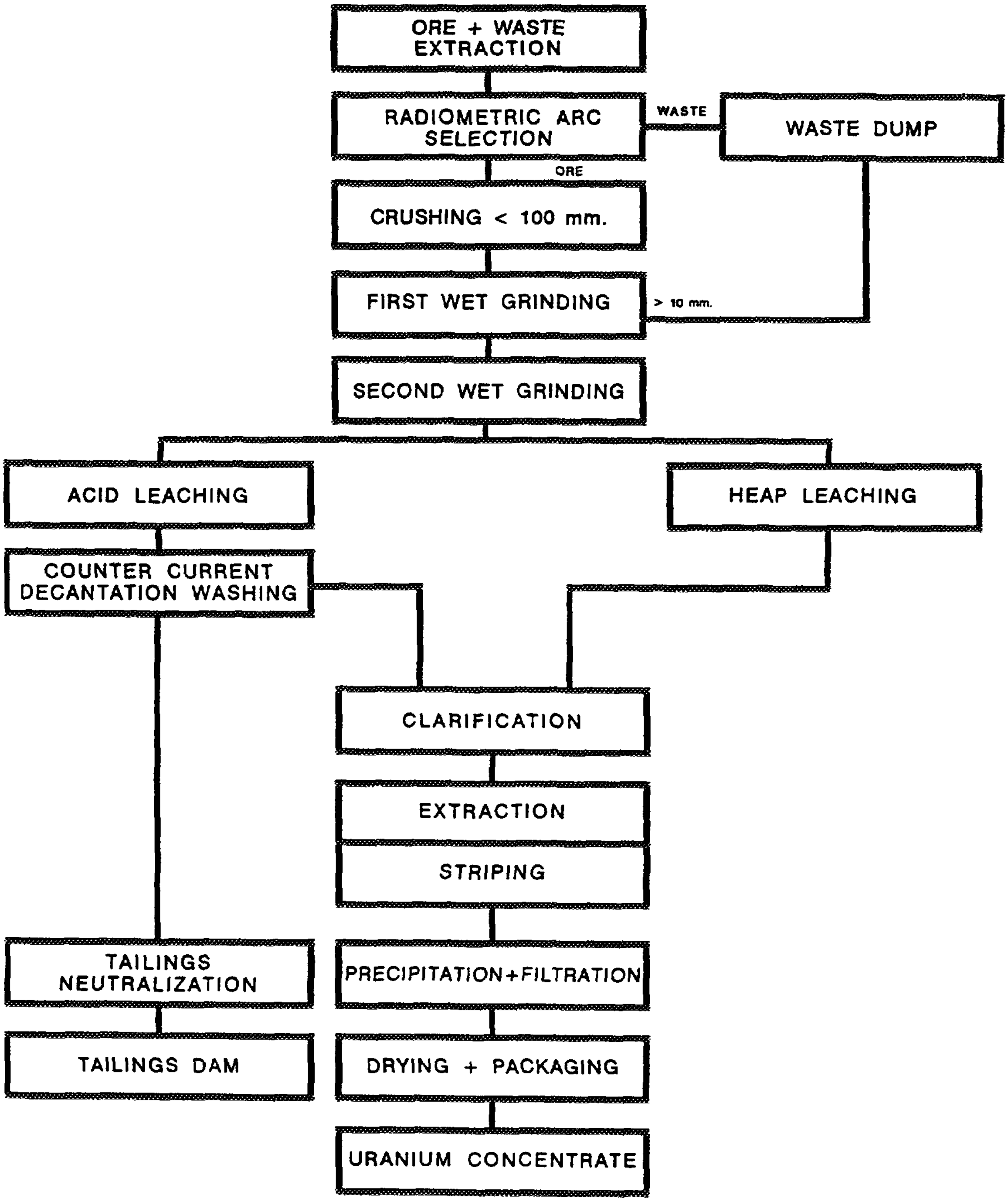


FIG. 18. Flow diagram of the Quercus Plant.

2.3. Decommissioning

The Andujar Plant was decommissioned by ENRESA (Spanish Radioactive Waste Disposal National Company), ending in 1993. Decommissioning of the LOBO-G plant in La Haba Mining Centre by ENUSA is scheduled to be completed in 1995. Within the Saelices Mining Centre (FE mine), the old ELEFANTE plant is being, presently, decommissioned.

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STATUS OF THE McCLEAN PROJECT, SASKATCHEWAN, CANADA

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Abstract

The paper describes the status of development of the McClean Lake uranium production project. The project includes development of a new mine/mill complex located 10 kilometres west of the Rabbit Lake mine site, in the Athabaska region of northern Saskatchewan, Canada. This first Canadian uranium project since Key Lake was developed in the late 1970s, is planned to help provide the increasing need for uranium production during the rest of the 1990s and beyond. The report describes the geological model for the 6 unconformity-type uranium orebodies named: JEB; Sue A, B and C; and McClean Lake A and B. These deposits will be extracted using both open pit and underground mines. The report describes the history of exploration and development, as well as the progression of the environmental clearance process under the joint review panel of the Canadian and Saskatchewan governments. The Canadian$250 million project, operated by Cogema Resources, is jointly owned by Denison Mines Limited, Minatco Limited and OURD (Canada) Company Limited. It is scheduled to start producing uranium concentrate in 1997.

1. INTRODUCTION

On March 16 1995, Cogema Resources, the operator, launched the McClean project, a new uranium mine and mill in Canada. McClean is located in the northeastern region of the Saskatchewan province, about 10 kilometres west of the Rabbit Lake mining site (see Fig. 1).

This decision followed the approval given in late 1993 by both levels of government after the careful review undertaken by a joint federal/provincial panel.

The McClean Lake project is a joint venture between 3 partners:

- Denison Mines Limited: 22.5%,
- Minatco Ltd (a wholly owned subsidiary of Cogema): 70%,
- OURD (Canada) Co Ltd: 7.5%.

About Can$ 250 million will be invested in the project with a production start scheduled for 1997.

2. THE OREBODIES

2.1. Geological setting

The McClean project includes various orebodies of the unconformity type occurring at depths varying between few tens of meters to about two hundred meters:

- JEB, the first to be mined (open-pit),
- the Sue orebodies (A,B,C...),

The McClean A and B orebodies.

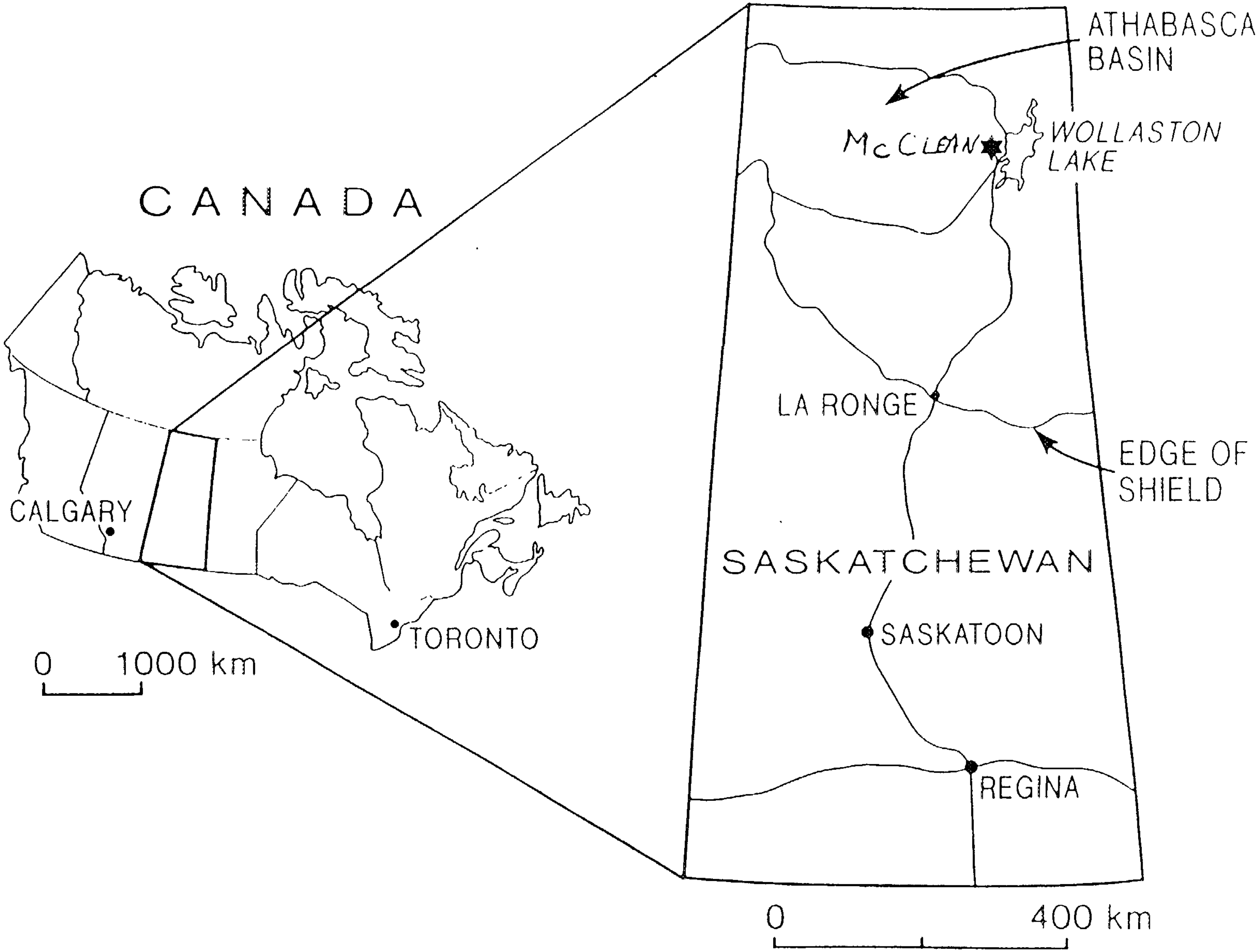
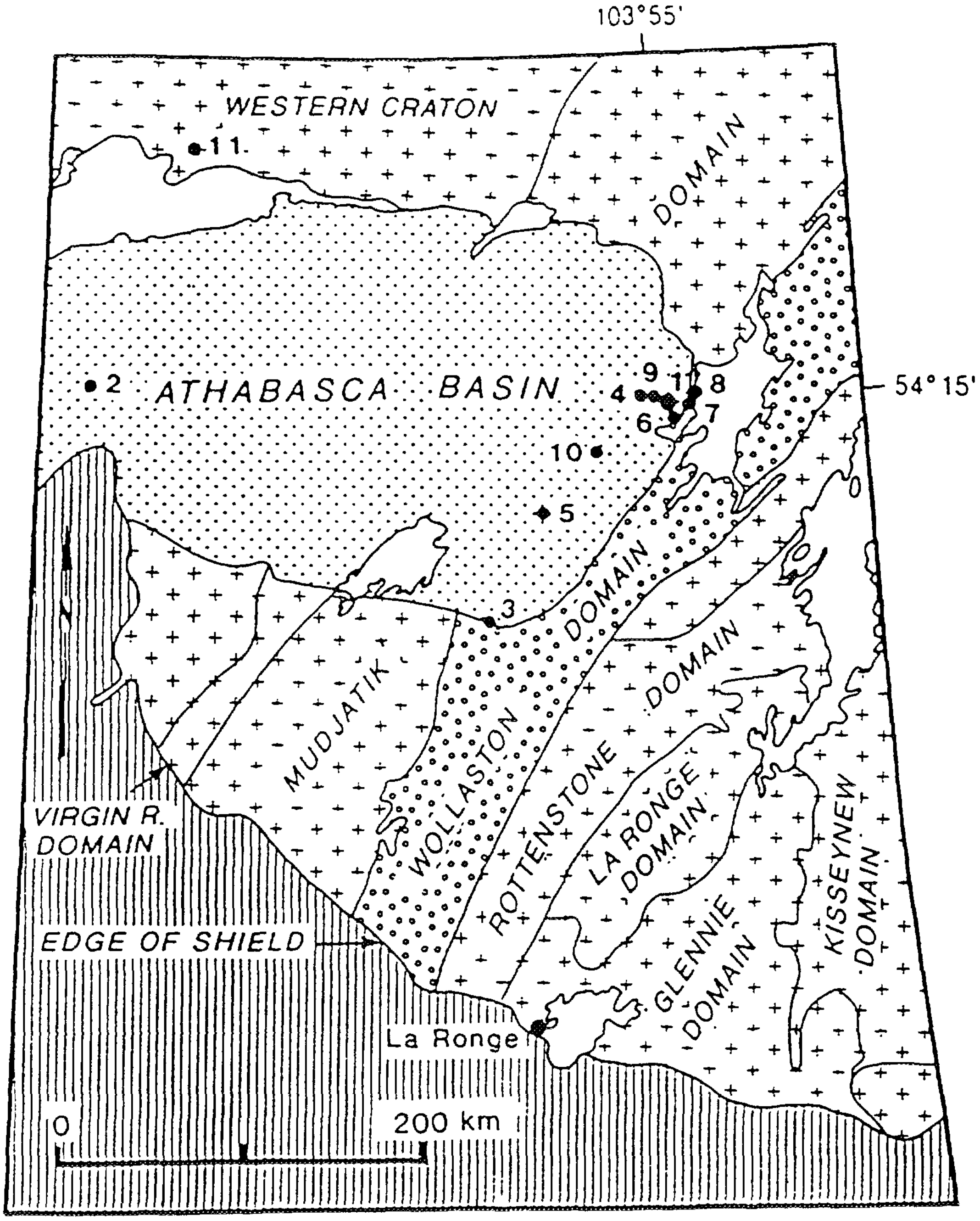


FIG. 1. Location of the McClean project.



1 **McCLEAN**	5 McARTHUR	9 DAWN LAKE
2 CLUFF LAKE	6 RABBIT LAKE	10 CIGAR LAKE
3 KEY LAKE	7 COLLINS BAY	11 URANIUM CITY
4 MIDWEST	8 EAGLE POINT	

FIG. 2. Subdivisions of the Canadian shield and U deposits.

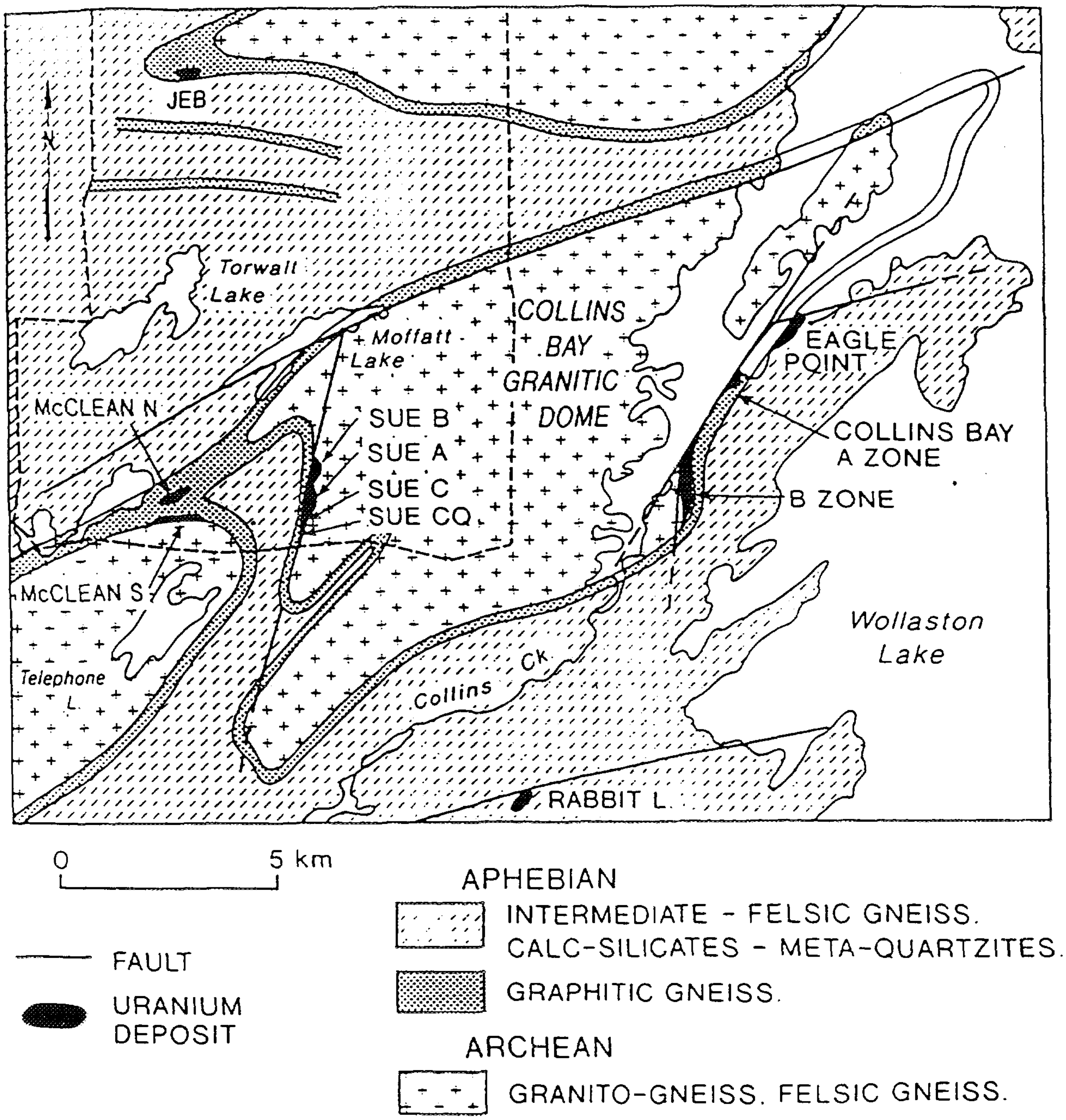


FIG. 3. Uranium deposits around the Collins Bay Dome.

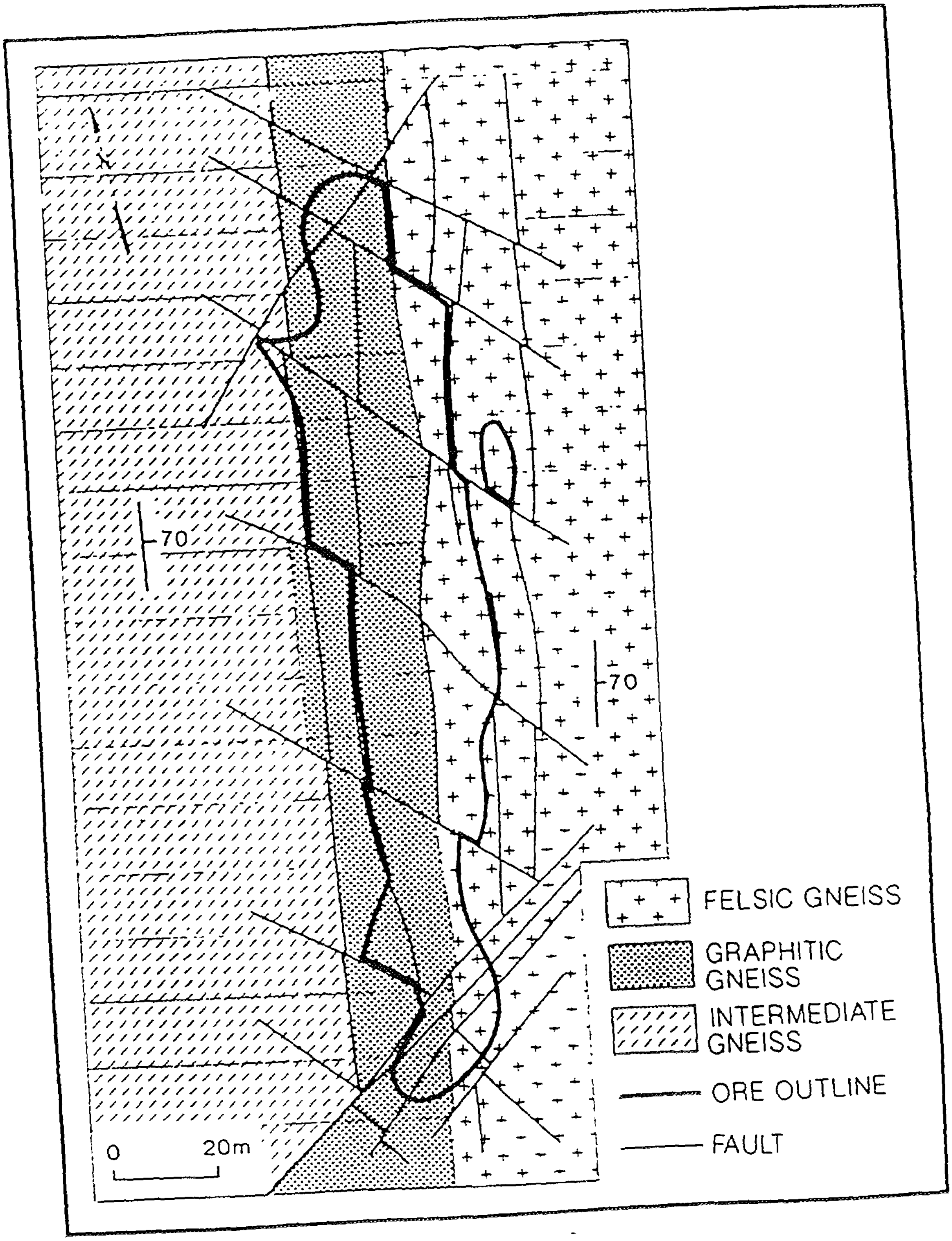


FIG. 4. Sue A deposit. Geology at the unconformity.

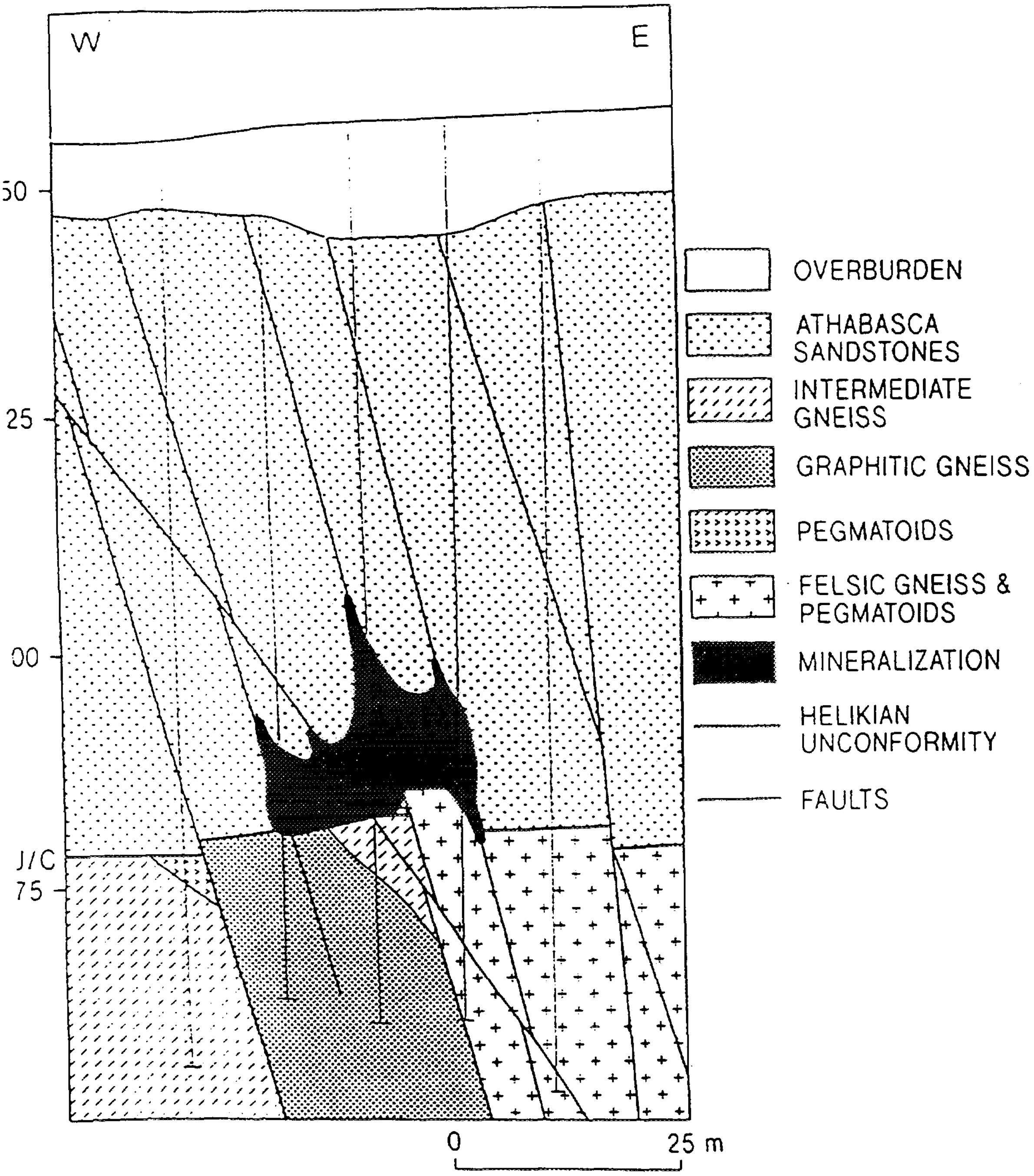


FIG. 5. Sue A deposit. Cross section (500 ppm cut-off).

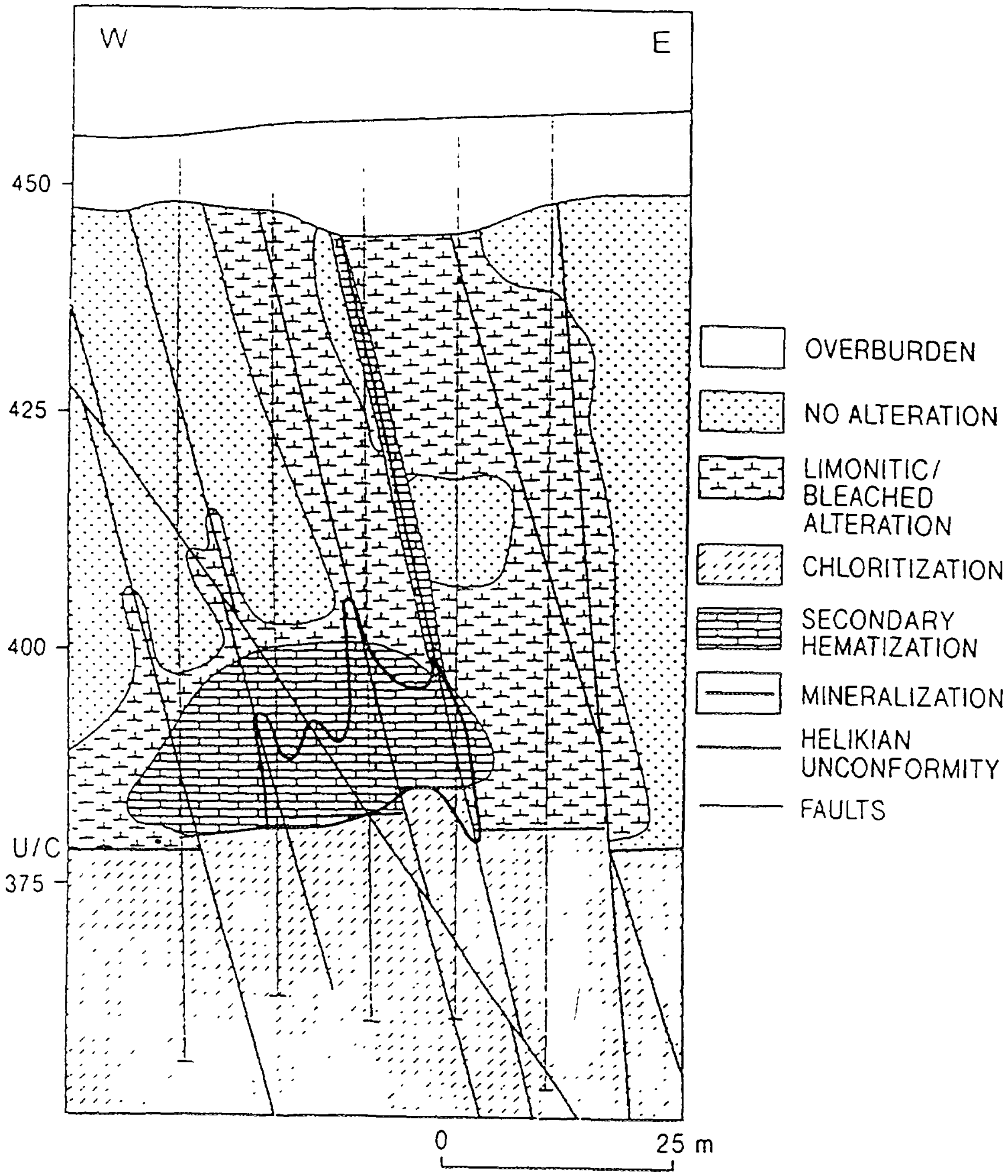


FIG. 6. Sue A deposit. Surrounding alterations.

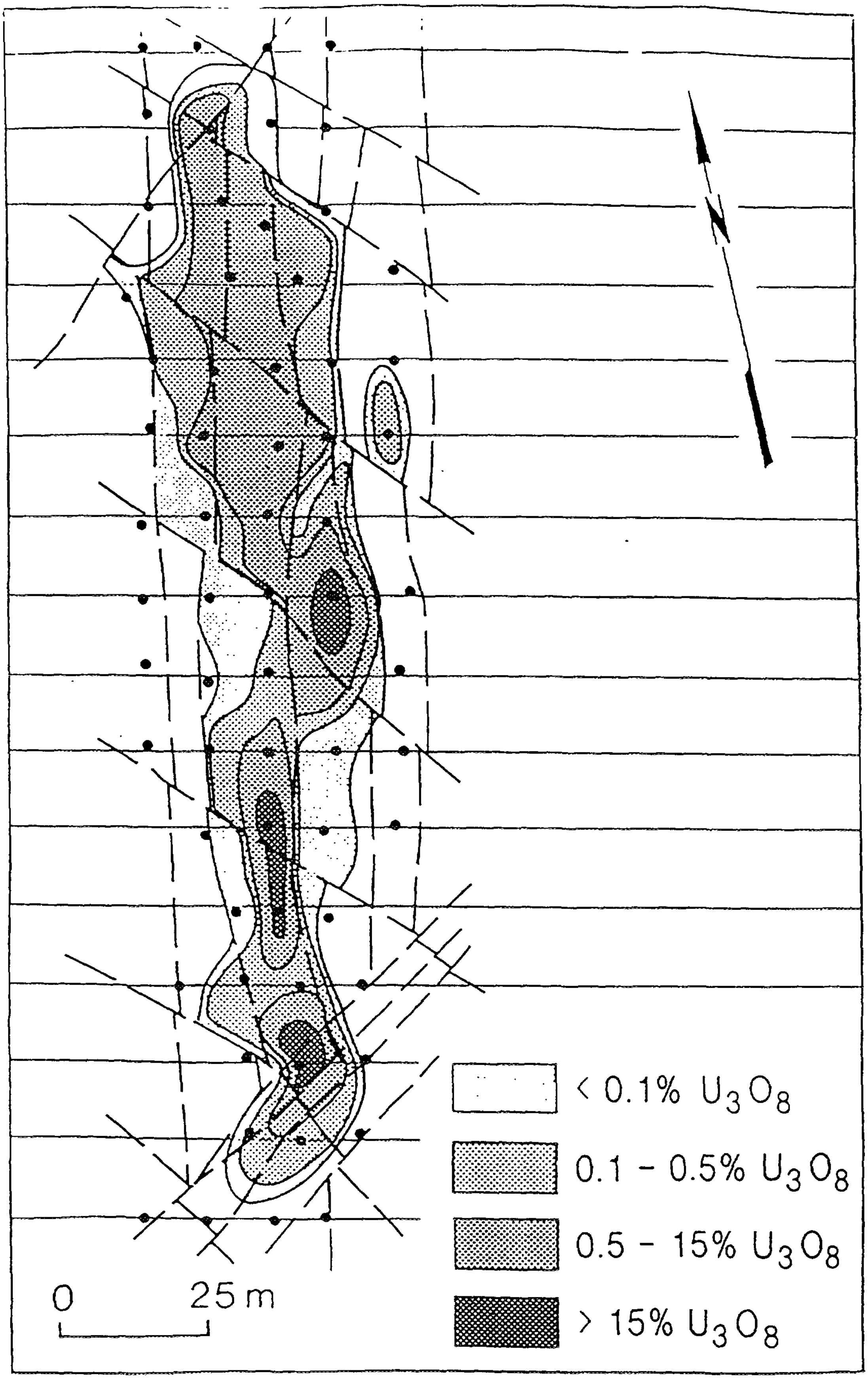


FIG. 7. Sue A deposit. Plan map of the ore outlines.

The deposits are located at the eastern edge of the Athabasca Basin (Fig. 2). The initial discovery of what has now been named the McClean orebody occurred beginning of 1979 (Fig. 3). It was followed in 1982 by the discovery of the JEB deposit and in 1985 by SUE A, the first of the series of the SUE deposits. To date, the total known mineable reserves amount to about 20 000 t U with an average uranium content of 2.8%.

The McClean deposits are spatially related to the unconformity separating the Helikian Athabasca sandstone group from the underlying graphitic metasediments of the Wollaston Group and are located at the edges of presumed Archean domes, the SUE deposits being located at the western edge of the Collins Bay Dome along a 3 km long NS trend.

The orebodies can be basement hosted or sandstone hosted. Like other orebodies in the area, the high grade core of the McClean orebodies are fault controlled and have a spatial relationship with a graphite rich pelitic gneiss. This association has allowed the development in the area of an exploration approach involving a combination of geophysical techniques. Various conductivity methods have proved very successful, pinpointing blind mineralizations at depths greater than 500 metres below the sandstone cover.

In the McClean area, uranium mineralizations can be alone or associated with nickel and cobalt.

2.2. The Sue A deposit

While each orebody presents its specific characteristics, the various orebodies have numerous common features. Therefore only Sue A is described with some detail. A more general description of the various Sue deposits can be found in IAEA-TECDOC-650 [1].

The Sue A deposit lies between 60 and 75 metres below surface (Figs 4, 5) and strikes to the north. The deposit is nearly 200 m long with a width averaging close to 20 m. Its average thickness is 9 m. The mineralization is highly fault controlled, resulting in irregular cross-sectional shape. Mineralization terminates against two sets of faults: northeast and northwest in direction.

The deposit (Fig. 6) lies on and immediately above the unconformity in an envelope of massive earthy-red clay. Argillic alteration extends almost to the sandstone subcrop along fault zones, leaving only scattered silicification in the cap rock. About 9 m of glacial overburden covers the sandstones.

Minor amounts of U mineralization extend downward into the basement as narrow roots along faults. Less than 2% of the Sue A deposit lies below the unconformity.

The distribution of uranium is confined to a few high grade (>5%) pods, mostly in the southern part of the deposit, where 70% of the total uranium is located (see Fig. 7). Grades exceeding 15%U occur.

2.3. The geological model

The McClean deposits display many of the characteristics of the Athabasca deposits (see Fig. 8). The mineralizations are genetically related to one or more graphitic metapelitic units ranging in graphite from 1 to 70% and associated with the unconformity between the sandstones and the aphebian horizons in various ways:

- straddling the unconformity generally in a pencil shaped form,

- as a single tabular vein or multiple lenses in the metapelitic gneiss,
- perched in the sandstones.

The sandstones and basement rocks surrounding the orebodies have been considerably transformed in various clay minerals during a widespread hydrothermal event. Argillization, mineralization and silicification are synchronous events associated with the main reverse fault as part of a continuous tectonic-hydrothermal process.

In general, the deposits are structurally controlled by reverse faults originating in and paralleling the graphitic metasediments. These faults control the lateral extent of the mineralization and create horsts and offsets of the unconformity surface.

3. THE AUTHORIZATION PROCESS

This lengthy process started in 1991 with the announcement by both federal and provincial governments that they would organize a joint review of proposed new uranium developments in the Saskatchewan province of Canada.

In August 1991 a joint federal/provincial panel was appointed. Its recommendations were submitted to both governments in October 1993. By the end of 1993, McClean was given green light.

The various stages

The review: A brand new mine and/or mill project must be reviewed by both control boards, the Canadian Atomic Energy Control Board (AECB), and the Saskatchewan Environment and Resource Management.

The preparation of guidelines: They had been prepared by the assessment office of Saskatchewan Environment and Resource Management.

The public hearings: After initial review lasting close to three months by a panel, chosen because among other criteria they had never been exposed to the uranium mining business, the public hearings took place. During these hearings, much broader issues than the only technical merits of the submitted project were discussed.

The Panel's Report: The recommendations were to allow McClean to proceed in 5 years (apparently with a view to implement a strategy of staged development of uranium resources in Saskatchewan).

The Government's decision: During the 30 day period to allow for comments on the panel's report, Cogema Resources, now operator of the McClean project, responded to the panel's recommendations, as did several agencies. This helped correct some misunderstandings and provided the opportunity to clarify some technical aspects.

The green light: 23 December 1993, both governments allowed McClean project to continue its licensing process.

4. THE MINING PROJECT:

Since approval to proceed, COGEMA RESOURCES undertook the licensing phase. Construction has now started.

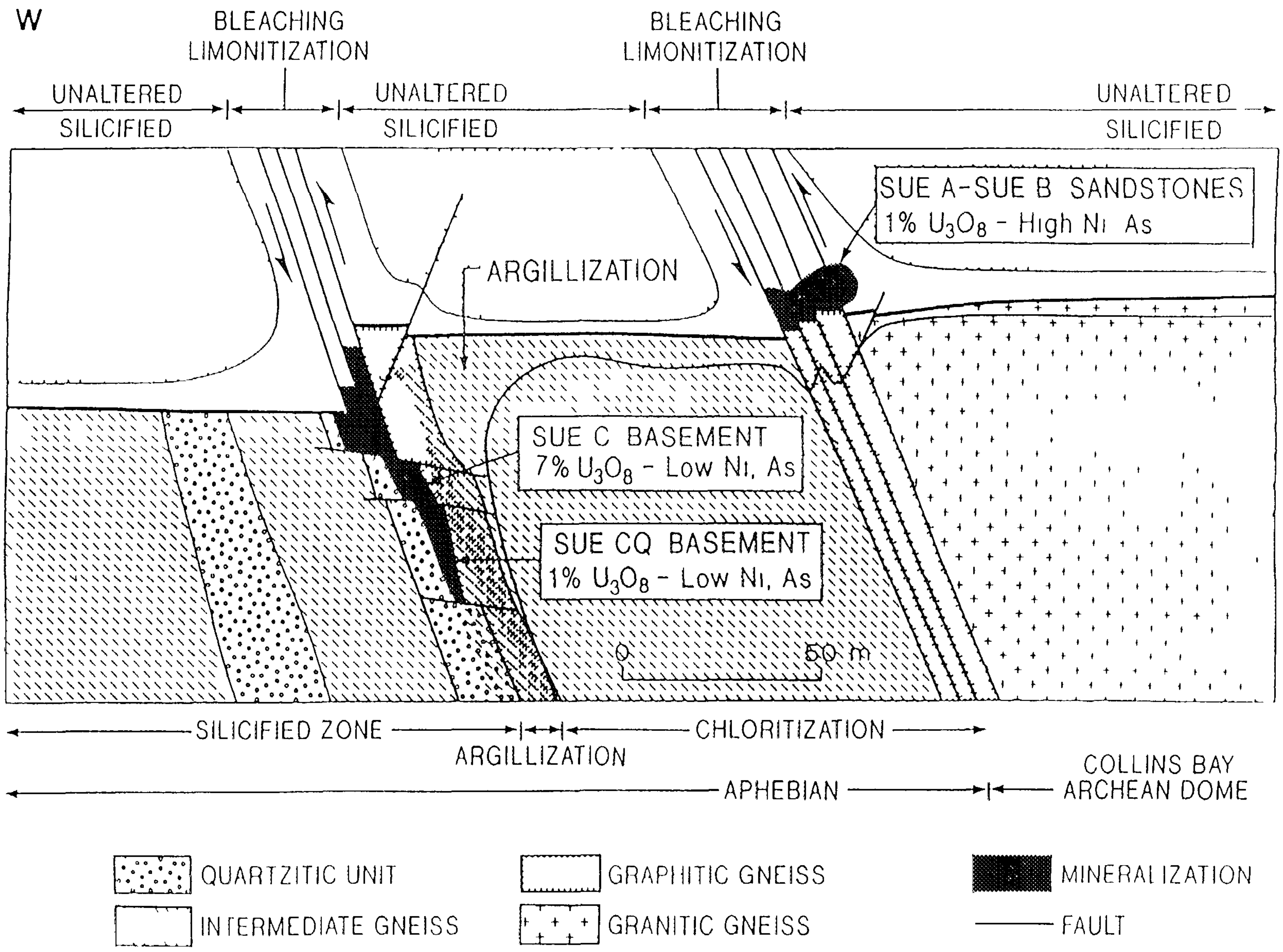


FIG 8 Schematic section across the Sue area

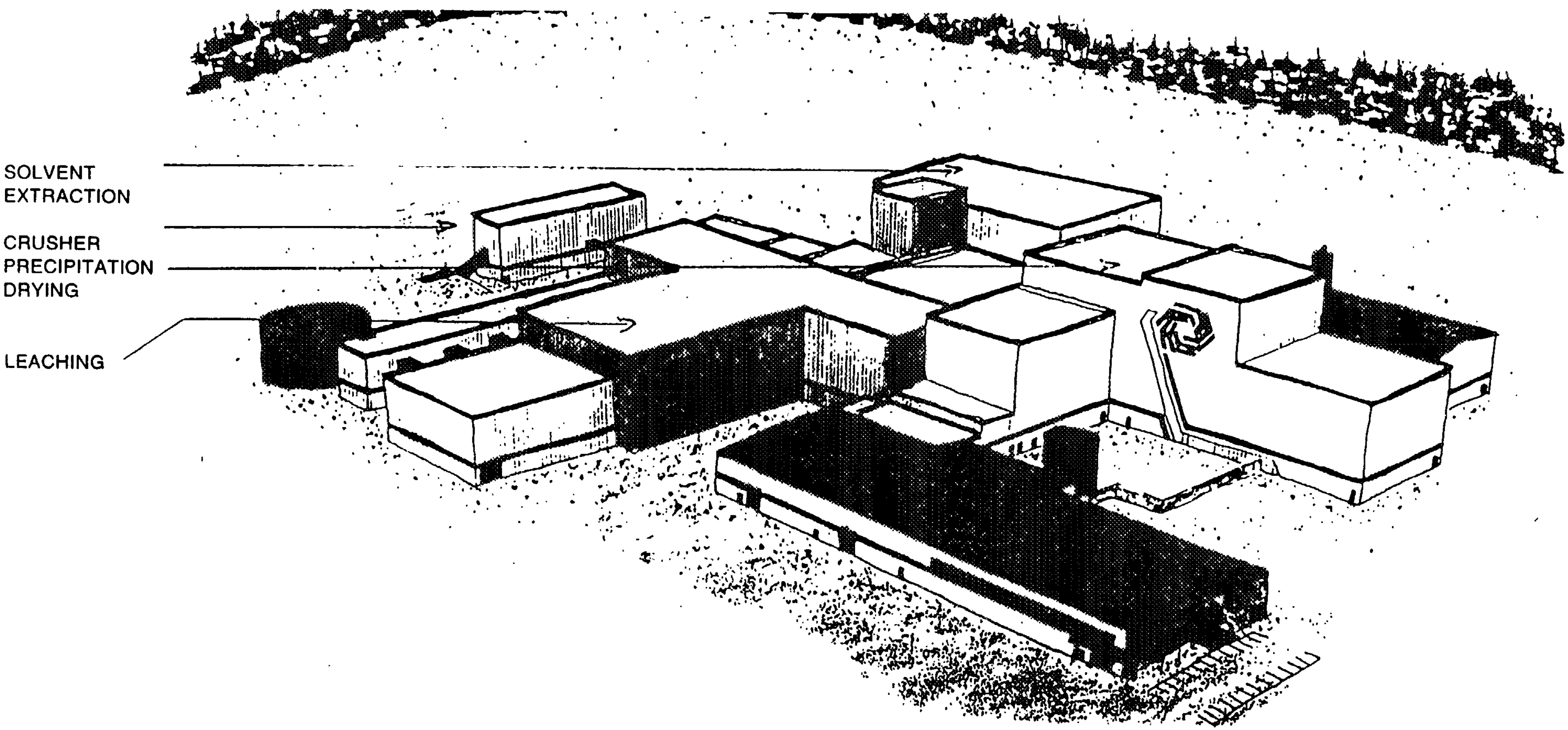


FIG. 9. The McClean mill.

4.1. Construction schedule

April 1995:	Construction of the temporary camp, and then the permanent camp, the water treatment plant and mill offices.
October 1995:	Start of open pit mining operations at the JEB orebody.
1996:	Construction of the process plant (see Fig. 9). Completion of mining of JEB orebody, by year end.
1st half of 1997:	Completion of construction of the mill. Preparation of the JEB open-pit as a tailings disposal facility. Beginning of mining of the Sue C orebody.
2nd half of 1997:	The mill will then be commissioned and production will start.
1998:	Full scale production of 6 million pounds per year expected.

4.2. Economic impact

Investment

In the next two years, until production starts, about 250 Mcan$ will be invested in the project.

Jobs and northern employment

Construction stage: 250 people on the average will be employed. Production stage: 200 permanent jobs will be created by mid-1995 with a company policy of maximizing the employment of northern residents. Experienced people will be transferred from our existing operation in Cluff Lake to supervisory positions in the McClean lake project.

Business opportunities

The purchase of equipment, goods and services, both during construction and production stage will boost the local economy. The Company will insure that on site contractors will follow its own practice of local employment preference.

4.3. Safety and protection of the environment

The performance of the facilities to insure a safe workplace for all personnel, and an excellent protection of the environment will be permanently monitored.

All critical parts of the facilities have been extensively reviewed during the regulatory process. However, in spite of the additional administrative burden, Cogema Resources will continue to propose and implement modifications to the approved facility, each time such are both reasonably achievable and beneficial to workers' safety and the protection of the environment.

For example in 1994, an application was made and approval obtained for a modification of the mill process resulting in a decrease of the volume of mill tailings, and a reduction of the total chemical loading to the environment.

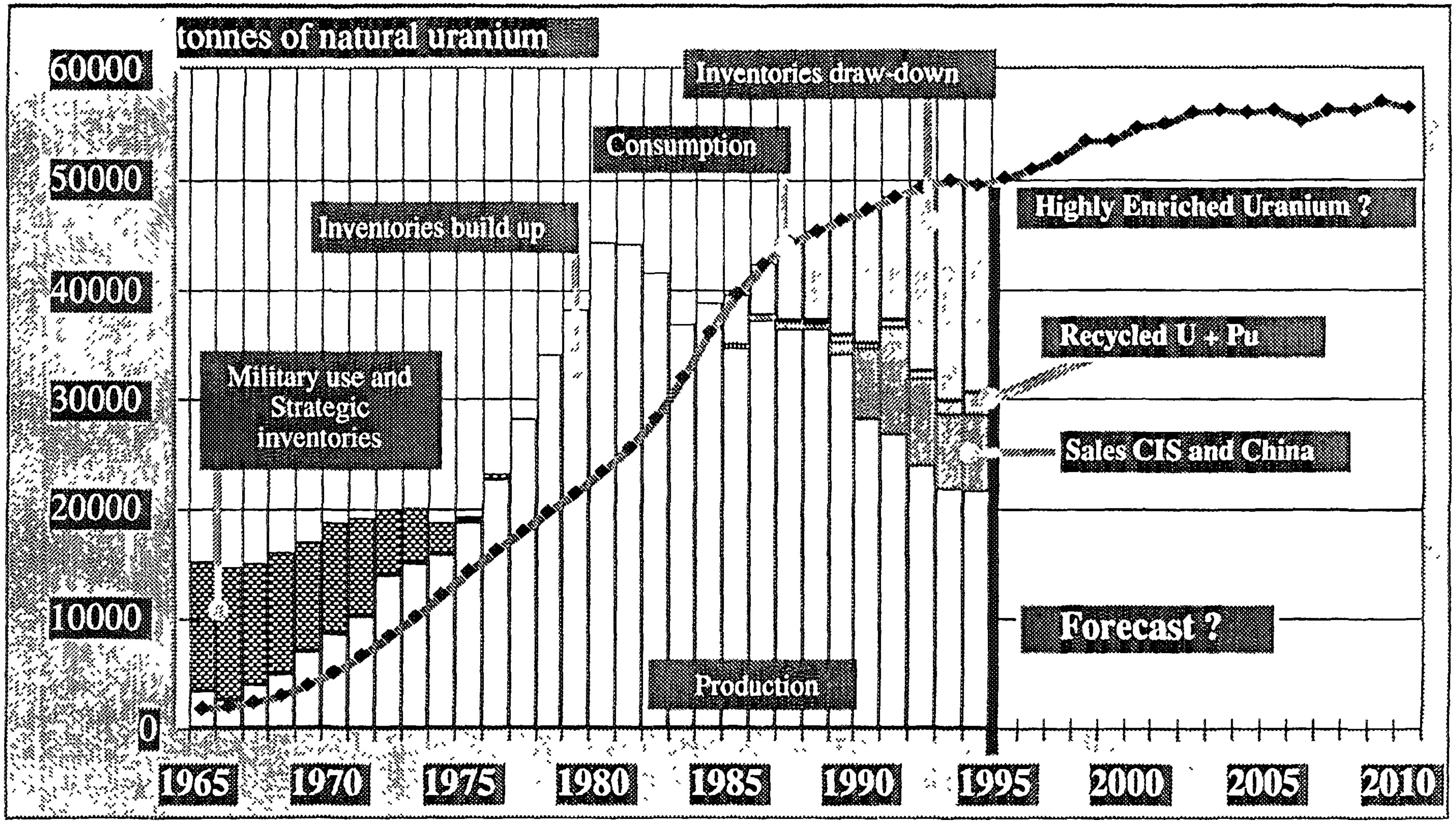


FIG. 10. Uranium supply and demand of the western world.

The concept of paste tailings now fully operational at Cluff mining will be proposed for McClean.

Reclamation and decommissioning were taken into account at the design stage to be optimized when production stops. The McClean project is the first uranium mine for which financial assurances for decommissioning will be implemented at the very beginning of production.

5. CONCLUSION

The production of this new mine, the first investment launched by the industry in Canada since Key Lake in the late seventies, will start in two years from now at a time the situation will likely be favourable for new production (see Fig. 10), taking into account the following factors:

- further closing down of mines in the years to come,
- a consumption level which is presently the double of the production level,
- the exhaustion of inventories in the western world,
- uncertainty of western world consumers on the available supply coming from the Russian Federation and other producing countries in the CIS, including the prospects of a somewhat limited flow coming from the blending down of highly enriched uranium from weapons inventories.

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ADVANCES IN THE EXPLORATION MODEL FOR ATHABASCA UNCONFORMITY URANIUM DEPOSITS

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Abstract

This paper covers the genetic model of ore formation and exploration techniques Uranerz Exploration and Mining is presently using to explore for unconformity uranium deposits in the deeper parts of the Athabasca Basin. The main objectives of this paper are: 1) to present a genetic model for unconformity uranium deposits which is being used in our current exploration strategy, and 2) to present the sequence of exploration techniques used by Uranerz to explore for uranium in areas of the Athabasca Basin with up to 1000 m of sandstone cover. The Athabasca unconformity deposits are located in northern Saskatchewan, Canada. Within the Precambrian Athabasca Basin, exploration companies have discovered 18 uranium deposits. These contain more than 500 million kilograms of uranium, with average grades ranging from 0.3 to 12%. Uranerz discovered the Key Lake deposits in 1975, currently the largest and richest open pit uranium mine in the world. Uranerz also holds interests in the Rabbit Lake, Midwest Lake and McArthur River deposits, all in Saskatchewan, and is also actively exploring for uranium worldwide. The first discovery in the eastern Athabasca Basin was in 1968 at Rabbit Lake, followed by Key Lake in 1975. Both deposits had surficial indicators, such as radioactive boulders, strong geochemical anomalies in the surrounding lakes and swamps, and well-defined geophysical signatures. After the Key Lake discovery, an exploration model was devised which incorporated the underlying graphitic horizon and its strong electro-magnetic signature. Since then, there have been numerous new discoveries made by systematically drilling along these electro-magnetic conductors. The advancements in geophysical and geochemical techniques have led to discoveries at increasing depths. In 1988, the McArthur River deposit was discovered at a depth of 500 m.

GENETIC MODEL FOR UNCONFORMITY URANIUM DEPOSITS

Archean lithologies

During the early Archean, accretion of crustal blocks formed large plates. The Archean lithologies consisted of granites, granitic gneisses and minor mafic assemblages, which were subjected to granulite facies metamorphism during the Kenoran Orogeny at 2560 Ma. The borders of the crustal blocks were zones of weakness and the sites of repeated faulting. Gravity data is used to differentiate between these crustal blocks.

It has been postulated by Heier and Adams [1] that uranium migrates upward in the crust during granulite facies metamorphism. Therefore, it is possible that the Kenoran Orogeny concentrated uranium in the upper Archean crust.

Paleoproterozoic lithologies

Paleoproterozoic pelitic, psammitic, quartzitic and carbonate sediments were deposited in a miogeosynclinal setting over the Archean lithologies. The basal, carbon-rich pelites were enriched in uranium derived in part from the enriched Archean crust. The Archean block boundaries had little effect on sedimentation during this stable depositional period.

Both the Archean lithologies and the Paleoproterozoic sediments were metamorphosed to an upper amphibolite to lower granulite grade (Annesley and Madore [2]) during the Paleoproterozoic Hudsonian Orogeny dated at 1780 Ma. The carbonaceous rocks near the base of the pelitic units formed graphitic layers.

During metamorphism, the carbon in the carbonaceous sediments was converted into graphite. Dehydration of the rock produced fluids, which transported the uranium and associated metals into areas of less confining pressure.

The Hudsonian orogeny also reactivated many of the structural zones between the Archean blocks. These zones may be up to several hundred kilometres long and 10 to 20 kilometres wide, herein called mega-shears. These zones of weakness were subjected to folding, faulting and downwarping, causing the metasediments to be preserved in linear troughs or keels. These were intruded by radioelement-enriched pegmatites, and were the focus for fluid migration, increased heat flow, chemical alteration and anatexis. All these events contributed to the further concentration of uranium within the faulted graphitic lithologies. Parslow [3] has shown that uranium can be concentrated in anatexites by up to 50 times the original content of the parent rock.

Upward heat flow within the mega-shears was aided by the presence of the newly formed graphite, which acted as a thermal conductor (Tilsley [4]). Graphitic units folded or faulted into near vertical attitudes transfer heat much more efficiently than those with a horizontal attitude. Regional thermal events, therefore, would have had a more concentrated effect within the graphitic mega-shears, allowing for longer periods of metamorphism and fluid flow in the structural zones than in the surrounding lithologies.

The mega-shear zones are now marked by preserved NE-trending keels of Paleoproterozoic metasediments, with the easternmost mega-shear in the Basin underlying all of the known eastern deposits. This has been described as the Wollaston/Mudjatik contact in numerous papers (Sibbald [5]).

The initial processes involved in the formation of the unconformity deposits of the Athabasca Basin and the Beaverlodge-type deposits near Uranium City, Saskatchewan, are thought to be similar. The concentration of uranium in the basement lithologies in both regions would be comparable in grade during the Paleoproterozoic, before deposition of the Athabasca Group sandstones occurred.

Athabasca group deposition

The Archean and Paleoproterozoic lithologies went through a period of uplift and erosion after the Hudsonian Orogeny. Then they were covered by the Mesoproterozoic sandstones of the Athabasca Group.

Deposition of fluviatile to shallow marine quartz sand and pebbles in the intracratonic Athabasca Basin, formed by tensional tectonics, covered the basement lithologies with up to 5 km of sediments. The present day thickness of the sandstones is estimated to be a maximum of 2,200 metres. The Athabasca Basin played an important role in the formation of the unconformity deposits by providing basinal brines to the relatively dry basement lithologies during the main deposit-forming hydrothermal event described below. These fluids concentrated the basement-hosted protore into the highest grade uranium deposits in the world.

While low grade uranium deposits occur in numerous localities around the world, the high grade unconformity deposits occur only in the Athabasca Basin and, to a lesser extent, in the Pine Creek geosyncline of northern Australia. Without the presence of the overlying sandstones, the protore developed in the basement lithologies would not have been concentrated beyond grades of 0.5% uranium, on par with the Beaverlodge type or the European Hercynian deposits. The final concentration step was a hydrothermal event which promoted circulation of the basinal brines of the Athabasca Group.

Deposit formation

The deposit-forming event, which took place at approximately 1350 Ma, increased the temperature at the bottom of the Athabasca Group to an estimated 200 degrees Celsius (Kotzer and Kyser [6]). It also re-activated basement structures, which extended into the overlying sandstones. This event mobilized the high salinity, oxidized basinal brines through the Athabasca Group sandstones, as they had a higher permeability than the underlying basement lithologies. The fluids were channeled into the upper portions of the mega-shears and flowed along strike due to the high permeability of these structures. Some of the basinal brines were forced down into the faulted graphitic lithologies due to both gravity induced hydrostatic pressure and convection. In the graphitic shear zones, the oxidized brines mobilized the uranium and associated metals and transported them along the strike of the mega-shear.

Some of the fluids travelled deeper within the graphitic package, and became reduced. Both reduced and oxidized fluids continued along the mega-shear until they reached a dilation zone in the graphitic package caused by extensional cross-faulting. Here, the fluids mixed together, causing the metal-bearing oxidized fluids to become reduced. The uranium and metals would precipitate, forming unconformity mineralization.

During, and subsequent to, unconformity mineralization, the mixed basinal brines also circulated upwards within the overlying sandstones. These followed the permeable fault systems which extended from the graphitic horizon into the sandstones, creating an alteration halo. The size of the halo above the deposit is proportional to the amount of fluid which flowed through the sandstone. The geochemistry of the alteration halo varies with the distance from the deposit area, ranging from several per cent uranium to one half of a ppm. Metals such as nickel, arsenic, lead, cobalt and vanadium are also common within the halo.

The brines also converted the interstitial clays to illite, and, closer to the deposit, to chlorite. Both silicification and desilicification may occur within the haloes. An increase in the boron content is also typical. However, not all alteration haloes contain uranium, or are associated with mineralization with economic grades.

EXPLORATION TECHNIQUES

The following is a description of our exploration techniques in areas of deep sandstone. These techniques are based on the genetic model described above. A progressive sequence of exploration steps is used, starting with large scale area selection involving a few thousand square kilometres, and ending with drill targets involving several kilometres of conductor strike length.

Area selection

Field evidence of the exploration criteria derived from the genetic model are sought using geophysics and geochemistry. The boundaries of Archean blocks and associated keels of Paleoproterozoic metasediments are located with geophysics. These define the NE trending mega-shear zones. Surveys of lake sediments and sandstone boulders locate geochemical anomalies at surface. Electro-magnetic surveys then delineate graphitic lithologies at depth. The following steps have been established by Uranerz for the exploration for unconformity uranium deposits in areas covered by thick sandstones.

Large scale attributes, such as NE-trending mega-shears, are defined by gravity and magnetic data. The gravity data outline the boundaries of Archean crustal blocks which are zones of crustal weakness. Magnetic data differentiate between the Archean and Paleoproterozoic lithologies, with the mag highs representing the Archean and the mag lows representing the Paleoproterozoic. Keels of Paleoproterozoic metasediments preserved over these zones of crustal weakness are sought.

After locating such a potentially favourable geological setting, the area is sampled using reconnaissance-scale lake sediment and boulder geochemistry. Boulder sampling is carried out in areas covered by glacial till, and is designed to locate sandstone boulders which carry the geochemical signature of an alteration halo. The anomalous boulders are present in the till, with the source of the boulders at the alteration halo subcrop.

Reconnaissance sampling of sandstone boulders is performed at 300 metre intervals on lines spaced 2 kilometres apart. These lines are oriented perpendicular to the prevalent glacial direction. If geochemical anomalies are encountered, a more detailed follow-up survey is done, sampling boulders at a 100 to 150 metre spacing on lines 800 metres apart.

Modelling and empirical data both indicate that geochemical responses become stronger closer to a deposit. The deeper deposits have weak but still detectable surficial signatures in the overlying boulders. In areas where the sandstone is 1 kilometre thick, only a subtle expression is seen in the boulders with uranium values less than 1 ppm.

Because of the subtlety of the geochemical signatures, improved techniques were used to lower detection limits for uranium, boron and lead. An axial ICP unit and fluorometry is used for the analyses, and larger sample sizes improve the uranium and lead detection limits to 0.02 ppm. The boron detection limit is 2 ppm, and illite and chlorite may be determined to a limit of 0.001%.

Areas with favourable geochemistry are then tested by electro-magnetic surveys, which determine the location of graphitic horizons in the basement. Two modes of operation have been used, moving-loop and fixed-loop time domain EM, which can accurately define conductive lithologies through 1 kilometre of sandstone.

The moving loop survey uses a transmitter loop size of 1 kilometre diameter, with the receiver 2 kilometres away. This entire set-up is moved on 300 metre intervals through the bush for each reading. The fixed-loop EM survey has a stationary transmitter loop of 1.6 kilometres in diameter and a moving receiver which takes readings from 50 metres to 3 kilometres away.

A combination of favourable gravity, magnetics, boulder geochemistry and EM responses allows for the placement of a drillhole.

In the next stage of an exploration programme, core drilling is employed to examine the targets defined by the previous surveys. The core from a drillhole is examined for lithologies and structure, and then geochemically analysed. This information is used to determine if another drillhole is warranted. Targets would continue to be drilled until the anomalies have either been satisfactorily explained or a deposit has been located. It is important to note that not all alteration haloes are related to a uranium deposit, and most alteration haloes are in fact barren.

SUMMARY

In summary, Uranerz has advanced the genetic and exploration models for unconformity uranium deposits within the Athabasca Basin, and has applied them in areas of up to 1 kilometre of sandstone cover.

Genetic model

The sequence of geological events which contributed to the concentration of uranium are as follows:

1) Archean crustal accretion, resulted in zones of weakness between the crustal blocks. The block boundaries have locally developed into NE-trending mega-shears.

2) Granulite facies metamorphism during the Kenoran Orogeny concentrated uranium in the Archean crust.

3) Erosion of the Archean and subsequent deposition of psammites and uranium-enriched pelitic sediments during the Paleoproterozoic

4) Metamorphism and deformation during the Paleoproterozoic formed linear basins of pelitic to psammitic metasediments over the Archean zones of crustal weakness, i.e., the mega-shears. This also involved further concentration of uranium by anatexis and fluid migration.

5) Erosion of the Archean and Paleoproterozoic lithologies, and subsequent deposition of the Mesoproterozoic Athabasca Group.

6) A hydrothermal event at approximately 1350 Ma caused basinal brines to concentrate the uranium present in the mega-shears at the unconformity contact with the overlying Athabasca Group sandstones.

Recent glaciation caused surface expressions of the hydrothermal event in the sandstones to be spread down-ice from where it subcrops.

Exploration model

Our exploration techniques for the search of deep uranium deposits commence with a geological compilation of the basement lithologies beneath the Athabasca Basin. Gravity and magnetometer surveys define NE-trending mega-shear zones with preserved keels of Paleoproterozoic metasediments. This provides target areas of up to 100 km long and 20 km wide.

Sampling of the glacially-derived sandstone boulders determines areas of geochemical anomalies in the till. These responses are the surface expressions of hydrothermal alteration haloes in the upper sandstones, and effectively reduce the strike length of the target to about 5 kilometres. EM surveys are then used to locate graphitic horizons in the basement Paleoproterozoic metasediments, further reducing the width of the target to several hundred metres. The initial drilling target area is then approximately 5 kilometres by 400 metres. Geochemical and structural analyses of each drillhole further refines the target area, until the source is discovered.

ACKNOWLEDGEMENTS

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PROVIDING RADIATION SAFETY FOR THE ENVIRONMENT AND PEOPLE AT URANIUM ORE MINING AND PRIMARY PROCESSING OPERATIONS AND TREATMENT OF RADIOACTIVE WASTES IN THE NAVOI MINING AND METALLURGY COMBINAT, UZBEKISTAN

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Abstract

The rise of the uranium industry in the Republic of Uzbekistan is closely connected with the discovery of a number of significant uranium deposits of sheet sandstone type in the Kyzylkum desert area, between the Amu-Darya and Syr-Darya rivers. Based on these deposits, in 1958 the construction of Navoi Mining and Metallurgical Combinat (NMMC) commenced. In 1965 the Hydrometallurgical Plant No. 1 (HMP-1), located in the industrial zone near the Navoi town, started producing the uranium protoxide-oxide (yellow cake). The structure of the NMMC uranium production operations includes HMP-1 and three mining facilities. Conventional open-pit and underground uranium mining were shut down here in 1994 and at present all the uranium is extracted by in situ leaching (ISL). Radiation safety of the environment and population inhibiting the areas involved in the activities of uranium materials mining and primary processing facilities is covered by a system of Republican legislative acts, standards, norms and regulations. The legislative basis covering the radiation safety activity is represented by the following acts of the Republic of Uzbekistan: "Public Health Service Act", "Environmental Protection Act", "Labor Act", "State Sanitary Inspection Act". The radiation and hygiene sanitary monitoring aimed at collecting information on the radiation conditions at the working places and in the environment, on the current and expected irradiation doses taken by the personnel and various population groups inhabiting the area involved in the activities of the existing, liquidated or temporarily closed NMMC facilities constitutes an integral part of the radiation safety providing system. The results of the radiation monitoring show that no radioactive contamination of any environmental objects has been detected outside the sanitary zones and production sites. The radionuclides content in the atmosphere, on the ground surface, in the underground water was found to be at the background level. Current annual average exposure doses of the limited critical population groups were detected to be essentially lower than the current international standards and were about 1 mSv per year. The strategic trends in uranium industry development include providing of ecologically safe conditions at all the NMMC operations based on implementation of the more ecologically "clean" ISL method, liquidation of mining and processing operations that have proved to be ineffective due to both economic and ecological reasons. The reclamation programme has been set up and is being continuously implemented which includes special measures for reclaiming of environmental objects that have been affected by uranium production operations in the course of more than 30 years of their existence.

1. INTRODUCTION

The Republic of Uzbekistan is one of the largest producers of uranium protoxide-oxide (yellow cake). The uranium industry origin in the Republic is connected with the discovery of a number of large deposits of uranium ore in the Kyzylkum desert, between the rivers Amu-Darya and Syr-Darya. Based on these deposits the construction of Navoi Mining and Metallurgy Complex (NMMC) was started in 1958. In 1965 the production of uranium protoxide-oxide was commenced at the Hydrometallurgical Plant (HMP-l) located in Navoi industrial zone.

NMMC production activity comprises the territory of sandy planes and low mountain elevations of central Kyzylkum with an area of about 100 000 km^2, which is included into a network of automobile roads, electric power lines, water mains, railways.

Since 1991, the moment of the formation of the independent Republic of Uzbekistan, NMMC with all its production facilities has become property of the Republic. In 1992 on the base of NMMC, construction-mounting and design organizations of Atomic Engineering and Industry Ministry of the former URSS, located in the territory of the Republic, the Kyzylkum State Concern of Rare Metals and Gold was established.

NMMC uranium industry is a complete cycle: from prospecting works to hydrometallurgical processing with production of uranium chemical concentrate in the form of protoxide-oxide (yellow cake). The structure of the NMMC uranium industry includes HMP-l and three mining enterprises located close to the towns of Uchkuduk, Zafarabad and Nurabad. Besides, NMMC comprises Muruntau gold mining and processing industrial complex, located near the town of Zarafshan. Currently Kockpatas gold mining and processing industrial complex is being constructed in the Uchkuduk region. It will be put into operation in 1995. The Mining Division No 2 for fluorite ores mining and enrichment is acting not far from the Krasnogorskiy settlement in the Tashkent region.

Five modern towns with a total population of about 200 000 people have been constructed in Kyzylkum, on the base of uranium and gold mining industry: Navoi, Zarafshan, Uchkuduk, Zafarabad, Nurabad. All towns are assets of the NMMC. They are connected to one another and to the region center Navoi town by railroads (500 kilometres), automobile roads (1000 kilometres), and an electric power grid, linked to the Republic's network.

There are several large uranium deposits (Uchkuduk, Sugrali, Ketmenchi, Sabirsay, Northern Bukinay, Southern Bukinay, Beshkak) within the NMMC activity sphere. At present, they are at various stages of working.

According to IAEA classification, uranium deposits taken by NMMC for operation and planned for commercial processing, are related to blanket sandstone type. The uranium content in ores reaches a few tenths of a percent. The ores consists of pitchblende, often in a coffinite mixture. Mineralization occurs in eight water-permeable beds of the Cretaceous period and in three beds of Paleogene.

Underground mining of uranium ore was completed in 1994. Currently uranium deposits, being assets of NMMC, are developed only by the in situ leaching (ISL) method. Several other large uranium deposits, which are planned for production by in situ leaching, are at various stages of preliminary and detailed prospecting. Full-scale development testworks have been conducted at some of these deposits.

2. RADIATION — ECOLOGICAL ASPECTS OF URANIUM MINING

2.1. Baseline radiation and mining waste

The top layer of the earth surface in a region of NMMC uranium mining enterprises is presented by desert and semi-desert brownish-gray not very productive soils, which are of mot much value for irrigated cultivation. They have been used before the beginning of mining mainly for pasturing cattle.

The regions have no constant flowing surface waters. Intermittent rivers flow only in spring and autumn.

The background indices of natural radioactivity of the soils are:

- gamma-radiation exposure dose rate is $10\text{–}17 \cdot 10^{-6}$ R/h,
- natural uranium content is 2–Smg/kg,
- Radium-226 content is $2\text{–}4 \cdot 10^{-9}$ Ci/kg,
- total specific alpha activity is 330–350 Bq/kg.

Background indices of natural radionuclide content in flora: natural uranium is 0.001–0.005 mg/kg, Radium-226 is $0.05–0.1 \cdot 10^{-9}$ Ci/kg, Polonium-210 is $0.05–1.0 \cdot 10^{-9}$ Ci/kg.

The dumps of substandard or subeconomic ores were formed during previous years in the process of open pit and underground mining. Up to now the dump total volume is about 2,420 thousand cubic meters. Subeconomic dumps consist of caked massifs of a broken rock mass of truncated prisms and cones of sandy-argillaceous rocks. Practically all dumps are covered by a natural argillaceous crust, partially broken by cracks. Dust and radon enter to the atmosphere from the surface of these subeconomic dumps.

The total specific alpha activity of subeconomic ores in dumps is $10–20 \cdot 10^{3}$ Bq/kg. The radon flux density from the surface is in range from 0.03 to 1.5 Bq/square meter·sec. The Gamma-radiation exposure dose rate at the surface is up to $300–350 \cdot 10^{-6}$ R/h.

The radon equivalent equilibrium concentration in atmospheric air, measured below the dump surface is 30–40 Bq/cubic metre. At a distance of 20–30 metres from the dump concentration decreases to the natural background of 10–15 Bq/cubic metre.

The average concentration of long-lived alpha-active nuclides in atmospheric air under dumps' surface is within the limits of 0.05 to $0.1 \cdot 10^{-15}$ Ci/l a year, i.e. This equals the natural background. As a result of measurements it is established that an aureole (or plume) of territory contamination in gamma-radiation exposure dose rate and total specific alpha-activity due to dusting from dumps surface is observed at a distance of 20–30 m. At a distance of 30–50 m from the dumps the radionuclide concentration in a surface earth layer is decreasing practically down to background values.

2.2. In situ leach mining

Full-scale commercial in situ leaching (ISL) uranium production was first put into operation in 1961 at the Uchkuduk deposit. At present, ISL mining method is in operation at Uchkuduk, Nothern Bukinay, Southern Bukinay, Beshkak, Sabirsay and Ketmenchi deposits.

The structure of the ISL mine includes three parts: a mining complex, a system of surface equipment and pipelines as well as a processing complex.

The mining complex consists of a system of holes drilled from the surface down through the productive bed. Well casings are installed. The area around the casing is cemented in order to isolate one aquifer from another. The wells in the ore interval are equipped with filters (i.e. screens). Solution lifting devices (submersible electric pumps, air lifts) are set in the recovery wells to recover producing solutions. The hole openings are connected with feeder or distributing pipelines by means of hoses.

The processing complex includes a system of sorption (i.e. ion exchange resin) and regeneration columns, as well as filtration and leaching solutions preparation equipment, a compression station and reagent stores.

A system of surface pipelines connects the mining and processing complexes in one unit. It consists of main distributing and feeder pipelines. They are usually put on the surface, or more rarely seldom under ground or in banting. It also includes local field pump stations with collectors of productive solutions and local distribution tanks and oxidation units.

The deposits are the assets of NMMC. They are developed using sulphuric-acid leaching systems, except for Uchkuduk deposit, where from 1983, a weakly-acid technological scheme was used. In this system of air is the oxidizer which has been used.

The negative impact of in situ leaching on the earth surface, soil and atmosphere is significantly less than of underground and open pit mining. The single contamination source of ISL mining is leaks and spilling of leaching solutions due to technological violations of producing and injection wells, repairing and restoring works at wells and surface pipelines.

Other location of spills, the soil layer and moisture are contaminated with sulphates, nitrates and natural radionuclides of uranium-radium series. Investigations of suraface and subsurface distribution of radioactive contamination at the ISL areas' surface indicates that they are local, both in area and depth.

Even at the location of intensive spils, as a rule, the contamination levels at a depth of 30–40 cm are reduced to background values due to the high sorption-and-capacitive and neutralizing properties of the upper layers.

Based on to the data obtained prior to reclaiming ISL areas, radionuclide contamination (a factor of area contamination) averages 26%. The contaminated ground, taken when cleaning the surface, is characterized by average values of gamma-radiation exposure dose rate of $60–80 \cdot 10^{-6}$ R/h in total specific alpha activity of $5–10 \cdot 10^{3}$ Bq/kg.

The total area contaminated by radionuclides at mined out deposit by ISL subject to reclaimation is about 13 000 thousand square meters. The volume of contaminated ground from the cleaned surface is about 3500 thousand cubic meters.

During ISL mining, the ore bearing aquifer is subject to the greatest environmetal impact. The extent of this impact is primarily determined by the technological ISL scheme. The type of reagent and the oxidizing agent.

During leaching with sulphuric-acid, the concentration of mineralization in mining zone increases by 5–15 times in comparison with background indices. The hydrogen index (pH) is reduced from 7 to 1.5–2.2. The increase in mineralization is primarily connected with accumulation of the sulphate-ion in circulating technological solutions. An aureole (or plume) of technological solutions spreading from the ore occurrence along the direction of a natural flow at the boundary of hydrogen index, exceeding 6, does not exceed 150–200 metres. Transport of the radionuclide conteined does not exceed 50–60 metres. According to other indices the spreading is less.

With the weakly-acid scheme a hydrogen index of stratal waters, general mineralization, composition and content of main macrocomponents during leaching and after its completing practically do not differ from background values in stratal waters, even inside ore occurrence contour.

The data from observation wells, developed in the productive aquifer, show that in all ISL operations of NMMC, at any technological scheme used, the natural geochemical character of stratal water is unchanged more than 200–300 m zone from ore deposits. The control and monitoring of the state of aquifers contiguous to the productive aquifers also show that there is practically no evident change in their natural state. It should be noted that underground water of productive aquifer of the NMMC ISL operations are all classified as category unsuitable for economic purposes. In this connection, the method based on natural demineralization of residual solutions in the process of migration with underground water flow has been adopted as the main method of decontaminated areas liquidation.

3. RADIATION — ECOLOGICAL CHARACTERISTIC OF THE HYDROMETALLURGICAL PROCESS

Uranium chemical concentrate,(i.e. yellow cake) is transported from ISL mines to Hydrometallurgical Plant No 1 (HMP-1), for further extraction and concentration, using organic extractants. The pregnant organic matter containing uranium is subject to re-extraction using a mixture of carbonate and ammonium bicarbonate.

Ammonium-uranyl-tricarbonate crystal slurry (pulp) is filtered. The filtered crystals are roasted in the revolving horizontal tube furnace and the final product is obtained in a form of uranium protoxide-oxide (yellow cake).

From yellow cake production waste gases to emission into atmosphere are subject to preliminary purification from ammonium and uranium dust in two series connected dust extractors, two film cooling absorbers and two scrubbers with a fitting of Rashig rings. The high purification effect ensures a low level of radionuclide emission into atmosphere, average annual quantity of which is 1.36 Ci in total alpha-activity. Radiation monitoring results show that average annual contamination of an atmospheric air at HMP-1 area and within the limits of sanitary defense zone by natural uranium and total alpha-activity of uranium-series' radionuclides does not exceed the admissible concentrations for a limited part of population[1].

At the distance of 500 m from HMP-1 perimeter, an authentic radioactivity increase in atmosphere, soils and grounds relative to the natural background is not detected. The HMP-1 tailings dump is located 4 km to the west of the plant. It occupies an area of 5.9 square kilometres. It is a tailings dump of a plain (flat) type, alluvial. Dams are 15 meters high. The dams are made of wood-rubble grounds and filled with a loamy aggregate. The sanitary defense zone with a radius of 700 m, guardzone of 110–140 m and observation zone of 2.5 km, including nearby settlements, are set around the tailings dump.

From the beginning of operation (1964) about 60 million tonnes of the solid-phase pulp have been accumulated in the tailing dump during uranium ore processing. Natural uranium residual content in solid wastes is 50–60 mg/kg, a total specific alpha–activity is $8 \cdot 10^4$ Bg/kg.

As for the granulometric composition, the tailings dump sedimentations are presented mainly by erosion-resistant fractions, the beach zone of maps is presented by incoherent material but transition and central zones are presented by coherent material. The state of beaches at the maps of the tailing dump at present is stable. Up to now the tailings dump does not significantly impact on the radioecological state.

An effective system of a drain screen, consisting of a row of 24 pump-out (recovery) wells, located along northern, western and partially eastern sides of the tailings dump at the distance of 50 m from the dam, is in operation with water diversion from aquifer and water return to the plant for further use in the process. This system has been made to protect underground water from filtration losses through the tailing dump basement by removing water.

According to the results of testing in the network of hydro-observing wells made around the tailings dump, it is estimated that radionuclide content in underground water in the sanitary-defense zone and beyond it did not exceed admissible concentrations for a "limited part of population" during the whole work period.

The density of radon flow from the tailing dump surface varies within considerable limits from 0.1 to 20 $Bg/m^2 \cdot sec$, and depends on the composition and state of tailing sedimentation surface. The tailing dump annually releases into atmosphere from its bare surface up to 2000 Ci of radon.

The average annual concentration of long-lived uranium series aerosols, formed due to dust coming to an atmospheric air from dry surface sites of beach zones of maps, does not exceed the admissible concentrations for a limited part of population living directly on the tailings dump territory.

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1 The term "limited part of population" means population living in the areas of probable impact of uranium production. The permissible rates by special standard (НРБ-76/87").

At the distance of 30-50 m from fencing dams it reduces practically down to background values. At the same time during 30 years of operation a 300 m aureole of radionuclide contamination of soils and grounds due to weathering (wind erosion) from dried beaches of the maps has been formed in the sanitary-defense zone of the tailing dump. Radionuclide concentration in this zone exceeds the natural background level by 5-10 times. Radionuclide concentration in the sanitary-defense zone at the distance exceeding 300 m from the tailings dump as well as in the observation zone including nearby settlements is at a natural background level.

From 1994 storage of radioactive wastes of uranium ore processing in the tailings dump has been stopped and it is planned to make their burial in 2000-2005, including radioactive decontamination and reclaiming of contaminated sites of sanitary-defense zone and pulp feed-line route.

Currently the research works are conducting in order to obtain the initial data for the development of main technical projects for the selection and substantiation of the tailings dump burial construction.

4. INFRASTRUCTURE OF RADIATION SAFEGUARD

Radiation safety of environment and population in the Republic of Uzbekistan is ensured by a system of legislative standards and legal acts, decrees of the President, resolutions of the Cabinet of Ministers at the President of Republic of Uzbekistan, Statements of Bodies of State Regulation and Supervision, the system of standards and rules of radiation safety.

The main legislative acts regulating the activity concerning radiation safety of the environment and population are the following laws of the Republic of Uzbekistan: "Care of public health", "Nature protection", "Labour", "State sanitary supervision". The former Soviet Union legislative acts, decrees and other standard technical documents, which are not in conflict with the Republic laws, are acting in radiation safety insurance.

The State Sanitary Epidemic Service, the State Committee of Supervision over Safe Conducting of Operations in Industry and Mining Supervision and the State Committee of Nature Protection exercise the state supervision over assurance of the environment and population radiation safety.

To realize their powers, the State Supervision Bodies, in compliance with their competence, control the observance of rules and standards of the radiation safety. Radiation safety of the environment and population living within the regions of uranium ore mining and processing, is ensured by NMMC organizations.

Basic requirements in the radiation safety assurance are regulated by "The Basic Sanitary Rules of Operation with Radioactive Materials and Other Ionizing Radiation Sources (ОСП-72/87)". The system of dose limits of irradiation and principles of their application is established by "The Standards of Radiation Safety (НРБ-76/87)".

The main standardization document regulating the complex of sanitary protective measures, which should be fulfilled in the process of liquidation and conservation of uranium mining enterprises for the purpose of the equipment and premises decontamination, territories reclaiming, burial of radioactive waste, is the paper issued in the former Soviet Union and called "Sanitary Rules of Liquidation, Putting into Long Term Storage and Changing the Type of Activity of Radioactive Ore Mining and Processing Facilities (СПЛКП-91)".

The rules have been developed taking into account the following acting documents: ОСП-72/87, "Sanitary Rules of uranium mines operation (СП-86-118) ", "Sanitary Rules of Radioactive Waste Handling (СПОРО-85)" and other official sanitation and safeguard standard documents.

5. RADIATION CONTROL

An integral part of the system of radiation safety assurance is a radiation and hygienic sanitary control, which is necessary for obtaining the information on the environment and working places' radiation situation as well as on the current and predicted doses of irradiation of the personnel and various groups of population living within the regions of probable action of the existing, conserved or put into long term storage NMMC enterprises.

The production radiation monitoring is performed by the NMMC departments controlling the labor conditions and environment protection (СКУТ and СОС). The departmental monitoring is performed by the Central Laboratory of Labour Conditions and Environment Protection by the Industrial and Sanitary Laboratories of Sanitary and Epidemic Services of the Concern. The State monitoring is performed by the local and central organizations of State Sanitary Supervision, State Committee of Nature Protection, State Urban Technical Supervision. Besides, the specialized research organizations are engaged in investigation of radiologic conditions at the operating facilities as well as in prior-to-reclaiming, post-reclaiming, periodic and routine investigations.

The following factors are subject to monitoring:

- gamma radiation exposure dose rate;
- the content of radon and its daughter products in premises, radon exhalation from tailing dumps and dumping grounds;
- general dust content and the content of aerosols of long-lived alpha-active radionuclides in air;
- radiochemical water composition;
- total specific alpha-activity of soils, bottom fills, isotope compositions;
- chemical factors (substances).

A volume and periodicity of radiation monitoring depend on the radiation situation and are determined by corresponding standardization documents. The results of radiation monitoring of radioactive environment contamination connected with the activity of uranium mining and processing NMMC enterprises show that the average annual effective equivalent dose of irradiation of critical population group living in these regions does not exceed 1 mSv/ year relative to a sum of all radiation-hazard factors and corresponds to the basic limit for population, adopted by the International Committee of Radiation Protection.

6. CONCLUSION

Navoi Mining & Metallurgy Complex engages the leading specialized and design organizations of the Republic and Commonwealth of Independent States, famous international research centers and companies with experience in various technologies of reclaiming of contaminated environment objects, connected with the activity of uranium mining and processing enterprises, in the development of scientific fundamentals and techniques of conservation works, entrails of the earth reclaiming, proving the efficiency of nature protection measures, study as well as prediction of radiation situation and fulfillment of design documentation.

The strategic trends of further development of NMMC uranium production are the following: to provide an ecologically safe situation for all NMMC objects by means of ecologically more "pure" in situ leaching method; to liquidate mining and processing enterprises, which will be less effective in further operation relative to economic and ecologic conditions; to isolate and bury an accumulated radioactive waste from the main environmental elements; to reclaim the grounds disturbed by the activity of uranium enterprises.

To realize these trends, NMMC has been developing and performing step-by-step the programme of actions for reclaiming of the environmental objects, which were being subject to the impact of uranium productions for more than thirty years of their existence.

URANIUM AND ENVIRONMENT IN KAZAKSTAN

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Abstract

Kazakstan's data on uranium as a state report has been included for the first time in the Red Book. Therefore the report contains two large themes presented in Suggested Topics for Papers: Country report, based on the 1995 NEA/IAEA Red Book Questionnaire and environmental impact regulations. Kazakstan is considered as one of the world leaders on uranium supply. In Kazakstan there are many well known types of deposits but the main one is the sandstone-rollfront type. That type is represented by the group of deposits of the Syr-Darya uranium ore province. Deposits of that type include the main part of uranium ore of the Republic of Kazakstan and supply almost all of its uranium mining. At the large three enterprises the uranium is extracted by underground leaching. The mining method of uranium extraction is stopped. Because of the poor development of nuclear energy, Kazakstan's need for uranium is not very high. Presence of a large amount of cheap and technological uranium ores allow the Republic to export uranium. There are plans to increase uranium mining and perhaps to establish new mining facilities including joint-ventures. More than 50 uranium deposits are known in Kazakstan. During prospecting and exploitation of these deposits a large amount of rad wastes in the form of ore dumps and tailings were generated. They have a sensible influence on the environment. Moreover, near the sandstone-rollfront type uranium deposits the large amount of underground water has been contaminated by radionuclides. Special investigation of the this phenomenon is necessary. In Kazakstan there are the rad waste disposal conception and contaminated earth recultivation regulations. At present "The Rad Wastes Management Low" is submitted for approval.

1. HISTORY OF URANIUM INDUSTRY IN KazakSTAN

Uranium prospections in Kazakstan were started in 1948 and have been proceeding up to now. The history of prospections and exploration work of uranium carried out can be divided in two stages, combine first with the development of prospection methods and second, with features of the geological structure of Kazakstan surface, because of the fact that the significant part of Kazakstan territory is submitted by friable Mesozoic-Cenozoic sediments overlapping Paleozoic complexes of rocks and performing depression structure (Fig. 1).

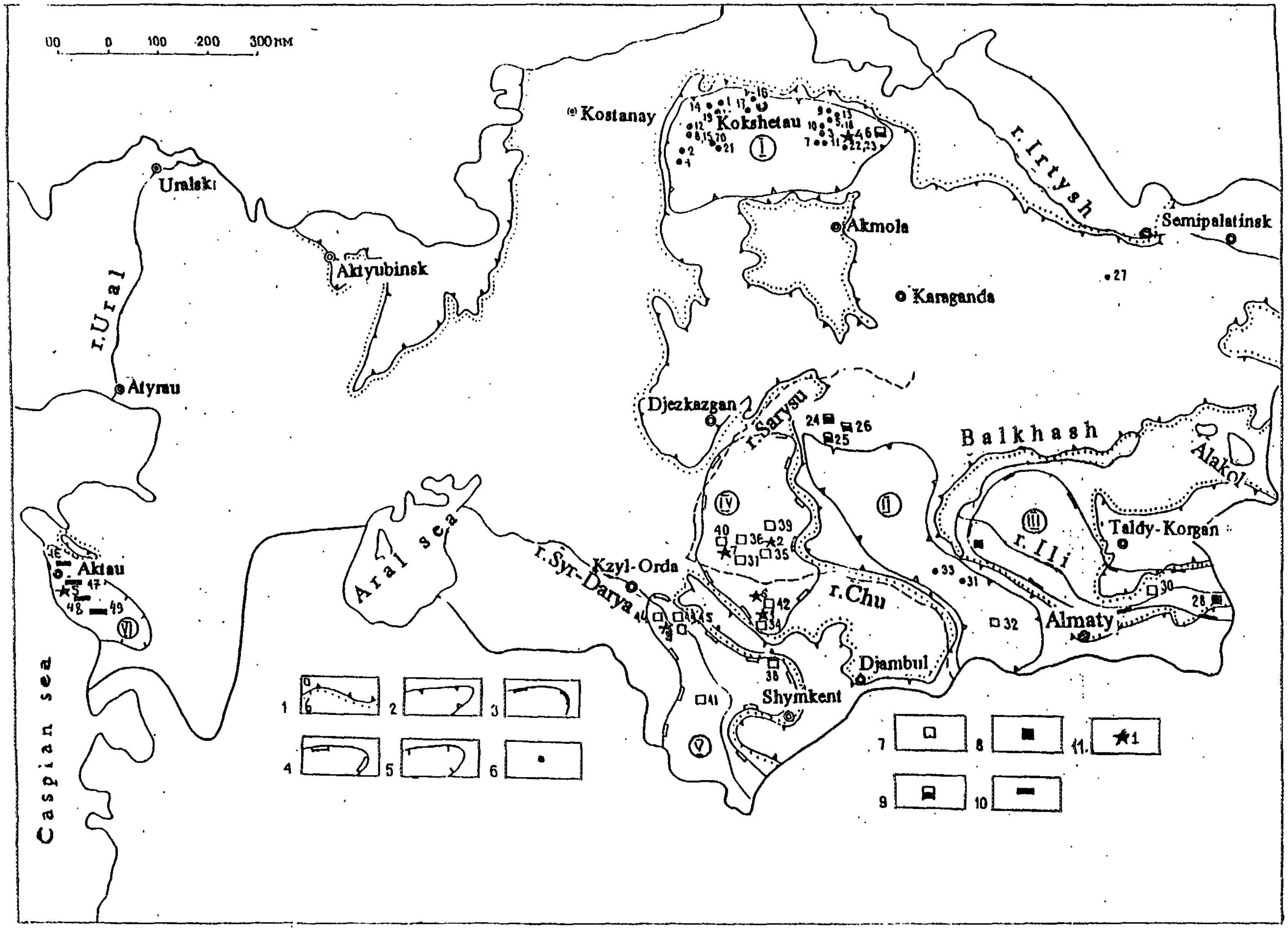
During the first stage (1948-1957) prospections were conducted basically with application of air- and pedestrian gamma surveys in the areas not closed by friable sediments.

During the second stage the prevailing method has become deep geological mapping with application of geophysical methods and drilling works in areas as well opened as basically covered by young friable sediments

Already during the first stage in 1951, the "Kurday" deposit was discovered for exploitation in the south of Kazakstan, and two more deposits were discovered soon at the same place. Kirgizsky Production Centre was then established, which at the present time is owned by the Republic of Kyrgyzstan.

The uranium deposits revealed in the south of Kazakstan form the Pribalkhash uranium province, where the general reasonably assured resources exploited amount to 22 000 t.

In 1953, in northern Kazakstan the deposits Kubasasdyrskoe and Balkashinskoe were opened which marked the beginning of discovering the Kokshetau uranium province and basis for creation of Tselinny Production Centre founded in 1957. Generally reasonably assured resources of the province are about 100 000 t and concentrated basically on large deposits: "Vostok", "Grachovskoe", "Kosachinoe", the ores of which are located in Paleozoic and more ancient rocks.



Kostanay
Kokshetau
Uralsk
Aktyubinsk
r.Ural
Atyrau
r. Irtysh
Semipalatinsk
Akmola
Karaganda
Djezkazgan
r.Sarysu
Balkhash
Alakol
Taldy-Korgan
r. Ili
r.Chu
Almaty
Djambul
Shymkent
Kzyl-Orda
r.Syr-Darya
Aral sea
Aktau
Caspian sea

1. Borders of Premesozoic (a) and Mesozoic-Cenozoic (b) sediments

2. U ore provinces with endogenic deposits in Premesozoic sediments (I- Kokshetauskaya, II- Pribalkhashskaya)

3-5. U ore provinces with exogenic deposits in Mesozoic-Cenozoic sedimentary formations:

3- with soil oxidation of coal beds (III- Iliyskaya)

4- with stratal oxidation in penetration sediments (IV- Chu-Sarysuyskaya, V- Syrdaryinskaya)

5- with phosphatic fossil fish bone detritus (VI- Prikaspiyskaya)

6-10. U deposits:

6- endogenic of different ore formations

7- infiltrations with stratal oxidation

8- infiltration with soil oxidation

9- infiltration with stratal-soil oxidation in sediments of paelovalley

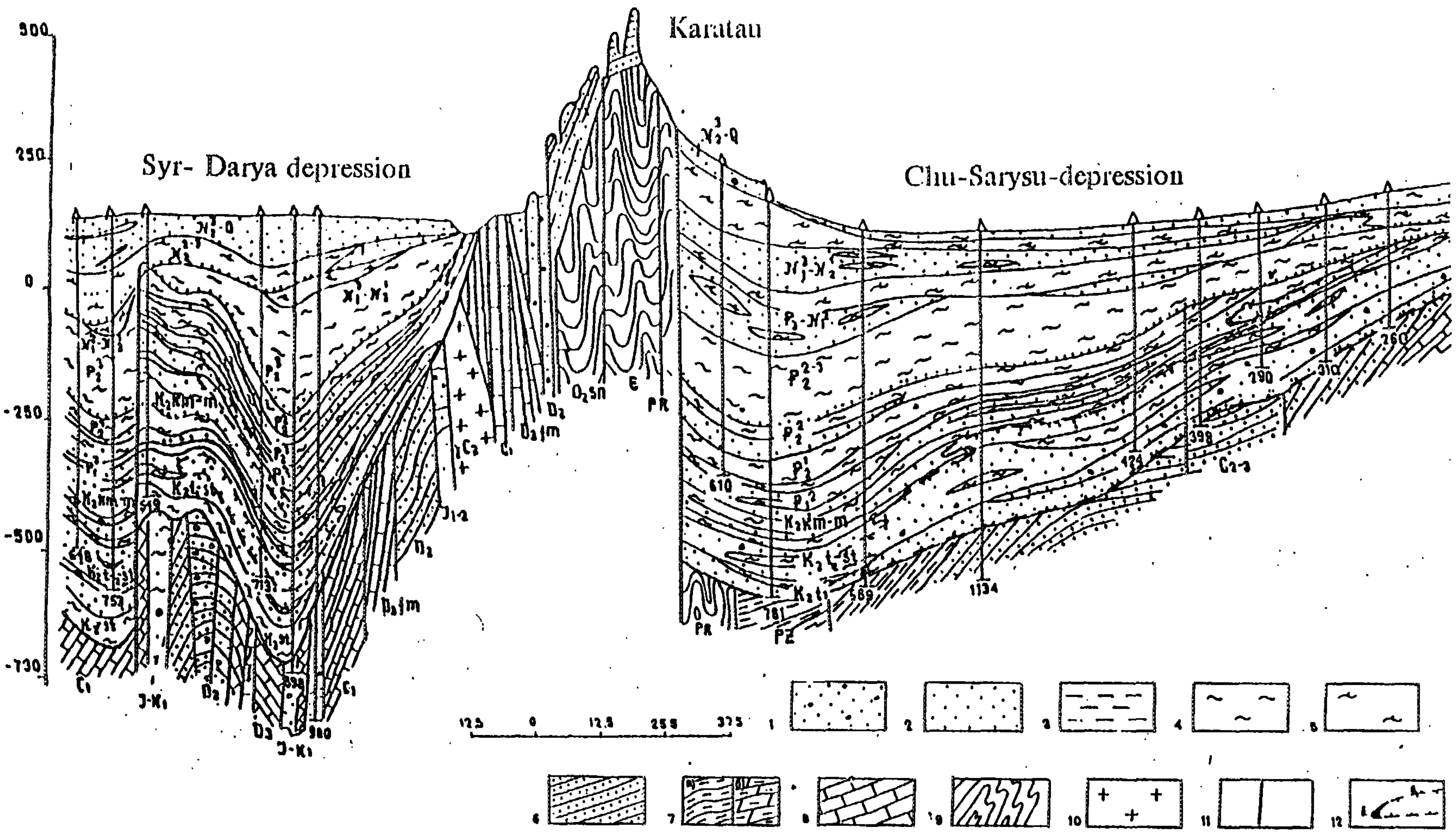
10- with phosphatic fossil fish bone detritus.

11 Production Centres

Numbers of deposits on scheme:

1- Grachyovskoe	17- Chaglinskoe	33- Kyzyltas
2- Shokhpak	18- Shatskoe-I	34- Kandjugan
3- Zaozyornoe	19- Kosachinoe	35- Uvanas
4- Kamyshevoe	20- Vostok	36- Mynkuduk
5- Shatskoe	21- Zvyozdnoe	37- Sholak-Espe
6- Semizbay	22- Manybayskoe	38- Kyzylkol
7- Tastykol	23- Yuzhno-	39- Zhalpak
8- Akkan-Burluk	Manybayskoe	40- Inkay
9- Glubinnoe	24- Shorly	41- Zarechnoe
10- Koksorskoe	25- Talas	42- Moyinkum
11- Vostochno-	26- Granitnoe	43- Severny Karamurun
Tastykolskoe	27- Ulken-Akzhal	44- Irkol
12- Victorovskoe	28- Koldjat	45- Yuzhny Karamurun
13- Agashskoe	29- Nizhne-Iliyskayay	46- Melovoe
14- Fevralskoe	30- Suluchokinskoe	47- Tomak
15- Burlukskoe	31- Djusandalinskoe	48- Taybogar
16- Slavyanskoe	32- Kopalysayskoe	49- Tasmurun

FIG. 1. Uranium gradation metallogenic scheme of Kazakhstan.



1-5 penetrated mesozoic-cenozoic sediments; 6-10 unpenetrated premesozoic sediments; 11-fractures; 12-borders of stratum oxidation and concerning uranium ore

FIG. 2. Geological section of Mesozoic-Cenozoic sediments of Syr-Darya and Chu-Sarysu depressions.

In 1954, the large "Melovoe" deposit was discovered in west Kazakstan, on the Magyshlak peninsula. Its uranium mineralization is concentrated in phosphatic fossil fish bone detritus. This unique type ore (so-called organogeneous phosphatic) is industrial despite low contents of uranium in ore since uranium containing bones can be easily enriched during the washing process. In 1959, the Pricaspian Production Centre was created on the basis of the "Melovoe" deposit, which together with three more deposits forms the Pricaspian uranium province. The general reasonably assured resources of the Pricaspian province amount to about 65 000 t.

Prospection works of the second stage, concentrated basically on the study of depressed structures, resulted in the discovery of a series of large and unique deposits in young friable sediments and in the radical reorganization of the structure of resources for the uranium industry of Kazakstan. These works in the south of Kazakstan revealed three uranium provinces, of which two: Chu-Sarysu and Syr-Darya, are the largest in the world for creation of uranium extraction enterprises by methods of underground leaching. A third province — Ili is characterized by ore of soil oxidation (so-called uranium-coal). However, in spite of high enough contents (up to tenths of percent) and significant reasonably assured resources (about 93 000 t), the industry has not been developed yet due to economic reasons.

In 1970–1971, extraction was successfully carried out, using underground leaching method, in the "Uvanas" deposits, Chu-Sarysu province. This marked the beginning of priority development of the deposits in the Chu-Sarysu and Syr-Darya provinces. At present, within the limits of these provinces, more than 10 large and unique deposits are discovered, the ore of which is connected with regional zones stratum oxidation, developing in north-western direction from Tyan-Shan deep into the artesian basins of Syr-Darya and Chu-Sarysu depressions. The zones of stratum oxidation are developed in several good penetrated sand water-bearing horizons, forming system penetration deep into artesian basins of oxygen water tongues (Fig. 2). Front ending of stratum oxidation zones of these tongues forms a regional geochemical barrier on which uranium ore of sand type of rollfront is formed. In this province there are 6–9 productive horizons located which contain ores with unique technological terms that allow to extract uranium very profitably by method of in situ leaching. The general reasonably assured resources of both provinces amount to 320 000 t which has allowed to create on their bases the uranium extraction enterprises by in situ leaching method.

2. THE CURRENT SITUATION

The discovery of highly profitable and technological deposits in the provinces of Chu-Sarysu and Syr-Darya has resulted in decreasing of mining uranium extraction in Kazakstan and increase (to 80%) extraction share by method of in situ leaching.

At present, in addition to three operating in situ leach enterprises, two more are created, and the creation of 2–3 enterprises are planned, so that in the near future all uranium will be extracted in Kazakstan by in situ leaching method. At all inconsistent evaluations of influence of the in situ leaching method on the environment doubtless one, that this method is the most economic and technological one and produces the least amount of radioactive wastes. The problem of restoration of water horizons after in situ leaching quite soluble, including with help of oxygen method of oxidation of working solutions without application of sulfuric acid.

Thus, at present Kazakstan has a well prepared basis for development of uranium extraction by in situ leaching method, which amounts to 320 000 t at total sum of prepared sticks 600 000 t.

It is not planned to carry out further prospection work for discovering new deposits or provinces. The current work is directed to revealing the stocks within the limits of known ore fields and to transfer additional and estimated stocks in the category of reasonably assured resources.

Revealed and prepared stocks suitable for extraction by in situ leaching method create favourable conditions for uranium extraction carried out by in situ leaching method. In this connection there is the task of conversion of two existing production centres.

3. THE SUPPLY AND DEMAND

At the present low level of development of atomic engineering in Kazakstan (presented by on power generating installation BN-350 on the Mangyshlak peninsula), there is practically no uranium demand in the Republic. All uranium concentrate goes to the world market. Unfortunately, the conditions of expert are at present adverse. Upon improvement of these conditions, Kazkahstan can increase, in short time, uranium extraction up to 5-7 thousand tonnes per year.

4. IMPACT OF THE URANIUM INDUSTRY ON THE ENVIRONMENT

With respect to the problem of the impact of the uranium industry on the environment in Kazakstan there are 3 aspects to take into account:

- availability of deposits of uranium ore,
- long functioning of uranium mines and processing operations,
- cessation of works of extraction and processing enterprises of uranium ore.

The impact of deposits of uranium ores on the environment is bets displayed at formation of ore on ending of stratum oxidation zones (sandstone rollfront type) where practically on all front endings on the band of width of 10-15 km marks natural pollution of water horizons by radionuclides. The extent of the front reaches 100-150 km and the polluted area of water horizons is 2000-5000 km^2. The water from such areas cannot be used. On the other hand availability of sand deposits permits to refuse mining of uranium extraction which forms huge quantities of radioactive wastes.

The production of uranium by mining method in Kazakstan carried out for over 40 years has resulted in an accumulation on the surface of more than 200 Mln.t of radioactive processing wastes which represent low radioactive wastes containing alpha beaming nuclides. These wastes are a threat to the environment in the form of soil and water horizon contaminations by radionuclides as well as in the air in connection with dusting of dry beach of tails of processing.

The specific care for Kazkahstan is presented radioactive wastes formed by enterprises which ceased their operation because these wastes have lost the "owner" and their disposal requires large budgetary appropriations.

5. FURTHER RESEARCH

As mentioned already, the discovery of new uranium deposits and provinces is not planned as the Republic has a large reserve of revealed stocks and stocks which can be revealed within the limits of known ore fields. Thus a large part of resources related to the category of highly profitable and technological ores suitable for extraction by in situ leaching method.

It is necessary to note that this way the sulfuric acid process odes not produce much RadWaste (as with the mining method) proceeds the pollution by radionuclides of water horizon from which uranium is extracted, that requires the special costs of restoration of the horizon. Probably the decrease of the cost is served application of regime of oxygen oxidation without application of sulfuric acid.

The other important direction of research is the reduction of the impact of mining and processing production wastes on the environment.

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URANIUM MINING AND REHABILITATION: INTERNATIONAL ASPECTS AND EXAMPLES FROM GERMANY

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Abstract

In the period from 1945 to 1994 about 1.87 million t U have been produced worldwide. The maximum of production reached about 70 000 t U in 1981, now the production has fallen to about 32 000 t U. Due to the decrease of the annual output, employment in uranium production has decreased, however the productivity has been increased in most countries. As any mining, uranium mining has an impact on the environment. Especially the radioactivity of the ores and waste material may create radiological hazards to the population when protection measures are not observed carefully. The impact of uranium production to the environmental is illustrated by various examples. The costs which are necessary to decommission and rehabilitate uranium production facilities can reach high levels depending on the specifics of the recultivation activities. International examples are given. The production of uranium in Eastern Germany is described briefly, and the reclamation activities of the former Wismut mining and milling facilities is illustrated by selected examples.

1. INTRODUCTION

Uranium has been produced during the past 50 years for both military and civil uses. Part of this production, which was higher than the demand, was stockpiled for strategic reasons. After the fall of the iron curtain, most of the stockpile has been made available for commercial use. Thus, less uranium is now required from production and producers are being forced to reduce their output or close their mines. Production has fallen below demand since the mid-1980s.

The closure of uranium mines and mills requires proper decommissioning and rehabilitation according to international radiation protection guidelines and standards and to national regulations.

Aspects of past and present uranium production are described in this paper, followed by examples of decommissioning and rehabilitation projects. It is not intended to deal with specific methods or regulations in individual countries; however, the example from Germany may illustrate the extent of decommissioning and rehabilitation work necessary in densely populated areas of Central Europe.

2. PAST AND PRESENT URANIUM PRODUCTION

World uranium production during the period from 1945 to 1994 is estimated to have been about 1 868 200 t U or about 4.7 billion pounds U_3O_8. At an arbitrarily chosen sales value of US$20/lb U_3O_8 this would amount to approximately $100 billion. It should be kept in mind however, that the uranium price in WOCA (World Outside Centrally Planned Economy Areas) countries was higher over extensive periods, meaning this value may represent the lower limit.

A breakdown of the estimated production of the different producer countries from 1945 to 1994 is given in Table I. Production figures for WOCA countries (total 1 083 000 t U) are fairly well known through the regular questionnaires on uranium resources and production (Red Book).

TABLE I. RANKING OF URANIUM PRODUCING COUNTRIES (OVER 10 000 t U CUMULATIVE PRODUCTION 1945-1994)
(Figures rounded to the nearest 100 t U)

	Country	World tU	% share		Country	WOCA tU	% share		Country	Non-WOCA tU	% share
1	USA	342,200	18.3	1	USA	342,200	31.6	1	GDR**	216,300	27.5
2	Canada	274,300	14.7	2	Canada	274,300	25.5	2	Czech Rep.	104,100	13.3
3	GDR**	216,300	11.6	3	Rep.S.Africa	148,600	13.7	3	Russ.Fed.	103,000*	13.1*
4	Rep.S.Africa	148,600	8.0	4	France	71,300	6.6	4	Kazakhstan	86,000*	11.0*
5	Czech Rep.	104,100	5.6	5	Niger	62,600	5.6	5	PR China	79,000*	10.1*
6	Russ.Fed.	103,000*	5.5*	6	Australia	57,900	5.4	6	Uzbekistan	70,500*	9.0*
7	Kazakhstan	86,000*	4.6*	7	Namibia	56,700	5.2	7	Ukraine	46,800*	6.0*
8	PR China	79,000*	4.2*	8	Gabon	24,400	2.3	8	Bulgaria	23,100*	2.9*
9	France	71,300	3.8	9	Zaire	23,300	2.2	9	Tajikistan	20,000*	2.6*
10	Uzbekistan	70,500*	3.8*	10	others (14 countries)	21,700	2.0	10	Hungary	17,500	2.2
11	Niger	62,600	3.4					11	Romania	17,100	2.2
12	Australia	57,900	3.1					12	others (2 countries)	1,800*	0,2*
13	Namibia	56,700	3.0								
14	Ukraine	46,800*	2.5*								
15	Gabon	24,400	1.3								
16	Zaire	23,300	1.3								
17	Bulgaria	23,100*	1.2*								
18	Tajikistan	20,000*	1.1*								
19	Hungary	17,500	1.0								
20	Romania	17,100	1.0								
21	others (16 countries)	23,500	1.3			58% of world total				42% of world total	
	total	1,868,200			total	1,083,000			total	785,200*	

* estimated production; ** production 1945 - 1990
1994 production is estimated
BGR,March 1995

TABLE II. RANKING OF URANIUM PRODUCING COUNTRIES IN 1993

	Country	tU	% share	cumulative
1	Canada	9,178	28.4	28.4
2	Niger	2,914	9.0	37.4
3	Russ.Fed.	2,600*	8.0*	45.4
4	Uzbekistan	2,600*	8.0*	53.4
5	Australia	2,256	7.0	60.4
6	Kazakhstan	2,110	6.5	66.9
7	France	1,734	5.4	72.3
8	Rep.S.Africa	1,703	5.3	77.6
9	Namibia	1,668	5.2	82.8
10	USA	1,178	3.6	86.4
11	PR China	1,000*	3.1*	89.5
12	Czech Rep.	950	2.9	92.4
13	Gabon	556	1.7	94.1
14	Ukraine	500*	1.6*	95.7
15	Hungary	380	2.2	96.9
16	Spain	183	<1.0	
17	India	180*	<1.0*	
18	Argentina	121	<1.0	
19	Romania	120*	<1.0*	
20	Germany	116	<1.0	
21	Mongolia	100*	<1.0*	
22	Bulgaria	60*	<1.0*	
23	Belgium	34	<1.0	
24	Portugal	32	<1.0	
25	Brazil	30*	<1.0*	
26	Pakistan	30*	<1.0*	
	total	32,333		

* estimated

BGR,March 1995

TABLE III. MAJOR URANIUM PRODUCING COMPANIES 1993

	Company	Production 1993 tU	% - share of production
1	CAMECO,Canada	5100	15.8
2	COGEMA,France	4200	13.0
	(production in France,		
	Canada,USA Niger,Gabon)		
3	Uranerz,Germany	2670	8.3
	(production in Canada,USA)		
4	Priargunsky (Russ.Fed.)	2600*	8.0
5	Navoi,Uzbekistan	2600*	8.0
6	KATEP,Kazakhstan	2110	6.5
7	Rössing,Namibia	1670	5.2
8	NUFCOR,Rep.S.-Africa	1660	5.1
9	ERA,Australia	1130	3.5
10	WMC,Australia	1120	3.5
		24860	76.9
	World total	32330	100.0

* estimated

BGR,March 1995

Official production data for the non-WOCA area have been provided by only four countries. Production could only be estimated for the remaining 13 countries, mainly CIS and PR China as major producers. Total non-WOCA production was estimated to be about 785 200 t U.

Production for 1993 of about 32,300 t U (see Table II) was less than half of the estimated peak production in 1981. At an average price of \$20/lb U_3O_8 the 1993 production represents a sales value of approximately \$1.7 billion.

As shown in Table II, ten major producing countries account for nearly 90% of the production. The leading producer country is Canada, with a share of 28%. The four producers of the CIS have a share of 25%.

For some countries, e.g. Niger, sales revenue from exported uranium is a major source of income. In 1989 the value of exported uranium from African countries, excluding the Republic of South Africa, amounted to \$530 million or about 7% of the value of all exported minerals.

Most producing countries are major uranium consumers. Other main producers, e.g. Australia, Kazakhstan, Namibia, Niger and Uzbekistan, have no domestic demand, and their entire production is exported.

The share of uranium production by company is shown in Table III. Ten companies accounted for more than three fourths of the 1993 production. The share of the top four producers was almost 50%. Estimated production from companies of the CIS amounted to 23%.

3. EMPLOYMENT IN THE URANIUM PRODUCTION INDUSTRY

The number of persons employed varies from country to country, depending on the number and size of the individual uranium operations. A world-wide survey of employment in uranium mines and processing plants for the past is not yet available. In some countries, however, it was very high. Figures from 15 selected countries show that employment decreased continuously over the past 15 years. In 1985, for example, about 85 000 persons were employed in these countries, in 1990 only 55 000 and in 1993 about 20 000 persons.

The downward trend can best be illustrated by comparing employment and production in two of the major producing countries, USA and Canada, as shown in the following compilation.

	1980	1985	1990	1993
USA				
Production (t U)	16 800	4 300	3 420	1180
Employment	20 000	2 450	1 350	700
t U per man-year	0.84	1.76	2.53	1.69
CANADA				
Production (t U)	7 150	10 880	8 730	9 180
Employment	6 100	5 300	2 500	1 300
t U per man-year	1.17	2.05	3.49	7.06

For comparison, employment by the Wismut company amounted to about 40 000 persons during the 1980s, now (1994), 4 600 persons are employed in the decommissioning activities.

Efficiency in uranium production in the USA and in Canada has increased remarkably, from around 1 t U per man-year in 1980 to 1.7 and 7 t U per man-year, respectively, in 1993. For other countries the trend to higher efficiency can be observed too, but not to the same degree.

4. THE IMPACT OF URANIUM MINING ON THE ENVIRONMENT

Like mining and processing of other minerals, uranium mining has an impact on the environment.

Mining requires land areas of various sizes (e.g. for open pits), which are then no longer available for agriculture or housing. The barren waste rocks and tailings have to be stored in the vicinity of the production centres, requiring additional ground. Dams have to be built to retain tailings; measures must be taken to ensure stability and impermeability.

The radioactivity of uranium means that special safety measures must be taken during mining and processing to prevent radiological hazards to the population and environment.

These measures have not been observed carefully in mining projects immediately after World War II. In the 1950s and 1960s, uranium production served mainly military purposes. This resulted in a growing state-supported uranium mining industry in the West and East. Major producers during that time were the USA, Canada, USSR, GDR, the Czech Republic, and the Republic of South Africa.

After termination of mining due to exhaustion or termination of government sales contracts, mine sites and production centres were closed. In most cases, legal provisions for proper decommissioning and rehabilitation were lacking, and the sites were abandoned without any safety or recultivation measures being taken.

The growing environmental awareness during the 1970s resulted in governmental regulations being issued for new projects and for recultivation of abandoned sites. One of the major objectives of the regulations for new mines is to ensure proper consideration of the impact on the population and overall environment in view of the economic and socio-economic interests. The potential release of radioactive and chemically toxic substances during production is avoided by requiring special operating conditions. Today, mining companies in many countries are legally required to include the cost of decommissioning and rehabilitation in their cost calculations. The operator has to demonstrate that sufficient funds for later decommissioning and rehabilitation are available. New mines receive permission only when an environmental impact study (EIS) has been carried out.

For abandoned mines the situation is different. Very often the previous owner is no longer available. To protect the population and the environment in those cases, many countries are now undertaking cleanup projects financed by the government.

Examples of this are the Uranium Mill Tailings Remedial Action (UMTRA) of the USA or the ongoing program for German uranium mines and mills decommissioning. The examples shown in Table 4 illustrate the burden on the taxpayer when rehabilitation has to be carried out long after mining was terminated.

The different types of rehabilitation projects, according to a proposal by URANERZ (1994), may be classified as follows:

1) Abandoned production sites:

no rehabilitation by the owner,

TABLE IV. COST OF DECOMMISSIONING AND REHABILITATION. FOUR EXAMPLES OF COMPLETED AND ONGOING PROJECTS

1) UMTRA Title I

This project encompasses 24 facilities which were in production in the 1960s and 1970s.

Uranium production: ca. 56,000 t U

Area involved: 1450 ha

Rehabilitation period: 1979 – 1998, by US government

Expenditures today: $1.3 billion,
estimated total: $2.1 billion

Specific costs: $9.3/lb U_3O_8 today, estimated total $14.7/lb U_3O_8

2) Beaverlodge, Canada

Production period: 1950 – 1982

Uranium production: 17,500 t U (underground mine)

Rehabilitation period: 1983 – 1995, by the mining company

Expenditures: C$ 16 million

Specific costs: C$ 0.36/lb U_3O_8 or US$ 0.3/lb U_3O_8

3) Quirke mine, Elliot Lake, Canada

Production period: 1956 – 1961, 1968 – 1990

Uranium production: 44,000 t U (underground mine)

Rehabilitation period: 1991 – 1994, by the mining company

Expenditures: C$ 46 million

Specific costs: C$ 0.4/lb U_3O_8 or US$ 0.33/lb U_3O_8

4) UMTRA Title II

Subject of this program is sites that are being decommissioned and rehabilitated by private companies through financial reserves set aside during the production period (surety bonds).

Production period. since before 1980

Uranium production 250,000 t U

Rehabilitation penod since 1980

Expenditures: $290 million so far, will become higher!

Specific costs: $0.44/lb U_3O_8

5) Average from 120 mining and 80 milling operations and 12 ISL projects in 14 countries (not including Germany)

Accumulated production: 1.1 million t U

Expenditures: $3.7 billion

Specific costs: $1.25/lb U_3O_8

rehabilitation at the expense of the government.
Examples: Port Radium, Canada;
several mines in western USA (UMTRA Title I);
several mines in the CIS.

2) Rehabilitation at government expense immediately after closure.
Examples: Wismut, Germany;
several mines in the Czech Republic.

3) Rehabilitation by the owner after closure,
financed by the owner through earnings (regular case).
Examples: Elliot Lake, Canada;
mines in France;
recently closed mines in the USA (UMTRA Title II)

4) Rehabilitation by the owner during the production period,
financed through earnings.
Examples: In situ leaching, e.g. in the USA

Which decommissioning and rehabilitation methods are used depends largely on the type of the deposit and the mining and processing methods.

The following parameters are associated with the specifics of the deposits:

- morphology of the orebody
- depth of mining
- rock stability
- hydrogeological conditions
- ore grade
- mineralogy and chemistry of the ore.

Additionally, the following mining and milling techniques have to be taken into consideration:

- open pit mining,
- underground mining,
- conventional extraction (acid or alkaline leaching),
- heap leaching,
- in situ leaching from the surface by injection of acidic or alkaline chemicals,
- leaching underground.

These aspects are only some of the general features to be taken into account. For new mines, which require licensing, consideration of the above parameters and mining and milling methods is part of the planning of costs during the feasibility study.

For example, open pit mining is considered as cost-advantageous due to the use of large-capacity equipment. On the other hand, large-scale operations generally produce huge amounts of barren waste rock and large amounts of low-grade ore. Safe storage of over-burden and waste rock requires solid ground and well-engineered dumps. The mineralogy of the waste rock has to be analysed to determine its potential for generating acids, which would pollute the surface and ground water. The stability of the open pit walls has to be investigated and carefully monitored. The hydrogeology of the mine area is also a factor to be assessed and monitored.

Safety measures for underground mines include monitoring of wall-rock stability, determination of the lithology and chemical composition of the wall rock and the hydrogeology.

The potential for the generation of acidic mine water is an important concern which has to be investigated prior to decommissioning.

Suitable ground conditions are required for the deposition of tailings containing radioelements and in many cases chemically toxic substances (e.g. heavy metals, As). Various options for the safe disposal of tailings are available:

1) In the past, an earth-dam across a morphological depression (e.g. a valley) was considered to be sufficient. However, leakage of water is a current problem which requires careful monitoring. Dam stability has to be assured, so that breaks or severe leakage of material is prevented.

2) Another option is the construction of a lined and covered pond. This requires careful monitoring.

3) When available, open pits may be used as disposal sites for tailings. This option was taken up again recently in Canada and in France. The open pit remaining from the mined out Rabbit Lake deposit e.g. is used for disposal of the tailings from the currently operating Collins Bay and Eagle Point deposits. The mined out Deilmann orebody will be used for disposal of waste from mines that will soon become operational.

Subaerial disposal of tailings has proved to be advantageous in terms of cost, since it simultaneously provides backfill for the open pit. Later covering and recultivation is regarded as low cost.

5. COST OF DECOMMISSIONING AND REHABILITATION

The cost of decommissioning and rehabilitation depends to a large extent on the type of project. Four examples of completed and ongoing projects are given in Table IV.

6. URANIUM MINING IN EASTERN GERMANY

Uranium mining started in 1946 in the Erzgebirge Mountains, Saxony. These deposits have been mined since the 12th Century, first for silver, and later for cobalt, nickel and other base metals. The uranium mining district is in late Paleozoic (Hercynian) rocks north of the Bohemian Massif. Uranium was mined from well-known mines of Schlema-Aue, Johanngeorgenstadt in Germany and Jachymov in the Czech Republic.

The deposits are of the vein-type. They occur mainly at the exocontacts of 300 to 330 My/old granites and are hosted by metamorphosed rocks (schists, amphibolites, metadiabase) of Ordovician to Devonian age.

The mineralization belongs to the classical five element association (Bi–Co–Ni–Ag–U) and was formed in two periods at around 275 My and 155 My. The uranium content of the mined deposits varied considerably; the average grade was 0.4% U. The mines extended to a maximum depth of 1750 m.

Mining in the German part of the Erzgebirge yielded about 88 000 t U from more than 12 mining sites. Mining was terminated at the end of 1990 due to economic considerations and depletion of the deposits.

Production in the second mining district began in Thuringia in 1950. At the beginning, uranium was mined in open pits from deposits hosted in Upper Permian sandstone and in black shales of Ordovician and Silurian age. The Lichtenberg mine, the largest open pit mine, was worked from 1957 to 1978. At the same time, deposits were mined underground to a depth of 1100 m. The host rocks of the uranium mineralization are Ordovician shale (Lederschiefer), Silurian graptolitic shale and Devonian diabase.

The mineralization occurs in lenses and stockworks and is fissure controlled. The ore-forming process was complex, starting with an initial enrichment of uranium in the black shale (protore). When the black shale was exposed at the surface during the Permian, uranium was leached by weathering and redeposited on geochemical barriers in the non-weathered parts of the host rock. This process was controlled by the fracture system. The ages of the major ore formations are 240 Ma and 90 Ma. The average content was 0.08 to 0.09% U. The Ronneburg district in Thuringia yielded about 97 000 t U from more than 6 areas. Mining was terminated in 1990 for economic reasons.

The third and smallest mining district is located near Dresden, Saxony. Uranium hosted in coal of Permian age in the Freital area was mined from 1947 to 1955 and 1968 to 1989. About 3 000 t U were produced.

Uranium mineralization in the Königstein area is hosted in Cretaceous sandstone (Cenomanian), similar to the Stráž-Hamr deposits in the Czech Republic. Initially, the deposit was mined by conventional underground methods (1967 to 1983). Block leaching of low-grade, underground parts of the deposit using sulfuric acid was begun in 1971, continuing until 1990. About 15 000 t U were produced conventionally and 3500 t U by leaching.

A total of 216 352 t U was produced in the former GDR from 1946 to 1990: 87% by underground mines, 9% by open pit mining and 2% by leaching methods.

Two major processing operations utilized acid and alkaline extraction methods. The Crossen mill had an annual capacity of 2.5 million t of ore and the capacity of the Seelingstädt mill was 4.6 million t.

The uranium mining districts of Saxony and Thuringia are among the most productive districts in the world. Their output may be compared to that of the Elliot Lake mines in Canada (140 000 t U) or of the Grants District, USA (125 000 t U).

7. RECLAMATION ACTIVITIES OF FORMER WISMUT MINING AND MILLING FACILITIES

A vast amount of land and facilities was contaminated by Wismut uranium production activities from 1946 to 1990. The environments of the mining areas have been adversely affected. Only minor rehabilitation was carried out during the mining period by the former joint Soviet-German company Wismut.

With the German unification the Federal Government of Germany took over responsibility for Wismut in 1990 and was faced with various problems. The first decision was to terminate all commercial mining activities for economic reasons. Second, a program was initiated to evaluate the extent to which cleanup activities will be necessary. On behalf of the Federal Ministry for Environment, Nature Conservation and Nuclear Safety, the Federal Office for Radiation Protection (BfS) was commissioned to conduct a radiological evaluation of abandoned uranium mining and milling facilities. On the basis of recommendations by the German Commission on Radiological Protection, the evaluation was conducted with special emphasis to 1 mSv/year dose rate as the threshold value for individual exposition of the population, additional to the pre-mining exposition. The study areas were defined and field inspections with measurements of radioactivity were carried out. About 5000 abandoned mining related sites originating from medieval silver

TABLE V. WISMUT SITES AT THE BEGINNING OF RECLAMATION ACTIVITIES

	Aue	Königstein	Ronneburg	Seelingstädt	Total
Surface (ha)	569.4	143.4	1 670.3	1 314.8	3 698.3
Shafts	8	10	38	0	56
Waste piles					
- number	20	3	16	9	48
- footing (ha)	342.3	37.9	552.0	533.1	1 517.7
- volume Mm^3	47.2	4.5	178.8	72.0	311.5
Tailings ponds					
- number	1	3	3	7	14
- surface (ha)	3.5	4.6	9.0	706.7	723.8
- volume Mm^3	0.3	0.2	0.25	159.7	160.45
Mine workings					
- surface km^2	30.7	7.1	73.4	0	111.2
- acc. length km	240	112	1 043	0	1 395
Open pits					
- number	0	0	1	0	1
- surface (ha)	0	0	160	0	160
- volume Mm^3	0	0	84 (open)	0	84

Source: Wismut 1994

mining and later base metal and uranium mining were identified in an area of 1500 km^2. The evaluation reduced this area to about 250 km^2, which will require further investigation and cleanup measures. The comprehensive evaluation will be finished in 1996/1997.

Other than the orphan mining sites all mining and milling facilities being active until 1990 were transferred to the new Wismut rehabilitation company. Administered and financed by the Federal Ministry of Economics (BMWi) this government-owned but privately organized and privately managed company is responsible for the decommissioning and remediation of its facilities and sites.

An overview of the mining and milling sites is given in Table V.

After evaluating the complexity and magnitude of the necessary restoration measures, it was decided to take a site-specific, risk-based approach. Because this agricultural and industrial area is densely populated, all remediation activities had to be carefully planned. The ongoing restoration activities are illustrated by the following examples:

- Open pit mining has produced about 600 million m^3 of ore and waste rock, of which about 160 million m^3 was taken from a single open pit (Lichtenberg) nearly 200 m deep with an area of about 1.6 km^2. After mining activities ceased the open pit was used for disposal of waste rock from the Ronneburg mines. About 80 million m^3 have been backfilled before 1990. About 100 million m^3 of waste material remains piled around Ronneburg. Most of this material will be backfilled in the open pit.

- Underground mining has yielded about 300 million m^3 of material, half of which was ore. In the Aue district of the Erzgebirge, there are about 40 piles with a total volume of over 45 million m^3 covering an area of about 3 km^2. A major program of stabilization, reshaping, covering and revegetation of these piles is being carried out.

- In addition to numerous shafts, drifts totalling about 1400 km have been driven.

- Mill tailings: Two major conventional mills have been operated (Crossen and Seelingstädt) besides a number of smaller ones, being active at the mining sites for a short period of time.

  At the Crossen mill, alkaline leaching methods were used for ore from the Erzgebirge. The tailings were disposed of in a nearby pond, about 2 km^2 in size, which now contains about 45 million m^3 of tailings and 6 million m^3 of water.

  The Seelingstädt mill used both alkaline and acid leaching methods and processed mainly ores from the Ronneburg district in Thuringia. The tailings were disposed of in two nearby ponds with a total volume of 107 million m^3, covering an area of 3,4 km^2.

8. STATUS OF WORK

Detailed engineering studies in 1990 and 1992 yielded conceptual models for remediation measures. The most important measures may be classified as follows (only a selection):

- Underground remediation:
  - cleaning and flooding of the mines,
  - backfilling of mine workings,
  - hydrological control,
  - groundwater protection and monitoring.

- Surface restoration:
  - demolition of buildings,
  - site rehabilitation for other uses,
  - repair of surface damage caused by mine subsidence,
  - cleaning of contaminated soil,
  - groundwater protection and monitoring.

- Mill tailings remediation:
  - in situ stabilization and covering of tailings,
  - cover design,
  - improvement of dam stability,
  - groundwater protection and monitoring.

At present, many of these activities are ongoing, e.g.:

- Underground mine remediation is far advanced. More than 5 000 underground barriers have been constructed to prevent exchange of groundwater with water in the flooded mines. Mine workings have been partly refilled or stabilized to protect the surface from mine subsidence, to minimize radon exhalation and infiltration of groundwater.

- Surface remediation includes backfilling of the Lichtenberg open pit from adjacent waste rock piles, reshaping of the remaining piles, and revegetation. Some buildings have been demolished, contaminated soil has been removed and the ground prepared for reuse.

- Covering of mill tailings after dewatering is one of the most challenging problems. With continuing dewatering, the ponds will be gradually covered using geotextiles and soil. The final cover will be designed to prevent radon emanation and water infiltration.

  Numerous boreholes and wells for the observation of groundwater control were drilled around the tailing ponds and are continuously monitored.

  DM 700 to 800 million are spent annually for these activities. It is estimated that about DM 13 billion will be required over a period of 10 to 15 years.

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THE IMPACT OF CANADA'S ENVIRONMENTAL REVIEW PROCESS ON NEW URANIUM MINE DEVELOPMENTS

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Abstract

Canada introduced an environmental assessment process in the mid 1970s. It was designed to ensure that the environmental consequences of all project proposals with federal government involvement were assessed for potential adverse effects early in the planning stage. In 1984, a Guidelines Order was approved to clarify the rules, responsibilities and procedures of the *Environmental Assessment and Review Process* (*EARP*) that had evolved informally under earlier Cabinet directives. The *EARP* process remained largely uncontested until 1989/90, when two decisions by the Federal Court of Appeal effectively converted the Guidelines Order into a legal requirement for rigorous application. The Supreme Court of Canada upheld the constitutionality of the *EARP* Guidelines Order in 1992, rendering compliance with the Order by all federal government decision-makers a mandatory requirement. Canada became the world's leading producer and exporter of uranium during the late 1980s. Since then, the Canadian public has become sensitized to numerous issues concerning environmental degradation, from the Chernobyl accident to ozone depletion. In 1991, during this period of increasing awareness, the Atomic Energy Control Board, the federal nuclear regulator, referred six new Saskatchewan uranium mining projects for environmental review, pursuant to the *EARP* Guidelines Order. Both federal and provincial governments and the uranium industry expressed concern about the potential impacts of an apparently burdensome public environmental review process on the development of new uranium mining projects. However, the successful advancement of three such proposals through the process has allayed much of the uncertainty and has confirmed that Canada's uranium-producing operations can meet high environmental, health, and safety standards. The public review process provided an extremely valuable focus on aspects of these developments that needed to be addressed by proponents and regulators. It has helped to demonstrate that new uranium mining projects are being developed in a responsible manner, after full consideration has been given to the potential impacts and public concerns associated with these facilities. The lessons learned in Canada could well prove to be useful in other jurisdictions where considerations are being given to the development of new uranium production projects.

1. INTRODUCTION

The establishment of the Canadian government's process for assessing the environmental impact of major new projects was precipitated in part by a growing appreciation among Canadians that a balance must be achieved between the activities that promote economic growth and the preservation of the natural environment. Governments have become increasingly aware that economic growth must be managed in a manner that is sustainable in the longer term. When public confidence in an environmental assessment (EA) process is achieved, and economic growth is seen to be managed responsibly, the continuation of development is supportable by everyone. When a viable process is accepted in one jurisdiction, the approach may quickly become the norm in others.

This paper will provide a brief examination of the evolution of Canada's EA process, focussing primarily on its application to the uranium mining industry. The new environmental assessment legislation will be compared with the previous federal EA regulations under which all the current uranium mining projects are, or will be, reviewed. The paper will provide some recent examples of the nature and scope of the reviews undertaken related to uranium mining projects, and of their outcomes. A brief analysis of this recent experience, together with some observations about how the effectiveness of the process might be improved, may be useful for those considering adopting the Canadian model as part of the approval process in the development of their uranium resources.

2. PERCEPTIONS AND PUBLIC AWARENESS

Canada has been a major producer of uranium since the inception of the industry in the 1940s. However, Canada's emergence as the world's leading producer and exporter of uranium in the mid 1980s coincided with a surge in anti-nuclear activity which sought to block further nuclear power growth. The prospect of uranium mining expansions in Saskatchewan, together with a Canadian public newly sensitized to environmental matters, afforded anti-nuclear advocates the perfect opportunity to discredit the uranium mining industry. In parallel, Canadians had become increasingly aware in the 1980s of the importance of maintaining a strong economy and a healthy environment. World events focused public concern on the need for policies and practices that promoted sustainable development.

Critics pointed to falling uranium prices, reactor cancellations, and lower uranium demand. The Three Mile Island and Chernobyl accidents together with the uranium mine-water spills in Saskatchewan became "proof" that nuclear power and uranium mining were environmentally dangerous. Detractors argued that new uranium production capability was not needed. A public letter-writing campaign was launched to persuade governments to reject new uranium mining proposals on environmental grounds. When it became clear that industry intended to proceed with new mining proposals, the anti-uranium lobby called for a review of uranium mining in northern Saskatchewan. When this failed, critics turned to the EA process as a possible means of blocking new developments. They argued that only by imposing a new stringent review process could the environment and Canadians be protected. It was alleged that Canada did not have any critical environmental review mechanism in place for uranium exploration and mining activities. Clearly, this is not the case!

3. REGULATORY FRAMEWORK FOR ENVIRONMENTAL REVIEW

3.1. Background

Canada is a federation of ten provinces. The respective jurisdiction of the federal government and the provinces is defined in the Canadian *Constitution Act, 1987*. Under the Constitution, the federal Parliament has the power "to make laws for the peace, order and good government of Canada," except for those areas which fall under exclusive provincial jurisdiction as specified in the Act. Many of these areas of federal jurisdiction are enumerated in the Act, such as defence, postal services, navigation, shipping, railways, international and interprovincial undertakings, money banking, and criminal law. Areas of provincial jurisdiction include such matters as natural resources, electricity generation, local works and undertakings, hospitals, education, property and civil rights, and the creation of courts and the administration of justice. There are also areas where the federal Parliament and provincial legislature share power.

3.2. The Federal Role in the Nuclear Industry

The federal government has overall jurisdiction over Canada's uranium industry by virtue of the *Atomic Energy Control Act* of 1946. All Canadian uranium operations are classified as nuclear facilities, and are controlled by the federal Atomic Energy Control Board (AECB) under the provisions of the Act and the regulations derived from it. Although uranium mining activities have always been subject to the requirements of the Act and its regulations, a strict licensing system has been in place since 1976. The AECB issues licences for the operation of uranium mines only after ensuring that they will not have a significant effect on the health and safety of the mine workers and the public, and after reviewing measures designed to ensure adequate protection of the environment.

Furthermore, the AECB has always imposed on its uranium mining licensees the responsibility of reducing a miner's radiation exposure to levels as low as is reasonably achievable. Considerable advances in radiation protection regarding the risk of cancer have been made since the beginning of uranium mining in Canada. The AECB also regulates waste management practices to ensure that the radiological impact of Canada's uranium tailings does not pose any undue public health and environmental risks.

3.3. Provincial Environmental Protection

In Canada, all levels of government share responsibility for environmental protection. With the growing awareness that EA was becoming an essential tool for ensuring effective integration between economic and environmental imperatives, Ontario, already an important uranium producer, became the first province, in 1975, to establish its own *Environmental Assessment Act*. The following year, shortly before the province became Canada's leading uranium producer, the Government of Saskatchewan established an Environmental Impact Assessment Branch in its Environment Ministry, and in 1977 became involved in scrutinizing and regulating its uranium mining industry in response to rising public concerns over proposals to develop new uranium mines in the Athabasca Basin. The provincial government appointed the Cluff Lake Board of Inquiry in 1977 and the Key Lake Board of Inquiry in 1979 to examine the Cluff Lake and Key Lake uranium mining projects, respectively, through a public hearing process. At these reviews, the public voiced concerns about environmental protection, the health and safety of workers, economic development, and the benefits to local communities. Both Boards of Inquiry found that the measures proposed by the uranium industry were adequate to protect environmental quality, safeguard occupational health and safety, and meet the requirements of Canadian and Saskatchewan law, regulations and policies in a satisfactory manner.

As a result of these and other non-uranium inquiries, the Government of Saskatchewan established a new *Environmental Assessment Act* in 1980, and created special units within its departments of the Environment and Labour to license and inspect uranium mines. Saskatchewan's EA review and regulatory processes have been structured to accommodate federal/provincial reviews for new uranium mining developments, as detailed later in the paper.

3.4. The Federal Environmental Assessment and Review Process

The federal EA process has parallelled the introduction of provincial procedures. Originally established by Cabinet Directive in 1973, and reaffirmed with some improvements in 1977, the federal Environmental Assessment and Review Process (EARP) was created to ensure that the environmental consequences of all project proposals with federal involvement were assessed for potential adverse effects early in the planning process. Specifically, EARP has been applied as an aid to predict the likely environmental effects of all proposals requiring federal involvement and decision-making. To oversee this process, the Federal Environmental Assessment Review Office (FEARO) was established, and operated within the federal Department of Environment.

In 1984, the Governor in Council approved a Guidelines Order to clarify the rules, responsibilities and procedures of EARP that had evolved informally under the earlier Cabinet Directives. The EARP Guidelines Order (EARPGO) set out a detailed assessment process for all proposals which would "include any initiative, undertaking or activity for which the Government of Canada has a decision-making responsibility." In this regard, "a decision-making responsibility" was interpreted as including proposals undertaken by any federal department, those likely to have an environmental effect on an area of federal responsibility, those for which the federal government makes a financial commitment, or those developed on lands or territories, including the offshore, administered by the federal government. While private-sector developments were not covered unless the development required federal involvement, for example the issuing of a licence, provincial regulations may apply to all projects within provincial boundaries. As will be discussed below, the current review of six uranium mining projects in Canada falls under the EARP Guidelines Order of 1984.

The EARPGO was written with a fair degree of flexibility and numerous areas were open to interpretation. Over time, it became clear that the EA process needed strengthening, clarification and reform; a revision of the process began in 1987. Nonetheless, the Order remained largely uncontested until 1989/90, when two decisions by the Federal Court of Appeal underscored the need for reform. In response to a challenge by environmentalists that approval of the construction of the Rafferty-Alameda and Oldman River dams in western Canada had been granted without an EA, the court ruled that what was thought to have been a non-enforceable guideline was, in fact, a legally enforceable law of general application that imposed additional duties to the existing responsibilities of federal decision-makers. This effectively converted the EARPGO into a legal requirement for rigorous application. Although these court decisions reflected a shift in public values, they also had a more significant impact in hastening reform. As the Order had not been drafted with strict legal interpretation in mind, the difficulty and uncertainty evident in its administration necessitated revisions in order to render the process effective, efficient, fair, timely and open. [See the section on The *Canadian Environmental Assessment Act* (CEAA) for a complete discussion of the new legislation.]

4. INDEPENDENT PUBLIC ENVIRONMENTAL ASSESSMENT AND REVIEW PANELS

Before addressing the issues surrounding EARP as they relate to uranium mine developments, it should be noted that all new uranium mining projects are automatically referred by the AECB for public review, and that the review of a uranium mining proposal requires the formation of an EARP panel. As will be discussed later, much of the concern expressed by government and industry relates to the activities of these independent public review panels.

In April 1991, six uranium mining projects were referred by the AECB for public review. A five-member *Joint Federal/Provincial Panel on Proposed Uranium Mining Developments in Northern Saskatchewan* was appointed in August 1991 to assess the *Cluff Lake Dominique-Janine Extension (DJX)*, the *Midwest Joint Venture (MJV)*, and the *McClean Lake* projects. A four-member federal *Rabbit Lake Uranium Mine Environmental Assessment Panel* was appointed in November 1991 to conduct public hearings on the *Eagle Point/Collins Bay A & D Expansion*, also proposed in northern Saskatchewan. (See *Case Histories* for specifics on the recommendations of these two panels and the responses to the recommendations by government.)

It should be noted that of the six uranium mining proposals referred in 1991 for panel review pursuant to the EARPGO, only three completed the review process before CEAA was proclaimed in January 1995. However, the remaining three uranium mining projects will be assessed under the EARPGO, since the review panels were appointed prior to CEAA being proclaimed.

5. ISSUES RELATED TO EARP, INCLUDING OVERLAP/DUPLICATION AND SCOPING

As noted above, the Canadian and Saskatchewan governments both developed independent environmental assessment and review processes for those projects in which they would be involved. As well, each level of government also assumed specific regulatory responsibilities for various aspects of the development of uranium mining projects.

In accordance with the federal EARP Guidelines Order, the AECB established an automatic referral list for proposals such as new uranium mining facilities. The expansion or extension of existing facilities also became referable under various sections of the Guidelines Order, following an AECB screening process. When six uranium mining projects were proposed for development in Saskatchewan (see *Case Histories* below and Table I), each requiring an EA by a public review panel pursuant to EARP, it became clear that the existence of parallel processes at the federal and provincial levels would create unnecessary duplication.

In recognition of the similar legal requirements for a public input process, Saskatchewan and federal officials cooperated closely in establishing a joint federal/provincial process to review five of the six new uranium mining proposals. Saskatchewan agreed to include all but one of the proposals in a joint review process. As Cameco Corporation's *Eagle Point/Collins Bay* project had received provincial approval in 1988, there was agreement that it be excluded from review by the Joint Panel; it was reviewed only by a federal panel. This teamwork proved very beneficial and is highlighted by two examples of excellent federal/provincial cooperation.

First, establishing the Joint Panel's Terms of Reference (ToR) was crucial in limiting the overall scope of the review, so as to exclude issues such as nuclear non-proliferation and other national or international issues not directly related to the impacts of these uranium projects. Annex 1, the product of considerable inter-governmental negotiation, reproduces the ToR for the Joint Panel.

Second, the finalization of guidelines for preparing Environmental Impact Statements (EISs) for the *Cigar Lake* and *McArthur River* projects was a major effort. The Joint Panel held scoping sessions to solicit views and opinions from the public and prepared guidelines with the help of a consultant. Circulated for comments in draft form in June 1992, these guidelines raised significant concern at both levels of government and in the uranium industry because they seemed to broaden the scope of the Joint Panel's review beyond that originally mandated. The guidelines also obliged proponents to submit marketing and operating information that could compromise their commercial positions, and sought data on social and health matters which were not readily, or in some cases legally, obtainable by the proponents.

The draft guidelines did not assign specific responsibility for the collection of data among the various expert groups, which might later be called upon to provide specialist testimony. They also suggested that governments provide guidance and information at the data-gathering stage and then critique the results presented at public hearings, without realizing that this might place governments in conflict of interest. Finally, they included questions about certain regulatory processes that were judged to be beyond the Panel's ToR. In summary, as drafted, the guidelines sought a great deal of information, significant amounts of which were not readily available and some of which was not directly relevant. All of these observations were submitted and the draft EIS guidelines were subsequently modified by the Panel. Annex 2 reproduces the table of contents of these draft guidelines as an indicator of their comprehensiveness.

6. GENERAL APPLICATION AND RESPONSIBILITIES UNDER EARP

Before reviewing the progress of the first uranium projects through the panel process, it is useful to outline the role of the various players involved in an EARP review and how the process proceeds.

6.1. Application of EARP

As defined under EARP, any department, board or agency of the Government of Canada, including the AECB, may be considered an "initiating department," that is, a federal department or agency that has "decision-making authority" for a project. The EARPGO requires all initiating departments to consider the environmental impacts of proposals as early as possible.

Section 12 of the EARPGO obliges initiating departments to assess all projects, including those proposals with potentially significant adverse environmental effects. When it is determined that impacts may be significant or unknown, proposals are referred to the Minister of the Environment for independent panel review. However, Section 13 of the EARPGO states that "Notwithstanding the determination concerning a proposal made pursuant to Section 12, if public concern about the proposal is such that a public review is desirable, the initiating department shall refer the proposal to the Minister for review by a Panel."

Upon receipt of a panel report with recommendations, it is the responsibility of the initiating department to decide, in cooperation with other departments, the extent to which the recommendations should become a requirement of the Government of Canada. It is worth stressing that recommendations developed by a panel are advisory to government and to the regulatory agencies.

As noted above, the AECB's automatic referral list included new uranium mining facilities. In 1991, the AECB referred the six Saskatchewan uranium mining proposals for independent panel review, through the then Minister of Energy, Mines and Resources (now Natural Resources). The referral of these proposals to EARP was done as early as possible and was based on the proponents' letters of intent, not on actual licence applications.

6.2. The Role of the Federal Environmental Assessment Review Office (FEARO)

Until the promulgation of CEAA, FEARO was responsible to the Minister of the Environment for the administration of the EARPGO, and for advising departments on their EA responsibilities. Once a proposal was referred for public review by an independent panel, it was the responsibility of FEARO, in consultation with the department or agency making the referral, to draft terms of reference for approval by the Minister of the Environment, to identify potential panel members, and to ensure procedures were in place to conduct the panel review. When the panel completed its work, FEARO transmitted the panel's report to the Minister of the Environment and the Minister responsible for the department or agency that made the referral. In preparing the government response, FEARO typically took the lead in ensuring that the government respected the integrity of the process by giving the panel recommendations due consideration.

6.3. The Role of a Public Environmental Assessment Panel

Environmental assessment panels are made up of unbiased individuals who are appointed by the Minister of the Environment to examine the environmental effects of the proposal and the directly related social impacts of those effects. With the approval of the Minister of the Environment and the Minister responsible for the initiating department, panels may also consider the general socio-economic effects of, and the technology and need for, new proposals. A panel is empowered to issue guidelines to the proponent for the preparation of an EIS, and to conduct public hearings on the project. It is the responsibility of a panel to prepare a report containing its conclusions and recommendations for decisions by the appropriate authorities. These recommendations result from a consideration by the panel of all the information submitted to it, including the public concerns the panel has heard.

6.4. The Role of Federal Ministers

Generally under the EARPGO, it is the role of the Minister responsible for a department, board or agency to refer to the Minister of the Environment for a public review by an independent panel any project with potentially significant adverse environmental effects (or projects where public concern is such that a public review is desirable). The Minister of the Environment, as Minister responsible for FEARO, is then responsible for appointing the panel and issuing the terms of reference for the review. Responsibility for making the panel report public rests with both the Minister of the Environment and the Minister of the responsible department. The decisions arising from panel reports are to be made by all Ministers with jurisdiction, including the Minister of the Environment. In making their decisions, the responsible authorities, including Ministers with jurisdiction, must consider the panel report, but are free to consider other sources of information and to make different value judgements.

Proposals regulated by the AECB are a special case in that many of the recommendations of panels fall within its jurisdiction. Although the Minister of Natural Resources has the power to issue special directives to the Board, this power is normally reserved for extraordinary circumstances. The distinction between recommendations directed to the AECB and those directed to the government is based on whether the recommendations are related to potential licensing conditions.

6.5. The Role of the Atomic Energy Control Board (AECB)

The AECB, an independent federal regulatory body established to control and supervise the development, application, and use of atomic energy, reports to Parliament through the Minister of Natural Resources. As noted, one of the roles of the AECB is to regulate the mining of uranium to ensure that the activity does not pose undue risk to health, safety, security and the environment.

Licence applications to the AECB for a project that has undergone a public review by a panel must also undergo a further internal review by AECB staff with contributions from other government agencies such as the federal departments of Environment, Human Resources Development, and Fisheries and Oceans, and their provincial counterparts. These agencies make up what is called the Joint Review Group, and this consultative process is known as the Joint Regulatory Process. All relevant comments from the Joint Review Group, and those from the public review panel, are then reflected in a recommendation from AECB staff concerning appropriate licensing action to the five-member Atomic Energy Control Board. If the Board is satisfied that the proposal is acceptable with respect to health, safety, security and protection of the environment, a licence is issued.

7. CASE HISTORIES — PROJECTS PROGRESSING THROUGH EARP

In April 1991, six uranium mining projects in Saskatchewan were referred by the AECB for public review. The map below (Fig. 1.) shows the location of the major uranium-producing operations in Canada, while Table I provides a summary of the six new mining proposals. Among the first projects to be referred for EARP review amid the controversy surrounding the above-mentioned Federal Court of Appeal decision, these six proposals entered the process at a very sensitive time. The five projects examined by the Joint Panel were referred under Section 12 of the EARPGO, while the sixth project, examined by the Federal Panel, was referred under Section 13 of the EARPGO (see page 5). By late 1991, specific ToR had been released for both Panels and the respective reviews had begun.

The Joint Panel commenced public hearings for the first three of five uranium mining projects on March 22, 1993, and completed this phase of the review on May 20, 1993. The Federal Panel also commenced public hearings early in 1993. The marathon of hearings for the Joint Panel alone covered 20 days, beginning in Regina and ending in Saskatoon, with six northern communities in between. Sessions averaged 10 hours a day, but often lasted 12 hours. Some 300 petitioners presented opinions and positions in public meetings averaging 80 attendees. To assist intervenors in preparing briefs to present at both panel hearings, some $500 000 was made available by the federal and provincial governments. Both levels of government presented formal briefs at the Joint Panel hearings in support of the three projects at the opening session in Regina, and provided more supporting documentation at the closing sessions in Saskatoon. The environmental assessment of the four uranium projects reviewed to date is estimated to have cost close to $3 million. The public hearings phase ended with less apprehension about the process than at the outset, but the outcome of these reviews was not to be known until the panels released their reports in late 1993.

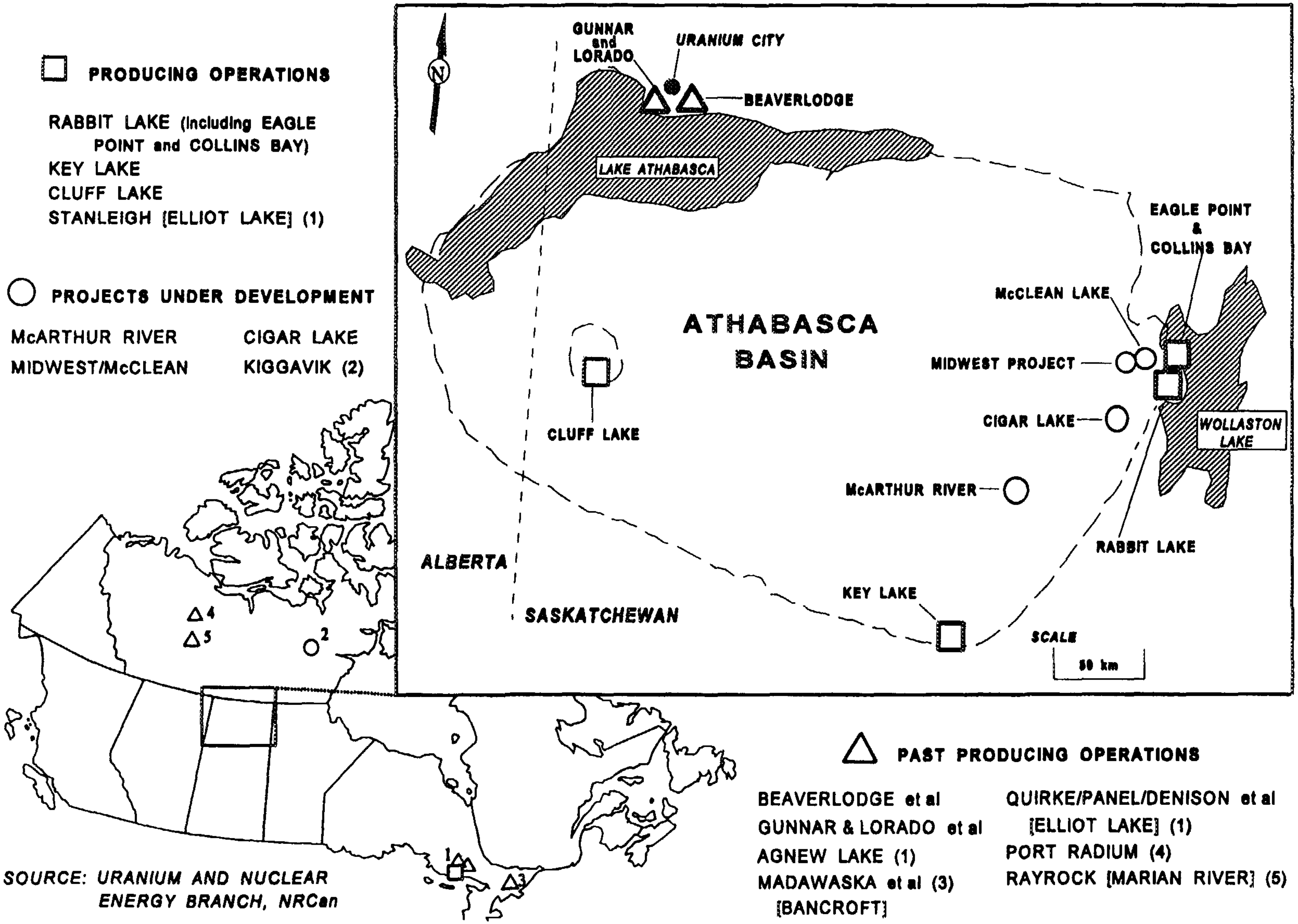

FIG. 1. Uranium mining in Canada.

While the scope of this paper does not permit exhaustive detail on all aspects of a panel review, the essential recommendations of the review panels and the responses to those recommendations by government are provided below. Readers are also invited to peruse Annexes 1 and 2 for additional insight into the mandate and scope of the uranium project panel reviews.

It is also worth noting that while both panels initiated their respective reviews in early 1993, the EISs for the *Cigar Lake* and *McArthur River* projects had not been finalized and thus the review of these two projects was postponed to a later date. As well, in 1992, the Joint Panel had been asked by government to review an Underground Exploration Program (UEP) for the *McArthur River* project, which was proposed in order to obtain data needed to prepare an EIS for the overall project. The Panel reported in early 1993, recommending that the UEP be allowed to proceed subject to certain conditions. Both governments agreed and work got under way as soon as possible.

TABLE I. NEW SASKATCHEWAN URANIUM MINING PROJECTS (AS OF 1995)

PROJECT/ OPERATOR	PROJECT TYPE	STATUS OF PROJECT	OWNERS (SHARE %)
Dominique-Janine Extension/ Cogema Resources Inc.	Mine Extension	Panel and Government Approval of Project; Mining Proceeding	Cogema Resources Inc. (100)
Midwest Project/ Minatco Limited	New Joint Production Centre [see McClean]	Approval Withheld but Project being Re-submitted by New Operator	Cogema Resources Inc. (56), Denison Mines Limited (19.5), Uranerz Exploration and Mining Limited (20), OURD (Canada) Co., Ltd (4.5)
McClean Lake Project/ Minatco Limited	New Joint Production Centre	Panel and Government Approval of Project; Construction Proceeding	Cogema Resources Inc. (70), Denison Mines Limited (22.5), OURD (Canada) Co., Ltd (7.5)
Cigar Lake Project/ Cigar Lake Mining Corporation	New Production Centre	EIS in Preparation (expected in 1995); Panel Review Expected in 1996	Cameco Corporation (48.75), Cogema Resources Inc. (36.375), Idemitsu Uranium Exploration Canada Ltd (12.875), Korea Electric Power Corporation (2)
McArthur River Project/ Cameco Corporation	New Mine [Milling at Key Lake]	EIS in Preparation (expected in 1995); Panel Review Expected in 1996	Cameco Corporation (53.991), Uranerz Exploration and Mining Limited (29.775), Cogema Resources Inc. (16.234)
Eagle Point-Collins Bay A & D/ Cameco Corporation	Mine Expansion	Panel and Government Approval of Project; Mining Proceeding	Cameco Corporation (66.67) Uranerz Exploration and Mining Limited (33.33)

8. PANEL RECOMMENDATIONS

In late 1993, the Joint Panel recommended that the *DJX* proceed, subject to conditions, that the *MJV* not proceed as designed, and that the *McClean Lake* project be subject to a five-year delay. The Federal-only Panel recommended that full-production underground mining of the *Eagle Point* orebody be approved, subject to certain conditions, but that approval be withheld for open-pit mining of the *Collins Bay A and D* orebodies until additional technical information on waste-rock management and decommissioning is provided by the proponents.

In early 1994, Cogema announced that it had decided to modify its plans for developing the *DJX* project at Cluff Lake, and submitted revisions to the government regulatory authorities. The revised three-phase mining plan would not require the damming and partial draining of the north end of Cluff Lake, but would require Cogema to access deeper portions of the *DJX* orebody by underground means after an initial phase of open-pit mining.

9. GOVERNMENTS' REACTION AND RESPONSE

The federal and provincial governments responded to the recommendations of the Joint Panel on December 23, 1993. Both governments agreed that *DJX* should proceed as submitted, subject to the AECB licensing process, that the *MJV* presented potential risks and should not proceed as presented, and that the *McClean Lake* project should proceed subject to the AECB's normal licensing process. Governments concluded that the AECB's licensing process would allow all of the technical issues raised by the Joint Panel to be considered within the context of a licence application, and provide sufficient time for the proponents to address them before the *McClean Lake* project comes into operation.

Cogema's proposed modifications were viewed by the AECB as presenting environmental impacts that were less than those predicted for the initial project and, as such, could therefore be adequately controlled. Nonetheless, the AECB invited public comment on the proposed modifications to the mining method at *DJX* to ensure that there was no significant public concern regarding Cogema's application. After receiving only minor comments, the AECB concluded that the project could proceed as re-submitted.

In March 1994, the federal government agreed with the Panel that underground mining at *Eagle Point* should proceed, subject to the AECB's licensing process, but opined that open-pit mining at *Collins Bay A & D* may also be able to proceed, subject to the AECB licensing process. The AECB process would address the conditions recommended by the Panel during the evaluation of the licence applications, and would require the provision of adequate information on waste-rock management and decommissioning, as recommended by the Panel.

On July 29, 1994, the AECB referred the proposal for a redesigned *Midwest Joint Venture (MJV)* to the Minister of the Environment for public review. The project is expected to be reviewed by the existing Joint Panel at the same time as the *Cigar Lake* project. ToR were prepared in close consultation with Saskatchewan's Department of Environment and Resource Management and FEARO. On November 9, 1994, the revised *MJV* uranium mining proposal was referred by the federal and provincial environment ministers for review by the Joint Panel. The EISs for the *MJV* and *Cigar Lake* are expected to be submitted in the summer of 1995 in the hope that the public review process could begin as soon as possible.

10. CANADA'S NEW LEGISLATION — THE CANADIAN ENVIRONMENTAL ASSESSMENT ACT (CEAA)

In June 1990, the Government of Canada introduced Bill C-78, the *Canadian Environmental Assessment Act* (CEAA), as a comprehensive reform of EARP. At the time, the government believed that the proposed legislation would have a greater impact on sensitizing decision-making and decision-makers to the needs of the environment than any other legislation then existing elsewhere in the world. The government intended that the EARPGO would remain in force until the new legislation was promulgated, but Bill C-78 died when Parliament was prorogued in early May 1991.

The legislation, reintroduced as Bill C-13 in the new Parliament later in May 1991, had numerous amendments made that required further comments from representatives of environmental groups and industry. Meanwhile, subsequent appeals to the aforementioned court decisions (see page 3) resulted in the Supreme Court of Canada upholding the constitutionality of the EARPGO in January 1992, rendering compliance with the Order by all federal decision-makers a mandatory requirement. Draft regulations required by Bill C-13 were reviewed across Canada and the Bill received approval in the House in March and in the Senate in June; it received Royal Assent on June 23, 1992. The necessary operating regulations and procedures took considerable time to be finalized, and it was not until January 19, 1995, that CEAA was proclaimed by Order in Council. Projects will henceforth be reviewed under CEAA, although as noted above the Saskatchewan uranium projects will proceed under the EARPGO. The Canadian Environmental Assessment Agency, formerly known as FEARO, will oversee the new environmental review process.

The new CEAA legislation replaces the old EARP Guidelines Order, and sets out, for the first time in legislation, the responsibilities and procedures for the EA of "projects" involving the federal government. It reduces legal uncertainties and the need for court interpretations, sets out a streamlined process, and establishes sustainable development as a fundamental objective of the federal process. CEAA provides an environmental process for new projects, and a participant funding program that supports public participation (see Fig. 2).

The reforms will help ensure that environmental considerations are integrated into federal decision-making processes, and will help develop greater harmonization of EA systems across Canada. By introducing a degree of certainty in the process, the reforms will also reduce costs and time demands for all participants.

CEAA applies to projects for which the Government of Canada holds the decision-making authority — whether as a proponent, land administrator, source of funding, or regulator (for listed statutes). The new CEAA process is similar to EARP in many respects, but several important changes have been introduced. These include the following: the definitions of a "project" and an "environmental effect," the introduction of "comprehensive study" and "mediation" as new EA tracks that a project may follow, the requirement to keep an ongoing record of all documents related to the assessment in a public registry, the requirement to consider the need for a follow-up program, and the mandatory public input into specified EA tracks.

CEAA has four stated objectives, namely: i) to ensure that the environmental effects of projects receive careful consideration before responsible authorities take action, ii) to encourage those authorities to take actions that promote sustainable development, iii) to ensure that projects carried out in Canada or on federal lands do not cause significant adverse environmental effects outside the jurisdictions in which the projects are carried out, and iv) to ensure that there is an opportunity for public participation in the EA process.

In addition, four guiding principles are to be followed in applying CEAA.

Early Application	The process should be applied as early in the planning stage of the project as practicable, and before irrevocable decisions are made.

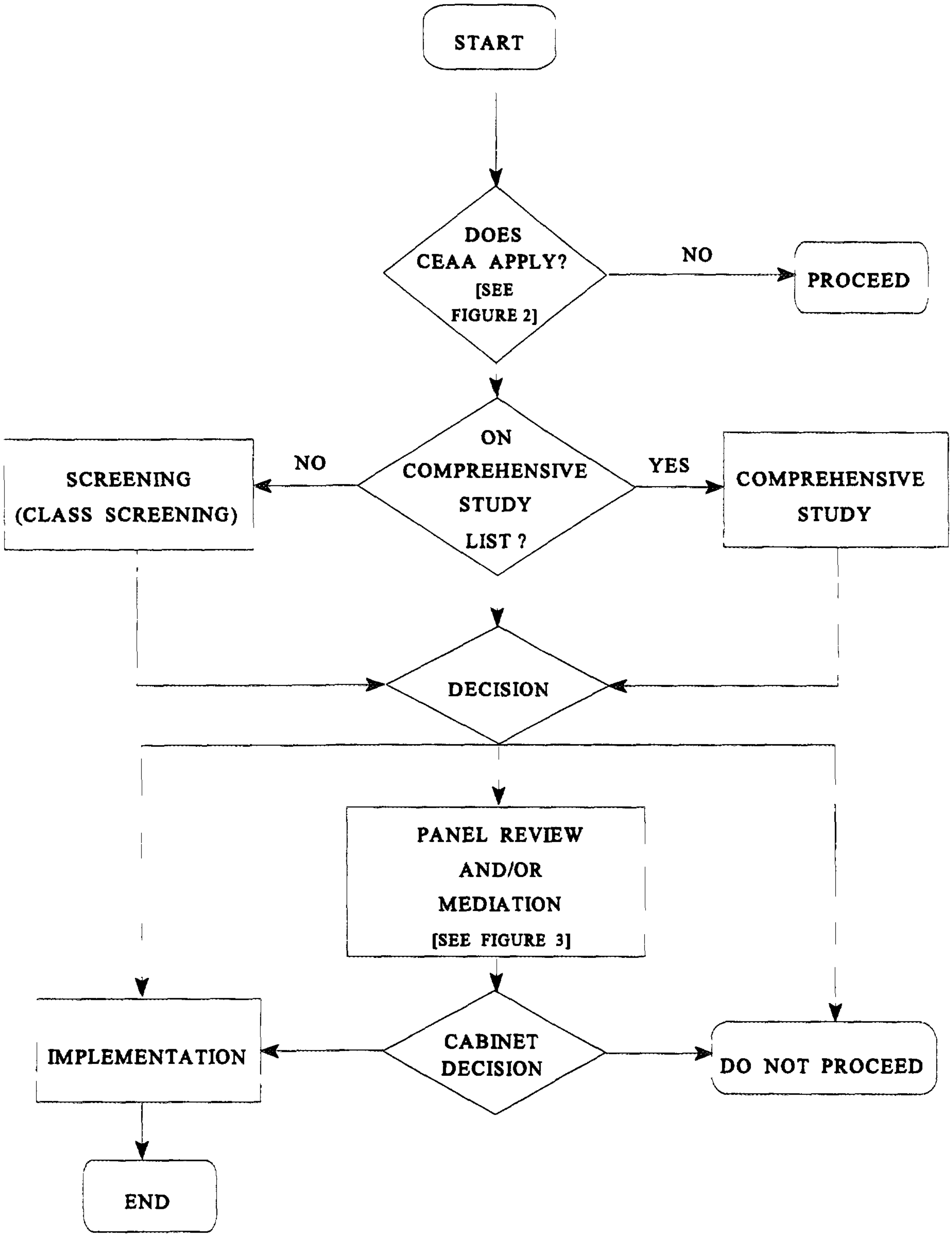

FIG. 2. CEAA Process overview flowchart.

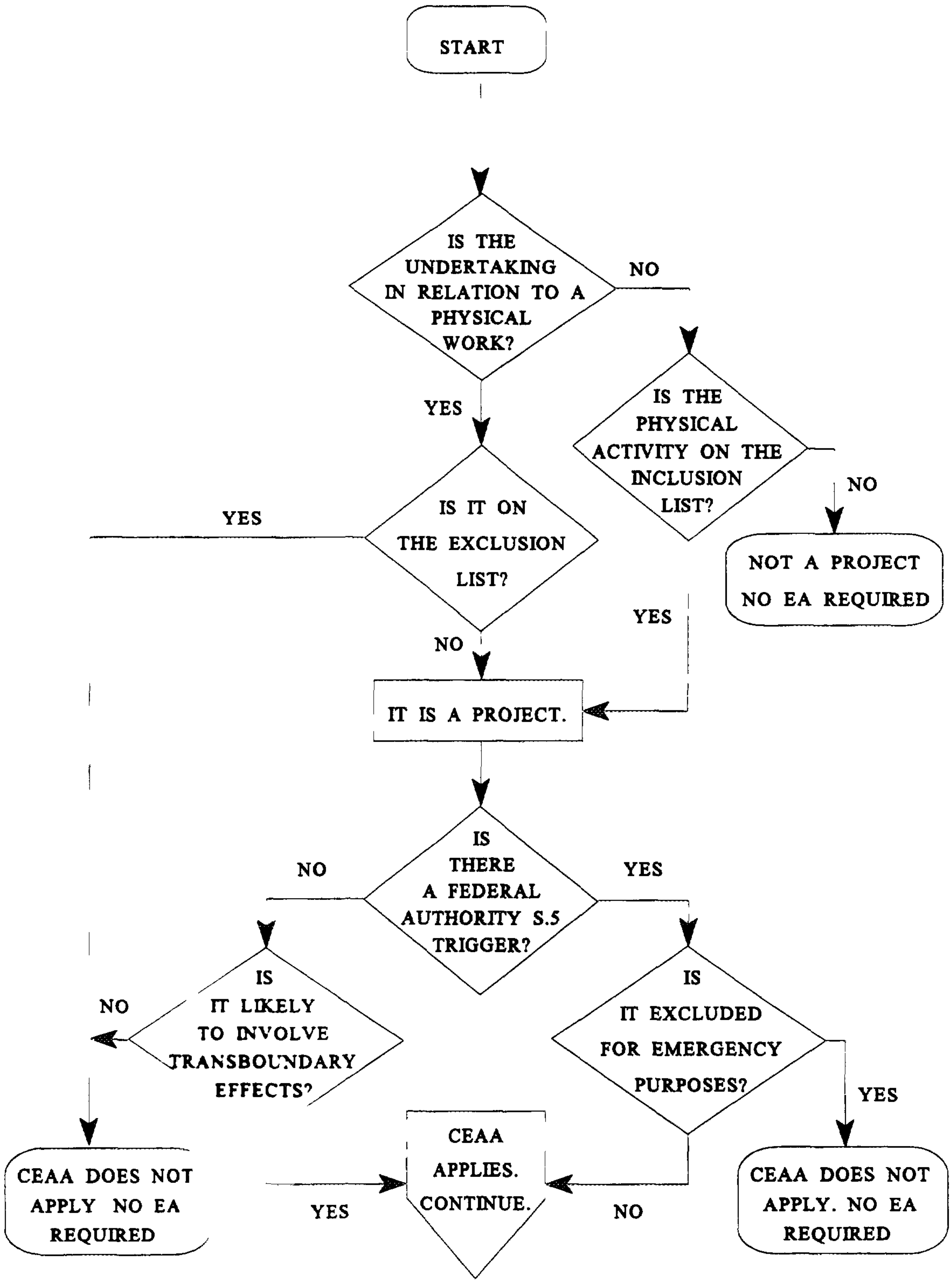

FIG. 3. Startup phase. Does CEAA apply?

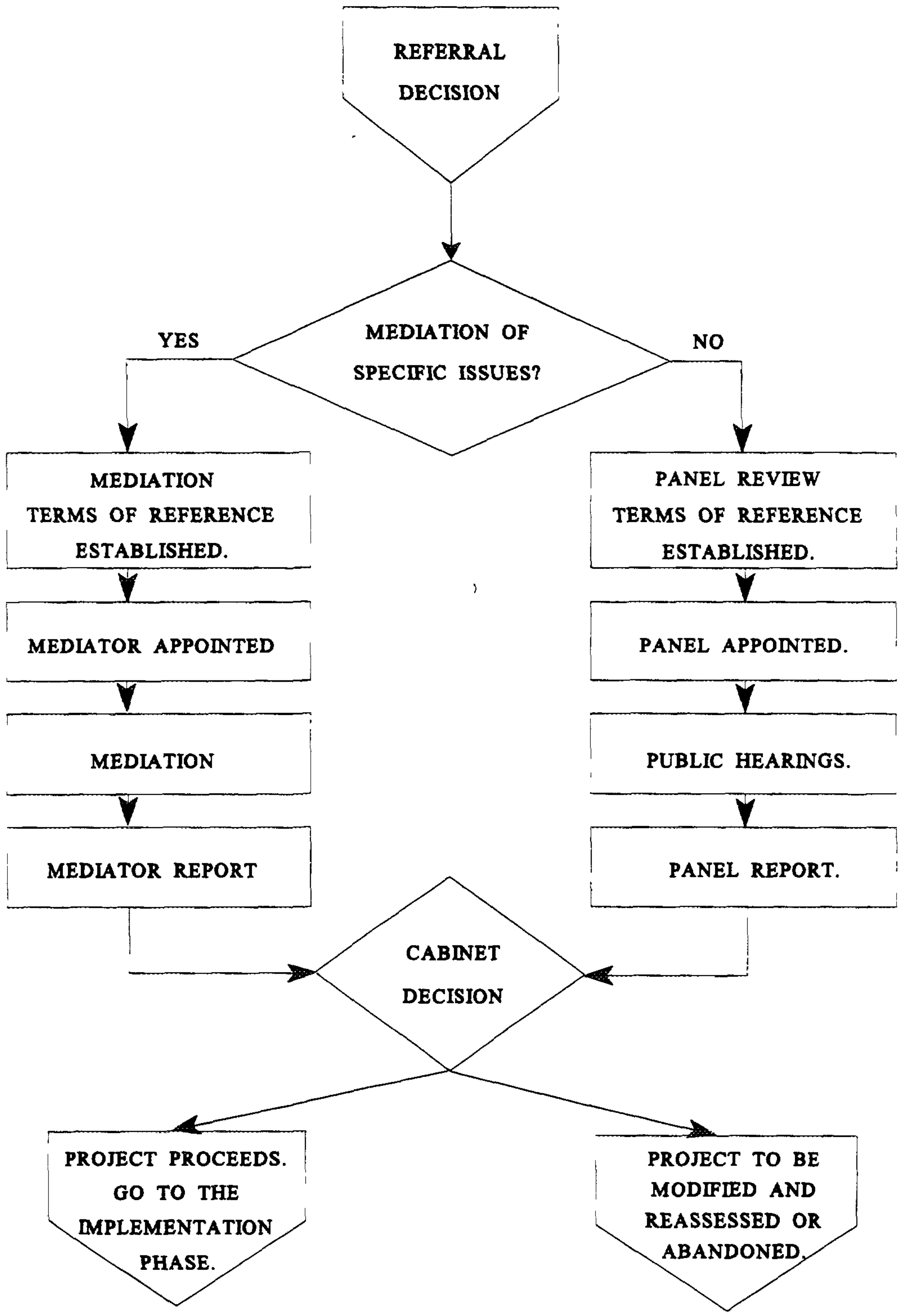

FIG. 4. CEAA public review flowchart.

Accountability — The self-assessment of projects for environmental effects by federal departments and bodies is a cornerstone of the process. [A Cabinet decision by Order in Council is required in response to the recommendations of a panel report.]

Efficient and Cost Effective — Each project should undergo only one EA, and the level of effort required to undertake an assessment for the project should match the scale of the likely environmental effects of the project.

Open and Participatory — Public participation is an important element of an open and balanced EA process. [A participant funding program exists to promote effective public participation in the process.]

10.1. Specific Highlights of CEAA - A Comparison with the EARPGO

Most importantly, CEAA defines a "project" as being either: i) an undertaking in relation to a physical work, such as any proposed construction, operation, modification, decommissioning, or abandonment, or ii) any proposed physical activity not relating to a physical work that is listed in the CEAA *Inclusion List* regulation, as shown below (see Fig. 3).

Once an EA is required or "triggered," because a federal authority is a proponent, provides funding, owns the land or is a regulator, CEAA provides several assessment options, compared to EARP. Four types of EA now available to meet different project circumstances include: screening, comprehensive study, mediation and panel review. The assessment track depends on the level of environmental risk represented by the project (see Fig. 4).

Screening — Systematically documents environmental effects and determines the need to mitigate these, or modify a project plan, or recommend further assessment through mediation or panel review. To improve process efficiency, small-scale or routine projects may be assessed through a *class screening* (see *Exclusion List* below).

Comprehensive Study — Applied to large-scale and environmentally sensitive projects usually undergoing more intensive assessment (see *Comprehensive Study List* below).

Mediation — A new voluntary approach in Canadian environmental assessment in which an impartial mediator, appointed by the Minister of the Environment*, helps interested parties resolve issues surrounding a project. Used when the parties are willing, limited in number, and where a consensus is possible.

Panel Review — If a project requires further evaluation, after screening, comprehensive study or mediation, it is referred to the Minister of the Environment[1] for review by an independent, public panel.

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1 The Federal Minister of the Environment plays a pivotal role in implementing the federal environmental review process under CEAA, and has the ability to: i) call for a public review by a panel, mediator or both, under certain circumstances and in consultation with a federal authority, at any stage of a screening or after comprehensive study, ii) appoint panel members or a mediator, and establish terms of reference in consultation with the responsible federal authority, iii) allow another federal process to be substituted for a panel review under CEAA to promote efficiency, avoid duplication and save time, iv) ensure that projects posing risks of significant adverse environmental effects on federal lands, or across provincial or international boundaries receive an EA, and v) prevent overlaps or confusion with other jurisdictions by developing coordinated EA procedures for conducting joint panel reviews with those jurisdictions.

Notwithstanding the above, it is noteworthy that while the intention of CEAA is to ensure that all projects undergo an EA, it is expected that less than 5% of all projects with federal involvement will be assessed in depth by panel review; the vast majority will require a screening only. [Under EARP, only some 48 projects have undergone panel reviews since the federal environmental assessment process was established in 1974.]

Several *Regulations* under CEAA are required to put its procedures into effect and clarify its requirements and scope. Four are critical to the proper functioning of CEAA, namely: the *Comprehensive Study List*, the *Law List*, the *Exclusion List* and the *Inclusion List*.

Comprehensive Study List — Describes those types of projects that must be assessed through a more detailed study, i.e., those having the potential of causing significant adverse environmental effects no matter where they are located and which often generate considerable public concern; includes projects in national parks, major pipelines or mining projects, nuclear power facilities and uranium mines.

This regulation was strengthened to reflect public comments. By lowering the inclusion thresholds, more projects will be subject to comprehensive study.

Law List — Defines the scope of CEAA by identifying those federal statutory and regulatory approvals that will be counted as triggers for an EA. [Under CEAA, an EA is required or triggered for a project when a federal department or agency is asked to provide a licence, permit, certificate or other regulatory authorization listed on the *Law List*; not every such decision will result in environmental effects.]

New provisions have been added following a review of public comments, bringing to 190 the number of federal triggers for EAs.

Exclusion List — Describes those undertakings in relation to a physical work that do not require an EA. Such projects are routine and relatively small-scale, and can be expected to result in only insignificant environmental effects; includes such undertakings as routine maintenance, minor renovations, etc.

The *Exclusion List* will help streamline the federal EA process by allowing departments and agencies to focus their assessment efforts on those projects with environmental effects.

Inclusion List — Relates only to those projects that are a physical activity not relating to a physical work, that is, activities that must be subjected to an EA if a federal department or agency proposes, funds, or otherwise authorizes the project by issuing a permit or licence; includes such activities as cutting and removing timber from a National Park.

Other important regulations are being developed for CEAA through an extensive process of consultations. One will describe procedures for conducting EAs of international development projects outside Canada involving the federal government, while respecting the sovereignty of states and international law. Another will articulate the principle of "one project/one assessment" to ensure that EAs relating to the same project, but involving more than one responsible authority, are coordinated to avoid duplication.

The foregoing provides a brief overview of CEAA. An exhaustive critique of CEAA as applied is not possible because no major projects have been reviewed under the new Act. Thus, any examination of Canada's EA process must be restricted to projects that have been reviewed under the

EARPGO. Although the new Act and the old Guidelines Order are quite similar operationally, it is impossible to predict if CEAA will be comparable to EARP in practice, for differences between the two processes may take some time to become clear.

11. COMMENTS ON THE ENVIRONMENTAL ASSESSMENT PROCESS (UNDER EARP/CEAA)

In January 1995, the federal environmental assessment and review process changed with the passage of the new CEAA. The initial stages of the process have been clarified through the introduction of regulations covering the *Comprehensive Study List*, the *Inclusion List*, the *Law List* and the *Exclusion List*, and the powers of the public review panels have been strengthened.

There are a number of areas where governments, regulators and proponents will be paying particular attention in order to improve the review process **in practice** under CEAA. In part, these stem from observations made during the recent EAs and panel reviews of the four Saskatchewan uranium mining proposals already reviewed under EARP.

Timing A major concern expressed by industry and government in completing an EA for a new uranium mining project has been the inordinate length of time taken to proceed through to completion. At most stages of the process, considerable delays were introduced that when taken together (more than one year) had an inordinate impact on the cost of the development, both in terms of total expenses and potential lost market opportunities.

Suggestions have been made that a defined schedule could be adopted at the start of the process, which would clarify for all those concerned the need to complete the assessment in a pre-determined time frame. This would help the proponent, the government, and the panel to identify the minimum requirements needed to fulfil the assessment obligations without extending the process beyond what was deemed necessary.

Panels The independence of a review panel can become problematic if public perceptions influence panel members to the extent that the scope of a review is broadened beyond the established terms of reference. The importance of nominating qualified experts to panels and encouraging panels to observe their mandates cannot be over-emphasized.

The CEA Agency could formally establish a pool of qualified "experienced" experts who could be called upon when selecting the best panel members.

Agencies The current EA process was not designed with independent regulatory authorities in mind. While a federal agency or board, such as the Atomic Energy Control Board (AECB), often triggers an EA, it must be seen as being free of conflict, and operating at arm's length.

In the recent assessment of uranium projects, governments qualified their response to allow the AECB to comment on those aspects of the panel recommendations directly related to the licensing process, while the broader policy issues (e.g., socio-economic) were dealt with by specific departments.

Policy Scoping an EA has proven to be problematic, particularly in separating environmental issues from socio-economic and policy issues. The public often perceives that underlying policy issues should be an integral component of the project assessment, for there are often no other opportunities for public expression of concern in these areas. Such concerns during the recent assessment of uranium projects led to an expansion of the "environmental" review to allow opinions to be voiced regarding Canada's policies on non-proliferation of nuclear weapons and uranium exports.

Although a panel chairman may permit presentations on such issues, in the recent panel reviews the chairmen did make an effort to limit the discussion and debate in the interest of examining the central environmental issues.

Priorities There is a risk that panel members or the public may lose sight of the EA priorities; they may expect that minor issues should be accommodated and reviewed in great detail.

It is critical to rank the essential issues and focus resources on the areas of major environmental concern, thereby permitting panels to concentrate on the higher risk areas, and save time and money in the process.

Scope Examining the cumulative effects of several projects was established as an important criterion for the EA of new uranium mining projects. Proponents argue that they should bear only the costs associated with their own project.

There are opportunities for government and industry cooperation in the pooling of resources to overcome such constraints without compromising future developments.

The proclamation of CEAA has afforded an opportunity for the Government of Canada to re-examine the EA process, and in particular the review procedures of the independent panels, and to make improvements where appropriate. While this responsibility falls mainly to the Canadian Environmental Assessment Agency and the Regulatory Advisory Committee (RAC) that represents key stakeholders, Natural Resources Canada has embarked on its own review, with a particular focus on suggesting improvements that would benefit natural resource projects.

In addition, the Ministers of the Environment and Industry have undertaken a Joint Monitoring Program (JMP) to review the implementation of CEAA during the first year. The JMP will monitor the impact of implementing CEAA on the competitiveness of Canadian industry and on sustainable development. The JMP will collect the views of all stakeholders on the implementation of CEAA, apply the Business Impact Test to the federal EA process, and identify public policy benefits of CEAA, especially with regard to its contribution to sustainable development.

12. CONCLUSION — CANADA'S ENVIRONMENTAL ASSESSMENT PROCESS AS A MODEL

The EA process in Canada has evolved into a fairly complex set of procedures involving all levels of government, the public and the proponents. As the process matures, it will be continuously improved, with the benefit of input from all players. The difficulties experienced to date will be resolved, but new problems will undoubtedly surface that require novel solutions. Canada's EA process is truly a dynamic one.

Today, EA has become an integral part of the design process of new projects. It is now part of sound engineering practice. Indeed, obtaining financing for new projects depends on minimizing environmental liabilities. The trend is established and will continue.

When the development of several new uranium mining projects in Saskatchewan was proposed, both the federal and provincial governments and the uranium industry expressed concern about the potential impacts of what appeared to be a rather burdensome public environmental review process. However, the successful advancement of three such proposals through the process has allayed much of this uncertainty and has confirmed that all of Canada's uranium-producing operations can meet high environmental, health, and safety standards.

In Canada, the impact of the EA process on new uranium mining developments has been profound. It has changed the way projects are designed and will change the way they are brought on stream. The process has been time consuming and often difficult, but it has revealed that these new uranium mining proposals are environmentally sound and can remain so over their lifespan.

The Government of Canada is convinced that the EA process has helped to demonstrate that new uranium mining projects are being developed in a responsible manner, after full consideration has been given to the potential impacts and public concerns associated with these facilities. The lessons learned in Canada could well prove to be useful in other jurisdictions where considerations are being given to the development of new uranium production projects. However, it is understood that all processes can be improved, and both levels of government in Canada will be working closely with the uranium mining industry to make improvements in the EA process wherever possible to reduce the time and cost of reviews, while meeting the fundamental objectives.

The new global appreciation of EA may also have an impact in the marketplace. A recent motion put forward in the Swedish parliament would require uranium buyers to pay for the environmental damage caused by uranium mining in other countries. This action confirms the growing awareness that environmental considerations could have an unexpected impact on world market opportunities. Canada's exemplary EA process could give Canadian uranium producers an edge in the future.

The real impact of Canada's EA process might be that the "Canada model" is applied beyond national borders. As the world's leading supplier of uranium, Canada has attracted much attention in areas such as uranium exploration and mine development technology. If that focus is extended to Canada's positive experience with EA, the wealth of knowledge gained in Canada could well prove useful in other jurisdictions considering the development of new uranium production projects.

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ANNEX 1

FINAL TERMS OF REFERENCE FOR THE ENVIRONMENTAL ASSESSMENT REVIEW BY THE JOINT FEDERAL/PROVINCIAL PANEL ON PROPOSED URANIUM MINING DEVELOPMENTS IN NORTHERN SASKATCHEWAN

MANDATE

1. The Panel shall review the environmental, health, safety and socio-economic impacts (hereinafter referred to as "impacts") of the proposed uranium mine developments (listed in Schedule A) in Northern Saskatchewan and assess their acceptability.

   In assessing the acceptability of the proposed developments, the Panel will include in its review and consider:

   a) the historical experience with past and existing uranium mining operations in Saskatchewan;

   b) the cumulative impacts of existing operations and the proposed developments;

   c) the short and long term impacts of the proposed projects, spanning their construction phase, operating period, decommissioning phase and post-decommissioning phase;

   d) the impact of employment and socio-economic opportunities afforded northern residents by the proponents and the measures necessary for implementation of those opportunities;

   e) the adequacy of measures proposed by the project proponents to protect environmental quality and to safeguard worker health and safety, and whether the measures can be expected to meet the requirements of Canadian and Saskatchewan law, regulations and policies applicable to uranium mine developments;

   f) the adequacy of monitoring, enforcement and compliance systems to ensure that measures necessary for mitigating adverse impacts can be implemented;

   g) the benefits afforded by the proposals.

2. The Panel shall determine from its review whether a project is acceptable or unacceptable.

   In concluding that a project is acceptable, the Panel may recommend that specified minimum terms and conditions, including any mitigative measures or any other measures relating to the impacts under the Panel's review, be implemented where it considers these necessary for the protection of health, safety and the environment or for dealing responsibly with socio-economic concerns. The Panel may also suggest measures that it considers would enhance the acceptability of the proposals.

   If the Panel concludes a project is unacceptable, it shall provide its reasons for this conclusion.

3. In fulfilling its mandate, the Panel shall provide full opportunities for public consultation and review.

REVIEW PROCEDURES

Detailed written procedures for conducting the review shall be established by the Panel and made available to the public.

TECHNICAL EXPERTS

The Panel may secure the services of independent technical experts to assist and advise on complex technical and/or socio-economic issues related to its mandate. Such experts will also be available to respond to inquiries from review participants.

STAGES OF THE REVIEW

Schedule A lists the five proposals to be reviewed by the Panel. The five proposals have been referred due to potentially significant or unknown adverse environmental effects and public concern.

While all of the proposals are in the planning stage, some are further advanced than others. Environmental Impact Statements (EIS) have been prepared for the first three proposals listed in Schedule A, one of which (Dominique-Janine Extension) is associated with the existing operating uranium mining facility and two of which are for new uranium mining facilities. EIS documents have yet to be prepared for the last two proposals listed in Schedule A. The Panel will take the differing stages of these projects into consideration in scheduling its review.

The Panel will seek public comment on the three available EISs and determine their adequacy before proceeding to public hearings. When the Panel is satisfied with the information provided, including that with respect to the cumulative impacts, it may report on one or more of these projects to the Ministers as described in the following stages of the review. The Panel shall submit its final report(s) on these proposals within 18 months of its appointment.

In reviewing the remaining two proposals, the Panel will conduct scoping sessions in appropriate communities to solicit public comment and, based on these comments and its own consideration, prepare and issue Guidelines to the respective proponents for the preparation of EISs. The cumulative impacts of these two proposals will be considered when the EIS documents have been submitted. The stages of the review following submission of these documents to the Panel are outlined below. The Panel shall submit its final report(s) on these two proposals within 18 months of receipt of the proponent's EISs.

1. Review of Information

   a) Review of the available information on the environmental, health, safety and socio-economic impacts of the uranium mining industry in Saskatchewan to date. The information and any related reports prepared will be made available to the public.

   b) Review of the past performance of the uranium mining industry in providing employment and socio-economic opportunities to northern residents. The information and any related reports prepared will be made available to the public.

   c) Review by the Panel of Environmental Impact Statements (EIS) submitted by the proponents. The EISs will also be made available to the public for review and written comment.

d) The Panel may draw on proponents, technical agencies from within federal or provincial governments, independent experts and the public for available information.

2. Should the Panel, after reviewing the above information and considering public comments, deem an EIS deficient it may request additional information from the project proponent.

3. Once the Panel is satisfied with the information provided, it will announce public hearings for the project in question. If appropriate, the hearings may be structured to address more than one project.

For the purposes of promoting public awareness and facilitating public comment, the Panel will hold meetings and/or hearings in the appropriate northern communities, Regina, Saskatoon and in such other Saskatchewan communities as the Panel may think necessary.

4. When the Panel is in a position, following the completion of public hearings, to provide a report on its findings, conclusions and recommendations relevant to a specific project, it will submit the report to the federal Ministers of the Environment and of Energy, Mines and Resources and to the Saskatchewan Minister of Environment and Public Safety.

The Panel should, to the extent possible, ensure that the timely review of a specific project is not jeopardized by delays in the review of another project included in its mandate.

LINKAGE TO OTHER POLICY PROCESSES

The Panel is not expected to interpret its mandate so as to duplicate the work of other public inquiries and policy processes or to focus on national or international issues which are not directly related to the impacts of the proposals.

However, concerns may be raised by the public which extend beyond the impacts of direct concern to the Panel, and in such cases the Panel will ensure that the public is provided a reasonable opportunity to express these concerns.

Schedule A

EIS SUBMITTED

1. Dominique-Janine Extension (Cogema Resources Inc. - operator)

2. South McMahon Lake Project [Midwest Joint Venture] (Minatco Limited - operator)

3. McClean Lake Project (Minatco Limited - operator)

EIS TO BE PREPARED

4. McArthur River Project (Cameco Corporation - operator)

5. Cigar Lake Project (Cigar Lake Mining Corporation - operator)

ANNEX 2

EXCERPT FROM THE DRAFT EIS GUIDELINES AND GOVERNMENT INFORMATION REQUIREMENTS FOR THE CIGAR LAKE AND McARTHUR RIVER PROJECTS

TABLE OF CONTENTS

URANIUM EXPLORATION TARGET SELECTION FOR PROTEROZOIC IRON OXIDE/BRECCIA COMPLEX TYPE DEPOSITS IN INDIA

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Abstract

Multimetal iron oxide/breccia complex (IOBC) type deposits exemplified by Olympic Dam in Australia, fall under low grade, large tonnage deposits. A multidisciplinary integrated exploration programme consisting of airborne surveys, ground geological surveys, geophysical and geochemical investigations and exploratory drilling, supported adequately by the state of the art analytical facilities, data processing using various software and digital image processing has shown moderate success in the identification of target areas for this type of deposits in the Proterozoic terrains of India. Intracratonic, anorogenic, continental rift to continental margin environment have been identified in a very wide spectrum of rock associations. The genesis and evolution of such associations during the Middle Proterozoic period have been reviewed and applied for target selection in the (i) Son-Narmada rift valley zone; (ii) areas covered by Dongargarh Supergroup of rocks in Madhya Pradesh; (iii) areas exposing ferruginous breccia in the western part of the Singhbhum Shear Zone (SSZ) around Lotapahar; (iv) Siang Group of rocks in Arunachal Pradesh; (v) Crystalline rocks of Garo Hills around Anek; and (vi) Chhotanagpur Gneissic complex in the Bahia-Ulatutoli tract of Ranchi Plateau. Of these six areas, the Son-Narmada rift area appears to be the most promising area for IOBC type deposits. The significant features of this important zone are: 1. Presence of a basement ridge bounded by two NW-SE to N-S trending faults with marked gravity and magnetic highs. 2. Deposition of a thick pile of Proterozoic metasedimentary rocks with a Palaeozoic cover. 3. Proterozoic rocks having been subjected to extensional rift tectonics with bimodal volcanics, often with alkaline affinity. 4. Presence of ferruginous breccia with as high as 14% total iron and significant U, REE and Cu along the marginal parts of the valley. Considering occurrences of the uranium anomalies near Meraraich, Kundabhati, Naktu and Kudar and positive favourability criteria observed in a wide variety of rocks spatially related to the rifts and shears, certain sectors in Son-Narmada rift zone have been identified as promising for intense subsurface exploration.

1. INTRODUCTION

Iron Oxide/Breccia Complex type deposits are recognized by their multimetal (Cu, Au, Ag, REE, U, etc.) character typified after the low grade, large tonnage deposit (U as by-product) of Olympic Dam in Australia (Roberts and Hudson [1], Dahlkamp, [2, 3, 4]). The concept that led to the discovery of this class of deposits along with its geological characters has become the guidelines to look for such a type of deposit in other parts of the globe. Initially, it was thought that the deposit was formed as a result of a thick pile of sedimentary breccia deposited in a graben, under a very high energy environment and the first mineralizing event was set during sedimentation itself along with strata-bound haematite, sulphide, uranium, rare earths, gold and silver, which was possibly related to geothermal activity resulting from volcanism. However, sulphide zoning and alteration related to mineralization plus high potassium, rare earths, barium and flourine contents were suggestive of alkaline-igneous activity in the region and a magmatic and hydrothermal affiliation, are now fairly indicated and recognized.

Beside the Olympic Dam deposit in South Australia, the Iron Oxide/Breccia Complex deposits are only known from few countries in the world, viz. Great Bear Magmatic Zone and Wernecke Mts. Canada; Kiruna, N. Sweden; Bayan Obo, China and S.E. Missouri, USA. The common characteristics of these deposits are :

i) Host rocks belong to the upper part of the Lower Proterozoic and Middle Proterozoic age (1800 to 1100 Ma). They are rich in iron-oxide, (Fe content being 20-60%) and associated with Cu up to 2%, U_3O_8 up to 0.06%, REE traces to 6.1%, Au 0.5-2 gm/tonne and Ag up to 6 gm/tonne Cobalt, nickel, tellurium, arsenic, barium and fluorine are also invariably associated.

ii) The host rocks are dominated by rift tectonics and are located in cratonic or continental margin environment.

iii) Mineralizations are generally related to igneous activity. However, these are invariably structurally related to major lineaments and show an indirect or spatial association with igneous rocks.

iv) Wall-rock alterations are seen both vertically and laterally (sodic, potassic, sericitic) from the deeper level to the shallower level. Iron metasomatism in general is predominant.

v) Morphology of the deposits are both transgressive and stratabound and orebodies occur as discordant veins or range from breccia to massive concordant bodies. Morphology and alteration are controlled by permeability along faults, shears and intrusive contacts or permeable horizon or welded tuff.

vi) It is believed that these deposits are formed in a shallow crustal environment (hundreds of metres to 6 km) and are the expressions of deep-seated volatile rich igneous hydrothermal system tapped by deep crustal rift tectonic structures.

In the light of the above characteristic features, an attempt has been made for selection of target areas for uranium exploration hosting Iron Oxide/Breccia Complex type mineralization in India. The multidisciplinary data like Airborne Gamma Ray Spectrometric (AGRS), ground geophysical, and geochemical, generated by AMD and the other institutions have indicated favourable target areas for this type of deposits in the Proterozoic terrains of India.

2. REGIONAL TECTONIC FRAMEWORK OF INDIAN SHIELD

The Indian sub-continent is essentially made up of three main cratons of Archaean age, viz. Singhbhum-Orissa, South Dharwar and Bundelkhand massifs with nucleus of Older Metamorphic Trondjhemite Gneiss (OMTG) ranging in age from 3800–3400 Ma (Sarkar and Saha [5]). These are skirted a by greenstone belt often of komatiitic affinity and further surrounded by Proterozoic mobile belts which have been the site of a long period of tonalization extending up to around 2800 Ma when the cratonic areas began stabilizing and the process continued till around 1600 Ma on the cratonic areas, both within and at the margins (Mukhopadhyay [6]). The areas were unconformably overlain by sedimentary quartz-pebble-conglomerates (QPC) and arenite sequences (grits and quartzites) deposited in an overall anoxygenic conditions during the Late Archaean to Early Lower Proterozoic period as reported from Singhbhum-Orissa and Karnataka areas. Instances from Rajasthan and adjoining areas of Uttar Pradesh around Bundelkhand craton are limited. Uranium, in the labile form, for the first time, was released and mobilized into a sedimentary system, along with copper and other precious metals (Au. Ag. etc) and became part of the geological system in getting mobilized and remobilized by the thermal and metamorphic events created by the basic and acid volcanics introduced into the sedimento-volcanic sequence. The granites were intruded at different times e.g. Singhbhum granite-A Phase I & II (3300 Ma) and Singhbhum granite-B phase III (3000 Ma) (Saha et al. [7]), and 1960-950 Ma Chhotanagapur granite (Mukhopadhyay [6]) related to Satpura Orogeny and at different levels in the lithospheric crust. Similar situations prevailed in other parts of the shield as well as South Dharwar Cratonic areas. These Early Lower Proterozoic sedimento-volcanic sequences were deposited under a typical plate-tectonic subduction regime dominated by basement fractures and rift-oriented tectonics with material transfer from deeper as well as shallower part of mantle domains. Finally, the whole pile of sediments together with iron-rich Banded Iron Formations (BIFs), both within the Craton and in the surrounding mobile belt, carbonaceous shales, phyllites and limestones deposited in euxenic environments and deep sea conditions (the latter belonging to Middle/Upper Proterozoic Period) have been subjected dominantly by the continental extensional tectonics and have been sites for acid and basic extrusive and intrusives, often of an alkaline nature, causing large scale direct or remote-controlled magmatic affiliations mobilizing U, Cu, REE, Au, Ag, etc. Such magmatic affiliations have been so dominating over the enveloping Proterozoic mobile belt around the three cratons that the central part of the Indian shield is wholly a reworked and refused mass of crystalline rocks and gneisses, as of now, with less metamorphosed Mid-Upper Proterozoic Cuddapah and Vindhyan sediments.

3. POTENTIAL AREAS FOR IRON OXIDE/BRECCIA COMPLEX (IOBC) TYPE URANIUM DEPOSITS IN INDIA

The Indian Shield as a whole on its periphery is bounded by rift related grabens and marginal sag basins formed by continental crustal extension. Thirty-six extensional cratonic features like basins, ridges and faults have been recognized by Biswas [8] which have been grouped under (i) intracratonic, (ii) pericratonic, (iii) transitional, and (iv) aulacogens (Fig. 1). Radhakrishna and Naqvi [9] mentioned that the development of the Indian grabens followed the inherent tectonic grains of the craton (Fig. 2).

In the initial stages of evaluating potential or known terrains for the Iron Oxide/Breccia Complex type deposits, six favourable areas were identified (Fig.3).

1. Son-Narmada valley areas, Uttar Pradesh and Madhya Pradesh.
2. Dongargarh Supergroup, Khairagarh basin, Madhya Pradesh.
3. Siang group of rocks, West Siang district, Arunachal Pradesh
4. Singhbhum district, Bihar
5. Chhotanagpur Gneissic Complex, Ranchi Plateau, Bihar
6. Anek and Darugiri, Garo Hills, Meghalaya

After preliminary evaluation, three areas namely the Son Valley areas in Uttar Pradesh and Madhya Pradesh, Khairagarh basin in Madhya Pradesh and West Siang district in Arunchal Pradesh were taken up for detailed follow-up. From the preliminary data it was not possible to pinpoint the target area as most of the information in the proposed areas is lacking or based on other supporting evidences. Thus, this paper aims at highlighting the most potential area.

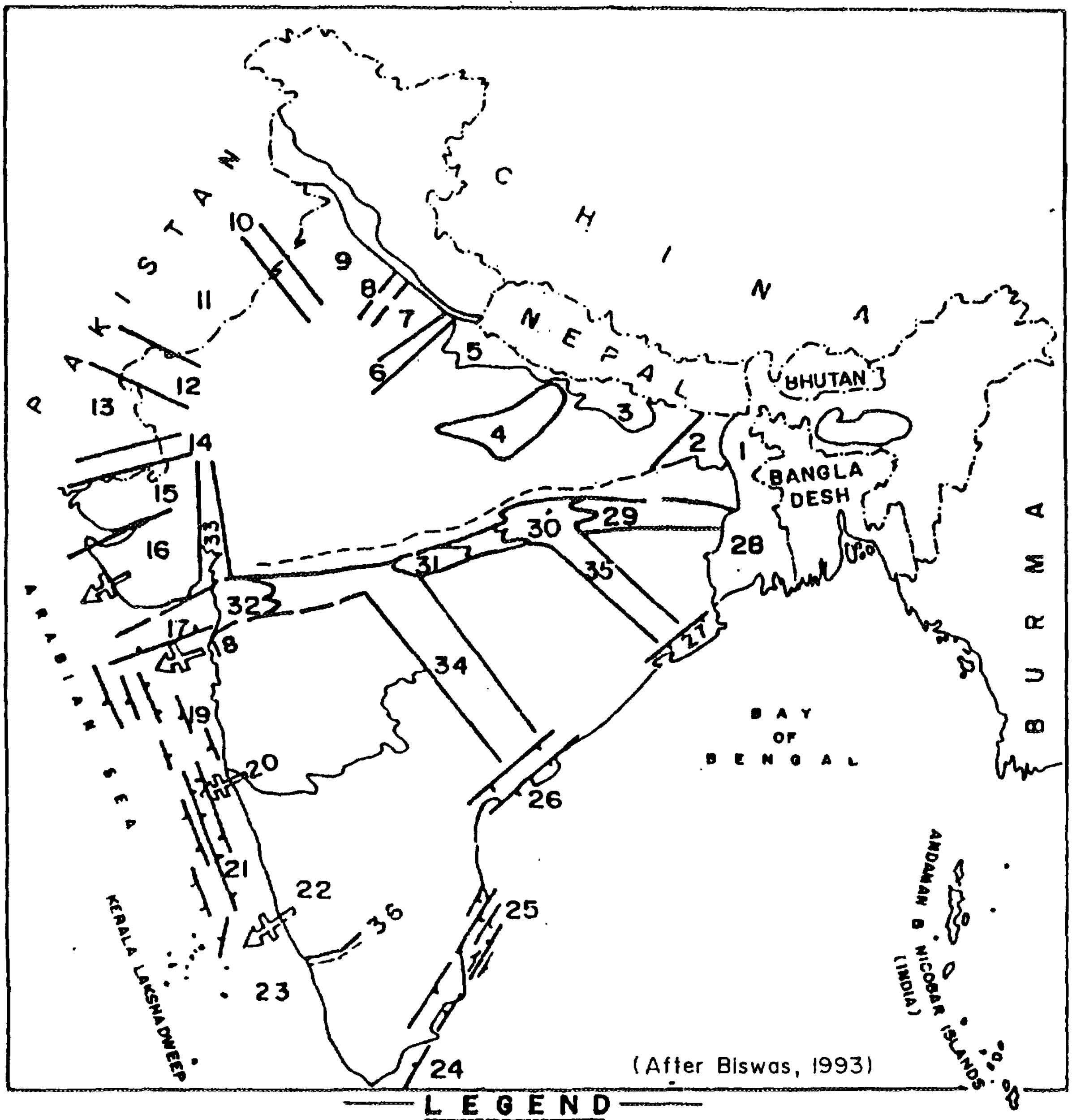
The salient features of the three main target areas selected for future follow-up work are presented below.

3.1. Son-Narmada rift valley zone

The possibilities of finding Iron Oxide/Breccia Complex deposits in the Son-Narmada rift zone in parts of Madhya Pradesh and Uttar Pradesh have been examined in the light of geological and geophysical characterization and evolution of the basin.

3.1.1. Disposition of basin and Tectonic setup

The Son-Narmada tectonic zone cuts through the central part of the Indian Shield as a major mid-continental rift (Figs 1, 2). The rift-dominated basin with its complex structure and geological history is essentially intracratonic at its early stage of development during the Late Archaean and Early Proterozoic times. Later, the basin was dominated by the Mid-Proterozoic continental-extensional rift or aborted rift tectonics finally developing into tectonic grabens during the Carboniferous period (Radhakrishna and Naqvi [9]).



LEGEND

1. PURNEA BASIN	13. S. RAJASTHAN BASIN	25. KAVERI BASIN
2. MUNGER -SAHARSA RIDGE	14. NAGAR PARKAR ARCH	26. KRISHNA-GODAVARI BASIN
3. GANDAK BASIN	15. KACHCHH BASIN	27. MAHANADI BASIN
4. FAIZABAD RIDGE	16. SAURASHTRA ARCH	28. BENGAL BASIN
5. SHARDA BASIN	17. SURAT DEPRESSION	29. DAMODAR BASIN } NARMADA-SON DAMODAR RIFT
6. CHANDAUSI RIDGE	18. BOMBAY ARCH	30. SON BASIN } NARMADA-SON DAMODAR RIFT
7. SAHASPUR BASIN	19. RATNAGIRI OFFSHORE BASIN	31. SATPURA BASIN } NARMADA-SON DAMODAR RIFT
8. DELHI-KALKA RIDGE	20. VENGURLA ARCH	32. NARMADA BASIN } NARMADA-SON DAMODAR RIFT
9. PUNJAB BASIN	21. KONKAN BASIN	33. CAMBAY BASIN
10. DELHI-LAHORE RIDGE	22. TELLICHERY ARCH	34. PRANHITA-GODAVARI GRABEN
11. N. RAJASTHAN BASIN	23. KERALA BASIN	35. MAHANADI GRABEN
12. JAISALMER-MARI ARCH	24. MANNAR BASIN	36. PALGHAT GRABEN

FIG. 1. Indian craton with radial basins and arches/ridges, intra-cratonic and pericratonic basins, major faults and tectonic lineaments.

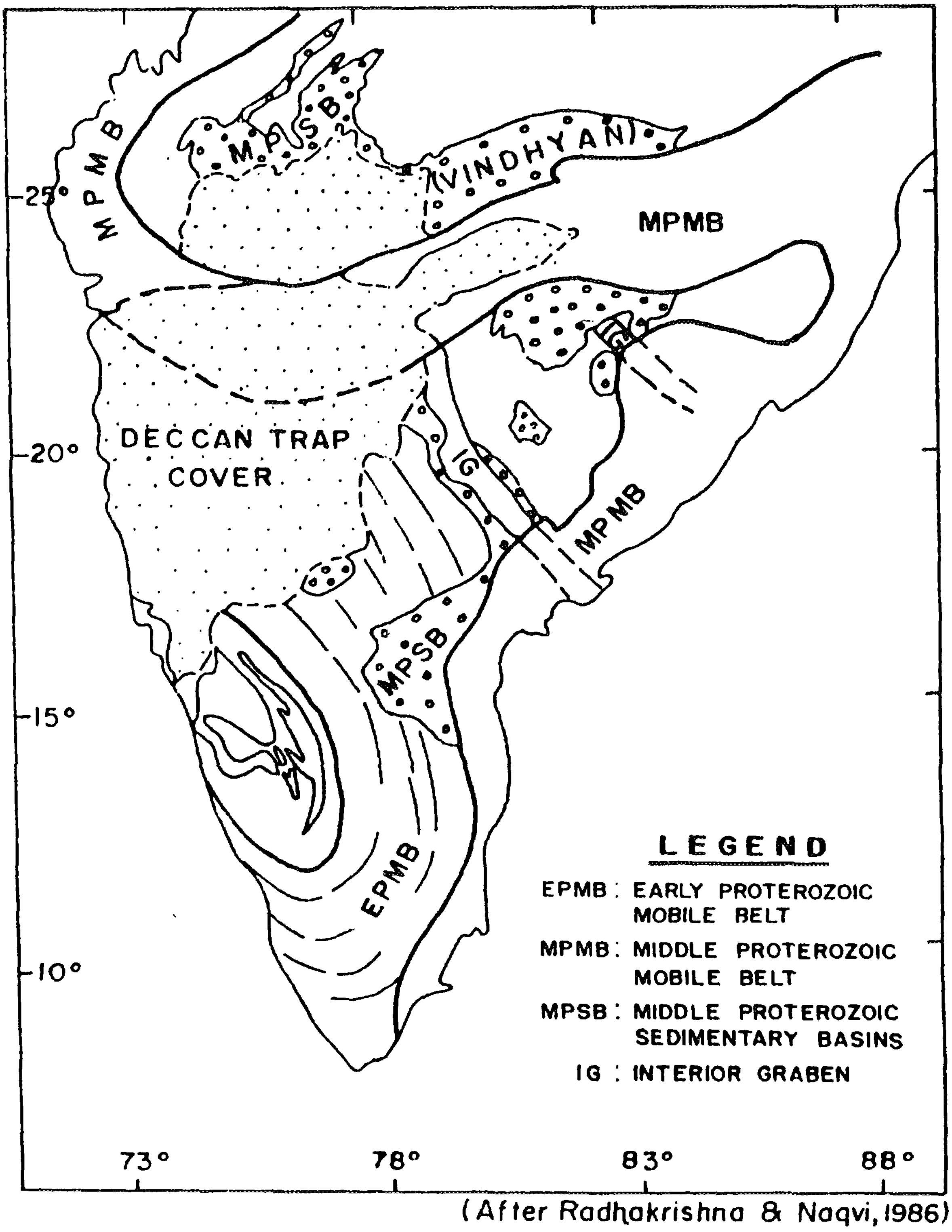


FIG. 2. Simplified geological map of peninsular India showing major tectonic zones (modified after Radhakrishna and Naqvi, 1986).

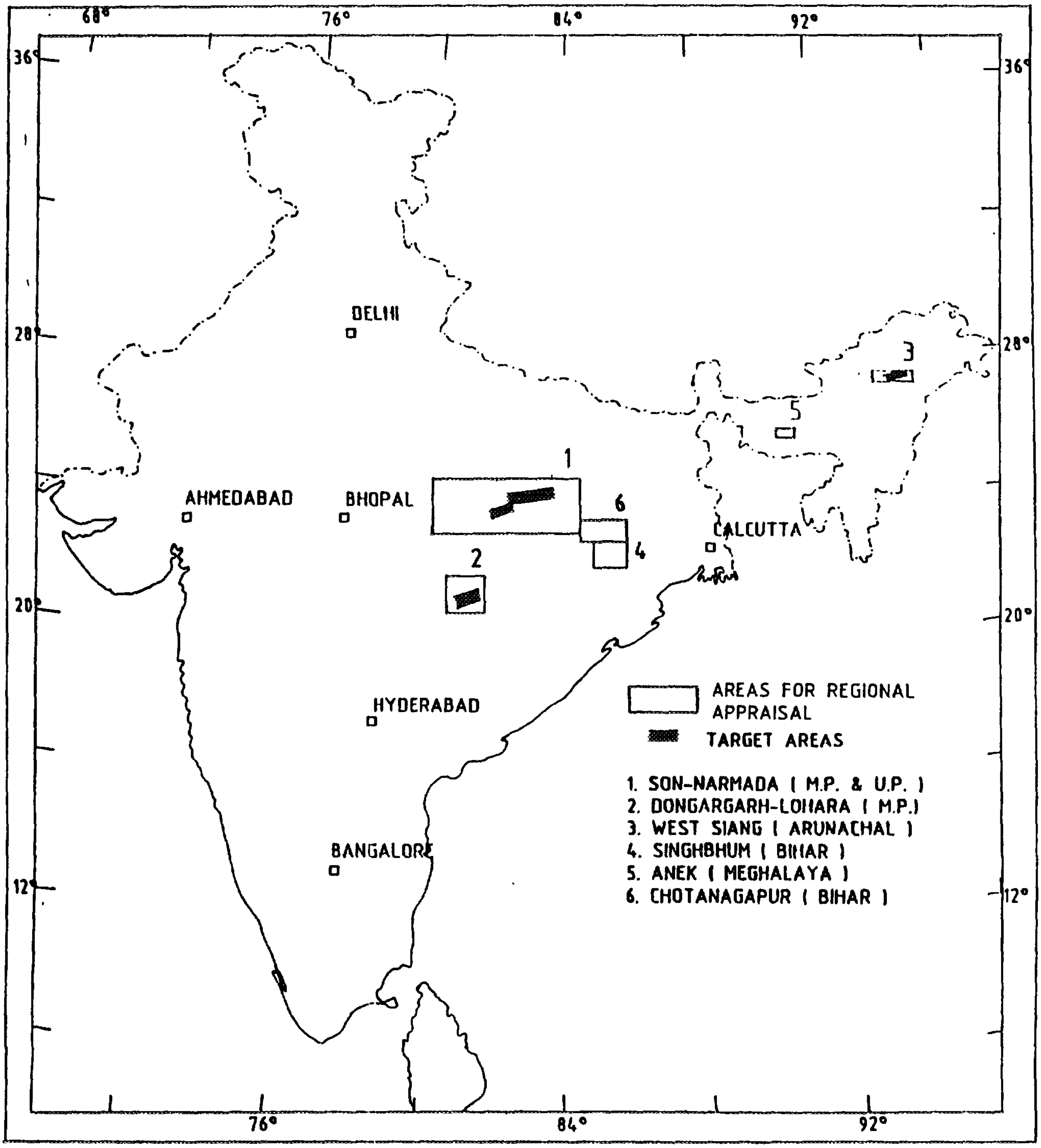


FIG. 3. Areas under evaluation for IOBC type of uranium mineralization.

3.1.2. Regional lithostructural setting of the study area

Geologically, the area comprises basement granitic and gneissic complexes, which are overlain by synsedimental-volcanic formations of Lower Proterozoic age (Mahakaushal Group of rocks) of greenstone assemblage made up mainly of phyllite, tuff and meta-volcanics (metabasalts, pillow lava, basic schists, etc.). Some of the associated ultramafic lavas have been considered to be of komatiitic origin. These are followed by the Bijawar Group of rocks which represent a regime of eugeosynclinal sedimentation. The rocks have been subjected to regional metamorphism resulting in slate, phyllite, schist, marble, metasubgreywacke, metaproto-quartzite, and banded iron formation (BIF). Further, these are sharply divided by a prominent ENE–WSW fault of deep origin. In the Son Valley areas the base of Bijawars towards north is marked by banded haematite jasper/chert and overlain by Vindhyan sediments consisting of quartzite, sandstone, shale, porcellanite and limestone with intrusions of basic volcanic suites comprising agglomerate, kimberlite (900–1350 Ma, Smith, [10]) and basalt. The Son river flowing E–W, in the central part almost follows the faulted contact between the Vindhyans and Lower Proterozoic volcano-sedimentary Mahakaushals/Bijawars — the latter are known to be intruded by granite and dykes of syenite and trachyte which are typical of rift regimes (Balasundaram and Balasubramaniyan [11]).

3.1.3. Broad Tectonic setting of rift zone and geological evolution

The tectonic setting and geological evolution of this belt has been reviewed by Biswas [8]. The observations made by various workers like Radhakrishna and Naqvi [9] and Biswas ([12, 13, 8]) can be summarized as:

1) Doming up of the lithosphere due presumably to hotspot activity and injection of high-density mass in the crust during the Early Proterozoic time and formation of the triple-arm geometry.

2) Regional dilation and injection of magma associated with volcanism and deposition of the volcanogenic Mahakaushal sediments in the Early Proterozoic.

3) Propagation of the rift system laterally under extensional tectonics, producing detachment systems and accommodation zones.

4) Intrusive activity and emplacement of alkaline magmatic rocks like kimberlites (at Panna and Jungel), carbonatite and lamproite (Sidhi) and other basi-cultrabasic dykes in the break-away zones (detachment systems) in the Middle Proterozoic.

5) Cessation of rifting and folding under compressive stresses in the Upper Proterozoic.

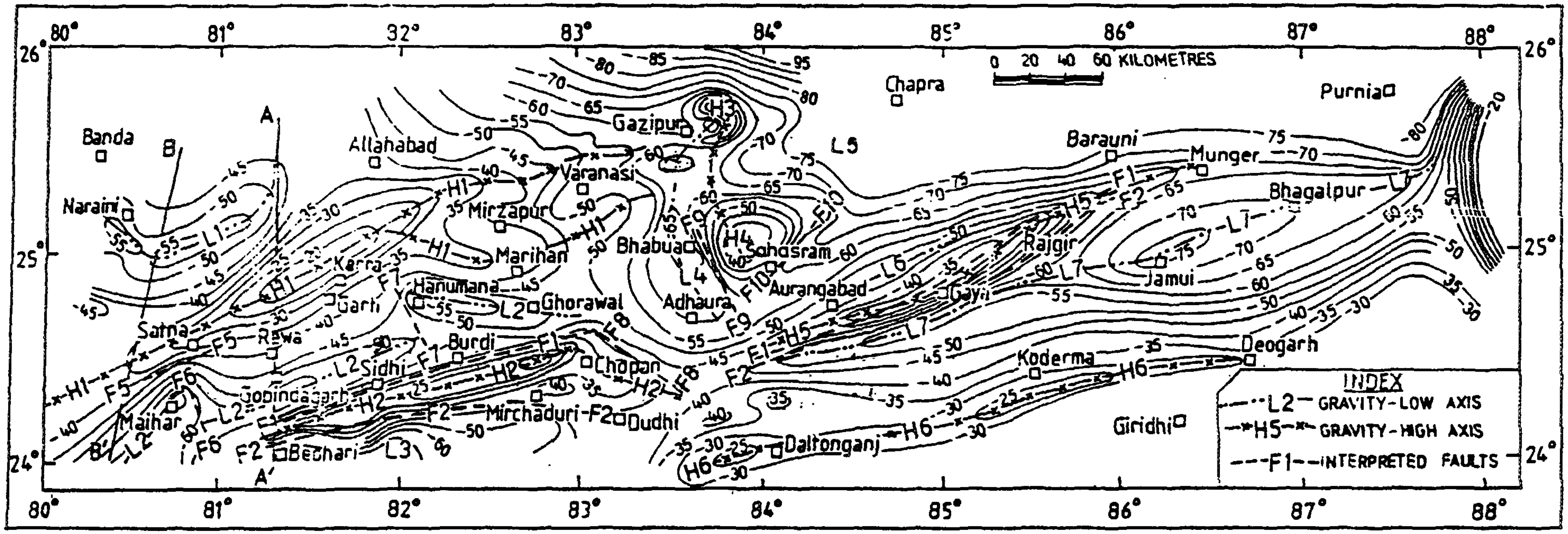
The above summary supports Early Proterozoic rifting of the Indian crust.

3.1.4. Geophysical signature of Proterozoic rifting

The magnetic and gravity anomalies over the Vindhyan basin in Son Valley have been used by Das [14] to trace the subsurface extent and derive the geometry of the Lower Proterozoic volcano-sedimentary rocks cropping out of the northwestern and southern margins of the basin. The Pre-Vindhyan topography and structural features with a rift-valley geometry have been described by him.

3.1.4.1. Pre-Vindhyan topography

The Bouguer gravity and magnetic anomaly (VF) (Fig. 4) reflects some prominent gravity-magnetic highs occurring with the Mahakaushal suite of rocks. The ultrabasic intrusives near Jungel



(AFTER DAS, 1993)

FIG. 4. Bouguer gravity anomaly map of the Son Valley and adjoining region.

(Srivastava et al. [15]) and Panna (Sarma and Nandi [16]) are characterized by sharp peaked magnetic highs. The dolerite dykes also are characterized by high magnetic anomalies.

The Vindhyan as a whole leaves a negative gravity anomaly and the Gondwana Group are represented by a marginal gravity high H-6 (Fig. 4) with feeble magnetic anomaly.

The extent of the magnetic rocks below the Vindhyan sediments has been interpreted using the locations of the magnetic anomaly pairs, the residual gravity highs and the preceding analysis of the possible sources of anomalies. These may possibly represent the Proterozoic iron-rich volcanic rift material such as the basalt flows and ultrabasic bodies (kimberlite) as seen near Jungel and in the Sidhi area. The magnetic anomalies of Domains 1 and 4 are considered to represent the subsurface extension of the Bijawar-Mahakaushal rocks under the Vindhyans in the Gangetic alluvium and forming the basement ridge.

The pre-Vindhyan topography in the west shows a basement ridge as the Satna-Semeria-Burdi ridge and in the eastern part a central ridge has been traced from Mirzapur to Varanasi related to the Vindhyan rocks. Parallel to this central ridge, there are two 'highs' to the north and south of Varanasi, forming a north-south striking dome-shaped plateau surrounded by depressions of the order of 2–3 km (Fig. 4) suggesting that they are basement 'high'.

3.1.4.2. Structural features with rift valley geometry

The 'stripped' gravity anomaly map, after the removal of the gravity effects of the supra-crustals like the Vindhyan and Mahakoshal groups from the observed Bouguer anomaly map (Fig. 4), reflects a central high around Rewa and extending northeast and southward. This represents a high-density intracrustal or subcrustal mass. The three regional lows suggest shallow protorift depression of the Pre-Bijawar-Mahakoshal in the Archaean basement. Regional dilation later must have caused injection of the magma, associated with doming and volcanism. Koide and Bhattacharya [17] and Mohr [18] have advocated a similar mechanism for formation of rift valleys.

During the Middle Proterozoic this rift system was reactivated, creating the Vindhyan basin between the uplifted shoulders (gravity highs) in the north and south. The Satna-Bargarh-Burdi buried ridge structure represents such an accommodation zone in the Vindhyan, while the Kaimur and Chopan escarpment represent the initial detachment systems (break-away zones). In the Son Valley area, the Kaimur escarpment in the western sub-basin and the Chopan escarpment in the eastern sub-basin indicate a 'locked' system. Similar rift asymmetry has been noticed in Lake Baikal, the Rhine graben, Central African rifts and the Gregory rift (Bosworth et.al. [19]).

3.1.5. Uranium mineralization and associated features in the Sidhi-Meraraich-Kundabhati-Dudhi-Naktu-Kudar tract of rift zone

South of the Son-Narmada rift valley the Chhotanagpur granite-gneiss Complex and Bijawar metasedimentaries have been surveyed in parts of Sonbhadra district, Uttar Pradesh and Sidhi district, Madhya Pradesh and a number of significant uranium anomalies have been located in migmatitic and granitic complex. Aerospace data integration using Airborne Gamma Ray Spectrometric (AGRS) and Landsat data has brought to light prominent radiometric fronts marked as breaks and structural trend E–W to ENE–WSW interpreted as faults and shears. Some of the uranium anomalies were found associated with these features. Ground verification indicated extensive radioactive breccia zones, often ferruginous and varying in length from tens of kilometres to a few kilometres at the southern fringe near the contact of the Bijawars with the crystallines and Gondwana sediments with basement granite gneisses. From the data similar indications are seen towards the north, near the contact with the Vindhyans. These breccias are heterolithic and vary in composition from granitic to syenitic, displaying, by and large, a volcano-plutonic association and alkaline affinity. Chemically, the samples

TABLE I. SUMMARY OF CHARACTERISTIC FEATURES OF PROTEROZOIC IRON OXIDE (Cu-U-Au-REE)-BRECCIA COMPLEX TYPE URANIUM DEPOSITS (after Hitzman et al., [20]) AND EVALUATION OF FAVOURABILITY OF THE AREAS REVIEWED (PRESENT WORK)

Characteristic Features	Son - Narmada area (Central India)	Rajnandgaon - Durgh-Khairagarh (Dongargarh - Supergroup)	West Siang and Upper Subsansiri Districts, Arunachal Pradesh
(1)	(2)	(3)	(4)
1. Age			
Early to Middle Proterozoic host rocks. (1800-1100 Ma).	Early-Middle Proterozoic	Partly older	Middle Proterozoic to Early Palaeozoic
2. Host rocks.			
Rich in Fe-oxides. (Fe :20-60%).	No Presently known U-mineralisation in brecciated rocks in;Fe<20%	Partly Yes	Favourable
3. Geochemical association.			
Cu : tr- 2% &	Favourable	Favourable	Favourable
U_3O_8: tr - 0.06%	Favourable	Favourable	Favourable
REE : tr - 6.1%	Favourable		Favourable
Au : 0.5 - 2 ppm	Favourable		
Ag : upto 6 ppm			
P_2O_5, Co, Ni, As, Ba & F invariably associated.	Favourable		
4. Geological and Tectonic setting.			
Areas dominated by rift tectonics especially within cratonic or continental margin environment during Lower to Middle Proterozoic controlled and influenced by the rifting of Proterozoic supercontinents.	Favourable	Favourable	A part of a thrust sheet
5. Structural relations.			
Most of them related to major lineaments or structural trend.	Favourable Syenite Syenite	Favourable	Favourable
6. Host rocks.			
Both igneous and sedimentary rocks many within silicic to intermediate rocks of anorogenic type.	Favourable Syenite (pofastic) Volcanic (?)	Favourable	Favourable
7. Mineralisation.			
(a) Relation to igneous rocks may be direct or indirect (not seen at the present levels of erosion).	Direct Favourable	Favourable	Indirect

(1)	(2)	(3)	(4)
8. Mineralogy.			
(a) Ores dominated by iron oxides (haematite (shallow) or magnetite or magnetite (deeper)).	No clear information on ores.	No clear information	No clear information; Fe ores of marine origin
(b) REE in apatite, monazite, xenotine, and bastenasite. (c) Au as native metal. (d) Cu as sulphides. (e) Co , Ba, P and F. minerals are common and often abundant.			
9. Alteration.			
Host rocks intensely altered. Alteration mineralogy depends on host lithology and depth of formation with zonal features and charecters.	-	Minor	-
(a) Sodic (deeper) (b) Potassic (shallow). (c) Sericitic and (d) Silicification at very shallow levels	Seen at Sonavani	Not documented	Sericitisation and silicification in presently known mineralised bodies
Locally the host rocks are intensely Fe-metasomatised.			
10. Morphology of deposits.			
(a) Stratabound (concordant).			concondant
(b) Transgressive. (discordant veins ; breccias).	Favourable	No data	
(c) Morphology and alteration are controlled by permeability along faults	Favourable		
11. Depth of formation.			
Shallow crustal environments (<6km depth).			
12. Geophysical signature.	Positive gravity features Distinct magnetic anomalies indicating subsurface bodies.	No data on gravity some isolated magnetic highs discerned.	No data
13 Genesis. Hydrothermal type linked to deep-seated, volatile rich igneous rocks by deep crustal rifts.	Favourable	Favourable	Favourable

analyse SiO_2 6075%, K_2O 8.75–14% Na_2O 4.00–8.14%, CaO 0.07–1.9%, Al_2O_3 13–20%, Fe_2O_3 1.11–13.35%, FeO 0.25–4.16% and contain Cu 5- >500 ppb, Ni 15- >300 ppm, Au up to 52 ppb and Ag <5 ppb. Petromineralogically the breccia consists of angular fragments and cluster of quartzite, migmatite and basic rocks, with a lot of cherty materials and quartz-veins. They are often ferruginous and sometimes carry highly haematitized pyroblastics with remnants of migmatites as xenotith. Biotite and amphiboles in the latter are completely altered and haematitic palagonitic fragments or divitrified shards are observed. Phenocrysts of sanidine and zoned plagioclase are also seen. The general nature of the pyroclats (ignimbrite ?) and their alterations indicate repeated volcanic actions through a wide range of geologic time. Bijawars/Mahakaushals, so far, are not seen having been intruded by the syenitic rocks, yet their being affected remotely by the thermal events generated by the intrusive syenitic rocks cannot be ruled out. However, the basic and acid volcanics associated with these Lower Proterozoic rocks are amply evidenced both in the form of flows as also in the form of dykes. In the light of recent models of ore genesis at Olympic Dam deposit — a major example of the IOBC type of uranium and associated mineralization — where granitic breccias, often haematitized, have largely been produced by volcano-plutonic hydrothermal systems.

3.2. Dongargarh supergroup (DSG) of rocks, Khairagarh Basin

The areas covered by the DSG of rocks (Fig. 3) fulfill several of the favourability factors for hosting iron oxide/breccia complex type uranium deposits (Table I). The foremost among these include the intra-plate, intra-cratonic rift tectonic association and the bimodal rhyolite-basalt/granite-gabbro volcano-plutonic assemblage.

Many of the favourability factors for IOBC type deposits are satisfied in the areas covered by the Dongargarh Supergroup of rocks (Table I).

The area between Malanjkhand and Lohara in Khairagarh basin suggests the possibility of finding IOBC type uranium mineralization in this tract.

3.3. Maro-Kau-Dupu, Arunachal Pradesh

The Banded Iron Formations (BIFs) are represented by magnetite quartzite, haematite quartzite and biotite magnetite quartzite and are reported from several localities in Upper Subansiri and West Siang Districts of Arunachal Pradesh (Fig. 3). The important occurrences include Maro, Bari-Rijo, Tai, Badak, Bate nalla, Lete nallah, Noko nallah, Gamkak, Tapior, Jaiyor and Kau nallah. The BIFs contain up to 50% volume of ironoxide minerals (magnetite/haematite) and up to 60% modal quartz with variable amounts of muscovite, biotite and garnet. Other minerals present are sphene, epidote, tourmaline, perthite, K-felspar, chlorite, apatite and monazite. The most common alteration features seen are 1) oxidations of iron oxides, magnetite altering to martite, limonite, goethite haematite, and haematite to limonite, goethite, ii) chloritization, iii) silicification and iv) sericitization. This suggests that these rocks have undergone alteration by pneumatolitic/hydrothermal process. Other minerals present include pyrite, chalcopyrite, chalcocite and covellite. These minerals occur in poorly disseminated form or as irregularly distributed clusters. Primary uranium minerals identified include uraninite, and brannerite. An epicontinental platform/shelf environment formed in shallow water and shallow tectonic conditions has been inferred for the volcano-sedimentary sequence. Minor veins of quartzo-felspathic material reported in these metasediments adjacent to mineralized iron oxide rock and the alteration effects suggest an epigenetic, hydrothermal uranium mineralization.

The inferred within-plate, oceanic tectonic association and the marine nature of the origin of iron oxides, and the structural disposition of the host rocks (nappe with shallow depth persistence), however, casts some doubts on these BIF related uranium association to be grouped with the IOBC types. Nevertheless, they represent an interesting association and more data to support their IOBC character are being collected.

4. CONCLUSION

In light of the above discussions on uranium exploration target selection for Proterozoic Iron Oxide/Breccia Complex (IOBC) type deposits in India, the areas in Son-Narmada rift valley zone which extends over 200 km, have been taken up for detailed evaluation. A multigeoscientific programme by a full time dedicated team of geologists, geophysicists, geochemists and geochronologists with a full laboratory support has been envisaged. A good number of uranium shows have been discovered some of which may lead to the discovery of a sizeable uranium deposit of IOBC type in this tract.

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DEVELOPMENT OF THE CERRO SOLO DEPOSIT AND URANIUM FAVOURABILITY OF THE SAN JORGE GULF BASIN, PROVINCE OF CHUBUT

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Abstract

The objectives of the CNEA are in the process of transformation in accordance with political and economical changes occurring in the country. Hence, in the future the uranium exploration activities of CNEA would tend to improve the knowledge of geology and uranium favourability; to perform prospection tasks, and research and development in exploration technologies, to contribute to be in a position to meet the requirements of the country in the long term. On the other hand, a strong growth of nuclear capacity is expected in the first two decades of the next century. Based on its promising grade, the Cerro Solo uranium ore deposit was selected in 1990 by the CNEA to carry out an assessment project. The intensive exploration level was accomplished, as follows: definition of general characteristics of the main orebodies; detailed geologic studies; estimation of resources with adequate data; and preliminary selection of mining-milling methods to estimate the potential profitability of the project. The deposit belongs to the sandstone type. The mineralized layers are distributed into the fluvial sandstones and conglomerates of the cretaceous Chubut Group, lying 50 to 130 m deep. Resources of the deposit, with an average grade of 0.3%U, in tonnes of recoverable uranium at costs of up to $80/kg U, are: Reasonable Assured Resources (RAR): 800 t U, Estimated Additional Resources, Category I (EAR-I): 2100 t U. Follow-up drilling programmes are being performed at present in some of the target sites defined in the paleochannel that hosts the Cerro Solo deposit, in order to establish the hypothetical resources of the area. The sites were determined as a result of the exploration that CNEA conducted in the Pichiñán uranium district. Recently, a regional research project was formulated, the goal of which is to contribute to selecting targets for detailed exploration in the San Jorge Gulf Basin, where the Chubut Group is distributed. Besides, the objective of the project is to improve the results of the studies that CNEA is executing in different regions of the basin, which is considered highly favourable for uranium, by making an integral analysis of the information and planning.

1. INTRODUCTION

The goals of the Comisión Nacional de Energía Atómica of Argentina (CNEA — National Atomic Energy Commission) and the scopes of the uranium exploration activities that it perform, are in the process of transformation in accordance with political and economical changes that are taking place in the country. An important milestone was the recent decision of the government to change the structure of the CNEA, in order to privatize the activities belonging to the production stage of the nuclear system, and to assign research and development activities in the nuclear field to the CNEA.

As the fuel cycle activities are involved in this new context, it is predictable that in the future, the start or continuity of uranium mining operations will depend upon more stringent economical conditions. This will be established by the commercial arrangements with the companies owning the nuclear power and fuel cycle plants. Competition with foreign sources of uranium will be of major importance in the development of such operations.

At present, the total nuclear installed capacity of 940 MW divided in two plants, is not expected to increase until the end of the decade, because of delays in the construction of the Atucha II plant. Besides, the competition of more profitable sources of energy in the short term, would postpone commitment of additional nuclear power plants. This indicates that the increase of uranium requirements curve will diminish in the short term [1].

However, a strong growth of nuclear capacity is expected in the first two decades of the next century. Hence, in the future the uranium exploration activities of CNEA would tend to improve the knowledge of geology and uranium favourability; to perform prospection tasks, and research and development in exploration technologies, to contribute to be in a position to meet the requirements of the country in the long term.

2. SITUATION OF THE CERRO SOLO PROJECT

In 1990 the CNEA started performing an assessment project in the Cerro Solo uranium ore deposit, based on their promising grade that may allow production in competitive conditions in the country. Two stages of the project have been completed: the first, exploration to delineate the main orebodies, and the second, geologic setting research and economic studies at the order-of-magnitude level. Then, the intensive exploration level was accomplished, as follows: definition of general characteristics of the main orebodies; detailed geologic studies based on drillhole samples and geophysical logging; estimation of resources with adequate data; and preliminary selection of mining-milling methods to evaluate the potential profitability of the project. At present, the third and final stage is being carried out, the goal of which is the detailed delineation of selected orebodies, and to carry out prefeasibility studies.

Conventional mining methods are being considered to make estimations about profitability of the project. On the other hand, the unfavourable permeability conditions existing in the main sectors of the deposit do not allow applying the in situ leaching technology, that is anyway taken into account in the studies about other targets in the region. Then, characteristics that seem to be favourable to applying this technology will be analysed in some areas; for instance, the Arroyo Perdido, Sierra Cuadrada and El Mirasol prospects, that show geologic indications of good permeability in the host layers, to trying to execute a pilot test. Besides, the attention has been focused on the borehole mining technology that may be an alternative in this case, taking into account that it was tested in deposits of this type.

With regard to the environmental aspects of a possible production stage, a systematic programme of studies in this field was initiated, with the participation of the group in charge of the waste management issues in the CNEA, and local institutions [2].

In the next two years it is expected to drill additional 20,000 m in the area. By that time it is expected to reach the general objectives of the project, which means to complete the development prior to the production stage of the deposit. This includes the following items:

- completion of the makeup of a comprehensible geological model of the deposit, to be extrapolated to the regional exploration,
- definition and application of resource estimation methods to establish a reliable categorization of the uranium resources,
- analysis of the potential profitability of the project with accuracy that can allow to make decisions about the production stage,
- survey the environmental baseline of the area, at a general level,
- research of the feasibility to use special technology, with emphasis on in situ leaching,
- expeditious exploration of the geological influence area of the Cerro Solo deposit, to estimate its hypothetical resources in a reliable way.

3. COMMENTS ABOUT GEOLOGICAL SETTING OF MINERALIZATION

Some reports have been issued that describe the geological characteristics of the deposits located in the Cerro Solo area [3, 4]. In the present report only some aspects of this matter related to the mineralization model will be mentioned.

The fluvial stratigraphic unit belonging to the cretaceous Chubut Group that hosts the mineralization reach up to 150 m thick in the Cerro Solo area. Conglomerates and sandstones corresponding to defined facies of the sedimentary environment [5] are predominant in the lithology of the high energy, braided type paleochannel.

It has been established that mineralization is related predominantly to the following features of the paleochannel section:

- sediments characteristic of reduced environment, gray or green color,

- quick alternation between different lithologic classes (as described by Marveggio [6]). Mineralized layers, up to 10 m thick, are made up of alternating thin sandstone and conglomeratic beds, that contrast with more lithologically homogeneous overlapping and underlying layers.

In Fig. 1 a typical drillhole log shows the close association between mineralization, organic material and sulfides; and the apparent increasing content of cement towards the mineralized layer. In the last column, the variations of maximum diameter of grain size indicates the lithologic characteristic of the orebodies mentioned above.

The grade, that averages 0.3% U in the orebodies identified in the main sectors of the deposit, is frequently higher than 2% U values in the sandstone layers interbedded.

Diagenes seems to have played an important role in preserving the mineralization, as it is indicated by the typical presence of abundant carbonatic cement in the mineralized layers, apart from organic material and sulfides that give them a distinctive hard feature comparing with more friable parts of the sections in the area.

Apparently, there are paleo-geomorphological aspects that play an important role in the mineralization process, which is indicated by the location of the higher grade layers in certain positions with regard to the border or the talweg of the paleochannel, depending on the stratigraphic level.

Typically, mineralization occurs in immature sandstone-size sediments, that may occasionally be the matrix of conglomerates, which are made up in the clastic fraction mainly by lithic fragments (ryolites, ignimbrites, and acid tuffs, and less frequent andesites, silica and granites-granodiorites), quartz and feldspars. There are abundant clays (predominantly montmorillonite) and calcite in the matrix. Uranium minerals are associated with disseminated "clastic" organic material, and sulfides [4]. In order of abundance they occur as coffinite, uraninite and undetermined uranium minerals linked with organic material [7].

The predominant tectonic system affecting the region follows the NW direction, and divides the deposit in three main blocks [8]. It is possible that the tectonic system have been important in the preservation or leaching, depending of the position of mineralization.

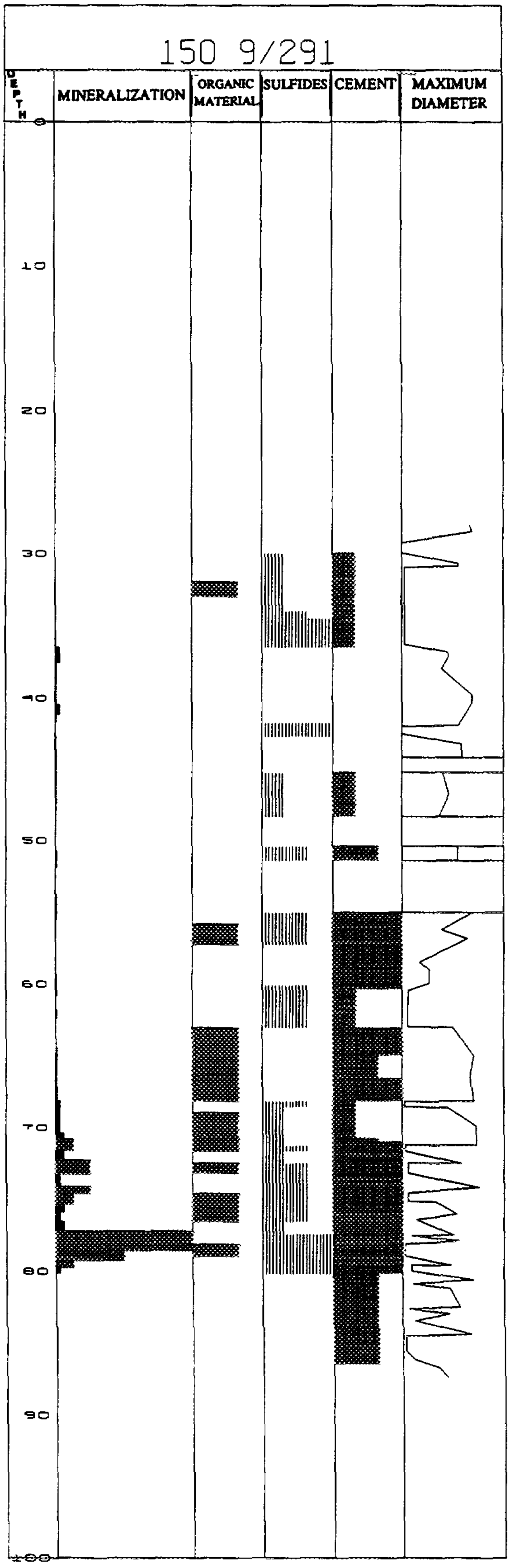

FIG. 1. Cerro Solo drillhole log.

5. THE RESOURCES SITUATION

Resources of the deposit were established by using conventional estimation methods, which were applied with data obtained in about 300 drillholes, in the 90 hectares area corresponding to the main sectors. With regard to the 320 hectares that include all of the Cerro Solo area, the studies have been based on 60 000 metres of drillholes, of which 36 000 m correspond to the Cerro Solo Project and the rest to previous programmes.

However, geostatistics was applied in the sector named C, what made an interesting contribution to the knowledge about characteristics and distribution of the mineralization. This was the first application of a software recently incorporated as a resource estimation tool by CNEA, with successful results, with IAEA technical assistance [9].

The situation of uranium resources in the Cerro Solo area is shown in the following table. The reference date is January, 1995. Most of the resources belong to the main sectors of the Cerro Solo deposit. The resources are expressed in tonnes of uranium as recoverable quantities, this means, the mining and ore processing estimating losses were deducted.

REASONABLE ASSURED RESOURCES RAR		ESTIMATED ADDITIONAL RESOURCES Category I - EAR-I	
Cost Ranges		Cost Ranges	
< $80/kg U	< $130/kg U	< $80/kg U	< $130/kg U
800	1 250	2 100	3 250

6. POSSIBILITIES OF INCREASING RESOURCES IN THE EASTERN SLOPE OF THE PICHIÑAN RIDGE

In the Pichiñán Ridge region, located 420 km West of Trelew, the host fluvial sediments were explored in an area which is limited by the Chubut River to the west and the Arroyo Perdido to the east, about 40 km east to west and 8–10 km north to south. In the western slope, where the paleochannel turns to south, small deposits were found. However, the eastern slope, where the deposit described in this report is located, shows a distinctive pattern of lithology, diagenetic and mineralization processes, that resulted in more favourable conditions [10, 11]. It was proposed that the eastern part of the paleochannel it is a different fluvial cycle, younger than the western part [5].

Data obtained in exploration drillholes indicate the presence of mineralization, and promising geologic characteristics, in different sectors within an area of about 180 km^2. All this taking into account the Cerro Solo model. The favourable area is about 60% of the total, i.e. 110 km^2.

Fig. 2 shows a schematic map of the deposition limits of the fluvial sediments, the location of the Cerro Solo and these favourable sectors, which it is expected will increase the resources, by carrying out drilling exploration programmes, based on the metallogenic and paleo-geomorphological pattern defined in the Cerro Solo deposit.

7. IDEAS ABOUT URANIUM FAVOURABILITY AND EXPLORATION OF THE SAN JORGE GULF BASIN

The Central Region of the San Jorge Gulf Basin was the objective of exploration tasks from 1959, which followed the anomalies discovered in the Chubut Group stratigraphic unit. This intracratonic basin covers a surface of 170 000 sq. km (about 68 000 sq. miles). It is located between

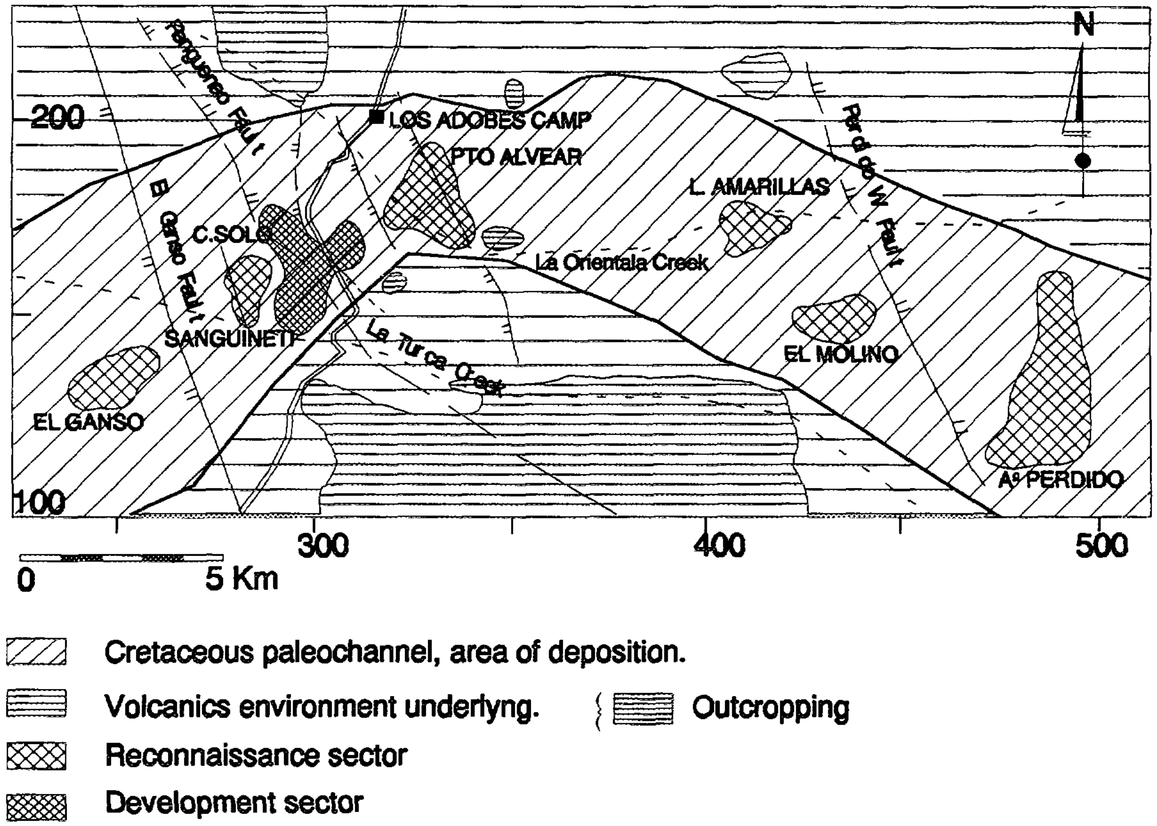

FIG. 2. Schematic map of the Cerro Solo deposit location and deposition limits of the fluvial sediments.

the North-Patagonic and the Deseado Massifs, separated due to the deformation produced by the continental drift. The basin has continuously subsided through normal faults, since the early Cretacic. The deposition of the continental Chubut Group occurred in this period [12]. At the same time an important volcanic activity took place in the region of the present Andean Orogenic Belt, which is located some hundred kilometres to the west of the central area of the basin. The pyroclastic rocks originated in this event were mentioned as uranium source in the region [13].

In wide areas of the basin, the cretaceous sedimentation began with high energy fluvial conglomerates and sandstones (Los Adobes Formation), filling the lows of a paleorelief scoured over the underlying paleozoic and mesozoic formations. The fluvial system was later covered by the tuffaceous sediments transported from the west that represent perhaps 90% of the volume of the cretaceous column (Cerro Barcino Formation). At the top it presents a second fluvial system interbedded with tuffs and silstones (Puesto Manuel Arce Formation). The first two members mentioned above reach an average depth of some hundred metres in some places. The third a maximum of some tens of metres. See summary of cretacic stratigraphic units in Fig. 3.

In the decade of 1960 a number of anomalies and ore deposits were discovered in the basin. This was a result of local aerial survey programmes (total gamma), carried out in the Chubut Group, basically to cover the fluvial members in the base and at the top. Two of them, small deposits belonging to the Los Adobes Formation, were mined in the decade of 1970.

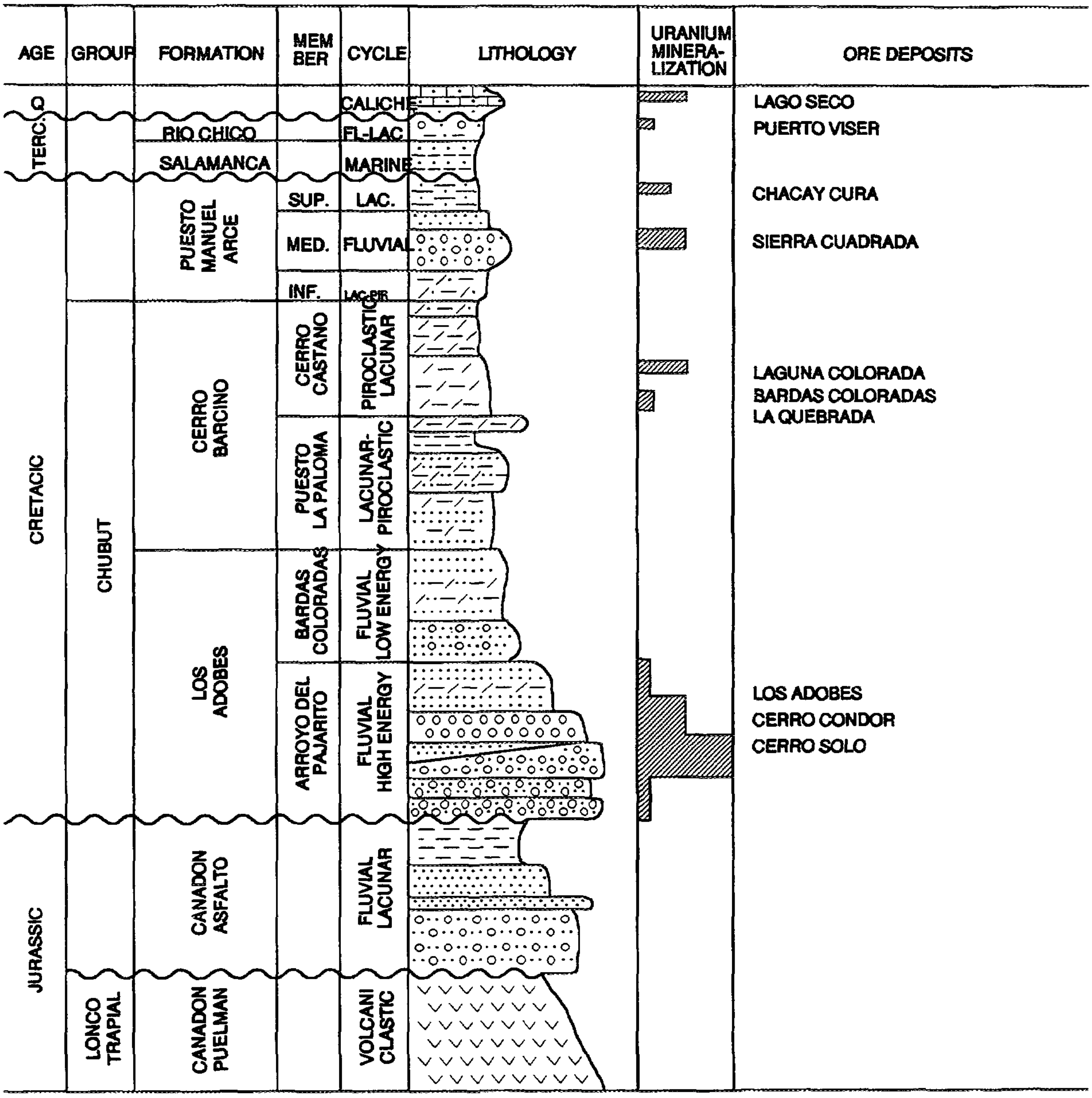

FIG. 3. Summary of cretacic stratigraphic units.

At that time, the exploration effort was concentrated in the Sierra de Pichiñán District. Up to the present, about 110 000 m of exploration drillholes have been carried out in the region, allowing to find some deposits and favourable areas, as mentioned above. At the end of the 1980s, regional geological mapping tasks were performed in the continuity to the south of the fluvial system [14]. Completing this program and a detailed analysis of the data is foreseen, trying to establish the location of new areas that may have adequate conditions to extrapolate the Cerro Solo metallogenic model.

A 100 000 sq. km aerial radiometric survey performed in the basin, at the end of the decade of 1970, allowed the detection of 2372 uranium anomalies [15]. An important number of this anomalies was located in the medium and higher parts of the cretaceous stratigraphic unit.

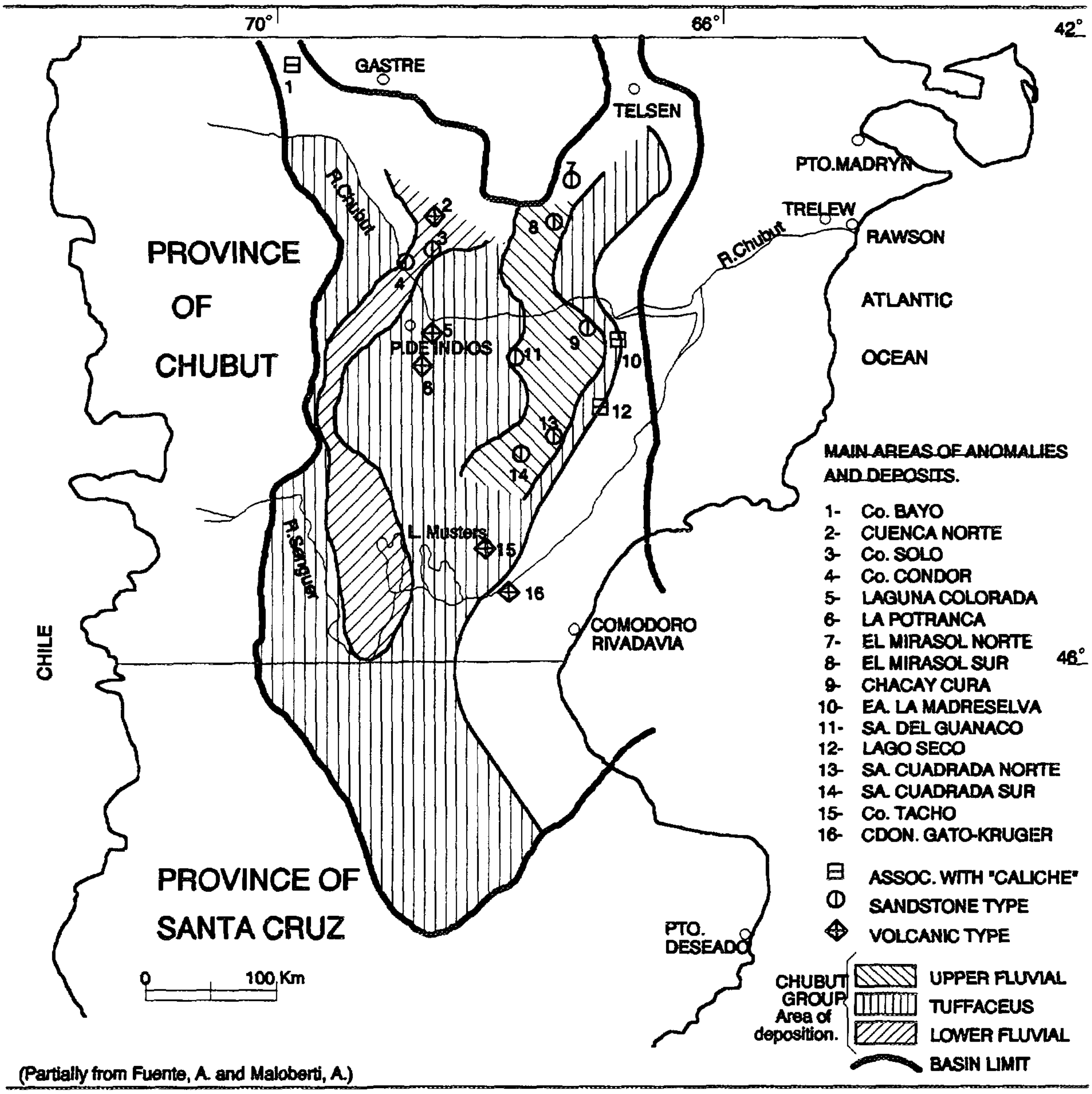

FIG. 4. Map showing the known and the inferred development of the two fluvial and tuffaceous systems of the Chubut Group.

Mineralogical studies carried out in tuffs and tuffites of the Cerro Barcino Formation, indicate that they liberated important quantities of uranium in the basin [5]. Part of it was transported through the fluvial members (made up of volcanic material) interbedded in the Chubut Group, and precipitated where conditions were adequate. However, tuff horizons hosting uranium mineralization were also found. In this case, mineralization would be related to hydrothermal episodes occurred in the Tertiary [5]. The wide distribution of the volcanic formation, and evidences of uranium mineralization and mobilization, encourage to face research programmes on the different mineralization models which are frequently related to this type of geologic environment.

Uranium occurrences are known in the upper fluvial member (Puesto Manuel Arce Formation) since the 1950s. In most of them exploration is in the reconnaissance phase. The Sierra Cuadrada deposit was explored with a shallow drillhole programme in 1978 [16]. Favourable geological features were observed in different areas where this formation outcrops, for instance, in the El Mirasol Norte y El Mirasol Sur occurrences, and some possible metallogenic models that seem to be applicable, were proposed.

Besides, in the east border of the basin, anomalies that correspond to carbonatic mineralization in soils ("caliche"), evaporitic type, have been put in evidence. They are spread in great "spots" that add up to about 100 sq. kilometers. Yet, some anomalies are lying in tertiary fluvial sedimentation (Río Chico Formation).

Fig. 4 represents a map that indicates the known and inferred development of the two fluvial and the tuffaceous systems of the Chubut Group. It also shows the position of the main deposits and group of anomalies. It is noted that the studies were concentrated on the central region of the Province of Chubut.

Evaluations of uranium favourability of the different geological environments in Argentina, have considered the San Jorge Gulf Basin in the higher level of priority. Such considerations are based on the elements described above that have been reported in detail [17].

The authors consider that, at present, it is advisable to perform a detailed research programme about the favourability of the basin, in order to contribute to its exploration. It is clear that it is important to obtain data about the tuffaceous intermediate member and the upper fluvial member to try obtain knowledge on the same level, about the features of the three members of the Chubut Group. This will be done taking into account the geological characteristics and the presence of deposits and anomalies in different areas. At the same time, it is convenient to improve knowledge about the mineralization models in the corresponding geological environments.

Finally, it is recommended that, considering the information about the presence of favourable lithology, attention be paid to the parts of the basin that were geologically recognized in an expeditious way, or even not recognized and devoid of radiometric surveys.

The methodology proposed is as follows:

1) Recognition programme, Scale 1:500 000, in the regions with almost complete lack of the information that it is needed to be included in the following step.

2) Geological survey programme, Scale 1:100 000, using satellite image technology. Regions of the basin to perform this stage will be selected based on their geologic characteristics.

3) Systematic survey of stratigraphical sections and geological features of interest, in representative localities, to make the necessary characterizations and correlations.

4) Definition of the models of mineralization present in the different stratigraphical units, making the convenient research on the deposits selected as typical.

5) Global analysis of data, to define target sites for exploration and priorities.

ACKNOWLEDGEMENT

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NEW RESULTS OF THE EXPLORATION FOR URANIUM ORES IN ROMANIA

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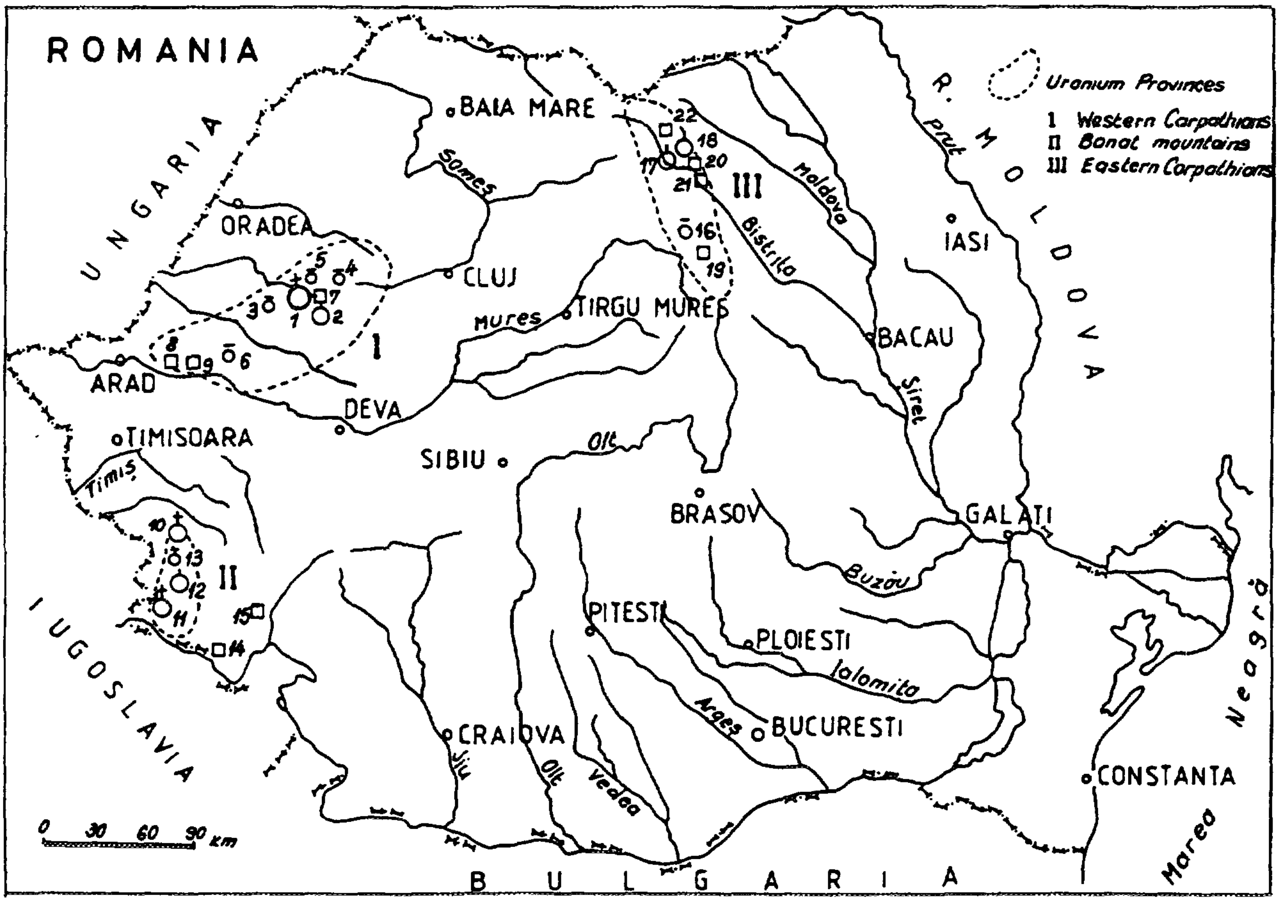
Abstract

The objective of the decentralization programmes of exploration activities for radioactive ores in Romania is the creation of specific sub-units which act with predilection in the extension of the three uranium metallogenesis provinces. As a positive result of this reorganization, new mineralizations of interest are identified presently in the Highis-Drocea Massif of the southern-western part of the Apuseni Mountains and in the eastern Banat at Mehadia, Svinţia and Ilişova. The uranium mineralizations in the Highis-Drocea Massif occur in several forms of presentation of which the intragranitic (Milova type) and those localized within the metamorphites of the Păiuşeni Series, have a practical importance. The intragranitic mineralization of the Milova type consisting of pechblende associated with secondary minerals of the autunit-törbernit type, is controlled by the disjunctive tectonics (fractures, cataclasis and mylonitization zones). In addition to the uranium mineralizations in the same conditions there occur sporadically metal sulphides of Cu, Pb, Zn and Co. The mineralization of the Păiuşeni type is represented by lentiliform bodies, concordants with schistosity within the grey or reddish grey quartzites, in which the mineral elements — pechblende and chalcopyrite — occur as impregnation (disseminations). In the eastern part of the Banat, the hydrothermal uranium mineralizations are closely associated with quartziferous rhyolite of areas. At Mehadis, the mineralization represented by pechblende and parapechblende, associated with Cu and Zn sulphides, is controlled by a fractures system which effects the metamorphic formations of the Corbu Series. In the southern zone of the eastern Banat, at Svinţia and Ilişova, the uranium mineralization also hydrothermal, represented by pechblende and coffinit in association with the metal sulphides, is hosted in the joints systems within the quartziferous rhyolites and pyroclastical rocks. As a consequence of the above mentioned, we can remark in the eastern Banat a new sub-province of uranium metallogenesis clearly different from sedimentary deposits in the western Banat.

The programme to decentralize the exploration for radioactive ores in Romania, has a main purpose to sitting up some subunits, which should operate more efficiently for extending actual mining areas connected to known metallogenic provinces (Fig. l). The positive results of this action are already significant in the western part of the country, starting with the Highis-Drocea massif in north and in the Eastern Banat at Mehadia, Svinita and Ilisova. By the genetic nature and the geological conditions under which the explored uranium mineralizations are found in these areas, they can already make up a new metallogenetic subprovince with specific features.

The uranium mineralizations in the Highis-Drocea massif appear in different presentations, but only the intragranitical (Milova type) and the perigranitical (Paiuseni type) veins forms placed in granite and in the metamorphites of the Paiuseni series have practical importance (Fig. 2). The Milova type mineralization is controlled by the disjunctive intragranite tectonics N–S oriented within the Highis-Drocea massif. This mineralization is represented by the primary uranium mineral pechblende and by the secondary minerals of the autunite and torbernite type. The orebodies located along the fractures have a large development at level of areas with strong cataclazation and breccification of the granitic rocks, where then can reach hundreds of metres in length, a thickness between 0.6–1.5 m, and contents varying between 0.03–1.50% U. Within these deposits, the uranium mineralization accompanied by polymetallic sulphides of Cu, Pb, Zn, Mo and Co, is hosted in a clayey gangue, impregnated by iron hydroxides. The associated polymetallic sulphide mineralization is devoid of economic importance. Recently, in this area mineralized bodies are known and also, a great number of radiometric anomalies, provide a good perspective to the area.

The Highis granite, which hosts these mineralizations has a massive texture, a hipidiomorphic granular structure, rarely pegmatoid and a yellowish white or pinkish colour. The granites have a normal mineralogical composition, in which predominate (in the following order): potassic feldspar, plagioclase, quartz and biotite. The accessory minerals represented by zirconium, apatite and allanite



URANIUM METALLOGENETIC PROVINCES

I WESTERN CARPATHIANS

ORE DEPOSITS

1 Băita Bihor
2 Avram Iancu
3 Rănusa
4 Răchitele
5 Budureasa
6 Păiuseni

MINERALIZATIONS

7 Arieseni
8 Milova
9 Conop

II BANAT MOUNTAINS

ORE DEPOSITS

10 Ciudanovița
11 Natra
12 Dobrei Sud
13 Dobrei Nord

MINERALIZATIONS

14 Ilișova
15 Mehadia

III ESTERN CARPATHIANS

ORE DEPOSITS

16 Tulghes
17 Crucea
18 Botușana

MINERALIZATIONS

19 Bicazul Ardelean
20 Piriul Lesu
21 Holdița
22 Hojda

○ Large deposits > 20.000 t metal
○ Medium deposits 5000-20 000 t metal
○ Small deposits < 2000 t metal

ȯ Ore deposits depleted
ȯ Ore deposits in explotation
ō Ore deposits in exploration
□ Mineralization in exploration

FIG. 1. Uranium in Romania.

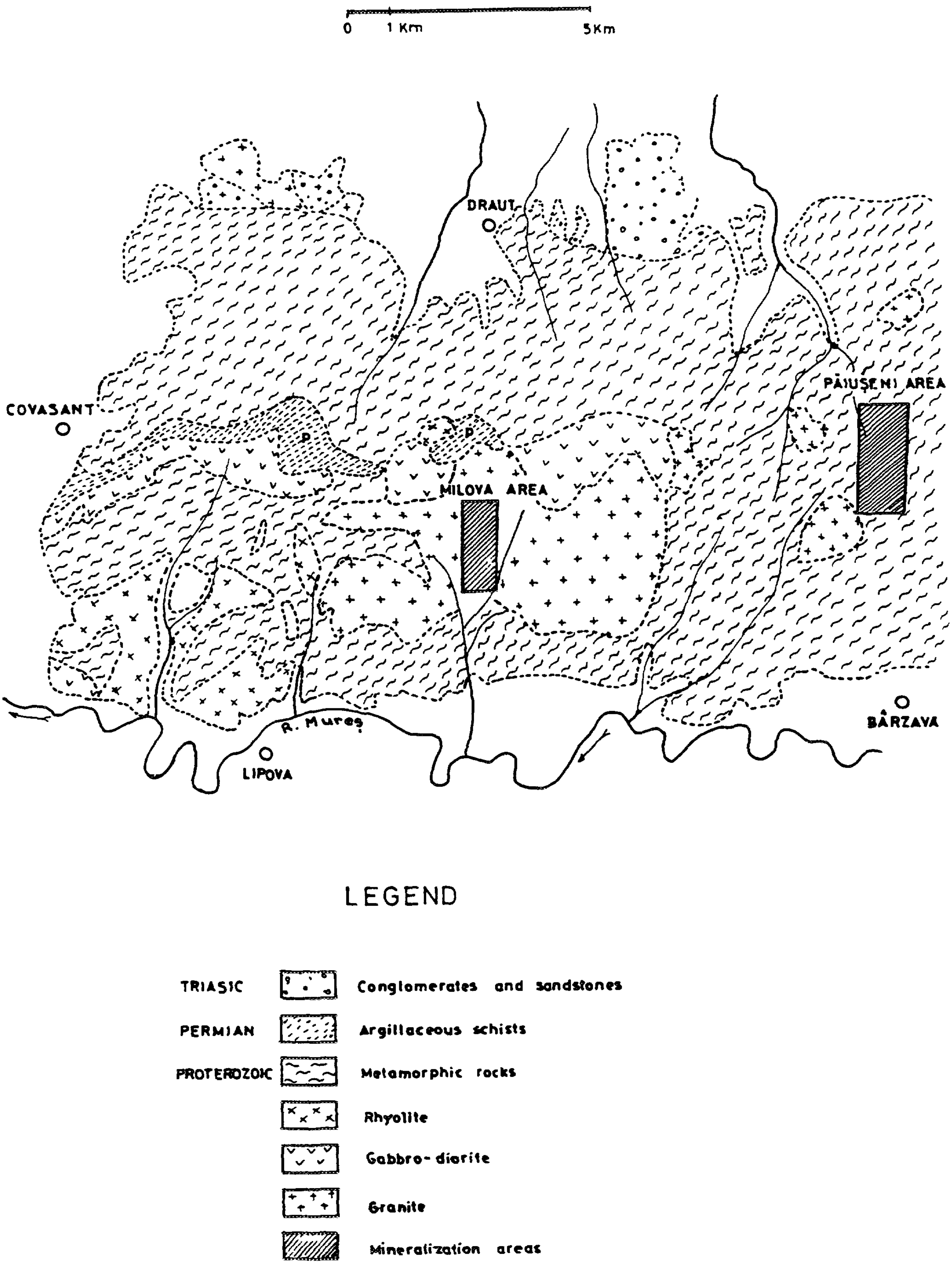


FIG. 2. Highis-Drocea geologial map.

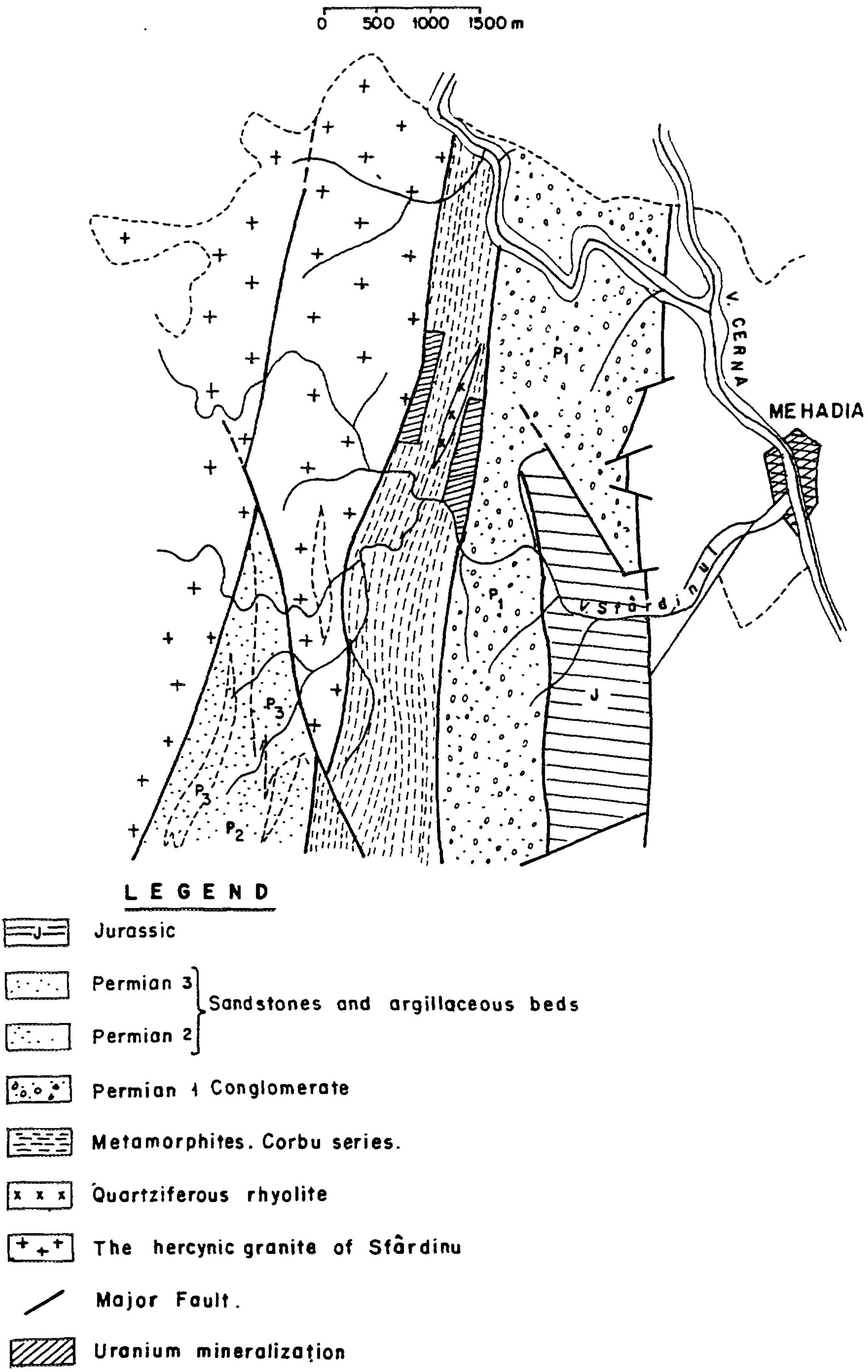


FIG. 3. Geological map of the Mehadia area.

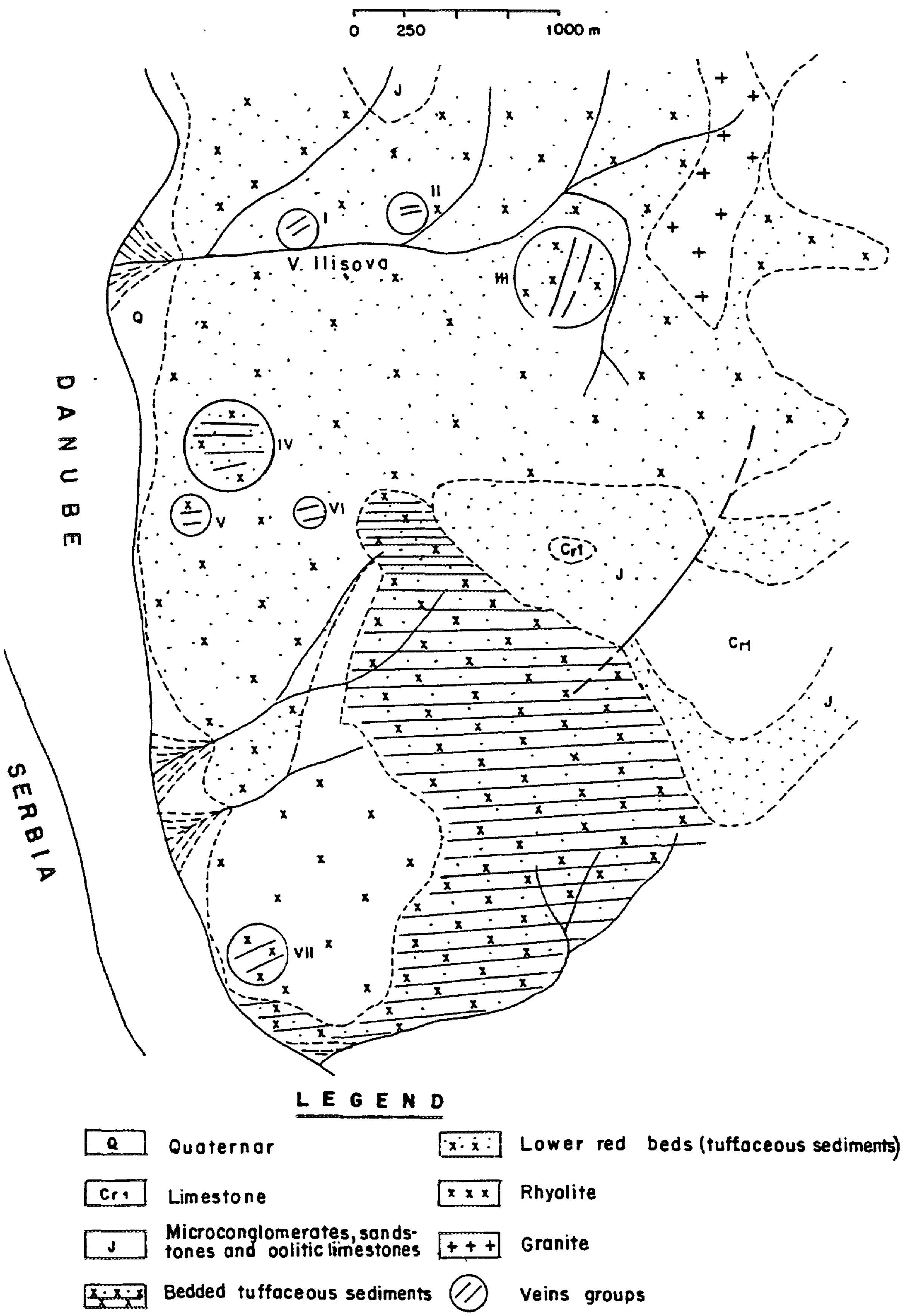


FIG. 4. Geological map of the Ilisova area.

are in a reduced proportion. Within the contact zone of the granitic body with metamorphic formations a large halo of hornfels develops.

The mineralization of the Paiuseni type, represented by pechblende and chalcopyrite impregnations is usually located at the leval of the gray quartzite, which are adjacent to the fractures within the inferior complex of the Paiuseni metamorphic series. The mentioned metamorphic complex, petrographically is composed by chlorito-sericite schists, quartzo-felspathic schists quartzites, basic and acidic metatuffs. These weakly metamorphosed formations are influenced by an older disjunctive tectonics and a newer one N-S oriented, which allowed the access of the mineralization solutions. At the level of the grey quartzite, the uranium mineralization is accompanied by the products of some intense albitization, carbonatation, sericitization and chloritization processes. In both zones, the uranium mineralization as well as associated metal sulphides is considered hydrothermal. Taking in place of these mineralizations appear to be in the Laramian phase of the Alpine orogenesis.

At Mehadia, the uraniferous mineralization represented by pechblende and parapechblende, accompanied by metal sulphides of Cu and Zn, is also controlled by N-S oriented, fracture systems with dips between 55-60° towards east. On these fractures (Fig. 3) located at the metamorphic contact of the Corbu series with the granites and the Permian sedimentary formations one can recognize the effects of some hydrothermal solutions which generated intense processes of chloritization, sericitization and silicification.

The uraniferous mineralization transported by these solutions was deposited in the support fissures of the main faults or in the cataclazation and breccification areas which were more developed within these faults. In all researched cases the primary uranium mineralization is represented by pechblende in the form of spherolites which offer incorporate corroded pyrite grains, or veinlets near the metallic sulphures. The secondary uranium minerals formed by pechblende alteration is the autunite, which forms crusts or flaky aggregates of yellowish colour. The Corbu metamorphite series, in which are located the uranium mineralization, belong to the green schists facies and are petrographically made up of chlorito-sericitic schists, compact phyllite and quartzite with graphite. The Permian sedimentary formations overlying discordantly those metamorphites, and they develop, vertically as two overlapping beds; lower conglomeratic and upper argillaceus sandstone beds.

In the southern area at Ilisova (Fig. 4) a hydrothermal uranium mineralization is located in the E-W oriented fracture systems, which are situated in the lower Permian red beds and in quartziferous rhyolite. The fault systems which host the uranium mineralization aggregates, forming several vein fields (Fig. 4). Within these veins the primary uranium mineral is pechblende, placed in the vein filling as ribbons 3-5 cm thick, veinlets and pockets, in which the mineral has a reniform or colomorph aspect. In all cases the uranium mineralization is associated with finegrained pyrite, disseminated or placed in pockets. Sporadically also appear metal sulphides of Cu, Pb, Bi or Zn. Among the secondary uranium minerals one can recognize the autunite and the zippeite. The vein filling which also represents the gangue of this mineralization is made up of clayey minerals, carbonates and quartz. In the fracture systems, the mineralized areas appear as an elongated lens, which can be over a 100 m and have a thickness of 0.8-1.0 m. The lower red beds, which host prevalent these mineralizations, lithological is composed by microconglomerate, red sandstone with calcareus concretions and several interlayers of red or grey rhyolite flows.

In the upper stratigraphical position the stratified pyroclastite level is made up of a thick pile of volcanic tuffs and breccias. The pyroclastite rocks bed also include levels (flows) from the quartziferous red, grey or violet rhyolites.

In conclusion, it was mentioned that, in the western part of Romania besides of known uranium deposits of the sandstone type in exploitation, a new metallogenetical area has been discovered in which the hydrothermal uranium presents vein forms. The mineralized veins are intragranitic, in genetical relationships with the Highis granite in Highis-Drocea massif, and perigranitic in the metasediments and pyroclastic rocks in other zones.

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THE STRAŽ BLOCK ISL PROJECT — CASE HISTORY

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Abstract

The ISL project on the Stráž deposit, located about 90 km north of Prague, the capital of the Czech Republic, is the only commercial in situ leaching plant, that has been operated in the Czech Republic. The facility began its first industrial production at the end of 1969, some 5 years after the discovery of the sandstone-hosted uranium deposits in the northern part of the Bohemian Cretaceous basin. The orebodies lie 180 to 280 m below the surface, depending on its configuration. The orebodies are situated in the lower part of Cenomanian sediments — in brackish sediments, and especially in marine sandstones. At present, the leaching fields have the area of about 650 ha (6.5 km^2). Some of these fields were closed, wells decommissioned and surface is being reclaimed. Because of the technological properties of uranium ores and host rocks, the leaching is very slow. Therefore some leaching fields have been in production for more than 25 years and they still produce industrial amounts of uranium. The plants were constructed for the capacity of 30 to 40 m^3/minute (400 to 650 litres per second). The highest annual production was more than 800 tonnes. The total amount of produced uranium was 15 000 tonnes between 1968 and 1994.

1 INTRODUCTION

The Stráž in situ uranium mine is located in the northbohemian part of the Bohemian Cretaceous Basin. These uranium ore deposits were discovered in the early 1960s. The exploration has focussed on the most promising part, the Stráž block.

There are eight deposits situated in the Stráž block — the Krizany, Brevnište, Hamr, Osecna-Kotel, Holicky, Stráž, Mimon and Hvezdov deposits. The Hamr and Stráž deposits are the biggest in the area with about 50% of all resources.

The exploitation development began in the second half of the 1960s. The newly discovered deposits were considered the most prospective uranium source in former Czechoslovakia, and they should have replaced the production from classical deep-mined deposits, such as Pribram, Rozna, Zadni Chodov etc.

Because of a false strategy in uranium production development (classical deep mine next to ISL fields) and other external influences, the uranium production is becoming more expensive and declining in this newest production area in the Czech Republic.

2. GEOLOGY

The Stráž block is a geological unit, bordered by faults. The north-eastern border is created by the Lusatian fault, which separates it from crystalline rocks of the Jested mountains complex of lower Paleosoic and upper Proterozoic age. The south-eastern border is formed by a belt of Tertiary volcanic dykes called "Devil's Walls". The Cretaceous sedimentation is changing its facial development in this direction. The Stráž fault creates the north-western border of the Stráž block and separates it from the sunken Tlustec block lying in the north-west. The last, south-western border is created by complicated south-eastern continuation of the Česka Lipa fault zone. Geological conditions of Cretaceous sedimentation do not change into this direction.

The deposits in the area of the Stráž block belong to the sandstone-tabular type uranium deposits. They are hosted in the basal part of the Upper Cretaceous sedimentary complex. It is overlying crystalline rocks of Proterozoic and Lower Paleozoic age with some depressions in their paleorelief filled by Carboniferous and Permian sediments.

This Cretaceous sedimentation began with fluvial, fluvio-lacustrine and other fresh water sediments of lower Cenomanian. This sedimentation continued in "wash-out" horizon, which lies between the freshwater and marine sediments. Marine sediments of the upper Cenomanian consists of two main parts — the lower one is called friable sandstones and the upper one fucoid sandstones. Ore is associated with freshwater, mostly argillaceous sediments and especially with the lower part of cenomanian marine sandy sediments. The whole thickness of the orebodies sometimes exceeds more than 10 metres, however, the average is about 6–8 m. The depth of deposits is given by their position in the Stráž block — from about 130 metres in the north-eastern part to about 250 metres in the south-western part. The whole area is influenced by saxon tectonics and Tertiary volcanism.

2.1. The Stráž deposit

2.1.1. Lithostratigraphy

Proterozoic

The complex of Proterozoic rocks is developed in the nortwestern part of the deposit. It is formed by grey sericitic phyllites and granitoids.

Paleozoic

Paleozoic rocks on the deposit are formed by sediments of Ordovician, Silurian, Devonian and Permo-Carboniferous. Ordovician rocks are formed by quartzy phyllites (with content of quartz higher than 50%) and sericitic quartzites. Silurian rocks are formed by so called "variegated series" — graphitic phyllites, sericitic-chloritic phyllites, chloritic phyllites, carbonatic phyllites and quartzy phyllites. Devonian rocks are formed by sericitic phyllites with layers of slightly metamorphosed limestones. Permo-Carboniferous rocks are formed by red sandy-clayey siltstones, melaphyres and quartzy porphyries.

Mesozoic

Mesozoic sediments on the deposit are represented by upper Cretaceous.

Upper Cretaceous

Upper Cretaceous sediments belong to the Lusatian facial area and are formed by sediments of Cenomanian and Turonian. Their thickness varies between 150 m in the north-east and 270 m in the south. The whole complex of proterozoic, paleozoic and mesozoic sediments is penetrated by ultrabasic rock dykes of Tertiary age.

2.1.2. Tectonics

Platform sediments in the area are penetrated by many fissures and faults. They create four main systems: NE-SW, NW-SE, submeridional (N-S) and subequatorial (W-E).

2.1.3. The shape of orebodies

Orebodies were formed in the shape of lentils and flat flags. The shape is influenced by lithological homogeneity of rock environment:

- volume and character of reduction agent dispersion,
- thickness of horizon,
- intensity of layer oxidation and the form of redox barrier.

3. HYDROGEOLOGY

Hydrogeological relations are very complicated in the Stráž block. Two aquifers are developed in the upper cretaceous sedimentary complex. The lower cenomanian aquifer has an artesian water level and the upper Turonian aquifer has a free surface water level. Separation of these both aquifers can be defined as semiconfining bed — the aquiclude.

3.1. Cenomanian confined aquifer

This aquifer is formed by semipervious freshwater sandy siltstones and silty sandstones of lower Cenomanian and marine sandstones (friable sandstones) and silty sandstones with fucoidal texture (fucoid sandstones) of upper Cenomanian.

3.2. Middle Turonian aquifer

This aquifer is separated by lower Turonian aquiclude, which is formed by marlstones, muddy limestones and marly siltstones. It is formed by middle and upper Turonian marine sandy-marly silstones, marly sandstones and sandstones.

4. THE HISTORY OF URANIUM PRODUCTION

The Stráž block deposits were discovered by structural borehole HT-I in 1963. The Stráž deposit proper was discovered by geological — exploration borehole profile XXX063 in 1967. The history of uranium production began immediately after its discovery.

In 1967, the first leaching test field (VP-1) started its operation. It was situated on the Hamr deposit. The alcaline lixiviant (sodium carbonate) was applied during the test and it did not give sufficient results At present, we can mention, that it could not have been successful because of:

- very primitive conditions given to this test,
- low experience with this leaching technology and
- orientation on sulfuric acid leaching technology used in the Soviet Union.

Leaching test field VP-2 was drilled near the new shaft of the Hamr mine and before it started it had practically no groundwater level for its operation because of the drainage of the sunken shaft. Afterwards the decision to remove the future leaching test fields farther from the deep mine area was made.

Leaching test field VP-3 was the first one situated in the middle of the Stráž deposit. It was drilled in the form of two hexagonal cells with 16 m long side and one well in the centre. It was the first leaching test, which gave the first real uranium production from ISL technology. The first tank of concentrate was sent for its processing to the MAPE Mydlovary uranium mill on December 13,

1967. It was the real beginning of semi-commercial uranium production using of ISL. Afterwards this leaching test field was extended to 9 ha under a new name VP-4.

Leaching test field VP-5 was situated on the Hamr deposit again. It should have ensured the possibility of leaching in the freshwater low permeable sediment in the lowest part of the Cenomanian sediments. The test with strong sulfuric acid (over 200 g/l) was also executed.

The last leaching test field was also performed on the Hamr deposit and it was named VP-6. It has the area over 30 ha. Because this field was situated in the close neighbourhood of the Hamr deep mine there ware many problems in its production and it also influenced the deep mining area by acidic solutions. Many corrective actions were done but they were not sufficient enough.

In 1971, after the government's decision about future uranium production in the nortbohemian area, the fast development of ISL fields and production started in the industrial scale. The area of leaching fields increased very fast, especially after the flooding of the Hamr mine in 1972. The area increased as follows:

1970	—	9 ha
1975	—	208 ha
1980	—	305 ha
1985	—	440 ha
1990	—	600 ha
1993	—	650 ha

Cumulative production was as follows:

1970	—	50 t
1975	—	2400 t
1980	—	6300 t
1985	—	9900 t
1990	—	13300 t
1995	—	15200 t

Unfortunately this development was done without any consideration to the environment, which will influence the future restoration procedure.

7. SPECIAL TECHNOLOGICAL REGIME APPLIED DURING 1992-1994

After the government's decision in 1992, the special technological regime for ISL plants was applied. Solution circulation was decreased to the minimum to protect ISL area surroundings. It also allowed for time for the evaluation of the present situation in consideration to the future production or remediation beginning. During this period the acidity of solutions was kept on the necessary level to avoid the back precipitation of dissolved solids in the layer (orebody). During that time extensive research work was carried out and its results were summarized in the detailed report called "Analysis of ISL -III".

8. RESTORATION PROJECT

Over the years the acid solutions and leaching products has spread into a large volume of underground water and it is necessary to clean this contaminated water in the case of the end of uranium production.

The main task of the Stráž deposit restoration is to solve the ISL technology environmental impacts on the cretaceous aquifers.

Wide laboratory research, geological and geophysical exploration were carried out in the frame of this solving. New mathematical models have been developed for the evaluation of hydraulic and hydrochemical situation of the deposit and for the restoration process economical evaluation, too. This work led to the determination of starting conditions for the restoration project:

a) The contamination of the cenomanian aquifer

Volume of contaminated water:		186 mil. m^3, area 24 km^2
Main contaminants:	SO_4^{2-}:	3 792 000 t, (out of which 948 000 t free H_2SO_4)
	NH_4^+:	91 400 t
	Al:	413 000 t
	U:	1 000 t
Total amount of TDS:		4 800 000 t

b) The contamination of the turonian aquifer

Volume of contaminated water:		ca. 80 mil.m^3, area 7.5 km^2.
Main contaminants:	$SO_4 2$:	22 000 t
	NH_4^+:	1 300 t
Total amount of TDS:		ca. 25 000 t

c) risk of the dispersion of contamination to the larger area and to the higher volume of underground water,

d) risk of the next contamination of the turonian aquifer, that is the source of drinking water.

The targets of the deposit restoration are as follows:

- to decrease the contents of dissolved solids in cenomanian water gradually to the environmental limit. The research results show that the safe concentration of TDS should be about 3 $g.l^{-1}$;

- to decrease the contents of dissolved solids in turonian water gradually to the quality given by the Czech water standards. It means practically to the pre-operational baseline.

8.1. The cenomanian aquifer restoration

is planned in two steps. The first one is to achieve the hydraulic underbalance in very short time and to obtain full control on underground contaminated solution. During this step it is necessary:

- to control the ISL process not to achieve the precipitation of solids in orebody,
- to prepare the well pattern for new system of pumping and injection,
- to remove uranium from solutions all the time,
- to start the evaporation station operation (first stage of desalination plant),
- to inject the concentrate from evaporators back to the central part of deposit.

The second step is to start with the removal of solids from the underground. This period will include:

- the construction of the second stage of desalination plant (for the treatment of the Stage I products),

- the controlled pumping of solution in order to use the full capacity of treatment plant for 7-10 years,

- checking and control of changes in underground solution composition — the construction of membrane technology units and their operation.

8.2. The restoration of turonian aquifer

will be performed by combining three methods:

a) Injection of contaminated water to the hydraulic barrier;

b) Pumping of the most contaminated water to the membrane technology plant. The projected start of operation is in 1996 and capacity 2 m^3/min.

c) Discharge of low contaminated water to the river. This method will be used only during the final phase of restoration.

8.3. Desalination Plant Stage 1

In February 1994, DIAMO awarded RCCI contract to clean up the acidic solutions and to produce a pure salt product using a system of evaporators, crystallizers and recrystallizers. The system will treat 6.5 m^3/min of acid solution, recovering 5.5 m^3/min of clean water for discharge to nearby river and 1.0 m^3/min of concentrated solutions. The start of operation is assumed in April 1996. This technology will produce two main products after crystallization and recrystallization of salts from the concentrate:

1. The crystals of ammonia alum, $NH_4Al(SO_4)_2.12\ H_2O$. The assumed production will be about 250 000 t per year for the first 8-10 years of operation, it will be until 2008. The production will decline (3-5% per year) after that year.

2. The crystallization filtrate of alum (the so-called mother liquor). The assumed production will be about 250 000 m^3 per year. The composition of this solution will change very slightly in the first 10 years of operation. A moderate fall down of individual components concentration is expected during following years. Most of components from the original solution and practically all of radionuclides will be concentrated in this mother liquor.

8.4. Desalination Plant Stage II

The products of the Stage I are practically wastes if it is not further treated and it is necessary to solve their treatment into commercial products or into products, which can be safely deposited in the environment.

The large research programme for solving the problem connected with the underground water desalination is realized in DIAMO at present. The first results show the possible ways for the Stage I products treatment

There are three technologies (or their combination) for decomposition of ammonia alum:

1. The calcination of ammonium aluminum sulfate to Al_2O_3 in one or two steps, to produce $Al_2(SO_4)_3$ at first and Al_2O_3 afterwards.

2. Hydrolytic decomposition of ammonium aluminum sulfate to ammonium alunit $NH_4Al_3(OH)_6(SO_4)_2$ and the calcination of ammonium alunit to Al_2O_3.

3. The decomposition of ammonium aluminum sulfate by means of ammonia under atmospheric conditions with production of $Al(OH)_3$ and calcination to Al_2O_3 afterwards.

The possible commercial products of these technologies are:

- Al_2O_3, about 30 000 t per year, or
- $Al_2(SO_4)_3$, about 100 000 t per year, and
- H_2SO_4 (produced from pyrolytic gases), 100–150 000 t per year.

The treatment of concentrate has to have the main goal to minimize the amount of solid wastes for their deposition. The possible solving is in 3 or 4 stages thickening with crystallization and separation of solids. The solid wastes will be solidified or vitrified before deposition. The liquid rest will be dried and solids will be calcinated afterwards. Gases from thermal processes can be used for sulfuric acid production.

The projected start for Desalination Plant Stage II operation will be in 2000.

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SHORT GEOLOGICAL DESCRIPTION OF THE INKAI URANIUM DEPOSIT IN SOUTH KAZAKSTAN

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Abstract

The Inkai deposit is located in the territory of the Suzakski region of South Kazakhstan, at 160 km from the railroad station Kzyl-Orda, at the south-western part of Chu-Saryssu uranium ore province. The Chu-Saryssuiskaya depression presents an artesian basin which was formed by water-bearing complexes of upper chalk and of Paleocene-Eocene. During the neotectonic stage of the later Oligocene-Quaternary period, the artesian basin was developed mainly in infiltration regime, this fact led to comprehensive developing of stratum oxidation zones, the boundaries of which are forming regional fronts systems in ore-enclosing complexes horizons. Industrial uranium mineralization is linked with boundaries of stratum oxidation zones in water-bearing horizons (from lower Turonian to middle Eocene ones). The most significant industrial objectives are: in Paleocene sediments — deposits: Uvanas, Kanzhugan, Moinkum; in chalk sediments — Mynkuduk, Zhalpak and the deposit discovered in recent years — Inkai.

1. GEOLOGICAL FEATURES OF THE DEPOSIT

Inkai is the largest deposit among the discovered uranium objectives of the province of Chu-Saryssuiskaya. Ore-enclosing rocks at the deposit are represented by small-average grade sands and gravel-shingle sediments of Mynkudukski (K_2t_1) and Inkudukski (K_2t_2-st) horizons.

The main feature of pinching out of stratum oxidation zone in ore-enclosing horizons is its developing layer by layer which is controlled by faced-geochemical conditions that, in their turn, determine the stage structure of the mineralization.

On the map, ore deposits have the form of long bands stretching for tenth kilometers. In the cross-section ore deposits have the form of rolls with different combinations of upper, lower wings and of "bag" part.

2. STRATIGRAPHY

In the vertical section of the deposit region one can choose the following:

1) Folded basement formed by dislocated Proterozoic and early Paleozoic formations;

2) Intermediate structural stage formed by lithified sedimentary rocks of middle and upper Paleozoic;

3) Platform blanket represented by Mesozoic-Cenozoic rocks involved industrial uranium mineralization.

3. URANIUM MINERALIZATION

The main ore-controlling factor at the deposit is connection of mineralization with the boundaries of stratum oxidation regional zones.

3.1. Lithological facied and geochemical description of ore-bearing horizons

Ore-bearing horizons are Mynkudukski (K_2t_1) and Inkuduksku (K_2t_2-st) ones. Mynkudukski horizons represent the alluvial cycle of the first turn where one can choose several elementary cycles with thicknesses from 1-2 metres to several metres, each of these cycles is beginning with rather hard-grade rocks and finishing with fine-grade ones. Accumulation of Inkudukski horizon rocks occurred under the condition of tectonic movement that led to the renewing of surface relief. The rocks are mainly large and hard fragmental weakly sorbed sediments, often move in the section.

3.2. Morphological types of ore deposits

Ore deposits move to the stratum oxidation zone boundary pinching out spatially and morphologically. Each of the deposits is located within one ore-bearing horizon. Deposits consist of main roll with strongly marked bag parts and wings and there are also comprehensive developed links of bag-wing elements of the orebody, the thickness of which is approaching 20-25 metres.

3.3. Substantial composition of ores

Inkai deposit uranium mineralization is developed in all lithological differences of later chalk rocks. Macroscopically mineralized sediments do not differ from barren ones. Uranium mineralization is represented by nasturan (82%) and coffinite (18%).

3.4. Description of ore-controlling epigenetic zonality

The stratum oxidation zone is divided into the subzone of completed oxidation and the subzone of inside-stratified oxidation.

The recovery zone is contiguous with stratum oxidated rocks and represents a chemical barrier, uranium and other accompanying elements are being accumulated on which. The zone of unaltered rocks does not differ visually from unoxidated ore rocks and is characterized by usual mineral composition and by natural grey and grey-green colours.

4. GENESIS OF THE DEPOSIT

The Inkai uranium deposit is referred to the group of deposits of exogeneous genesis. Its ores are spatially and genetically linked with the boundary of oxidated and recovered friable water-permeable rocks.

Large scales of ore formations are stipulated by significant thickness, high permeability of ore enclosing horizons, firmness of composition. Accumulation of uranium at the recovering barrier has occurred in many stages during a long time.

THE EXPLORATION OF URANIUM DEPOSITS OF UKRAINE BY THE ISL METHOD

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Abstract

The geological and hydrogeological conditions of uranium deposits within the Tertiary coal-clay-sand sediments in the paleodepressions of the Ukrainian shield have been investigated for mining by ISL method. All of the natural indexes for determining the efficiency of using ISL technology are appraised. All deposits of this type can be divided into three groups.

The region of the Ukrainian shield is one of the largest uranium provinces of the world. The main prospected uranium resources are represented by deposits in albitites within early Proterozoic crystal basement. In addition, significant uranium resources are concentrated in middle- and small-sized deposits of low-grade uranium ores in Tertiary rocks of sediment cover (Devladovsky type), as well as in zones of fissured crushed granite-gneisses (Michailovsky type). These two types can be exploited by ISL method because of low quality of ores and very difficult hydro-geological and technical conditions for conventional mining.

The deposits of Devladovsky type are located in depressions in the crystalline basement (i.e. paleochannels and paleovalleys) at a depth of to 80–100 metre (m). The relief of basement surface is eroded and characterized by old (Tertiary) river valleys. These valleys comprise about 80% of the territory of the Ukrainian shield. The paleodepressions are of erosional-tectonic origin. Their areal distribution is controlled by tectonics and petrographical structure of the crystalline rocks. As a rule, modern river systems commonly inherit paleodepressions. All of the known uranium deposits are located on slopes of modern plateaus near watersheds of the second and third orders.

The uranium deposits are located in productive water-bearing horizons formed by alternating of sedimentary coal bearing rocks which have very different lithological and grain-size characteristics. The productive horizons, with a thickness of 1–2 m to 20–30 m is bouded above and below by impermeable rock units. The lower impermeable unit is a Mesozoic weathering crust of the crystalling rocks. The overlying waterproof consists of Paleogene clays and rocks of mixed lithologic (sand-coal-clay) structure). The thickness of counting units within the limits of deposits changes from 1 m to 10–12 m. The position of ore bodies and their morphology are controlled by development of zones of ground-bedd oxidation of the sedimentary rocks (Fig. 4).

The ore bodies extend in plan along the paleochannel or alongside the paleodepression. The width of the zones range from 50–14 m. thickness. The producting ore bearing zone, as a rule, ranges from one sixth to one third of the mineralized zone. The average uranium content in the ore intersections average is 0.015–0.03%.

Four main lithological-mineralogical types of uranium ores are identified in these deposits:

1. Sand is the main type.
   It is represented by quartz, sometimes quartz-glauconite and quartz-feldspar-glauconite minerals. The sands include coaly and clay particles.

2. Clays.
   This mineral is predominantly of kaolonite structure. It contains a significant quantity of coaly material.

3. Ores of mixed coaly-clay-sand structure.

4. Brown coals.
   They occur as thin beds interbedded between rocks and ores of other types. The Coal consists of coalified organic material with impurities of sand and clayey material.

All uranium deposits of the Devladovsky type contain little carbonate material but a large quantity of coaly material. They can be leached using sulfuric acid solutions (1-1.5%).

The geological structure and hydro-geological conditions of the Devladovsky type deposits are very uniform. They defined by the following characteristics:

- two-layer structure of rocks section;

- absorption of uranium ores on Tertiary coaly sediments with different grain-size structure; their distribution is controlled by paleovalleys and paleochannels eroded in crystalline basement;

- supply of the productive horizon by atmospheric oxygen-bearing precipitations forming uranium bodies;

- position of low-grade uranium ores in endocontact of zone of ground-bed oxidation (i.e. roll front) in permeable sedimentary rocks within the limits of productive horizon bordered by impermeable rock units;

- single layer distribution of ores in section in the form of ribbon showed zones of significant sizes with a depth of up to 100 m from the present surface;

- uniform lithological types and structures of ores, composition of cement and contents of admixtures in ores (coaly material, sulphides, carbonates).

At present 12 uranium deposits and prospective occurencies have been identified. Two of them have been completely and successfully mined out using by ISL method (Devladovskoye and Bratskoye). The uranium resources of these deposits have been concelled from the national inventory. Within the third deposit (Safonovskoye), only one ore body was cancelled.

The investigation of the deposits is conducted using standard methods and techniques. It is done in the following manner:

- drilling on a network of 200–100 m × 100–50 m;
- core testing. for geotechnological evaluation researches;
- gamma and electric logging of wells;
- evaluation of required solution quantity in hydro-geological and geotechnological wells;
- experimental filtration activities in hydro-geological wells.

With reference to uranium recovery by ISL method based on a majority of natural factors uranium deposits of Ukraine are rather similar. However, a series of factors is present and deposits are distinguished as follows:

1. geological structure;
2. amout of uranium resources determined by the areal sizes of ore bodies;
3. grain-size of ores and country rocks including the quantity of clay and coaly material;
4. relationship between permeability of uranium bearing rocks and country rocks;
5. vertical filtration heterogeneity of the productive horizon;
6. regime of underground waters;

7. chemistry and quality of underground waters;
8. geo-engineering conditions.

Uranium deposits of Devladovsky type are controlled by two characteristics of one geological structure: paleovalley. One is the slope of the paleovalley and the other one is paleochannels. The ore bodies are classified as middle- and small-sized. Most of the deposits are conturn uranium resources of between 1000 5000 t U.

The main distinctive features of uranium deposits of the Devladovsky type are the very high variability of grain-size and the quantity of coaly material in ores and country rocks. The characteristic feature of all uranium deposits of the Devladovsky type is the high permeability of ores in comparison with permeability of country rocks. According to this attribute all deposits can be divided into two groups. For one group this parameter is less than 2.0; for the other group it is more than 2.0. The first group of deposits is more suitable for uranium extraction by the ISL method.

Based on comparison of all identified uranium deposits of the Devladovsky type according to the natural characteristics with reference to exploitation by ISL separate them into two groups:

1. Group A contains deposits with better characteristics for ISL mining:

   - Devladovsky deposit,
   - Chervonoyarskoye deposit,
   - Safonovskoye deposit.

2. Group B contains deposits with middle-grade characteristics for ISL mining:

   - Bratskoye deposit,
   - Novoguryevskoye deposit,
   - Surskoye deposit.

During exploration and investigation of uranium deposits a series of new methodical approaches were developed:

1. The classification of uranium bearing sediments of the central part of Donets basin is developed according to grain-size and quantity of coaly material.

2. The distinctive attributes for ISL method exploitation are defined, and the deposits are divided into 2 groups.

3. The classification of sands of the productive horizon of Safonovskoye deposit is developed.

4. On the basis of results of using the ISL method in the limits of three deposits the significance of vertical filtration heterogeneity of productive ore-bearing horizon (Figs 9 and 10) is appreciated.

5. We have made the lithological-technological typification of uranium ores for the first time. Four types and four subtypes are allocated (Figs 11 and 12).

6. For prognostic determination of the ISL method efficiency in the limits of uranium deposits of the Devladovsky type we have also developed the principles of determination of ore quality and the principles of geotechnological dividing of deposits into districts (ore bodies, blocks), based on analysis of such attributes as:

a) uranium content of the horizon;
b) share of the first grade ore in section of the productive horizon;

c) linear ore-bearing factor (ratio of ore thickness to total thickness of productive water-bearing horizon);
d) adducted uranium contents;
e) geochemical condition;
f) permeability of productive horizon;
g) availability of subbalance ores in productive horizon;
h) nature of vertical filtration heterogeneity of productive horizon.

RADIOMETRIC MAP OF THE CZECH REPUBLIC AND URANIUM MINERALIZATION

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Abstract

Intensive U exploration and radiometric mapping in the Czech Republic in past decades yielded numerous radiometric data. The whole area of the Czech Republic has been covered by airborne radiometric measurement what formed the database for the compilation of the map of the terrestrial radiation. 122 regional ground gamma ray spectrometry profiles were measured and used for the back calibration of the digitized map and its conversion into the *gamma dose rate units. The regional radioactivity of rocks of the territory is in the range 6–245 nGy.h*$^{-1}$ *and is* linked with the U mineralization of the Bohemian Massif.

1. GEOLOGY OF THE CZECH REPUBLIC

The territory of the Czech Republic, of the area of 78 863 km^2 is formed by two regional geological units. The Bohemian Massif, a part of the European Variscan system, built up by the basement of Proterozoic crystalline and Prevariscan Paleozoic rocks and the platform cover, forms the majority of the territory. The Western Carpathians, with rocks of Alpine development, occurs in its eastern part. Magmatic, sedimentary and metamorphic rocks of Proterozoic to Quaternary age with complicated structural-tectonic setting correspond to the paleographic development of the territory.

2. RADIOMETRIC MEASUREMENT OF THE CZECH REPUBLIC

Uranium exploration and radiometric mapping in the Czech Republic in past decades produced data describing the radioactivity of rocks of the whole territory and formed the base for the compilation of the radiometric map of the country.

Regional airborne gamma total count measurement of the whole former Czechoslovakia was performed by Geofyzika Brno with the analogue airborne radiometric instrument ASGM-25 fitted up with GM tubes, with flight mines separation 2 km, at the flight height of 100 m, in the period 1957–1959. The equipment was calibrated by means of a Ra-226 point source and the results of the surface rock radioactivity were expressed in units of the surface rate (μR/h). The maps of profiles [1] and contour lines [2,3] on the scale 1:200 000 and 1:500 000 were compiled.

Detailed airborne gamma total count measurements were carried out by means of airborne analogue instruments ASGM-25 and ARS-2 with scintillation counter of 1006 cm^3 NaI(Tl volume in individual regions of interest, with flight lines separation 250 m, at the flight height of 80 m, in the period 1960–1971. The instruments were calibrated by Ra-226 point source and the constructed maps of contours on scales of 1:25 000 and 1: 50 000 were expressed in exposure rate. The detailed total count measurement covered most of the territory of the Czech Republic.

Detailed airborne gamma ray spectrometry with the digital, spectrum stabilized airborne spectrometers DiGRS 3001 of 14 800 cm^3 NaI(Tl) volume, and alter GR-800D of 33 600 cm^3 NaI(Tl) volume, were used for the survey in regions of interest with flight lines separation 250 m, and at a flight height of 80 m from 1976 onward, and 50% of the area of the Czech Republic was covered. The instruments were calibrated by flights over natural calibration strips. Results are the maps of contours of gamma dose rate and K, U, Th ground concentration in rocks on scales of 1:25 000 and 1:50 000.

A car-borne total count survey with the analogue Ra-69 ratemeter fitted up with GM tubes, and with the digital scintillation DiGRS-2000 car-borne gamma ray spectrometer, was conducted in the U potential areas in the sixties. A ground gamma survey with portable total count instruments and portable gamma ray spectrometers were applied on a wide scale. Laboratory radiometric analyses of more than 7000 rock samples from the region of the Czech Republic completed information on the regional radioactivity of rocks.

Calibration facilities for the portable and airborne gamma ray spectrometers, built in the Czech Republic in 1975 [4], checked by the intercomparison measurement in 1992 [5], and the use of IAEA geological reference materials for laboratory gamma ray spectrometry, manufactured by the IAEA in 1987, were important technical means for the consistency of radiometric data.

3. COMPILATION OF THE RADIOMETRIC MAP OF THE CZECH REPUBLIC AND ITS BACK CALIBRATION

A uniform database for the compilation of the radiometric map of the Czech Republic was the map of contours of the exposure rate of regional airborne measurement of Czechoslovakia 1957–1959, carried out by means of one instrument and a uniform method within a relatively short period of time, which was completed using the detailed successive airborne and ground total count and gamma ray spectrometry measurement of the country.

With respect to the initially used (1957–1959) airborne instrument ASGM-25, detection efficiency of its GM tubes and the way of equipment calibration by means of Ra-226 point source, the resultant reported values of the exposure rate (μR/h) should be considered for relative data. The main reason is the difference in energy gamma ray spectra of Ra-266 calibration source and of rock radiation in the geometry of the field measurement, and the respective instrument count rate response [6,7]. Back calibration was applied to level the radiometric map of the Czech Republic [8].

Portable gamma ray spectrometer GS-256 of the Faculty of Science, Charles University, calibrated at the calibration facilities in Bratkovice near Pribram (Czech Republic) and in Langenlebarn (Austria), and checked by comparison measurement with the GR-256 spectrometer of the Geological Survey of Canada, calibrated in Canada, in Berlin in 1992, was used for the back calibration. A possibility to convert the ground gamma ray spectrometric data into gamma air dose rate was further verified by means of pressurized ionization chamber Reuter-Stockes, similarly as was performed in Switzerland [9]. In 1994, 79 regional profiles of a length of 1-5 km, evenly distributed over the area of the Czech Republic, situated in low, medium and highly radioactive regional rock units, were measured by portable GS-256 gamma ray spectrometer and concentrations of K, U and Th in rocks were determined (Fig. 1). In addition to that, similar data from 43 regional gamma ray spectrometry profiles, quoted in Uranium Survey reports, were used too. The data on K, U, Th concentrations were recalculated into gamma air dose rate at the height of 1 m above the earth's surface [10]. Regression analysis between the air dose rate data, determined by ground gamma ray spectrometry, and the data of the airborne map derived the multiplication correction constant 0.85 for the airborne map data (Fig. 2).

The exposure rate airborne map of contours, on the scale 1:200 000, has been converted to vector form by digitizing in the Czech Geological Survey, Prague, in 1994, and expressed by 871 652 data in regular grid 300 × 300 m over the territory. Digitized data were recalculated to gamma absorbed dose rate (nGy.h^{-1}), using the relation 1 μR/h = 8.69 nGy.h^{-1}, and the multiplication correction constant 0.85 was applied. A new terrestrial gamma dose rate map of contours of the Czech Republic, on the scale 1:500 000, was compiled by computer processing with the step of contours 10 nGy.h^{-1} in 1995. A simplified radiometric map is shown in Fig. 3 [11].

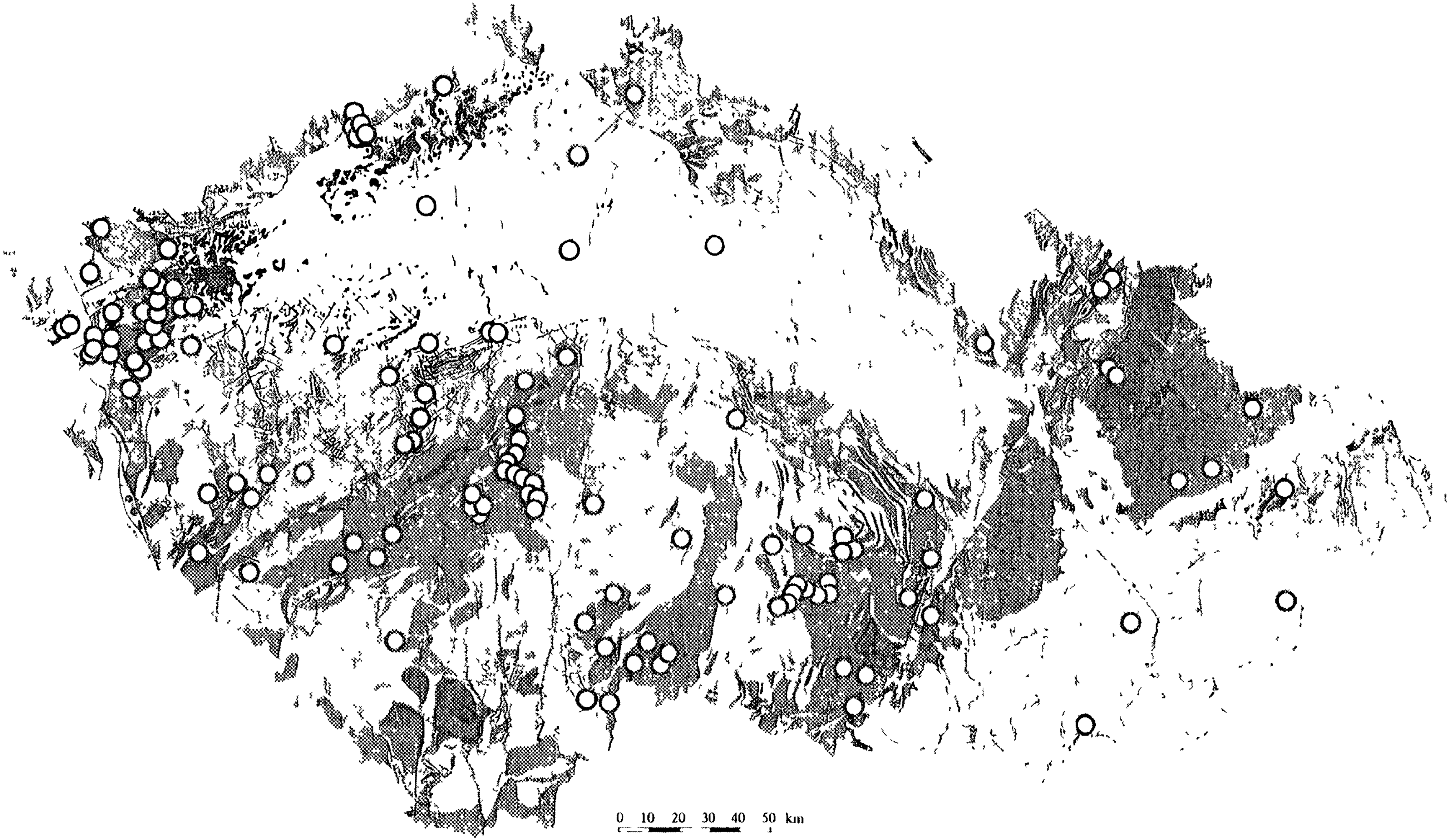

FIG. 1 Geological map of the Czech Republic and situation of regional gamma ray spectrometry traverses for the back calibration of the radiometric map.

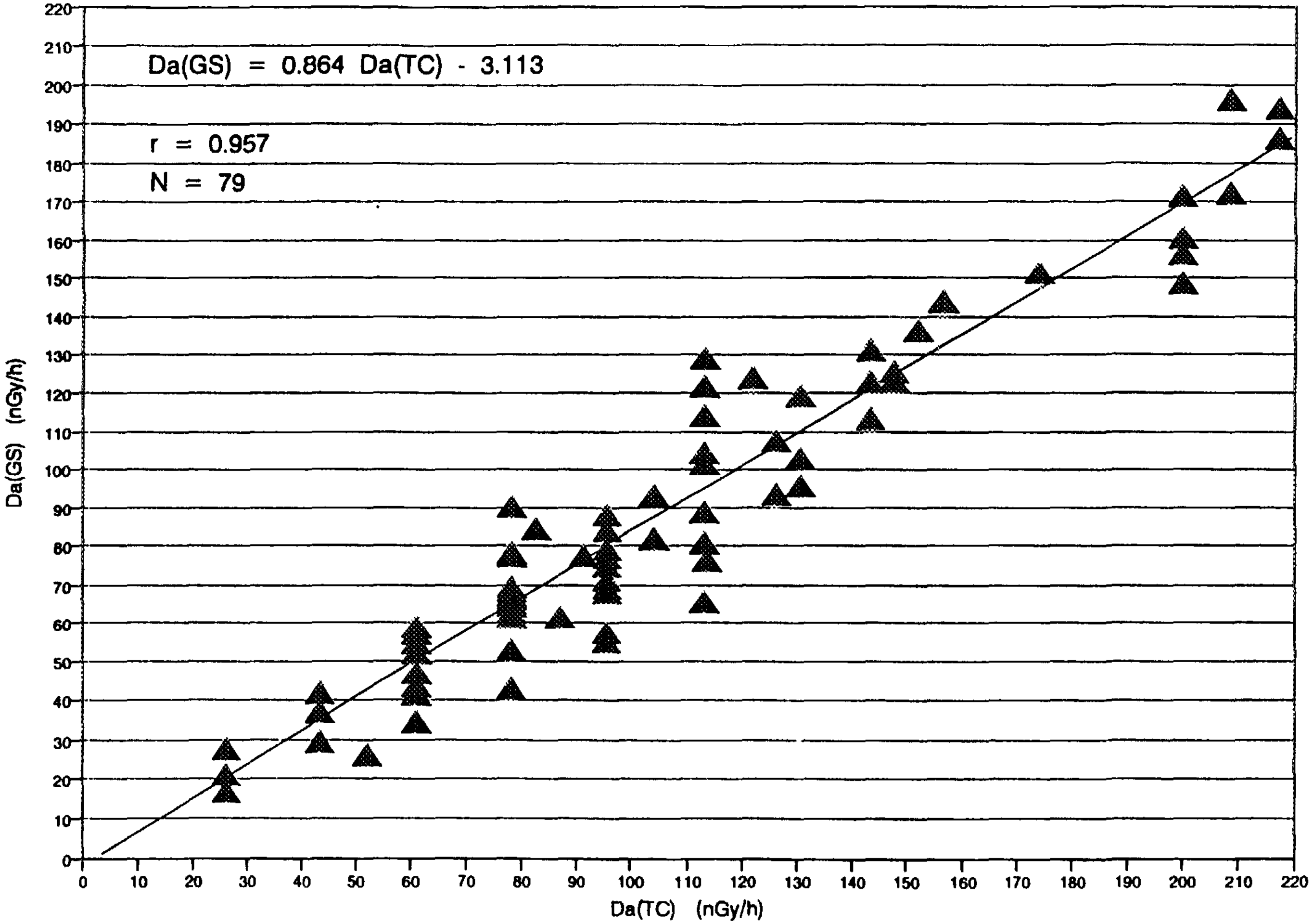

FIG. 2. Regression between gamma dose rate determined by ground gamma ray spectrometry (GS) and airborne total count (TC) measurement.

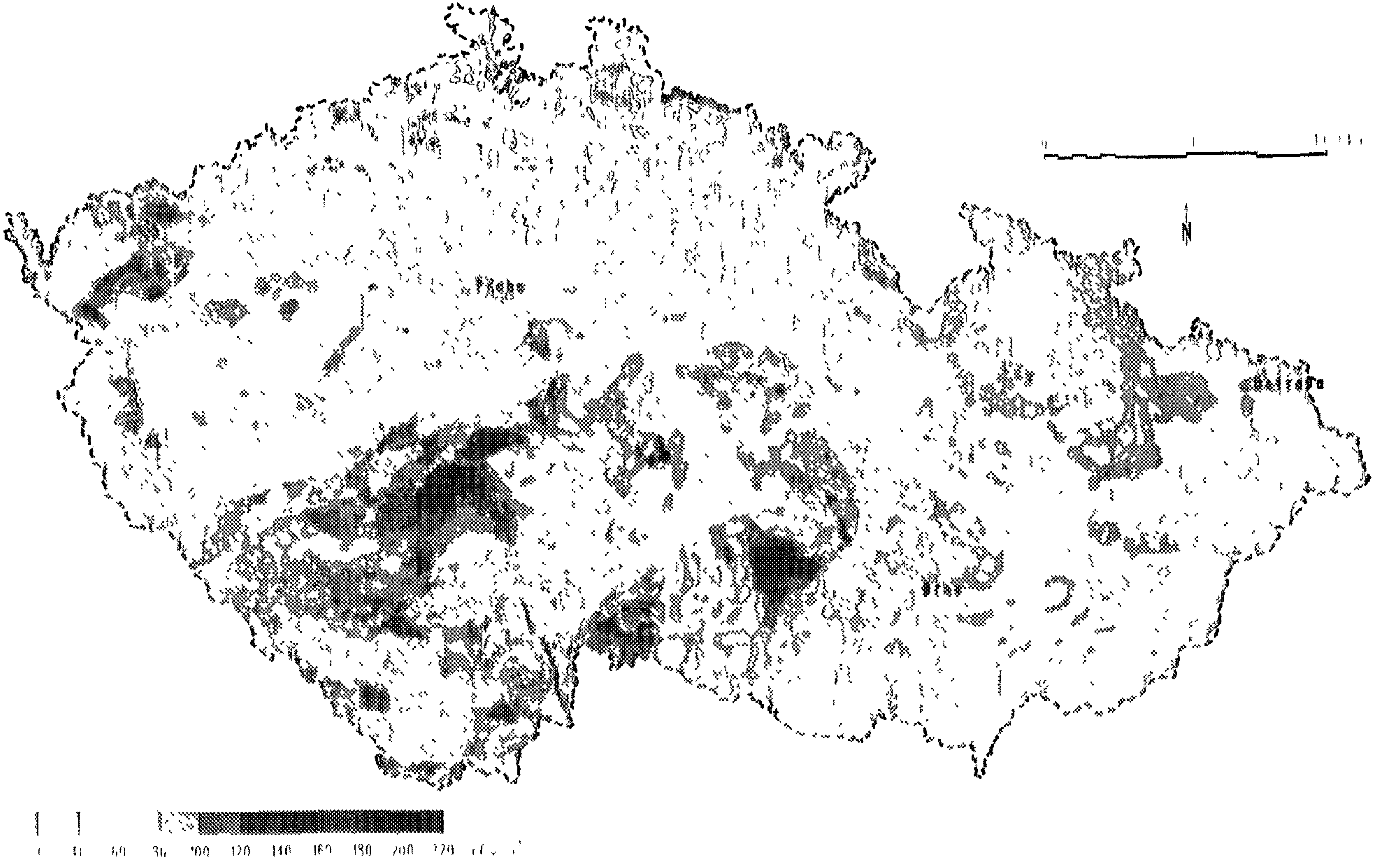

FIG. 3. *Map of terrestrial gamma dose rate of the Czech Republic.*

4. REGIONAL RADIOACTIVITY

Regional radioactivity of rocks of the area of the Czech Republic is in the range of 6–245 $nGy.h^{-1}$, with the mean 65.6 ± 19.0 $nGy.h^{-1}$. In comparison to the estimation of the global mean 55 $nGy.h^{-1}$ [12] and other collected data on the terrestrial radioactivity of various countries [13] it illustrated the above average potential of natural radioactivity elements in rocks, namely in the Bohemian Massif.

5. URANIUM MINERALIZATION AND REGIONAL RADIOACTIVITY OF ROCKS

The Variscan tectogenesis had fundamental significance for the U accumulation in the Bohemian Massif. The endogenous U mineralization corresponds to late-Variscan (265 ±15 Ma) and Kimmerian (185 ±15, 150 ±20 MA) periods, the exogenous mineralization is considered to be of Upper-Cretaceous-Miocene age. The study of spatial distribution of numerous U accumulations in the Bohemian Massif shows the general link with deep seated faults of the earth's crust and significant relation to acid Variscan plutonic bodies. Approximately 17 000 radiometric anomalies and objects of U mineralization were located by the Czechoslovak Uranium Industry in the past. They occur mostly in regions of increased regional radioactivity of magmatic and crystalline rocks. The majority of U mineral bodies was discovered in the exocontact areas of Variscan magmatites or the link with the nearby granitoids can be presumed.

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THORIUM DEPOSITS IN THE COMMONWEALTH OF INDEPENDENT STATES AND THEIR PROSPECTIVE CHARACTERISTICS

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Abstract

Since 1956, the All-Russian Research Institute of Chemical Technology has been engaged in the research of assessing thorium deposits and ore occurrences, as well as developing its production technology from various ore types. From the known CIS thorium and thorium-bearing deposits and occurrences (2500) only 241 sites have their resources estimated. They include 132 monazite placers of the Quaternary age, 6 complex Quaternary deposits of placer type (4 polarite, 1 uranium-thorianite and 1 thorium-platinum placers), 66 endogenous deposits and occurrences and 38 complex ones (including zircon-ilmenite Tertiary and older buried placers). This paper gives a summary of the author's attempt to classify thorium deposits according to their genetic types. The proposed classification scheme is based on formational principles and integrates geological-tectonic, magmatic and other criterions. The deposits which are located in igneous, metamorphic and sedimentary rocks are further observed according to their geological setting and types of mother rocks. Thorium deposits are known in the numerous metallogenetic provinces of the CIS.

1. INTRODUCTION

Large scale thorium-oriented geological explorations and surveys were conducted in the Soviet Union in 1946-1951. The accent was made on monazite Quaternary placers, since during those years as well as nowadays the main source of thorium is monazite. During that period, 132 monazite placer deposits were found and explored. In most cases they were small sediments of continental type. Genetically they vary from alluvial, proluvial, cone evacuation, beach, bar, delta and other placers.

The main regions of continental placers development are the regional fields of monazite-bearing granites — the major source of heavy accessory minerals. They are the Aldan and Ukrainian crystalline shields, the Transbaikalian, some regions of the Urals. Presently the placers have no practical significance due to the very low contents of monazite in the sands (O.n $kg.m^3$) and their small size.

Since 1951 no special exploration for thorium has been undertaken. As a rule, thorium was regarded as a useful component in complex deposits. However, the State Committee on Resources did not show any interest in its reserves. There are practically no developed commercial deposits of this metal. Up to the recent moment it has been recovered as a by-product from the ores of a few complex ore deposits. Presently, they are the loparite deposit of Lovoserskoe (the Kola Peninsula) and the uranium-phosphorus deposit of Zaosernoe (Kazakhstan).

In comparison with uranium and many rare metals, the knowledge of thorium available in the CIS territories is rather small. However, there has been some information accumulated from various sources such as:

- large-scale geological, geophysical, technological research on uranium ores with evaluation of thorium contents,
- information on contents, geochemistry, mineralogy of thorium in the complex ores of deposits bearing thorium in rare metals and rare earths;
- some topical studies on geochemistry of radioactive elements, geological formations, radio-geochemical mapping, etc.

Since 1956, the All-Russian Research Institute of Chemical Technology has been engaged in comprehensive activities directed to evaluation of the potential mineral base for thorium, determining genetic and commercial deposit types, developing processing technologies for thorium-bearing ores and recovering thorium from them.

Potential thorium regions have been determined. A one-to-ten-million scaled map has been compiled for thorium-bearing areas of the CIS. According to the metallogenic analysis of the map, there are three types of metallogenic structures:

(1) three belts of endogenic and exogenetic thorium mineralization (the Kola-Urals-North Kazakhstan, the Ukraine-South Thian Shan, the Baikal-Okhotsk coast);

(2) eight provinces (the Ukrainian, Kola, Kokchetavsk, the Yenisei-Sajany, the Sajano Tuva-Mongolian, the North Thian Shan, the North Baikal, Aldan);

(3) nine zones of endogenic and 8 basins of exogenetic accumulation of thorium.

Of the 2500 thorium and thorium-containing deposits and ore manifestations determined by us in the CIS territories, the reserves and resources have been calculated for 241 entities. They are 132 monazite Quaternary placers, 6 complex Quaternary deposits of placer type (4 loparite placers, one uranium-thorianite, one thorite-platinum), 66 endogenic deposits and manifestations and 38 complex Tertiary monazite-zircon-ilmenite and more ancient buried placers.

On the whole, the reserves evaluation was presented by authors' work.

The prognosticated reserves of thorium in the CIS are assessed to be 1 700 000 tonnes by January 1, 1995. The predominant portion (86.7%) is presented in endogenic complex, generally polymetal deposits of sometimes large and even unique size. As a rule, the thorium content in the ores rarely exceeds 0.01–0.1%. The 0.1–2% and richer ores comprise about 4.4% in the present CIS reserves balance.

Uranium deposits bearing off-grade and poor thorium ores comprise 3.1% in the reserves balance. In the complex buried placers, the thorium resources comprise 5.8%.

We suggested a formation-genetic classification for the CIS thorium deposits and ore manifestation. The general formation analysis of the deposits takes into account their genesis peculiarities. The consecutive selection of formations corresponds to the genetic sequence of the thorium accumulation processes.

The term "ore formation" means a group of deposits and ore manifestations with similar genesis possessing stable association of commercially valuable elements and major ore and ore-forming minerals. Ore formations are singled out according to their relation to geological formations. As a rule, the thorium ore formations are complex considering the set of elements.

Altogether, there have been eight ore formations singled out (see Table I). Regarding their relation to geological formations, they are subdivided into four groups. The first group comprises the alkaline and ultra-basic alkaline sodium derivatives of abyssal (subcrustal) centers. They are agpaitic nepheline-syenites, ultra-basic alkaline rocks with carbonatites and other ore metasomatites.

The second group are high-temperature metasomatic sodium and potassium formations related to alkaline syenites, alkaline and sub-alkaline granitoids and metamorphogenic rocks. The source of substance for this group is mainly crustal. They are characterized by a quartz-feldspar composition containing microcline and micas of the biotite group in potassium metasomatites and albite and alkaline amphiboles and micas — in sodium metasomatites.

TABLE I. CLASSIFICATION OF THORIUM ORE FORMATIONS

Class	Group	Ore formations	Mineral ore types	Useful elements major/secondary	Mean Th content in ore, %	Geologic-techtinic position	Geologic age	Geologic forma-tions	Commer-cial viability	Example
1	2	3	4	5/6	7	8	9	10	11	12
ENDOGENIC	I. Magma-alkaline formations of abissal origin	1. Thorium-rare earth in agpaitic nepheline-syenite and m soma-tites	1. Loparite	Ta,TR/Nb,Th,Ti Sr	0.02	In TMA zones on shield	Upper Paleozoic	Nepheli-ne-syenite agpaitic	Limited	Worked Lovoserskoe deposit
			2. Lovozerit-eudialyte	Zr,TR/Th,Sr	0.01					
			3. Pyrochlore-thorite	Ta,Th/Nb	0.1					
			4. Rinkolite-lov-chorrite	TR/Th	0.01-0.05					
		2. Thorium-rare earth-rare metal in carbona-tites and other metasoma-tites	1. Gatchettolite	Nb,Ta/Th,P,U	0.02-0.05	In TMA zones on shield and its fringes	Upper Protero-zoic-Me-sozoic	Ultra-basic al-kaline rocks with carbona-tites	Feasible with recovery as by-product	Kiey, Blosimen-skoe, Tomtor and others
			2. Thorite-bastnaesite	TR,Th/P,Ta, Nb	0.02-0.5					
			3. Titano-magneti-te-perovskite	Ti,TR/Th	0.01					
			4. Gatchettolite-baddeleyte-magnetite	Fe,Zr/Ta,Nb,Th	0.08-0.1 (to 0.2)					

1	2	3	4	5/6	7	8	9	10	11	12
ENDOGENIC	II. Metasomatic alkaline incrustal formations	3. Thorium-rare earth -uranium in pegmatoids	1. Thorite-xenotime-monazite	TR,Th/Zr,U	0.02-0.2 (to 1)	In TMA zones and protoactivation of shields	Middle Upper Proterozoic, Paleozoic	Migmatite-granite metamorphogenic and plutonogenic	Not profitable	Deposits of Kalinovskoe Losovatskoe and others
		4. Thorium-rare metal in sodium quartz-feldspar metasomatites	1. Thorium-zircon-pyrochlore 2. Zircon-thorite-columbite 3. Thorite-malacone-priorite-fergusonite 4. Thorite-phenakite-bertrandite (genth helvine)	Ta,Nb,Zr,Th/TR Ta,Nb,Zr,Th/TR TR,Th/Zr,Nb,Ta U Be/Th,TR,Zr,Zn	0.02-0.1 (to 0.7) 0.02-0.1 (to 0.4) 0.02-0.05 (to o.5) 0.02-0.3 (to 1.0)	TMA zones of early consolidation (median massives, etc)	Upper Proterozoic, Mesozoic	Alkaline and subalkaline granitoids, alkaline syenites, alkaline metamorphic complex	The most feasible formation	Deposits of Ulug-Tansek, Katuginsk, etc.
ENDOGENIC	III. Acid hydrotherm lites bound with incrustal alkaline rocks	5. Thorium-phosphorus-uranium in eusites	Thorite-fluorine-apatite-pitchblende	U,P,Th/-	0.02-0.1 (t0 0.2)	TMA zones of median massifs	Middle Paleozoic	Alkaline complex	Viability is not clear	Worked deposit of Zaosernoe
		6. Thorium-rare earth in acid hydrothermalites	1.Xenotime-thorite 2. Monazite-columbite-xenotime-thorpit 3. Brannerite-thorite-uraninite 4. Monazite-thorite-xenotime-bastnaesite 5. Thorite	TR,Th/Li TR,Th/Nb,Ta U/Th TR,Th,Pb/Zn Th/-	0.2-0.8 (to 3.0) 0.2-0.5 (to 1.0) 0.04-0.02 0.03-0.05 (to 0.5) 0.1-0 4	Blocks of TMA zones of early consolidation	Middle Paleozoic-Mesozoic	Alkaline and subalkaline granitoids, alkaline syenites, alkaline volcanogenic complex	Rather promising	Chesten, Prjamoy, Akit, Kutesai, Aktjus, Oktjabrskoe, etc.

1	2	3	4	5/6	7	8	9	10	11	12
EXOGENETIC	IV. Terrigenno-clastogenic transferred or residual ancient and modern formations	7. Thorium-rare metal-rare earth in carbonatites weathering crusts	Thorianite-thorite-columbite-bastnaesite	TR,Th/P,Nb	0.1-0.2 (to 0.4)	TMA zones of shields and their fringes	Mesozoic-Cainozoic	Weathering crusts complex of carbonatites	Single formations are viable	Deposit of Kiey, etc.
		8. Thorium-rare earth-rare metal (sometimes gold or uranium) in ancient and modern placers	1. Monazite 2. Loparite 3. Uranothorianite 4. Xenotime 5. Monazite-rutile-zircon-ilmenite 6. Gold-brannerite-monazite-uraninite	TR,Th/ - Ta,TR/Nb,Th Th,U/ - TR,Th/ - Ti,Zr/TR,Th U,Au/TR,Th	0.002-0.05 0.003 0.003-0.005 0.00n 0.002-0.005 (to 0.04) 0.02-0.03	Regions of Paleoepairogenetic movement of Earth crust swells	Middle Proterozoic-Quaternary. Modern formation of placers	Marine coastal and continental (alluvial, proluvial, etc.) placers	Viability on thorium is not clear	Formation is presented by a number of deposits

The third group of ore formations are acid high- and medium-temperature hydrothermolites related, as a rule, to geological formations of higher alkalinity. Their forms are manifested as veins, stockworks, metasomatites.

The most important feature of the third group is the thorium-rare earth mineralization character with the formation of thorium minerals.

The fourth group is represented by terrigeno-clastic (dislocated or residual) both ancient and modern formations. They include weathered crusts of kaolin, bauxite, ferroxide-clayey composition, placers of both continental and coastal marine genesis, ancient lithified sedimentary strata. The mechanism of these formation genesis is one and the same and is related to the enrichment of both residual and transported material by minerals which are resistant to physical and chemical weathering.

The groups of ore formations are combined in accordance with their relation to geological entities of various material origin as follows:

(1) the first group — from subcrustal center;

(2) the second and third groups — from the crustal material differentiated in the direction of rising alkalinity;

(3) the fourth group — originated from exogenetic sedimentary differentiation of material.

The most characteristic representatives of deposits are to be considered below.

2. DEPOSIT OF LOVOSERSK

The deposit is related to the Lovosersk massif of Hercynian agpaitic nepheline-syenite. It had developed under platformic conditions of the Baltic shield, and is situated in a thick tectonic zone deposited in the stratum of Archean rocks.

The massif is laccolithic in form. The plan area is 660 km^2. Its formation took four phases of intrusive activity. The first phase: rocks of the poikilitic nepheline-syenite complex, the second: those of the loparite-bearing differentiated complex (77% of the studied massif volume), the third: rocks of the eudialytic lujaurites, the fourth: alkaline dykes of various composition.

The deposit ores are ones from the second phase rocks. They form a stratum of rhythmically alternating beds of urtites-lujaurites-foyaites. The beds slightly dip to the massif center. The differentiation degree of the complex is very high; monomineral nepheline rocks urtites were singled out. The agpaitic coefficient of the rocks of the complex comprises 1.25.

The ore mineral is loparite. Its content throughout the ore horizons varies from 0.48 to 0.72%. The most loparite-bearing minerals are urtites, juvites, malignites. The maximal mineralization generally occurs at the lower boundary of the layers.

The thickness of the differentiated complex averages 1500 m. There have been 200 layers of rock singled out, and 30 of them contain large quantities of loparite. Eleven horizons bear commercial quantities of loparite.

The orebodies form relatively thin sills well persistent along the dip and strike. The commercial concentrations of loparite are related to rich nephelines and melanocratic rock facies. The major rock-forming minerals are feldspars, nepheline, sodalite, aegirine, arfvedsonite. The secondary are alkaline amphibole, villiaumite, apatite, ilmenite, eudialyte, murmanite, sphene, lamprophyllite, rinkolite, etc.

The ores contain 4.6–5.4% of loparite, 0.39–1.04% of thorium dioxide in loparite, 0.020–0.027% of thorium in the ores. The deposit produces loparite as a complex mineral. A technology for concomitant recovery of thorium is available.

3. DEPOSIT OF KIEY

The deposit is located in the region of the Yenisei massif belonging to the Kiey massif of ultra-basic alkaline rocks and carbonatites. The massif area of 18 km^2 is irregular in shape and in its present erosion cross section reveals a set of alkaline series rocks: ijolite-melteigites, nepheline and alkaline syenites, veined alkaline rocks. This complex of rock has well developed carbonatites.

The orebody (native ores) presents a zone of the most carbonatized rocks 2.5 km long and 300–400 m wide. It is a carbonate ore stockwork formed with feldspars (microcline), carbonates-siderite, rarely with calcite and dolomite. The ores are rare earths and enriched with thorium. Thorium are bonded by metaloparite, thorite and thorianite. The main rare earth mineral is bastnaesite. The average thorium content in the native ores is 0.043%.

The native rocks are overlain with the weathering crust of Upper Triassic and Jurassic ages. The thickness of the weathering crust is from 10–15 to 60–70 m. The weathering crust of ore carbonatitic stockwork presents certain commercial interest. Its composition is as follows: 27–30% of goethite-hydrogoethite, 34–36% of iron hydroxides mixed with clay minerals, 28–30% of ferri-halloysite, 6.0% of fluorite. There are present quartz, magnetite, microcline, apatite, zircon, perovskite, thorianite, thorite, loparite, pyrochlore, rutile, sphene, monazite, parisite, weinschenkite (churchite), etc.

The major rare earth minerals are parisite, rhabdophanite. Thorium both occurs in the rare earth minerals and forms its own minerals — thorite, thorianite.

The weathering crust contains 0.22–0.4% of thorium.

4. ULUG-TANSEK DEPOSIT

The deposit is situated in the south-eastern region of Tuva within the limits of the Sangilensk median mass. It is related to the intrusion of sub-alkaline syenites of absolute age of 260–265 million years. The massif is stock-like formed and takes up an area of 0.9 km^2. The intrusive rocks are overlain with the developed granitelike metasomatites (qualmites) of albite-quartz-microcline composition with riebekite, lithium micas and rare metal minerals.

The entire massif is a single orebody. The rare metal mineralization is presented by pyrochlore, columbite, malacon, ferri-thorite. Thorium occurs in pyrochlore, columbite, malacon and ferri-thorite, but more than 70% of the element is related to ferri-thorite, the content of which in the ores is 0.12–0.19%.

The ores are stockwork-disseminated. The highest contents of the useful components are held in zinnwaldite facies. A rich thorium mineralization is located in the central part of the massif. The average content of thorium in the massif rocks is 0.084%, in the zinnwaldite facies 0.13%.

The deposit is unique in its thorium mineralization extent.

5. NORTH BAIKALIAN ORE FIELD (DEPOSITS OF PRJAMOY, CHESTEN, AKIT)

The ore field is known to have over 50 less studied deposits and ore manifestations of thorium. The ore region is confined to the joint of the Siberia platform with its southern folded fringe. It is situated in a strong long-lived zone of tectono-magmatic activation. Sub-alkaline and alkaline granites, granosyenites, alkaline and nepheline syenites of Lower Paleozoic and Lower Mesozoic ages are developed there.

The orebodies are vein-shaped and of complicated structure containing a complex of ore and vein minerals. The ores contain quartz, microcline, fluorite, barite, carbonates. The major ore minerals are thorite, xenotime. Sometimes they form large bimineral veined bodies (Prjamoy deposit) containing a few per cents of rare earths and thorium.

The Baikal-Amur Railway passes through the southern part of the ore region, which makes it quite promising.

In conclusion, regarding thorium, the most perspective for the nearest future of the CIS countries are loparite-bearing agpaitic nepheline syenites, zirconium-thorium-phosphorus-uranium formation in eusites and carbonate metasomatites.

Later on, for a more distant future, it would be possible to involve into production the deposits of thorium-rare metals-rare earths formation in the weathering crusts of carbonatites, thorium-rare metals in quartz-feldspar (sodium) metasomatites, rare earths-thorium hydrothermolites.

The future of complex monazite placers containing thorium, situated in the CIS countries, has not been considered yet.

URANIUM RECOVERY FROM PHOSPHONITRIC SOLUTIONS

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Abstract

A new technology for uranium and rare earth recovery applied in a semi-industrial plant processing 5 m^3/h phosphoric acid has been extended to phosphonitric solution, resulting in the process of nitric acid attack of phosphate rock for complex fertilizer production. In this process uranium and rare earths are obtained at larger quantities due to the complete dissolution of elements involved. The method is based on a one cycle extraction-stripping process using as extractants: di(2-ethylhexyl) phosphate (DEPA) in mixture either with tri-n-butylphosphate (TBP) or tri-n-octylphosphine oxide (TOPO) in view of obtaining a synergic effect for U (VI). A mixer-settler extractor in four steps was used. Two stripping steps are involved for the elements mentioned. Before uranium stripping a scrubbing with urea was introduced to eliminate nitric acid extracted. Uranium was obtained as green cake (hydrated uranium tetrafluoride) which can be easily transformed in hexafluoride or converted to a diuranate. At the same time the radium is also eliminated leading to a non-radioactive fertilizer product.

1. INTRODUCTION

Uranium recovery from phosphoric acid was carried out in the USA, using a two-cycle extraction-stripping method developed by ORNL [1, 2], and applied at industrial scale in the USA, Belgium and Taiwan.

A one-cycle extraction-stripping process was successfully developed in Romania [3] and applied in a large pilot plant processing 5 m^3/h phosphoric acid. Three industrial units were built on this technology.

In the Rumanian process the uranium product is different from the one based on the ORNL method, and the result is a uranium tetrafluoride compound which can be easily transformed to uranium hexafluoride of high purity. Uranium is produced at $25/kg U.

In the Rumanian process rare earth elements (REE) are also extracted resulting in an yttrium concentrate [4].

Until now no uranium recovery process from a phosphonitric (PN) solution has been carried out except for the one described in this paper.

Worldwide there are 80–100 plants processing phosphates of sedimentary origin with an average uranium content of 0.014% U, i.e. approx. 120 t/year recoverable uranium. The rare earth element content is approx. ten times higher, i.e. 1200 t/year (sedimentary phosphates). At Kemira Oy (Finland) REEs were extracted from PN solution [5] but uranium is neglected.

In this process both uranium and REES are extracted, the last one being more important than in the case of phosphoric acid obtained by sulfuric acid attack [4]. Due to the present unfavourable uranium market, REEs recovery might be an incentive.

In the experimental work carried out in our laboratory it was established that in all cases uranium and REEs are completely dissolved in nitric acid attack of phosphate rock [6]. At the same time uranium decay products like ^{226}Ra are also dissolved.

At present, the fertilizers resulted from phosphates are radioactive. They contain up to 100 mg/kg uranium and also 20–40 pCi/g ^{226}Ra, It must be noted that natural materials (concrete, bricks etc.) have 0.7–2 pCi/g ^{226}Ra [7] or Kola fertilizer 2–4 pCi/g ^{226}Ra.

2. DESCRIPTION OF THE PROCESS

Uranium and rare earth extraction. Radium elimination. PN solutions are taken from the fertilizer plant obtained by nitric acid attack of phosphate rock. No organic matter is present in the PN solution (different from sulfuric acid attack) because only calcinated phosphates are used. This is an important simplification, and important savings are obtained.

The PN solution used for the solvent extraction process is the one resulting from the fertilizer production process after calcium nitrate separation obtained by cooling. Uranium and REEs are not affected by calcium nitrate crystallization, being left in soluble form in the PN solution. ^{226}Ra is also found dissolved in the PN solution.

Uranium is always present in hexavalent state due to HNO_2 (oxidant catalyst) existent in the PN solution which is a mixture of phosphoric and nitric acids.

After calcium nitrate separation the PN solution still has 4% solids. Therefore the PN solution must be clarified otherwise the solids hinder the extraction process. At this stage ^{226}Ra can be eliminated introducing Ba^{++} and SO_4^{2-} (as Na_2SO_4). Radium is coprecipitated 80% on $BaSO_4$ and carried in the next stage with the flocculant at the same time with solids.

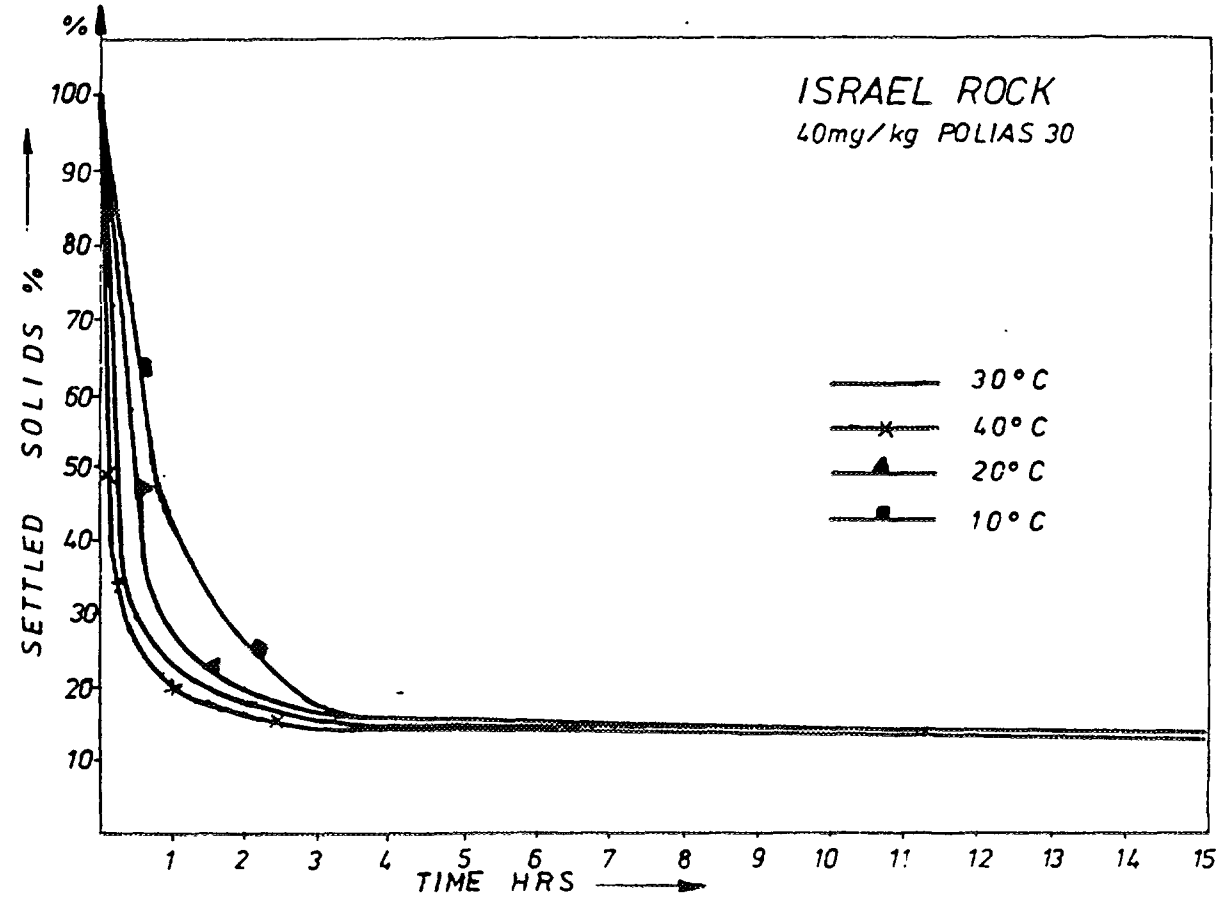

FIG. 1. Clarification process.

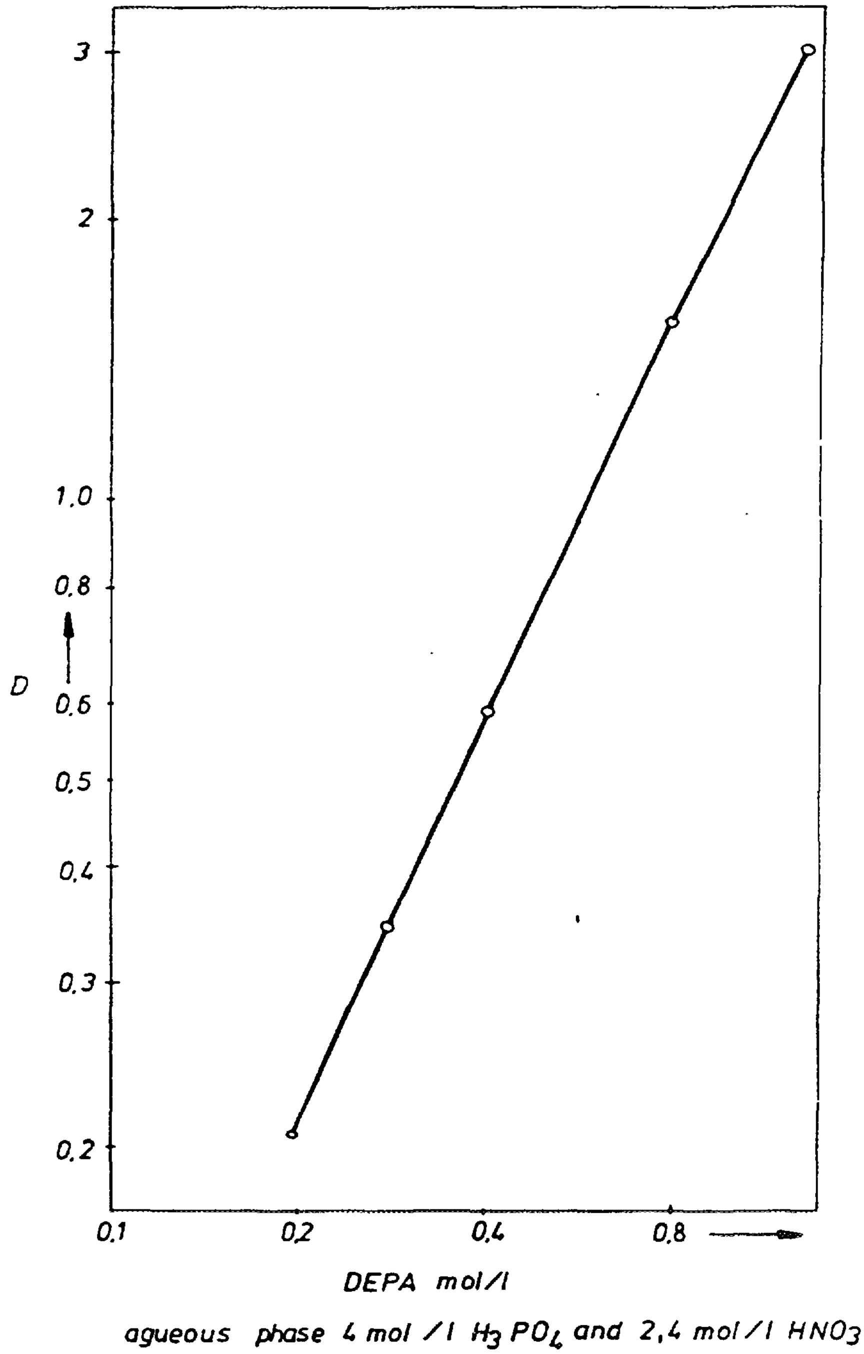

FIG. 2. Uranium extraction with DEPA.

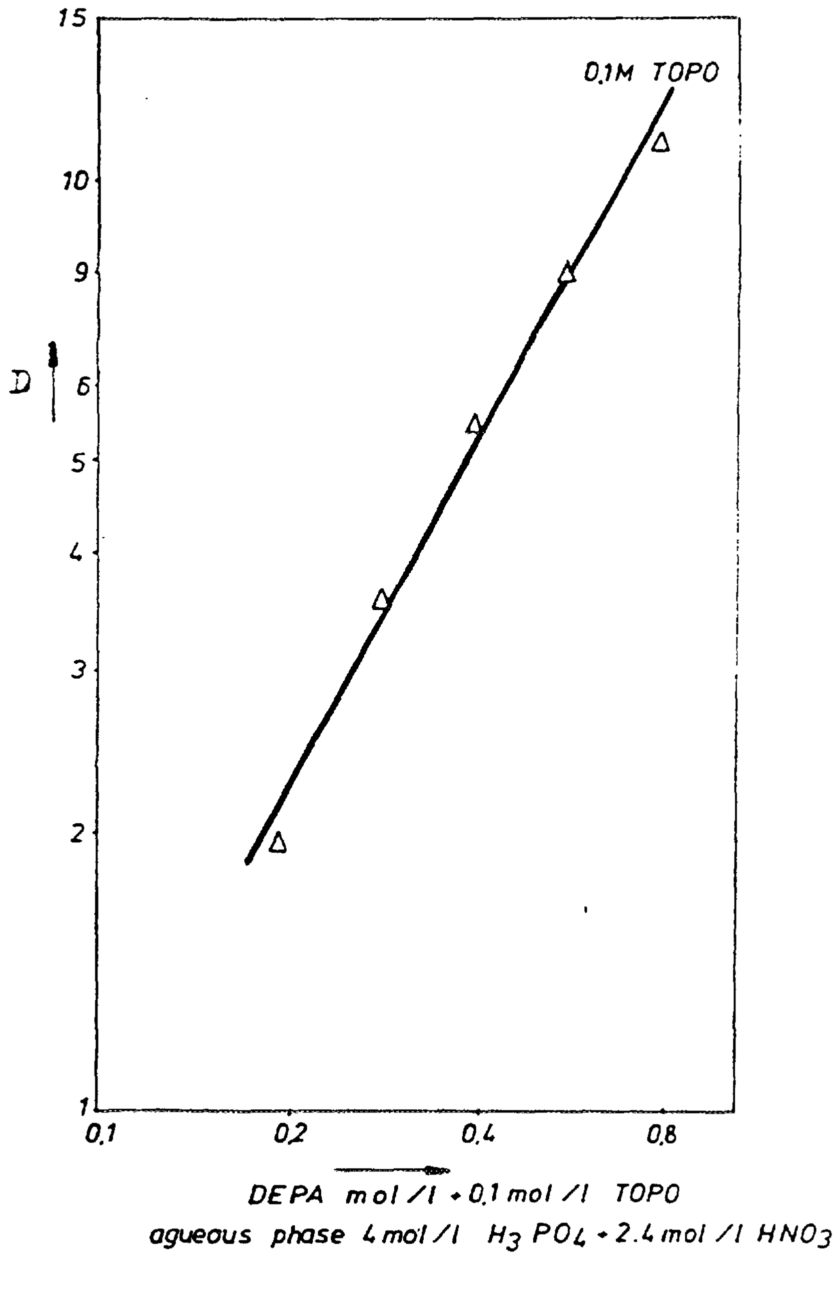

FIG. 3. Uranium extraction with DEPA+0.1 mol/TOPO

The clarification process is carried out using a polyacryl amidic flocculant efficient between 5–15°C which is usually the temperature of the PN solution after calcium nitrate separation. Best results were obtained with Polias 300 flocculant as shown in Fig. 1.

The PN clarified solution has an average uranium content dependent on phosphate rock used:

Morocco	110–140
Jordan	80–120
Israel	100–120
Florida	100–140 U/L.

The average content of REE is 1–2 g/l except Kola which has a higher content.

The typical analysis of the PN solution (mixture of phosphoric acid and nitric acid) is: 7% N, 8–9% P, Ca/P = 0.5, specific gravity 1.5 kg/dm^3, and HNO_3 approx. 10%. Due to this strong acid mixture only organophosphorus acid esters are efficient.

In the laboratory experiments several compounds as: octylpyrophosphoric acid (OPPA), nonylphenyl phosphoric acid (NPPA) and di(2-ethylhexyl) phosphoric acid (DEPA) were studied.

It was established by IR spectra, pH-metric analysis and has chromatography that OPPA and NPPA are very unstable versus hydrolysis. Therefore the only efficient and stable extractant is DEPA. It was also used in synergic mixture with TBP (tri-n-butyl phosphate) or TOPO (tri-n-octylphosphine oxide) in kerosine as diluent. The best efficiency is obtained in the presence of DEPA+TOPO selected as extractants for uranium and REE recovery. The results in this case of uranium are shown in Figs 2 and 3.

The best extractant for uranium is 0.6 mol/L DEPA + 0.1 mol/L TOPO, but for REE extraction a higher concentration of DEPA was chosen. In this case 1.2 ml/L DEPA + 0.2 mol/L TBP [8] gives acceptable results for uranium but better yields for REE extraction.

There is no synergistic effect in the case of REEs as it is with uranium as U(VI). Therefore uranium and REEs are simultaneously extracted from PN solution.

2.1. Extractant scrubbing

At the same time with U(VI) and REEs some nitric acid is also extracted from aqueous PN solution. The presence in the next stage of HNO_3 in the organic phase interferes seriously with uranium stripping. Therefore the extractant undergoes a scrubbing process when HNO_3 is eliminated. The most suitable scrubbing reagent is an urea aqueous solution which retains HNO_3 as urea nitrate (used as fertilizer). The scrubbing process takes place in a mixer and the dispersion is discharged in a separator where organic-aqueous phases separate.

2.2. REE stripping

The extractant leaving the scrubbing stage is sent to the REE stripping unit. The stripping reagent is hydrofluoric acid 15% or a mixture of ammonium fluoride and sulfuric acid. The REEs are transferred to the aqueous phase, uranium is left in the organic phase. The REEs in presence of F^- precipitate.

The stripping process takes place in a mixer and the dispersion is sent continuously in a separator where the three phases separate; the organic phase via overflow goes to uranium stripping unit, the aqueous stripping reagent is recirculated, eventually corrected. The precipitate settles and is unloaded periodically on a filter.

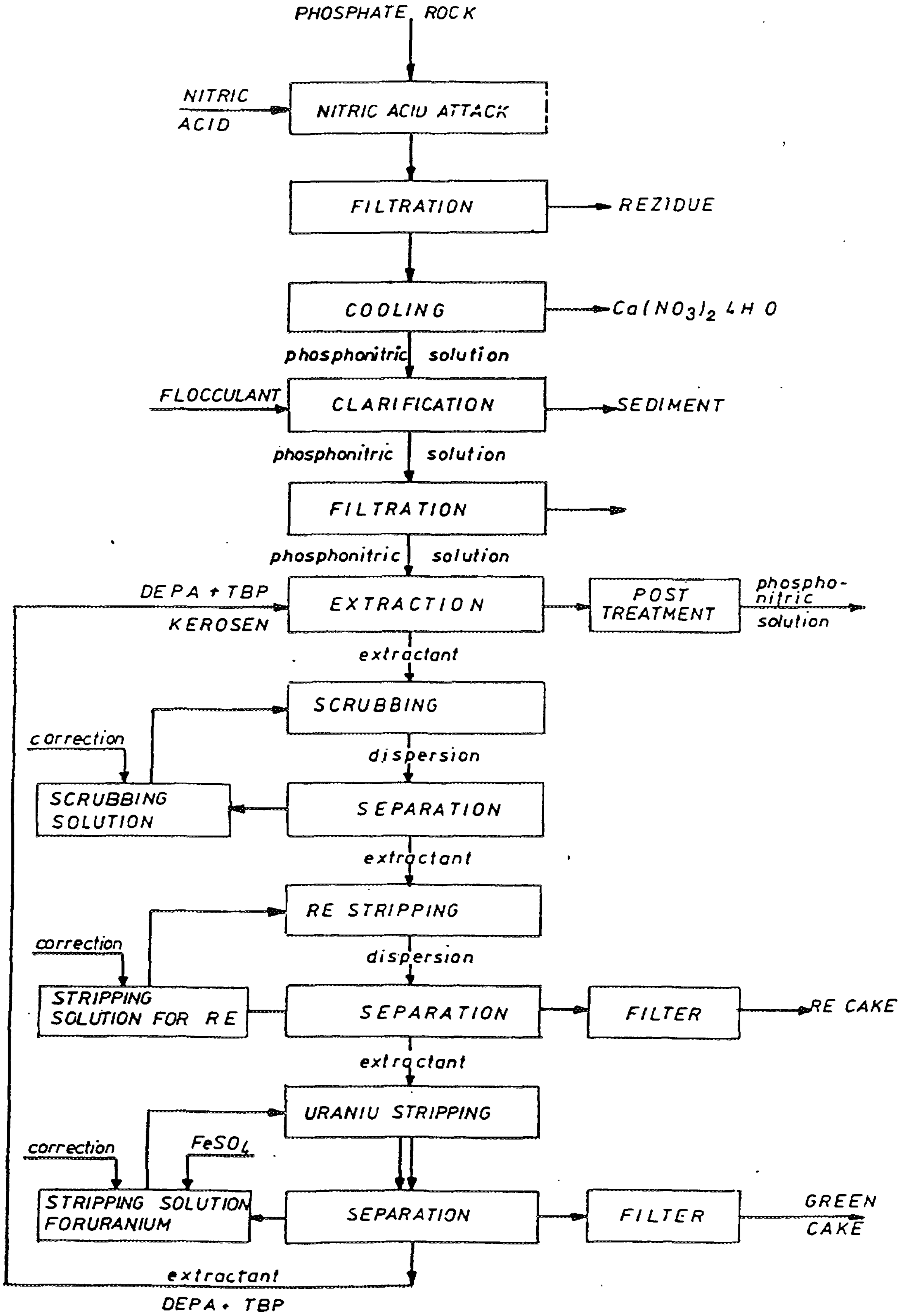

FIG. 4. Uranium and rare earth recovery from phosphonitric solution.

2.3. Uranium stripping process

The extractant leaving the REEs stripping unit is loaded with U(VI) and by gravity flow is discharged to the uranium stripping unit consisting of a similar mixer and separator. The stripping reagent is either 15% hydrofluoric acid or ammonium fluoride and sulfuric acid, in both alternatives in the presence of 3-5 g/L Fe(II). The presence of F^- acidic media and Fe(II) is a stronger reductor for U(VI) comparable with the mixture phosphoric acid and Fe(II) as used in the ORNL process. The redox potential is lower.

Uranium in hexavalent state is reduced by Fe(II) to U(IV) in the presence of strong F^- complexing medium for Fe(III).

Tetravalent uranium in the presence of HF instantly precipitates as $UF_4 \times H_2O$ or if NH_4F (strong acid medium) is used, as $(NH_4)_7U_6F_{31}$ as determined by thermogravimetric analysis.

The stripping reaction is sensitive to $HNO_3(HNO_2)$ presence therefore it must be removed from the organic phase. The scrubbing operation is important.

The dispersion from the mixer is transferred to the settler: the organic phase via overflow is recirculated to extraction battery without any further treatment bearing in mind that only acidic media is used. The stripping reagent is recirculated after separation, eventually corrected. The green precipitate separates on the bottom and is periodically unloaded on the filter where it is washed and obtained as green cake.

As in the ORNL process the oxygen form air affects the Fe(II), therefore a previous nitrogen sparging of the organic phase is required.

2.4. PN solution post-treatment

The PN solution from the extraction process settles in a separator where most of the extractant is recovered but still 50–200 mg/kg extractant is present in the aqueous phase. This must be eliminated on activated carbon. A chromatographic method capable to determine 2–4 mg/kg organic phase in PN solution was carried out. The flowsheet of the process if shown in Fig. 4.

The two products obtained are: green cake and rare earth concentrates. The uranium content of the green cake is 55-59% U and is impurified by Fe, Ca, Al, REEs. However, at 400°C, in nitrogen atmosphere, this product is transformed to UF_4, which treated with F_2, the only volatile product was UF_6. The green cake could also be transformed to a diuranate.

The REE concentrate has 30–40% REE, where both ceric and yttric elements are represented however predominating cerium and yttrium.

The fertilizer obtained after this treatment is of very low radioactivity with a uranium content of 10 mg/kg and 3-5 pCi/g ^{226}Ra. Beside uranium and rare earth recovery an incentive might be the non-radioactive fertilizer obtained.

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XA9745141

GEOLOGICAL-GENETIC CLASSIFICATION OF URANIUM DEPOSITS

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Abstract

The paper describes a system for classifying uranium deposits based on geological and genetic characteristics. The system is based on the interrelation and interdependence of uranium ore formation processes and other geological phenomena including sedimentation, magmatism and tectonics, as well as the evolution of geotectonic structures. Using these aspects, deposits are classified in three categories: endogenic — predominately hydrothermal and hydrothermal-metasomatic; exogenic — sedimentary diagenetic, biogenic sorption, and infiltrational; and polygenetic or composite types. The latter complex types includes: sedimentary/metamorphic and sedimentary/hydrothermal, where different ore generating processes have prevailed over a rock unit at different times. The 3 page classification is given in both the english and russian languages.

1. INTRODUCTION

The following scientific statements are of utmost significance for solving difficult problems of uranium metallogeny and classification of uranium deposits

(1) Interrelation and interdependence of uranium ore formation processes and other geological phenomena: sedimentation, magmatism, tectonics, etc., and the evolution of geotectonic structures. A specific role of tectonic and tectonomagmatic activation processes, orogeny and riftogenesis during formation of uranium ore zonation.

(2) Structural-petrological and system approach to the analysis of geological environments, resulting in establishment of the most objective associations between metallogenic structures and geological and tectonic bodies of the same rank and extent, i.e. geological-formational type of deposits.

(3) Effect of inhomogeneities of the Earth's crust and the upper mantle deep structure on the formation of uranium ore regions, geodynamics of tectonic and ore-generating processes.

(4) Interrelation between the processes of dispersion, mobilization and concentration of uranium and its accessories in the Earth's crust.

Taking into account the above statements, classificational categories of uranium deposits form three groups of deposits, each of them having the common petrological-energy nature of mineralization sources, specific features of localization and differing from the other ones by geological conditions of the shows of deposits. Among them are:

(1) Endogenic group of deposits of predominantly hydrothermal and hydrothermal metasomatic genesis, showing up in association with crushing and metasomatic zones in activated structures of Precambrian shields, median masses and volcano-plutonic belts.

(2) Exogenic group of deposits (sedimentary diagenetic, sorptive-biogenic, infiltrational deposits), developed in association with activated platform covers, orogenic and riftogenic troughs and depressions.

(3) Polygenetic group of composite telescoped deposits (sedimentary metamorphic, sedimentary hydrothermal, etc.), emplaced during space coincidence of various ore-generating processes

occurring at different time within single structures, for instance regional zones of structural stratigraphic unconformities, centra type structures, etc.

A complex character of deposits, in certain cases, results in indefinite and contradictory theories concerning their genesis.

Let us analyse the composition of the groups and the most important specific features of their representatives.

2. ENDOGENIC GROUP OF URANIUM DEPOSITS

Geological environments during emplacement of deposits of this group are noted for the active tectonic regime with pauses of a relative stabilization of movements. The leading types of geological ore-controlling structures are represented by crushed lithophile crustal blocks with intense shows of granitoid and alkaline magmatism within shields and median masses, or continental volcanism in the form of volcano-plutonic belts or isolated volcano-tectonic structures. Fault tectonics of different extent is typical, as well as intense metasomatic processes.

The following types of deposits are distinguished within the group (see Table I):

A. In folded areas (median masses):

- Fluorine-molybdenum-uranium in systems of linear tectonic dislocations within volcano-tectonic structures (calderas, etc.) and their basement, accompanied by extensive aureoles of hydromicaceous (argillizitic) and berisitic metasomatites in volcanites and alkaline-sodic metasomatism in the basement. Vein, stockwork, sheet-like type of orebodies. Age: Middle–Late Paleozoic, Mesozoic (130–140 Ma), less frequently Proterozoic (1500–1700 Ma).

- Uranium in beresites and eucites of crushing zones in granites, terrigenous carbonate and carbonaceous sequences:

  - phosphorus-uranium in eucites,
  - molybdenum-uranium in beresites (depending on geochemical features of emplacement of ore-bearing hydrotherms). Vein and stockwork morphological type. Age: Paleozoic (350–370, etc.).

B. Within activated shields in association with regional processes of alkaline metasomatism:

- Uranium in albitites, in zones of the Early–Middle Proterozoic activation of ancient shields. A possible subtype: titanium-uranium in apogabbroid albitites. Stockwork morphological type. Age: 1800 Ma.

- Uranium, gold-molybdenum-uranium in potassic metasomatites (gumbeites) of regional fault zones in activated shield blocks.
  Subtype: thorium-uranium in alkaline rock masses. Vein stockwork type. Age: 130–165 Ma.

- Uranium and thorium-uranium in alkaline metasomatites, syenite and alkali granitic masses, associated with activation epochs of ancient shields (Proterozoic: 1000 Ma, Mesozoic, etc.). The known deposits of this type (vein-impregnated) are characterized by a significant extent, but have low uranium contents in ores (Greenland-Ilimaussah, E. Brazil).

TABLE I. ENDOGENIC GROUP OF DEPOSITS

1. Эндогенная группа месторождений 1. Endogenic group of deposits 1.1. Гидротермальные месторождения в зонах тектоно-магматической активизации фанерозойских и докембрийских складчатых областей. 1.1. Hydrothermal deposits in zones of tectono-magmatic activation of Phanerozoic and Precambrian fold areas.		
Геолого-формационный тип месторождений Geologic-formational type of deposit	Геолого-морфологический тип месторождений Geologic-morphological type of deposit	Сопутствующее урану оруденение Mineralization, accompanying uranium
1.1.1. Урановый в аргиллизитах и полевошпатовых метасоматитах вулкано-тектонических структур. 1.1.1. Uranium in argillizite and feldspathic metasomatites in volcanogenic-tectonic structure.	Жильный, штокверковый Vein, stockwork	Mo, F
1.1.2. Урановый в березитах и эйситах зон дробления в гранитах, углеродистых и терригенно-карбонатных толщах. 1.1.2. Uranium in beresites of fracture zones in granites, carbonaceous and terrigenous-carbonate strata.	Штокверковый, жильный Vein-stockwork	Mo, P
1.1.3. Урановый в калиевых метасоматитах (гумбеитах) зон региональных разломов 1.1.3. Uranium in potash metasomatites (humbeite) in zones of regional faults	Жильный, штокверковый Vein-stockwork	Au, Mo, Th
1.1.4. Урановый в альбититах 1.1.4. Uranium in albitites	Штокверковый Stockwork	Fe
1.1.5. Урановый и торий-урановый в щелочных метасоматитах сиенитовых и щелочно-гранитовых массивов 1.1.5. Uranium and thorium-uranium in alkali metasomatites of syenite and alkali-granite massifs	Жильно-штокверковый Vein-stockwork	TR, Zr, F, Ta, Nb, Sn, Li

TABLE II. EXOGENIC GROUP OF DEPOSITS

2. Экзогенная группа месторождений. 2. Exogenic group of deposits.		
2.1. Инфильтрационные месторождения в активизированных чехлах платформ, орогенных и рифтогенных впадинах. 2.1. Infiltration deposits in activated covers of platforms, orogenic and riftogenic depressions.		
Геолого-формационный тип месторождений Geologic-formational type of deposit	Геолого-морфологический тип месторождений Geologic-morphological type of deposit	Сопутствующее урану оруденение Mineralization, accompanying uranium
2.1.1. Урановый в зонах пластового окисления в терригенных и терригенно-карбонатных толщах. 2.1.1. Uranium in zones of stratal oxidation in terrigenous rock bodies.	Стратиформный, ролловый Stratiform, roll-type	Mo, Se, Re, V, Sc
2.1.2. Урановый в зонах пластового и грунтового окисления в угленосных толщах. 2.1.2. Uranium in zones of stratal and soil (ground) oxidation of coal-bearing strata.	Стратиформный, ролловый Stratiform, roll-type	Se, Mo, Re, Ge, Ag
2.1.3. Урановый в зонах пластового и грунтового окисления в песчано-глинистых толщах палеодолин. 2.1.3. Uranium in zones of stratal and soil oxidation of sandy-clayer strata of paleovalleys.	Стратиформный Stratiform	Se, Mo, Sc
2.1.4. Битумно-урановый в зонах восстановления терригенно-карбонатных толщ. 2.1.4. Bitumen-uranium in zones of reduction of terrigenous-carbonate strata.	Стратиформный, в том числе ролловый Stratiform, roll-type	Se, V, Mo
2.2. Син-диагенетические месторождения в чехлах платформ и орогенных впадин. 2.2. Syn-diagenetic deposits in covers of platforms and orogenic depressions.		
2.2.1. Урановый в морских сульфидоносных глинах с костным детритом. 2.2.1. Uranium in marine sulphide-bearing clays with bone detritus.	Стратиформный Stratiform	TR, P
2.2.2. Урановый в континентальных пестроцветных терригенных толщах. 2.2.2. Uranium in continental variegated terrigenous strata.	Стратиформный Stratiform	Se, P
2.2.3. Ураноносный в фосфоритах. 2.2.3. Uraniferous in phosphorites.	Стратиформный Stratiform	P
2.2.4. Ураноносный в торфяниках, лигнитах, карстах. 2.2.4. Uraniferous in peat bogs, lignites, karst.	Стратиформный, гнездовой Stratiform	

TABLE III. POLYGENIC GROUP OF DEPOSITS

3. Полигенная группа месторождений 3. Polygenic group of deposits		
Геолого-формационный тип месторождений Geologic-formational type of deposit	Геолого-морфологический тип месторождений Geologic-morphological type of deposit	Сопутствующее урану оруденение Mineralization, accompanying uranium
3.1. Урановый в конгломератах докембрийских впадин 3.1. Uranium in conglomerates	Стратиформный Stratiform	Au, Th
3.2. Урановый в докембрийских песчаниках и доломитах 3.2. Uranium in precambrian sandstones and dolomites	Жильно-штокверковый, стратиформный Vein-stockwork, stratiform	Cu, Co, Au
3.3. Урановый в углеродисто-кремнистых сланцах 3.3. Uranium in carbonaceous-siliceous schists	Стратиформный Stratiform	V, Mo
3.4. Урановый в цеолитовых метасоматитах аляскитовых гранитов 3.4. Uranium in zeolitic metasomatites of alaskite granites	Стратиформный, жильный Stratiform, veins	
3.5. Урановый в кальциево-магнезиальных и глинистых (Kl-He-Chl) метасоматитах зон структурно-стратиграфических несогласий 3.5.1. Австралийский подтип 3.5.2. Канадский подтип 3.5. Uranium in calcium-magnesium and clayer (Kl-He-Chl) metasomatic zones of structurae-stratigraphic unconformaties 3.5.1. Australia - type 3.5.2. Canadian - type	Стратиформный Stratiform	V, Au, Ni, Pt
3.6. Ураноносный в карбонатитах структур центрального типа 3.6. Uraniferous in carbonatites of Central type structures	Жильно-штокверковый Vein-stockwork	TR, Nb, Ta, Th, Cu
3.7. Урановый в гранитах, щелочных метасоматитах и пегматитах („порфировый") 3.7. Uranium in granites, alkaline metasomatites and pegmatites („porphyry")	Штокверковый, вкрапленный Stockwork	Th, TR

3. EXOGENIC GROUP OF URANIUM DEPOSITS

Geological environments, characteristic of the emplacement of deposits of this group are clearly classified under two subgroups — epigenetic, essentially infiltrational, associated with activated platform covers and systems of depressional valleys and paleovalleys; - syn-diagenetic, associated with essentially terrigenous (including clayey, phosphate, etc.) sequences of platform covers and orogenic depressions.

The most important of them, epigenetic subgroup, is noted for an active infiltrational hydrodynamic regime of artesian basins, determining the movement of pressure oxygen water from recharge areas (orogens) deep inside the basins with generation of oxidizing and reducing zonation which control the distribution pattern of uranium and complex deposits on geochemical barriers. Genetic similarity of deposits is also emphasized by characteristic roll shapes of orebodies. Differences are associated with types of geochemical barriers — stratal or stratal-ground oxidation zones (2.1.1, 2.1.2, 2.1.3) and reduction zones (2.1.4). The age of ores is predominantly Neogene or Quaternary, as well as Mesozoic (for paleovalleys). Accompanying mineralization is shown in Table II.

Syn-diagenetic subgroup of uranium deposits comprises orebodies of a stratiform type, mainly associated with sedimentation and partial alteration in the process of diagenesis.

The most important geological economic type among them is phosphorus-rare earth-uranium sorptive-biogenic, associated with sulfide-bearing clays of young platform covers. The emplacement of these deposits is due to mass extinction of fish in certain parts of sea basins with subsequent separation of bone detritus which sorbed uranium in accumulative structures. The age of deposits is Late Oligocene.

Uranium type in variegated terrigenous continental sequences, representing the sedimentary class of deposits, sometimes forming major bodies with low grade or run-of-mine ores. The age range of the emplacement of these deposits is rather extensive (Proterozoic-Paleozoic) and varies for different regions. The morphological type is sheet-like, lenticular, impregnated and concretionary.

Other types of deposits in the exogenic group (see Table II) are, in fact, uranium-bearing; they are associated with phosphorites (2.2.3), lignites, karsts (2.2.4) in which uranium plays the role of a by-mineral.

Mineralization is in certain cases characterized by a large extent, along with a low uranium content in ores. The age range of the emplacement of deposits is extensive.

4. POLYGENETIC GROUP OF COMPOSITE (TELESCOPED) URANIUM DEPOSITS

Geological environments for the emplacement of these deposits are diverse intra- and peri-cratonal, partly riftogenic ancient platform depressions; stabilized blocks in boundary zones of platforms; granite gneiss domes and aureoles in basement; zones of structural unconformities at boundaries of the crystalline basement and depressional structures; long-lived faults; a composite combination of endogenic and exogenic ore-generating processes polychronous ore genesis.

The following geological-genetic types of deposits are distinguished within the group:

- Gold-uranium in conglomerates of Precambrian depressions. Stratiform orebodies formed as a result of placer accumulation of metals in the process of reiterated redeposition of uranium and gold. Lately, there appeared convincing evidence of a sedimentary-hydrothermal genesis of gold in Witwatersrand. Therefore, possibly, this type of uranium deposits has a sedimentary-hydrothermal-metamorphic genesis.

- Uranium in Precambrian sandstones and dolomites. Association with intracratonal depression. Proximity to "sandstone" type deposits (common stratigraphic level, association with fossils, etc.). However, subsurface uraniferous hydrotherms were supplied to sedimentary basins, resulting in emplacement of rich lenses.

- Uranium (with V and Mo) in carbonaceous-siliceous shales of Riphean and Paleozoic, forming under conditions of sedimentation and subsequent hydrothermal and crust-forming processes. Stratiform morphological type.

- Uranium in calcium-magnesian metasomatites of structural-stratigraphic unconformity zones (Australian and Canadian subtypes).
  A polygenetic character of this type (in the generally adopted interpretation) shows up primarily in the evolution of ore-generating processes — ore accumulation, activation with selective mobilization of substance, in certain cases, hypergenesis leading to uranium mobilization, etc.
  Age of mineralization is 1300–1350 Ma, 1600–1700 Ma. Being characterized by common emplacement (basic criteria: association with regional unconformities, carbonaceous sequences in the basement, large extent, etc.), the Australian and Canadian subtypes differ as regards metal concentration in ores, age, lithification of the overlying sandstones and other features.

- Uranium in zeolite metasomatites of alaskite granites. Mineralization is associated with zeolitization zones and weathering crusts of highly radioactive granite masses. Magmatic *accumulation — metasomatism — crust formation.*

- Uranium in granites, alkaline metasomatites and pegmatites ("porphyry"). A combination of magmatic, metasomatic and soil-infiltrational processes with a significant effect of fault structures. Impregnated and sheet-like type of orebodies.
  Age: 2000–1850, 1050–950 Ma, etc.

- Uraniferous rare metal-rare earth in carbonatites of central type structures. A polychronous evolution of certain masses is characteristic, as well as a combination of magmatic hydrothermal-metasomatic and crust-forming processes, determining the ore potential of structures.
  Age: Proterozoic-Mesozoic.

The present paper highlights on the types of uranium deposits which are of economic interest. Besides, uraniferous placers are known, quartzite skarns and other types of uranium mineralization of a vague practical significance, which also correspond to certain "cells" of classificational tables.

Presumably, the proposed classification of uranium deposits, based on a comprehensive metallogenic analysis of ore-bearing geological structures, petrological analysis of ores, evolution of ore structures and their regular interrelations will favour a more efficient study of uraniferous areas and prediction of the types of uranium deposits which are new for them.

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THE STRELTSOVSKOYE URANIUM DISTRICT

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Abstract

This paper describes the geology of the Streltsovskoye uranium district located in south-eastern Zabaikalie region, Chita Province, Siberia, Russia. This district hosts Russia's only currently active uranium production centre. The uranium ore was discovered from 1963 to 1967 by drilling below fluorite veins which had minor associated uranium mineralization and radioactive anomalies. The uranium occurs as large scale vein stockwork deposits of hydrothermal origin within a volcano-tectonic caldera formed by continental volcanism of Late Mesozoic age. Rocks occurring in the caldera include basalt and trachydacite, overlain by rhyolite, and with associated interbedded sediments. The ore bodies occur in steeply dipping faults, with the greatest concentrations located where faults along the margins of the caldera intersect steeply dipping, cross cutting, northeasterly and northwesterly striking faults. The Streltsovskoye caldera extends over an area of 150 km^2 and is underlain by a large batholith. The 19 identified uranium deposits occur in structural features that cut through the caldera sequence and extend into the basement rocks. The caldera has a maximum thickness of 1400 metres. Details of several deposits are given, including descriptions of mineralization and associated alteration.

The Streltsovskoye uranium district is located in south-eastern Zabaikalie in the economically developed region of the southern Chita Province of the Russian Federation. Due to geographical conditions, the region is easily accessible. However it took about 15 years to discover the uranium deposits. During this discovery period, the opinions on the uranium potential of the territory changed several times. The evaluation of the uranium potential of the Streltsovskoye fluorite deposit, where local radioactive anomalies and minor uranium mineralization were already known at a depth of 50 m, was undertaken in 1963.

The first hole drilled below the thinning out of the fluorite vein intersected a thick ore body at a depth of 220 m. It was located in trachydacites in the lower wall of the fault bounding the fluorite vein. This was the first discovery of one of the largest deposits in the Streltsovskaya caldera. By 1967, the Streltsovskoye ore field was defined as a large industrially important uranium ore region with unique reserves and ore grade. The bases of these deposits construction of the Priargunsky Mining and Chemical Processing Works was started in 1968.

The deposits of the Streltsovskoye uranium district are very typical representatives of large-scale hydrothermal uranium deposits, formed in areas of continental volcanism during the final stages of Late Mesozoic tectono-magmatic activity. The deposits are located within the Streltsovskaya volcano-tectonic caldera which covers 150 km^2 (Fig. 1).

The position of the caldera is defined by the junctione of long-lived deep faults of various orientations at the arch of a local gneiss-granite dome. Granitoid rocks, originated from silicapotassic metasomatism and anatexis, which developed throughout Proterozoic to Early Mesozoic time, are widely distributed in the basement and flanks of the volcano-tectonic depression. Various Precambrian metamorphic rocks (quartz-plagioclase-biotite gneisses, biotite-hornblende gneisses, dolomitized limestones, etc.) occur as xenolithes among granitoids of various ages.

The sedimentary-and-volcanogenic rocks forming the caldera have an average thickness of 500–800 m, and are as much as 1400 m thick in the deepiest parts of the caldera. The geological section is represented by the Upper Jurassic Priargunskaya series. The series consists of three basalt sheets alternating with three trachydacite sheets, separated by thin horizons of sedimentary and tuffaceous rocks. The upper part of the section is composed of the Lower Cretaceous Turginskaya

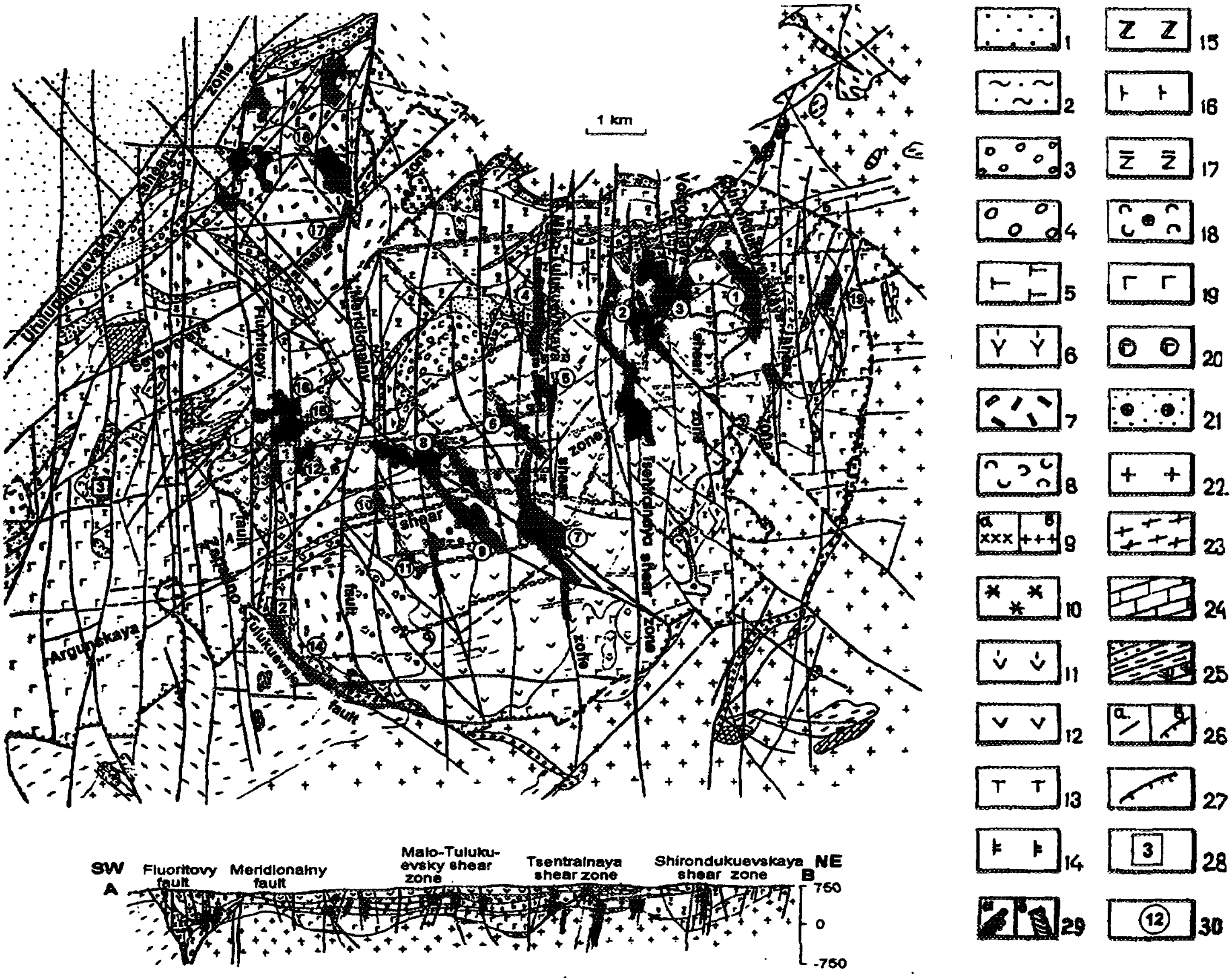

Fig. 1. The Streltsovskoye ore field. Geological map.

Sedimentary-volcanogeneous rocks (upper structural level):
1-13 - the Turginskaya series (Lower Cretaceous): 1 - sandstones, 2 - aleurolites, 3 - gritstones, 4 - conglomerates, 5 - basalts, 6 - liparites of neck facies, 7 - liparites of sheet facies, 8 - acid tuffs, 9 - granosyenite-porhyries (a), liparites (b) - extrusive bodies of subvolcanic facies; 10 - spherolitic liparites, 11 - felsites of neck facies, 12 - felsites of sheet facies, 13 - plagioclasic trachydacites; 14-21 - the Pruargunskaya series (Upper Jurassic); 14 - basalts of upper sheet, 15 - trachydacites of upper sheet, 16 - basalts of middle sheet, 17 - trachydacites of lower sheet, 18 - "ocellar" trachydacite tuffs, 19 - basalts of lower sheet, 20 - conglomeratic breccias of basalts, 21 - basal conglomerates.
Lower structural level:
22 - granites of the Variscian epoch of granitization, 23 - granites of the Caledonian epoch of granitization; 24-25 - metamorphic rocks; 24 - dolomitized limestones, 25 - biotite-amphibole gneisses, amphibolites, metasedimentary rocks; 26 - tectonic faults: a - steeply dipping, b - gentle; 27 - the boarder of the Streltsovskaya volcanotectonic caldera, 28 - volcanic apparatuses: 1 - Krasnokamensky, 2 - Yugo-Zapadny, 3- Zapadno-Tulukuyevsky; 29 - molibdenum-uranium ore bodies: a - run-of-mine ahd high-grade ores, b - lean ores (at the geological map - ore body projections on the surface); 30 - uranium deposits:
1 - Shirondukuyevskoe, 2 - Streltsovskoye, 3 - Antei, 4 - Oktyabrskoe, 5 - Luchistoye, 6 - Martovskoye, 7 - Malo-Tulukuyevskoye, 8 - Tulukuyevskoye, 9 - Yubileinoye, 10 - Vesennee, 11 - Novogodneye, 12 - Pyatiletneye, 13 - Krasny Kamen, 14 - Yugo-Zapadnoye, 15 - Zherlovoye, 16 - Argunskoye, 17 - Bezrecnoye, 18 - Dalnee, 19 - Vostochno-Shirondukuyevskoye.

series where rhyolite sheets, which are divided into felsites and liparites using texture and structure features, predominate. The section is completed by liparites alternating with basalt sheets and conglomerate and sandstones horizons. Sub-volcanic feauters occur along the center shear zone at junctions with faults of the Argunskaya shear zone. The roots of the volcanoes are necks of liparites and syenite-porphyries extended along the faults. In the upper zone the cone-shaped pipes consist of eruptive breccias of rhyolites. The eastern part of the caldera is exceptional and is composed of stratified gently pitching effusive sheets and sedimentary rocks. As the result of the processe of caldera formation, the rocks of the basement and cover were broken into blocks which underwent movement in opposite directions.

The Argunskaya shear zone of the north-eastern and sub-latitudinal trend is the major ore-controlling zone in the Streltsovskaya caldera. It was initiated at the stage of plicated dislocations. It remained tectonically mobile throughout the Proterozoic-Paleozoic history and the complete period of sedimentary-volcanogenic cover formation. It consists of numerous tectonic fractures with a northeastern (70°) and latitudinal strike accompanied with zones of close spaced jointing of the rocks. The total thickness of tectonically broken rocks is 3–5 km. Within the Argunskaya shear zone, quartz-K-feldspar-albitite metasomatites and greisens occur together with pre-ore and ore-accompanying low-temperature hydrothermal alterations (argillization, albitization). Alternation occurs both in basement and in sedimentary-volcanogenic deposits of the caldera.

The meridional shear zone also consists of a series of tectonic joints that are second order to the major meridional fault. The junction of the meridional and Argunskaya deep shear zones was the main magma- and fluid-transporting channel in the post-granitization period and during volcanism, as well as the ore-transporting channel during the final period of activization.

Meridional faults, grouped into zones of 500–900 m thickness, were important ore-controlling structures in the caldera. The majority of the deposits are located within the Argunskaya shear zone at its junctions with the meridional shear zones. Both faults and zones of steeply dipping jointing with a northwestern (330°) strike, accompany the faults. They formed at junctions of the meridional and northeastern fractures and host uranium mineralization in the sedimentary-volcanogenic strata. As this took place, zones of contiguous jointing were developed between the meridional faults. They are for the most part second order joints. Zones of steeply dipping jointing were formed mainly in the effusive sheets and less brittle commonly in sedimentary rocks. The presence of brittle rocks at several levels in the section resulted in the appearance of mineralized fissure zones on several lithological levels.

Faults with either a northeasterly (30) or northwesterly (0) strike host uranium ore in the basement rocks. Channels for percolating hydrothermal solutions were provided by steeply dipping faults which restrict the caldera, and cross cutting faults that extend through basement rocks and all sedimentary-volcanogenic strata.

In addition to the steeply dipping tectonic fractures there are several structural features present with a shallow dip. These include gently pitching fractures formed at the contact between the basement rocks and overlapping sedimentary-volcanogenic strata, as well as at the border of the Priargunskaya and Turginskaya series. These occur mainly in the horizon of tuffs and sedimentary rocks, at the base of the felsite sheet.

Gently drapping fractures consist of numerous cracks filled with clay alterations. These clay bearing zones are the screening surfaces during of percolation the ore solutions. In some cases they host ore bodies. A combination of ore-treating, ore-controlling and ore-hosting structural elements in unified space with a few numbers of drainage faults and numerous screening fractures appeared to be the major factor which caused favourable thermobaric conditions in the area of ore deposition.

The Streltsovskoye ore district includes 19 uranium deposits. The two largest are located in the basement rocks (Argunskoye, Antei). Seventeen occur in sedimentary-volcanogenic rocks of the caldera fill of thirteen occur in *stratified effusive* sheets and in sedimentary rocks, while four are in effusive rocks of the vulcanic neck facies. Some of the deposits in the sheet facies volcanic rock also belong to the large class of deposit, including the Streltsovskoye, Tulukuyevskoye and Octyabrskoye. These three deposits together with the two deposits (Argunskoye, Antei) in the basement are the only ones on the reserves and ore grade.

Geological structure is the major factor controlling uranium deposit development. The chemical composition of the rocks does not have an influence on ore development richness; all rocks of very different composition — granites, acid, intermediate and basic effusives, sedimentary types, and dolomitized limestones — host ore.

The bedded structure of the sedimentary-volcanogenic series and the repetition in the geological section of the rock types, favourable for fissure zone formation, caused multi-layer distribution of the ore. It occurs at 6 lithological-structured levels: levels 1 in 5 in the sedimentary-volcanogenic sequence with the 6th level represented by the basement rocks. Three major morphological body types are recognized: stockwork, veine and bedded. Every deposit is represented by these three (or rarely two) are recognized: types of ore bodies located as a rule at several lithological-structural levels.

The third and the fourth levels, where uranium mineralization is concentrated in the trachydacite sheets as stockwork-like or rarely vein-like bodies, contain the richest ore. The Antei deposit, mineralization is located in the basement rocks in a large vein-like body which also includes thicker stockwork-like zones. In the Argunskoye deposit — a thick stockwork occurs with vein-like apophyses. Ore bodies along bedding occur at the second lithological-structural level where they are located in a gently dipping fracture at the base of felsite sheet. Smaller bed-like bodies occur in the sandstones of the basal horizon of the sedimentary-volcanogenic strata.

Uranium mineralization occurs in various altered rocks. Haloes of pre-ore metasomatic alterations (hydromica-carbonate-quartz, sericite-carbonate-quartz, kaolini-carbonate-quartz) were formed as a result of the processes of acidic leaching. Alteration, which developed in close association with uranium deposition, is also developed. They are manifested in the metasomatic-streaky formation of albite and hematite, as well as silicification and carbonization.

The uranium mineralization is represented by pitchblende, with rare coffinite and, as very small amounts of brannerite at some deposits. The ores are characterized by impregnations, vuggy impregnations, streaky and brecciated structures. The uranium content varies over a wide range — from the cut-off[1] to the a few percent. Average content in some bodies and deposits ranges from 0.15–0.33 % and in the largest bodies up to 0.6–3.0%.

In addition to uranium the ores have a complex composition. They contain molybdenum, and rarely fluorite in commercial quantities. The deposits belong to the hydrothermal low-temperature type of molybdenum-uranium formation. They were formed in several phases of a single hydrothermal event. The process of ore formation took place in 6 phases:

1 Phase of argillization (facies of kaolinite and hydromica alteration);
2 Cryptoquartz-carbonate-sulphide phase;
3 Albite-brannerite (the first ore) phase;
4 Quartz-molybdenite-coffinite-pitchblende (the major ore) phas);
5 Quartz-molybdenum-sulphide phase;
6 Calcite-fluorite-dickite (post-ore) phase.

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[1] Editor's note: The normal cut-off grade used for conventional reserve estimation (i.e. non-in situ leach) in the Commonwealth of Independent States B 0.0390 U.

The ore and ore associated minerals were deposited from hydrothermal solutions in tectonic fractures, in rock pores and by metasomatic replacement. Vuggy-disseminated, streaky-disseminated, and brecciated ore structures are the most common. The age of the uranium ore is determined as Early Cretaceous. It is mainly 130–125 million years, with youngest age of 110 million years.

All deposits of the Streltsovskoye ore field are hidden, and not exposed at present on the day surface. Most of the ore bodies occur at a depth of more than 200 m. The majority of them are also located in the interval of 400–900 m below the surface. Only a single body occurs at a depth of 50–100 m.

The Streltsovskoye deposit is the largest of the deposits. It occurs in the sedimentary-volcanogenic cover, in the eastern part of the caldera. It is comprised of 6 structurally interrelated ore bodies, each of which is classified as an average or large sized deposit.

A significant part of the reserves is contained in the Streltsovskaya vein. It has a length of 750 m and an average thickness of 6 m. The average uranium content is 0.33% . All rocks cut by the fault host ore mineralization. However, the highest contents of uranium (up to 0.8%) and molybdenum (up to 0.4%) are in the basalts (Fig. 2). The main part of the uranium reserves at the deposits are concentrated in stockwork-like bodies in the lower trachydacite sheet. The bodies consist of contiguous steeply dipping ore-bearing fractures feathered large faults (Fig. 3). The uranium content in ore bodies increases near the lower or upper limiting surfaces such as gently dipping fractures in tuffs or conglomerates (Fig. 4, 5); the stockworks split into short vein-like bodies when they thin out. The length and width of the ore bodies reaches a few hundreds of metres.The uranium content varies between 0.15 and 0.5%.

Hydrothermal wall-rock alterations in the Streltsovskoye deposit is manifested by hydromicatization, albitization-2, carbonatization, streaky and metasomatic silicification and pyritization, and the development of ankerite and chamosite veinlets. Veins of fluorite and veinlets of dickite and calcite formed in the post-ore stage. Pitchblende, and rarely coffinite, represent uranium mineralization. Mineralization forms finely disseminated, vuggy-disseminated aggregates, streaky segregations along cracks, saturates tectonic breccias and borders their fragments. Molybdenum mineralization is represented by jordisite which is transformed to ilsemanite during oxidation. The association of uranium, with pyrite; isolated quartz veinlets and coarse-flanked molybdenite are rarely noted. Berylium (bertrandite) is also present in noticeable quantities in some uranium and molybdenum ore bodies.

Many of the other deposits formed in the sedimentary-volcanogenic strata are characterized by similar geological structures. The Tulukuyevskoe uranium-molybdenum deposit, is one of these and it is of major importance.

This deposit is located in the central part of the Streltsovskaya caldera. It occurs within the northwestern strike shear zone of the same name where it cross the Argunskaya shear zone in a terrain of stratified Upper Jurassic volcanites. It consists of a series of contiguous, steeply dipping fractured-veined, stockwork-like and gently pitching ore bodies of complex morphology. They are located at the second lithological-structural level and do not outcrop (Figs 6 and 7). Molybdenum occurs in commercial concentrations in the ore. Insignificant concentrations of lead, beryllium and rhenum occur with the uranium. The length of the deposit is 1300 m. The richest part is 400 m long and the width of the productive zone is from 150 to 250 m. The section containing ore is 180–270 m high.

The fifth ore-bearing zone, controlled by tectonic fractures with a northwestern strike, is the richest and contains 60–70% of the total reserves. The ore bearing rocks are felsites, lava breccias of felsite composition and tuffaceous-sedimentary rocks: a minor part of the lower grade ore occurs in underlying basalts and trachydacites. The uranium ore grade is high. The average uranium content exceeds 0.4%, and ranges from the cut-off to 5–7% in some intervals; the highest uranium contents

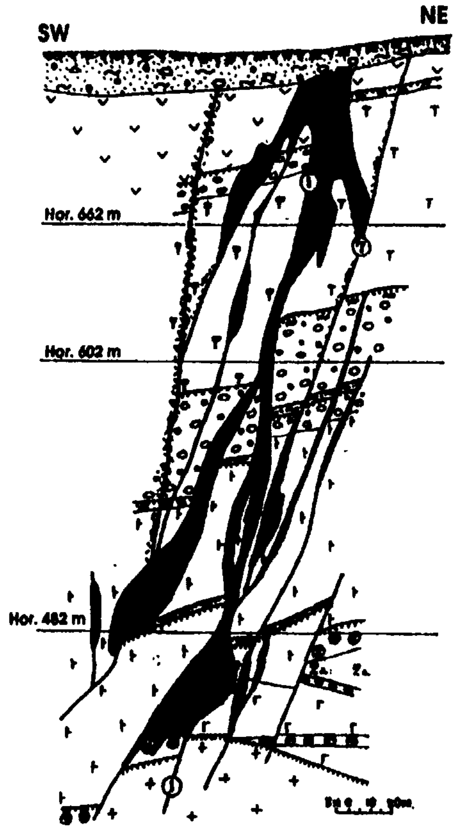

Fig. 2. The Tsentralny area of the Streltsovskoye deposit. Geological section on the 115+50 prospecting line. Legend see on Fig.1.

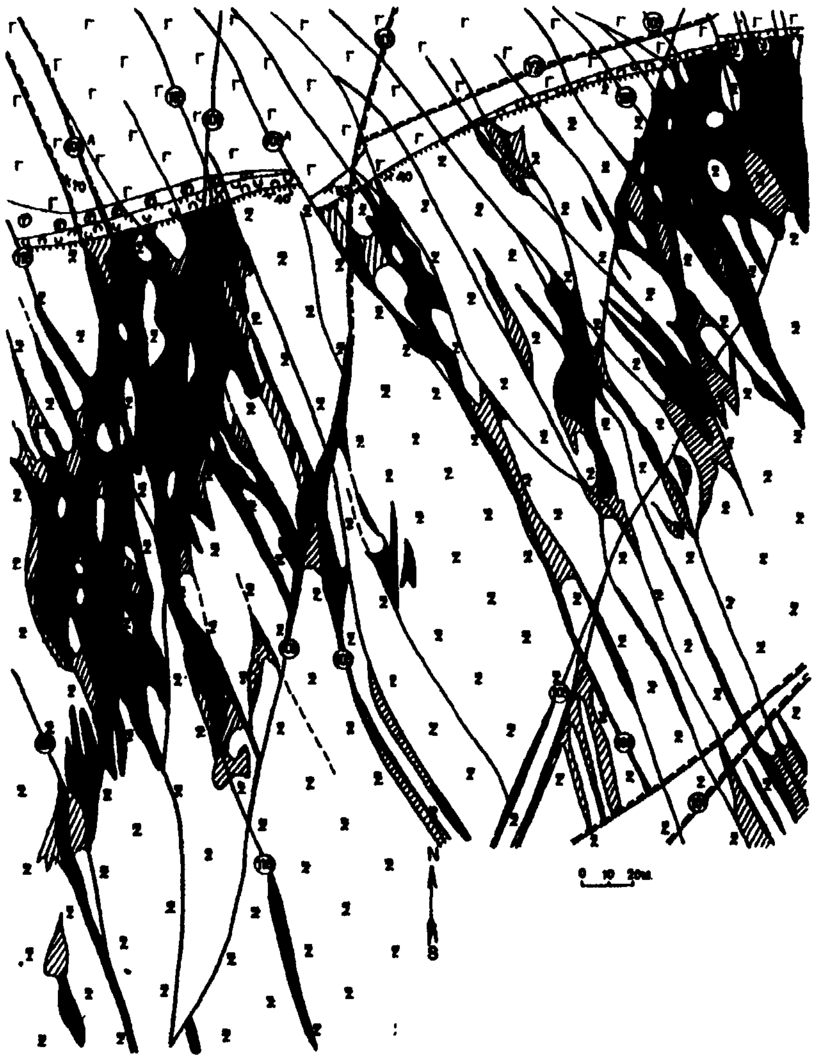

Fig. 3. The Glubinny area of the Streltsovskoye deposit. Geological plan of the horizon of 332 m. Legend see on Fig. 1.

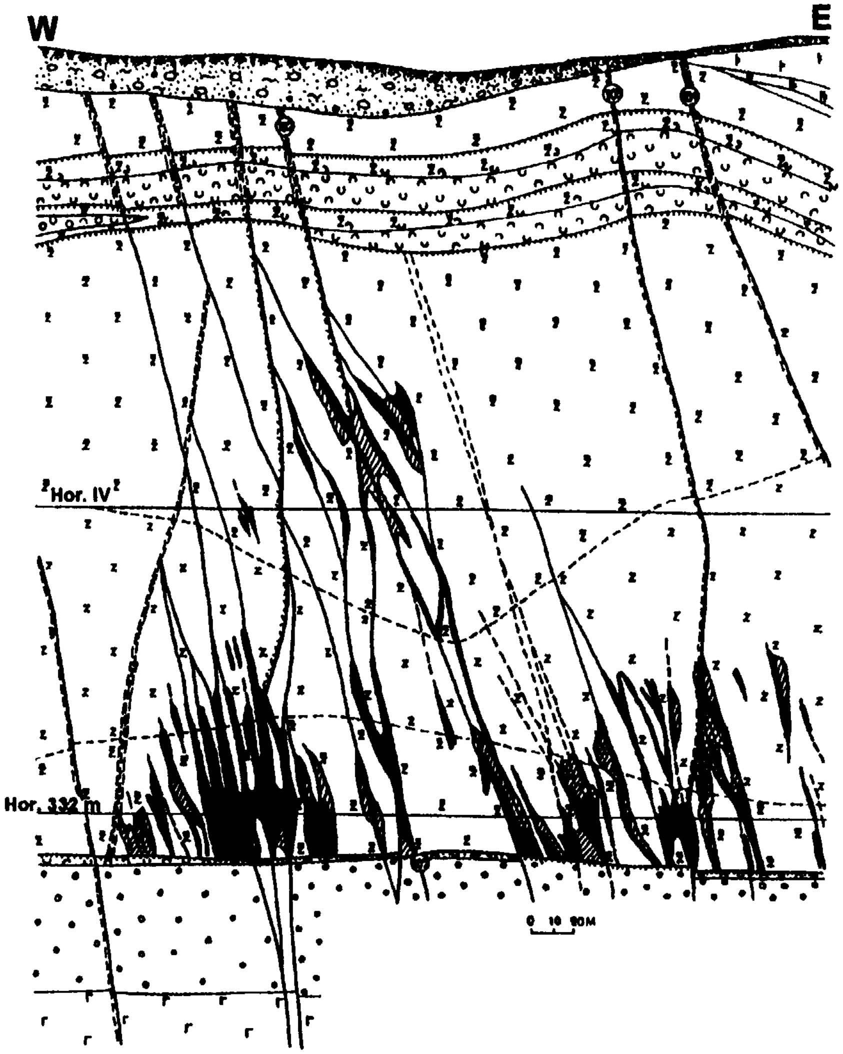

Fig.4. The Glubinny area of the Streltsovskoye deposit. Geological section on the 97-th prospecting line. Legend see on Fig.1.

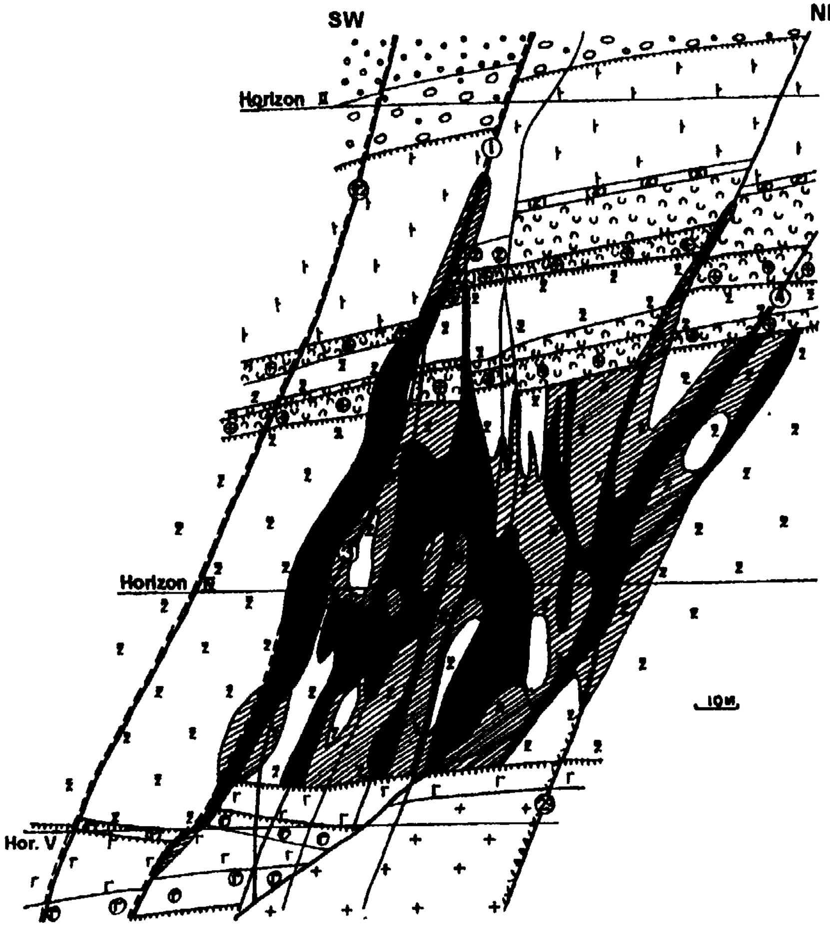

Fig. 5. The Streltsovskoye deposit. Geological section on the 113+50 prospecting line. Legend see on Fig. 1.

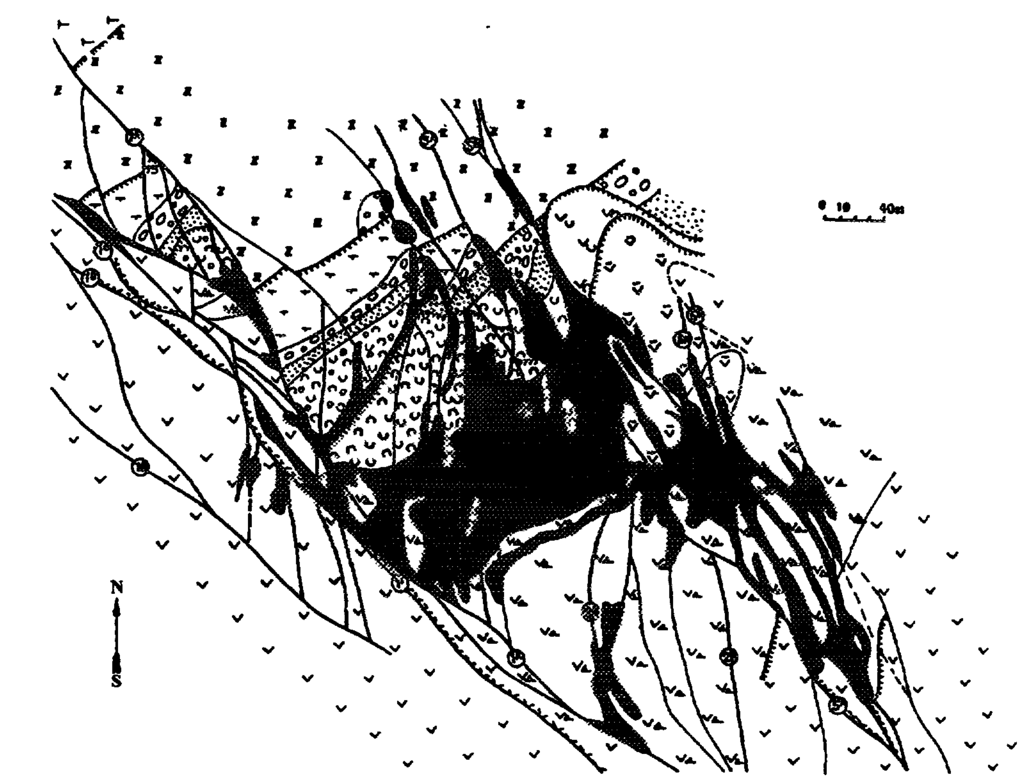

Fig. 6. The Tulukuyevskoye deposit. Geologocal plan of the horizon of 600 m. Legend see on Fig. 1.

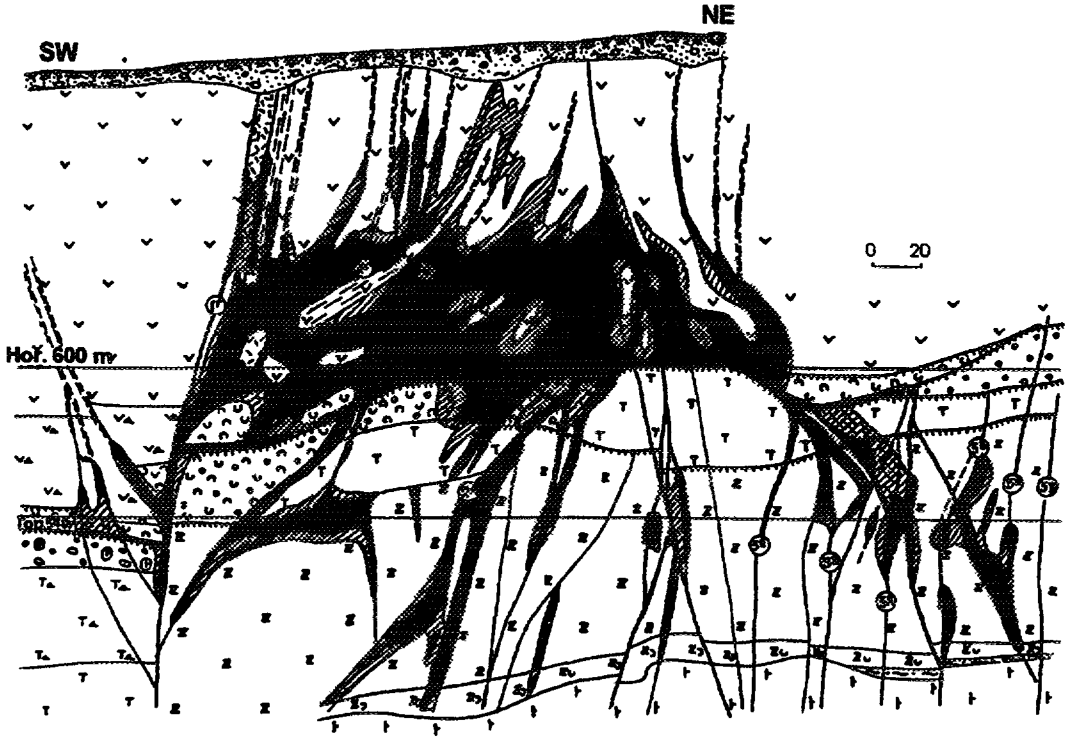

Fig. 7. The Tulukuyevskoye deposit. Geological section on the 35-th prospecting line. Legend see on Fig. 1.

are 30–40% over a thickness of 5 m. The thickness of ore bodies varies from a few tens to 50–60 m. The second ore-bearing zone represents the central part of the deposit. It is controlled by fractures of the meridional and northeastern strike, restricted by faults with a northwestern strike. Uranium mineralization forms large concentrations at the junction of different striking faults. The average uranium content is about 0.3%. A gently dipping bedded ore body also occurs in a lit-by-lit Tint located within a tuff-sandstone horizon under a felsite sheet. The average uranium content is 0.2%, and reaches 5–10% in intersections of steeply dipping fractures with the lit-by-lit zone.

Molybdenum is present in commercial contents at the Tulukuyevskoye deposit. It is mainly concentrates in the lower part of rich uranium ore bodies. The highest grade concentrations, occur in basalts and felsite tuffs. Concentrations of Molybdenum in different ore bodies vary in the range from a few hundreds of a percent to 10–12%. The average molybdenum content is 0.2%. The average rhenium content is 146 ppm based its presence in molybdenum concentrate.

Hydrothermal wall rock alteration is well developed, It is represented by silicification, hematitization, hydromicatization, carbonatization and albitization. Streaky silicification and chloritization are confined to large tectonic fractures. Uranium mineralization is represented by pitchblende forming metasomatic and streaky segregations. Coffinite occurs in very minor quantities in association with pitchblende. Uraninite and uranium titanite (brannerite) are always rare. Molybdenite occurs in ores as finely flaked and cryptocrystalline (jordisite) varieties that form metasomatic and streaky separations. Pyrite and lollingite are of limited.

The unique Antei deposit is situated directly under the Streltsovskoye deposit. It occurs a depth of 350–1400 m below the surface in the basement granites (Fig. 8). At the Antei deposit, the commercial reserves have an average uranium content of 0.2%. Of this, 78% of the ore has an average bofuranium content of 1.33%.

The major ore body is located in a large tectonic joint of the north-eastern (30°) trend in the Late Paleozoic metasomatic and intrusive-anatectic granites. The strike length of the body is 1000 m, and the dip extension is about 900 m. Its upper border is represented by a gently dipping fracture on the contact of structural eluvium of granites and the overlying dacites which enclose ore bodies of the Streltsovskoye deposit. The body has a complex structure. Ore stockwork-like swells the thickness, of which reaches up to 50 m, alternate with vein-like intervals with a thickness of a few metres. Most of the uranium reserves are concentrated in the central part of the body, the ore body is chimney shaped in section and stockwork-like in plan (Fig. 9). The height of this body is 200 m, the length is 300 m, the thickness is from 10 to 50 m. The uranium content exceeds 0.7–0.9%, reaching more than 4% in ore intersections. The average content is 0.954% in the central part. Molybdenum occurs in insignificant amounts of less than 0.03%.

These granites enclosing ore are characterized by intensive pre-ore pneumatolitic-hydrothermal alterations such as microclinization and early albitization. Zones of sericitization and silicification with polymetallic mineralization (galenite, sphalerite and molybdenite) were formed along tectonic faults developed mainly at deep levels during early stages of ore-accompanying alterations. Native silver is observed in galenite from these zones.

Low-temperature hydrothermal pre-ore processes caused formation of wide haloes of hydromica, veinlets of quartz, siderite, and pyrite along faults. Mixed-layered hydromica-montmorillonite and chlorite occur in central part of the haloes. At the beginning of the early ore stage, streaky-metasomatic albitization-2 was widely manifested and accompanied by brannerite segregation and ankerite veinlets in the lower parts of ore bodies. During the final uranium-ore depositionstage, numerous veinlets of quartz and chlorite (chamosite-type) were formed. Uranium mineralization is represented by pitchblende, less of ten coffinite and, insignificant quantities of branderite. The latter was developed only at the bottom of ore bodies at a depth of more than 800 m below the surface. Only pitchblende occur spread above this level. Molybdenum mineralization is represented by dispersed segregations of molybdenite, in association with cryptocrystalline quartz and

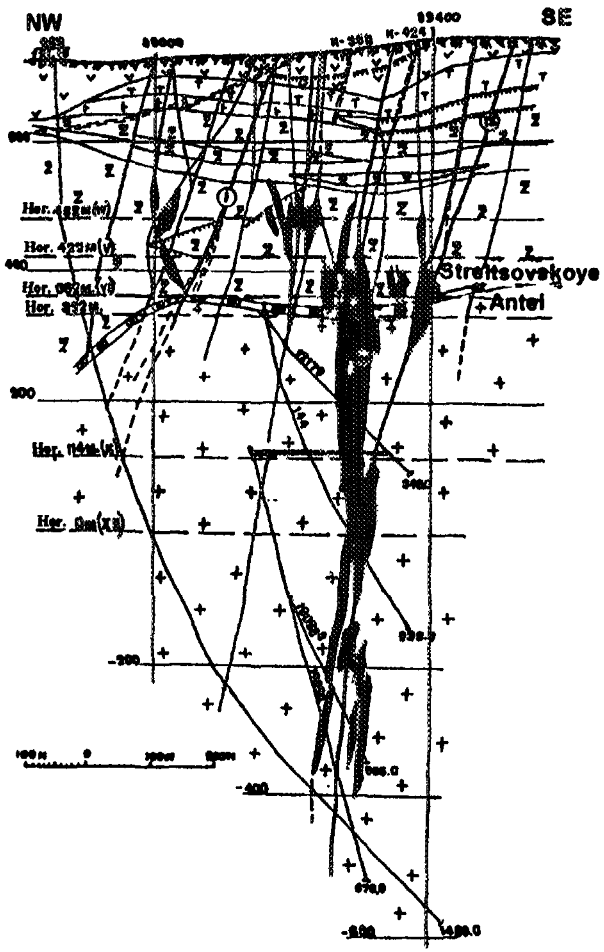

Fig. 8. The Antei deposit. Geological section on the 633-th prospecting line. Legend see on Fig. 1.

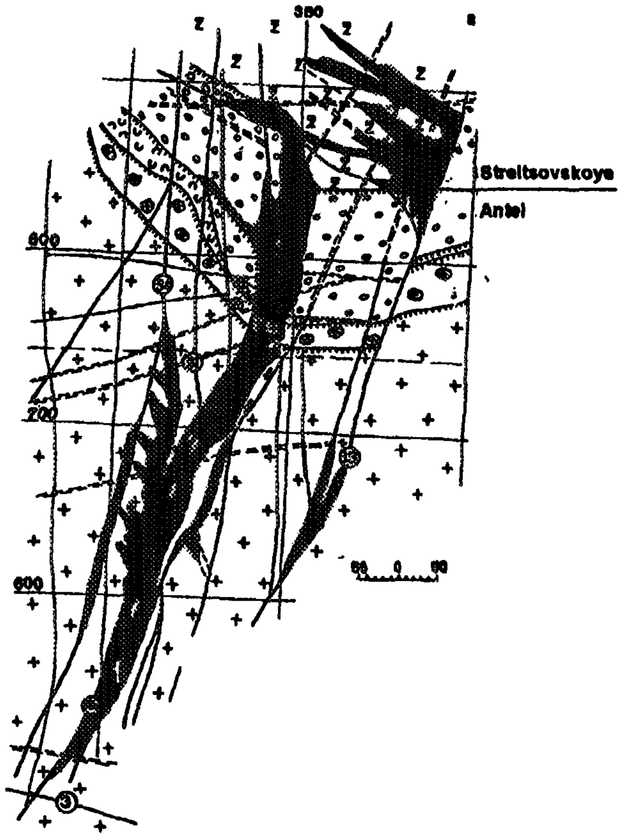

Fig. 9. The Antei and Streisovskoye deposits. Geological plan of the horizon of 302 m. Legend see on Fig. 1.

fine flaked molybdenite, together in vuggy-disseminated segregations with pitchblende and lath-like quartz. Post-ore wall rock alterations are slightly developed in granites slightly. Veinlets of dickite, druzy quartz, calcite, pyrite and fluorite, cross cutting uranium mineral ratio, were formed in faults.

The large-scale Argunskoye deposit is located in the basement rocks. It is situated in the western part of the Streltsovskaya caldera at the intersection of the Argunskaya and the meridional deep shear zones. The deposit was formed on the northern side of the Krasnokamensky volcanic neck. The Argunskoye deposit is the only in the Streltsovskoye district where most of uranium ore body is concentrated in cabonaceous rocks.

The deposit was discovered 16 years after the start of exploration and the discovery of the Krashny Kamen deposit in the territory. The upper parts of ore bodies occur at a depth of 140 m below the surface under a basalt sheet, making them difficult to discover.

The deposit is located on the northern limb of an anticline of metamorphic rocks. The core and the southern limb of the anticline are composed of polychronic metasomatic granites. Metamorphic rocks are represented by steeply dipping strata of dolomitized limestones, thin intercalations of high-alumina quartz-mica-andalusite schists, and biotite-amphibole gneisses intruded by ortho-amphibolites. The limestones are about 200 m thick (Fig. 10).

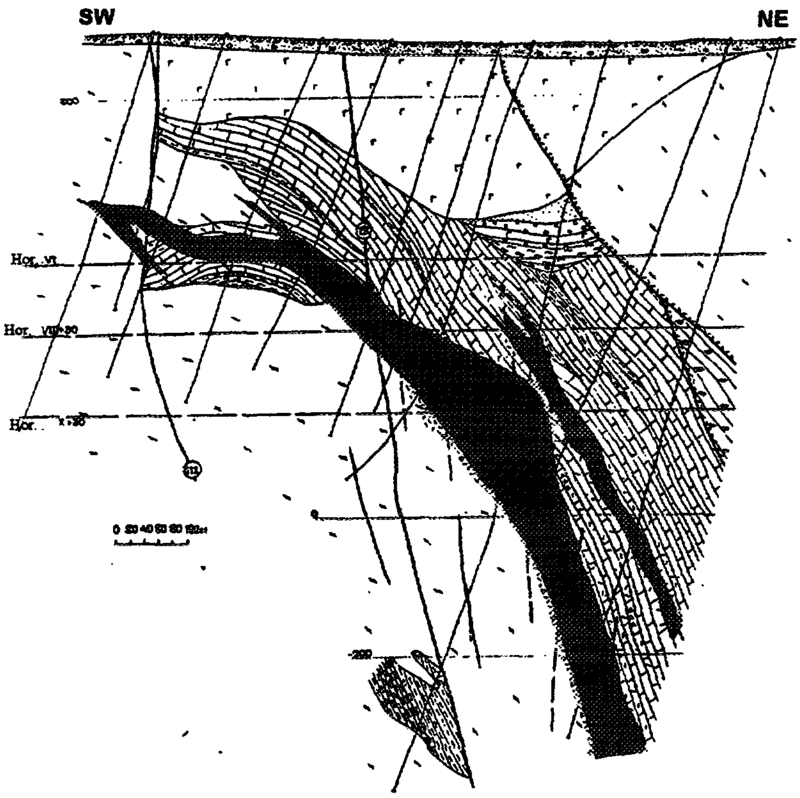

Fig. 10. The Argunskoye deposit. Geological section on the 2-nd prospecting line. Legend see on Fig. 1.

The granites and limestones are overlain by thick sheets of basalts and trachydacites. Ore-controlling structures are joints of the meridional, northwestern, sublatitudinal and rarely northeastern strike. The major host for uranium mineralization is a thick zone of breccias formed on the bottom of the limestone horizon of less importance are granites which occur under the limestones in the knot of intersections of differently directed steeply dipping faults. The limestone is brecciated over a thickness of 50–100 m; the breccia body has an isometric shape in plan and steep dip conformable with bedding dip. The main ore bodies of the Argunskoye deposit are concentrated in the zone of these breccias. Its width is 200–300 m, the vertical extent of the mineralization is more than 1000 m. The upper limit of the ore bodies is a fracture along the contact between the basement and cover rocks. This causes a screening effect for percolating hydrothermal solutions. Elongated on vertical line ore bodies, as well as vein-like bodies, which often are tongues of stockworks, occur in this ore-bearing zone. Uranium mineralization is irregular, contents vary from the cut-off to 3.5%. The thickness of ore intersections is in the range of 16 to 70 m. The major part of ore reserves is concentrated in ore shoots characterized by increased thickness of mineralization and high uranium contents. This results in about one third of the reserves being concentrated in blocks with rich ores (more than 0.3%).

Pre-ore high-temperature metasomatic rocks, such as microclinites, albitities, skarns, phlogopite metasomatites and greisens, are widespread within and near ore bodies. Low-temperature wall rock alterations is represented by argillization and silicification. Haloes of argillization have zoned structure. Kaolinite is developed in the upper parts. It is replaced by montmorillonite and chlorite depth and, deeper than 700 m, by hydromica. Chlorite and chlorite-montmorillonite metasomatites, related to the post-uranium fluorite process, are observed along faults that have been tested by deep drilling to a depth of 2500 m. Pitchblende and, less, coffinite occur in ores. The molybdenum content in carbonaceous ores is about to 0.15%, and in alumosilicate ores up to 0.26%. Molybdenum mineralization, represented by coarse flaked molybdenite and jordisite, in association with fluorite and sulfidized quartz, fills crack cavities, saturates breccia cement and wall rocks, forms veinlets. The fluorite content varies in the range from a few percent to 51%; the average content is 12%.

This brief description of the unique aspects at the reserves and ore grade of the molybdenum-uranium deposits of the Streltsovskoye district it shows that an important peculiarity controlling the formation of large-scale deposit mineralization is the coincidence of a single geostructural block ore-process, responsible for the generation of ore solutions, channels control transportation to the area of ore deposition, and favourable conditions for location of ore bodies. Specific conditions of the ore-preparing processes are defined by peculiarities of the endogenous development of the concrete block of earth crust.

The processes of polychronic granitization (PR_2–PZ_2) and dome formation in the post-granitization epoch includes silica-alkaline metasomatism and the formation of local metasomatic zones of quartz-K-feldspar-albitite and greisens along faults.

The most significant pneumatolitic-hydrothermal alterations took place in the Late Mesozoic period of activation. It is marked with tectonic rebuilding of the region and more intensive manifestation of silica-alkaline metasomatism and acidic leaching processes along reactivated shear zones. Here formed haloes of silica-potassic-sodic metasomatites and greisens in the basement rocks.

Evidence for the recurrent link in time between the ore deposits and the deep-seated, slowly evolving magmatic chamber include: the indications of multi-stage ore related processes in the basement of the Streltsovskaya caldera, occurring together with products of magmatism and low-temperature hydrothermal processes of ore formation within the deep-seated zone. The slowly evolving magma chamber was capable of generating fluid flows which introduced huge masses of ore forming, as well as other elements, in the area of deposition. The products of magmatism and subsequent pneumatolitic-hydrothermal and hydrothermal processes give evidence of directed migration and concentration of elements forming ore mineralization within deep-seated transcrustal faults.

The continental volcanic belt, where the Streltsovskoye ore field is located, has been traced for more than 1000 km across Russia, China and Mongolia.

The Dornotskoye uranium ore field of Mongolia was discovered and explored by Russian specialists as the continuation of this belt, by using criteria which were established as a result of the Streltsovskoye deposit investigation. Positive signs of uranium potential of volcanotectonic structures on the territory of northeastern China, similar to the Streltsovskaya and Dornotskaye calderas on the geological structure, were revealed within this belt by joint work of Russian and Chinese specialists.

A uranium-bearing in southeastern China is known in volcanotectonic caldera with commercial ores and other occurrences of uranium mineralization. From our point of view, this area has not been yet completely evaluated.

It is proposed that Meso-Cenozoic intracontinental volcanic belts in other regions of the earth which underwent long evolution are also potentially uranium-bearing. It is necessary to use all the available data on the formation conditions of deep deposits in volcanotectonic structures for discovering large uranium deposits within their limits.

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THE VERTICAL DISTRIBUTION OF URANIUM ORE MINERALIZATION IN THE VEIN AND METASOMATIC DEPOSITS

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Abstract

The vertical distribution of the uranium resources (VDR) 43 vein and metasomatic hydrothermal deposits is observed. The common features and the reasons of this distribution are discussed. From the surface to the lowest levels of prospecting works the VDR is defined by the concrete lithological-structural situation (the presence of "traps") and does not depend on the distance from the earth's surface. The vertical range of uranium ore mineralization is determined on the basis of VDR data, taking into account the size of post-ore erosional shear, the zonality of ore-enclosed cataclasites and the notions about the uranium transportation and deposition. The maximum range of uranium ore mineralization is equal apparently to 4-4.5 km. The evaluation of the deposit's deep levels should be based on the tendencies of changing of those geological conditions which were discovered by the geological interpretation of VDR diagrams.

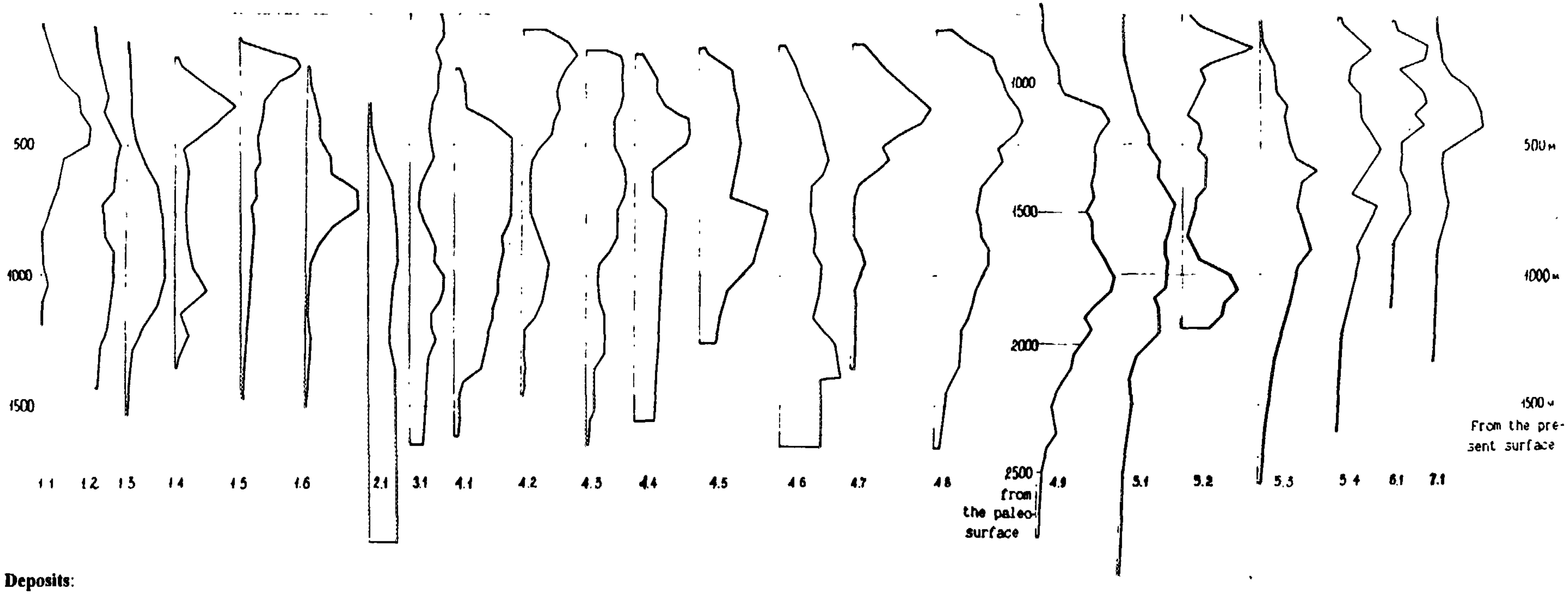
At present, the working and surveying depth in vein and metasomatic deposits reaches 1.5-2 km and more. We have studied 43 deposits in the CIS countries, Czechoslovakia and former East Germany. Due to long experience in the subject, we have much information accumulated on the vertical distribution of reserves (VDR), which could be valuable for both theory and practice. Special attention was paid for clearer understanding of factors affecting the shape of VDR curves and the maximal extent of mineralization.

The deposits under consideration and geotectonic sedimentation are confined to Pre-Cambrian shields (7 deposits), Caledonian (26), and Hercynian (10) faults. The VDR diagrams of more than 20 deepest deposits are given in Fig. 1. The age of the deposits corresponds to the formation period of geotectonic entities they are confined to, except for deposits 2.1 and 7.1, the formation of which took place during the Mesozoic tectono-magmatic activity.

Out of the 43 deposits, 15 had been completely developed, 11 — almost one half — i.e. at 60% of the sites, the larger portion of reserves was assessed by recovery and the smaller belonged to the RAR category. The resources of other sites are less proven and belong to the RAR and EAR categories. With the deepening of the working horizons and more knowledge attained, the maximal in the diagrams go down. The reserves in deep strata of long-producing deposits appear to be smaller than those in the upper ones due to a sharp decrease of the surveying grid density and an increase of the minimal commercial "metro percent" — both measures resulting from profit-raising interests and growing cost of mining.

The VDR curves shape is variable enough. The diagram of deposits with simple geological structure (one deposit in one single dislocation) and shallow ones are similar to the curves of normal statistically obtained data distribution. Extenuated deposits of simple structures are shown as platformic (Fig. 1./1.3, 4.1, 4.6). The deposits with complex structures are presented by curves of most peculiar shapes, often even dentiform (Fig. 1./ 1.4, 5.2, 6.1).

The VDR curves reflect the primary distribution of uranium minerals accumulated at the ore genesis stage during the hydrothermal process (the period of uranium transport). The followed hydrothermal regeneration of uranium and the effect of hypergenic processes had not influenced the shape of the VDR curve noticeably [3]. It is noteworthy to mention the regeneration at the deposits of Pribram and Zadni Chodov. In the first of the lower horizons, when pitchblende was replaced by U-antraxolite, the productivity decreased by 20%, the reserves decreased accordingly, and a slight



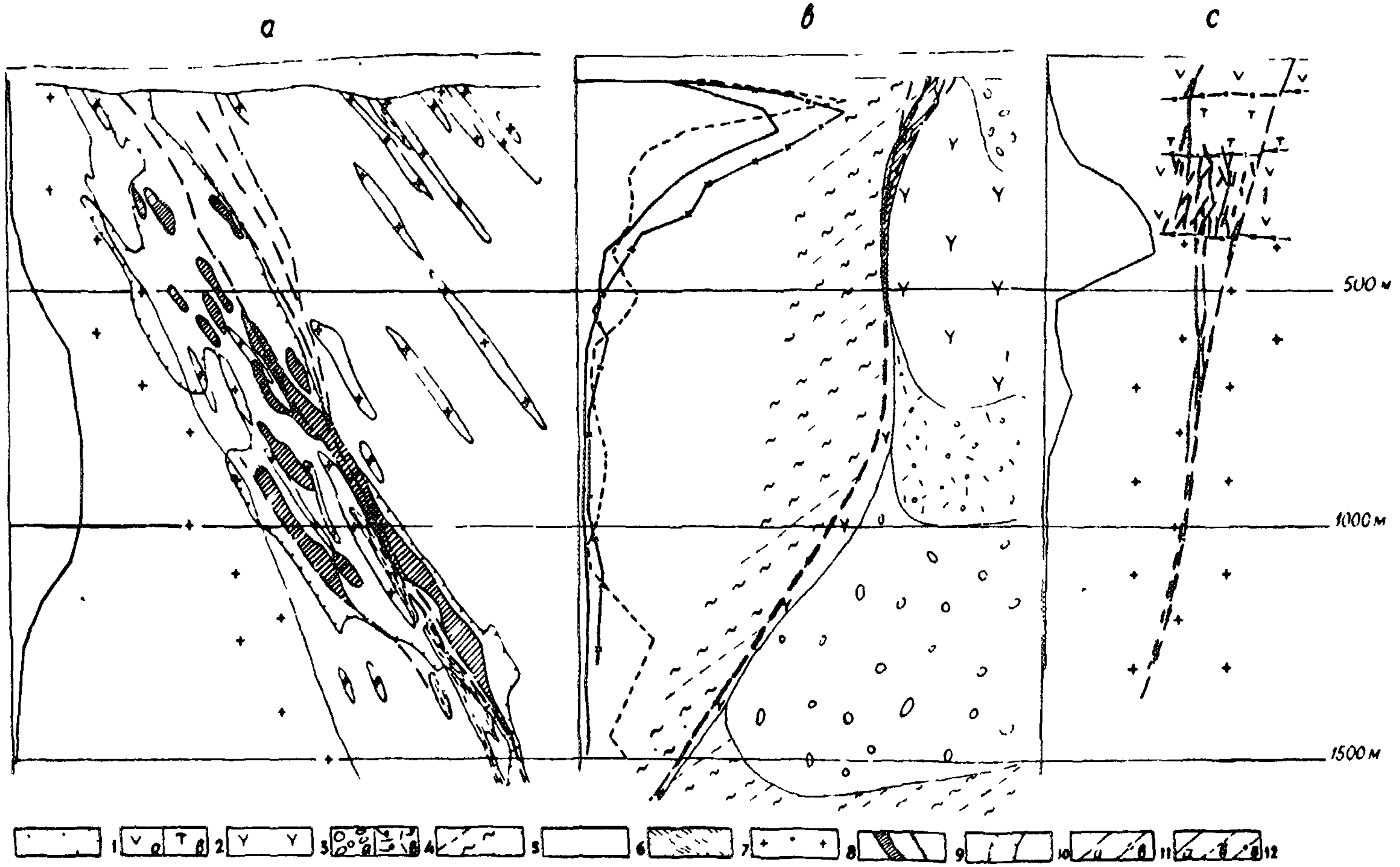
Deposits:

1. Ukrainian Shield:
    - 1.1. Vatutinskoe
    - 1.2. Novo-Konstantinovak
    - 1.3. Severinka
    - 1.4. Tsentralnoe
    - 1.5. Michurinskoe
    - 1.6. Zheltorechenskoe
2. Aldan Shield:
    - 2.1. Elkonskoe Plato + Kurung
4. Kokchetav Caledonian Massif:
    - 4.1. Kamyshovo
    - 4.2. Vostok + Zvezdnoe
    - 4.3. Kosachinoe-Tsentralnoe
    - 4.4. Kutuzovskoe
    - 4.5. Sartubek-1
    - 4.6. Zaozernoe
    - 4.7. Manybai
5. Czech Hercynian Massif:
    - 5.1. Niderschleme-Alberode
    - 5.2. Zadni Chodov
    - 5.3. Pribram
    - 5.4. Rozna
6. Chatkalo-Kuraminsk Hercynian Folded Region:
    - 6.1. Alatanjga
7. Priargunsk Hercynian Massif:
    - 7.1. Streltsovskoe + Antey

Additional diagrams:

3.1. Area of ore deposits between Ace and Fay mines (Beaverlodge, Canada)
4.7. Deposits in relation to reconstructed paleosurface at the ore formation moment
4.8. Distribution of total reserves in 4.1.

FIG. 1. VDR diagrams.



The confinement of the major part of reserves:
a) to the site of rocks with a complicated lithological structure,
b) to the sloping part of the fault,
c) to the "broken" contact of rocks by various structural stages

Schematic sections:
a) Deposit of Severinka
b) Glavnaja orebody of Vostok deposit
c) Deposits of Vostok + Antey

1 loose sediments Kz-Mz
2 volcanites Ms acid (a), basic (b)
3 volcanite of medium composition S-D
4 conglomerates (a) tuff conglomerates, (b) S-D
5 flyschcides O
6 migmatites Pr
8 granites

9 orebodies
10 borderline of albitized rocks
11 tectonic dislocations intersecting (a), conformable (b)
12 alteration diagrams reserves (a), contents (b), horizontal section area of ore deposits (c)

FIG. 2. The confinement of the major part of resources.

rise in reserves (a few percent) occurred in the second horizon and the near-surface zone (Fig. 1./ 2.10). However, the altering conditions of uranium deposition during the ore stage had been a decisive factor throughout the whole vertical extent of the deposits.

The conditions change might have been attributed either to the geological restructuring or to the chemical properties of uranium with their different behaviour at different depths.

Geological interpretation of the VDR curves shape shows that in most cases the appearance of the peaks and dips is related to certain geological factors, regardless the depth (Fig. 2.). The better the deposit has been explored and studied, the clearer the VDR curves indicate the changes in lithologo-structural conditions.

Out of 43 deposits, the VDR is determined by structural conditions at 24 sites, by structural and partially lithological — at 6, and by both equally — at 13. The structural elements are presented as "traps" at the sites of flexures, joints or transversions of continuity breaks; in four cases a folding break had additional effects.

The lithological factor is revealed through the physical-chemical properties of the rocks, it is shown in selective confinement of continuity breaks to lithological horizons with favourable conditions for fission formation and their absence in unfavourable rocks, in screened mineralization. The manifestation of chemical properties in a deposit scale has been proven in single cases. However, the location of a deposit within the limits of an ore field, or even a province, points out to their confinement of the strata with higher reduction capacity (high concentration of organics and Fe^{+2} minerals). In the Chetkalo-Kuramin region, 90% of reserves belong to the lower series, containing organic components [3]. Within the limits of the Czech Massif, the mineralization is concentrated in metamorphosed rocks, containing organics and other reducing agents, in the esocontact with granite intrusives. They are absent in granites [10]. In the Kokchetav province the mineralization is presented by sedimentary and effusive-sedimentary rocks with organics. In all the above provinces, the ore contains solid bitumen of hydrothermal origin.

In the geological interpretation practice there were cases when certain significant alterations of the curve's shape could find no reasonable explanation. These facts might be attributed to insufficient study or some other reasons (a weak supply of uranium, unfavourable hydrodynamic conditions etc.).

Diagram 4.9 (reserves distribution in relation to paleosurface) shows a lithologo-structural environment within a whole ore province. While plotting it, one could find that the proven reserves of similar significance happened to be rather distant. The error of underestimating the reserves in lower spaces was eliminated The parallel vertical lines of "platforms" on the diagram correspond to the length of 0.9 km. This length has been underestimated, since the upper region of six deposits was sheared by erosion, and the lower parts of four deposits have not been explored yet. The length of the "platform" of the actual diagram and corresponding interval for maintaining geological conditions should increase at least on the account of the eroded portions up to 1.1–1.3 km; with the addition of the lower parts, it might reach 1.5 km and more.

Several mineralogical and geochemical data and indications of the uranium content within the ore indirectly indicate that the favourable conditions for ore deposition remain with the growing dipping.

It is common knowledge that uranium minerals occur in paragenesis with minerals of many chalcophilic elements (Mo, PB, Zn, Cu, Bi, etc.) and iron. At that, the uranium minerals are often spatially more widely developed than the minerals of associated elements. This factor might imply that uranium could be relatively more stable in solutions.

The composition and ratio of uranium minerals at the ore stage do not change up to the depth of 2 km from the present surface (3 km and more from the paleosurface) if the lithologo-structural conditions remain unaltered, i.e. the dependence of their deposition on the distance from the surface is not evident. One or another uranium mineral present in the ore cannot be indicative of the stripped deposit depth [3].

Such dependence, based on the chemistry of uranium, might be evident in deeper spaces, since the uranium regeneration, being in principle affected by the depth, was observed at the Zadni Chodov deposit [2.10]

Such pitchblende specimen were sampled from the depth range 300–1350 m at Pribram, and the elementary cell A_0 size was determined, which revealed no noticeable divergence in any of the regularities [1].

The results of the study, conducted in uranium metasomatites, have shown that the peculiarities of changes around the ore, deposited at least 1.2–1.5 km from the contemporary surface, are determined by the influence of local factors (composition of enclosing media, properties of solution-conducting structures, etc.) [6].

The diagrams on ore contents, changing with the depth, were analysed which verified that the curves maximals generally depend on geological factors — the position of structural traps with predomination of rich veined ore, the location of rock horizons with favourable chemical properties — they result in large accumulations of uranium minerals. When the geological conditions retain their quality in the depth, the contents value remains the same, sometimes it may even grow. The structural environment can change, e.g. the number of ore-enclosing fissures may decrease, but if the morphology and size of the remained fissures are the same, then the structural conditions will generally stay unchanged.

Apparently, this is the explanation of accumulations of rich ores throughout all vertical ranges of deposits. Thus, the Niderschleme-Alberode deposit, despite a sharp decrease of veins at 1.8 km depth, has several veins at that level with a productivity exceeding 30-fold the average productivity of the deposit [1].

The theoretical and experimental data testify on the carbonate uranium-bearing system being capable to withstand considerable variations of the pH value in T, PCO_2 and smaller in Eh.

The given facts — the deposition of uranium minerals simultaneously with minerals of many other elements, the constant composition and ratio of uranium minerals at the ore stage throughout a wide range of depths, and, apparently, the stability of physical-chemical properties and stability of carbonate uranium-bearing systems in a changing physical-chemical environment — imply that uranium-bearing hydrothermal solutions should be relatively stable.

At the developed depths, the vertical variations of physical-chemical properties appear to be unimportant for uranium under unchanged geological conditions, i.e. one can suppose that the deposition conditions generally undergo no alteration and there is no particular chemical environment necessary for depositing uranium at various depths. As it follows, the main reason affecting VDR is the alteration of lithologo-structural conditions.

The information on VDR makes it possible to determine the vertical extent of a mineralization more correctly which requires data on the upper and lower mineralization limits.

The results of the geological survey and considerations about the dimension of erosion searing testify on the distance from the upper part of the uranium mineralization to the surface at the moment of ore formation having been less than a few hundred metres.

The lower limit of a mineralization can be determined by the depth of stripping at a number of deposits such as Sheltorechenskoe, Niderschleme-Alberode, Pribram, the deposit of Beaverlodge region, where it approaches 1.6–2.3 km. At that, the mineralization is not delineated. It is probable that the size of the sheared upper parts and the lower, yet not completely explored comprise 0.5 km. The lower limit of the mineralization measured from the paleosurface at the ore formation moment can be assessed to be 3–3.5 km. The reconstruction of the paleosurface in the Chatkalo-Kuraminsk region has made it possible to evaluate the lower limits of ore deposition to be 4–4.5 km [4].

The lower limits of ore formation can be estimated by the depth of various deformation manifestations (structural zonality) which led to ore-bearing zones formation. Thus, the Ukrainian medium-temperature uraniferous albitites, formed both metasomatically and by filling various hollows, are characteristic for brittle deformations (cataclasites) formed under hypabyssal conditions 3–7 km deep. The medium- and low-temperature deposits of vein and vein-disseminated ores originated by way of filling open hollows on the background of well developed jointing and branching at the depth of 0.5–4.0 km [8].

On the basis of theoretic assumptions, the lower limit can be evaluated only in approximation due to absence of any comprehensive theory on uranium source in hydrothermal deposits, as well as on the uranium transport forms.

Temperature is also a limiting factor fore uranyl-carbonate solutions, making them unstable at 200–300°C. Proceeding from geothermal gradient (3° per 100 m) and assuming it as high as possible in the early geologic periods, taking into account some other factors, the maximal depth of a formation can be 5–7 km [1.7].

In the cases of uranium having been transported as high-temperature (300-500°C) haloid complexes, the depth of deposit formation is limited by the depth of the magmatic centre (source of uranium) only, i.e. it will greatly exceed the technically feasible working depth [7]. According to a suggestion by A.G. Betekhtin, the depth of uranium sediments transported with haloids can be limited by certain minimal levels of oxygen concentration. However, the existence of such a level is questionable.

For comparison, the lower formation limit of hydrothermal deposits bearing non-ferrous and rare metals is evaluated as 5.0 km, with the surveying and working carried out down to 3.2. km [5].

The lower limit of medium- and low-temperature uranium deposits, evaluated by various methods, could be set at 3.5–7 km. Using the practical data on VDR of uranium, non-ferrous and rare metals in hydrothermal deposits, it would be wise to accept the 4–5 km depth lower limit for an ore formation of uranium. Apparently, the maximal vertical extent of a mineralization can reach the same amount (4–5 km) minus the depth of the upper mineralization limit, i.e. a few hundred metres. Tentatively, for evaluation reasons one can accept the lower limit to be 4 km and the maximal extent 3.5 km.

The multiform VDR curves resulting from a combination of factors do not permit to elaborate a universal model diagram for depth evaluation. Though the structural alterations bound with the depth have certain regularities, the lithological environment changes and peculiarities of uranium regeneration bear a local character and cannot be generalized.

An unchanged lithologo-structural environment should make the quality and quantity of reserves unaltered, and the central part of the diagrams will ideally present a straight line, parallel to the vertical. When the ore enclosing dislocation gets diminished with the depth, the ores become depleted and the reserves value decreases. The VDR diagram shapes are similar to the diagrams of log normal distribution of values.

The mineralization depth extrapolation should be based on the alteration tendency peculiar to just those geological conditions which were found by means of the VDR curves interpretation.

The quantity of metal reserves in one metre of dipping, taken as initial for extrapolation, should depend on the relation of the VDR diagram and the geological conditions change. If the relationship is clear, the lower section of the diagram should be taken, if not, the average reserve value. It should be noted that the reserves of the lower sections are often unjustly underestimated.

Information on VDR sometimes makes it easy to reveal the basic relationships of mineralization locality, thus assisting in more correct evaluation of depth. For instance, some sudden changes in VDR may testify about altered geological conditions, still latent in the deposit. On the other hand, "gaps" in the diagrams of large deposits, ore field and provinces, which failed to be properly interpreted in geological terms, could be indicative of still unstripped orebodies at the edges.

The absence of geological factors reflected in the curves' shape may indicate errors in the reserves calculation.

The information on the maximal extent of mineralization and VDR of uranium deposits can be applied to evaluation of the depth of other metals in hydrothermal deposits under similar geological conditions.

CONCLUSIONS

(1) At surveyed depths, the VDR of uranium deposits is determined by the actual lithologo-structural environment (presence of "traps") and does not depend on the distance to the day-surface.

(2) Maximal vertical extent of uranium mineralization appears to be 4–4.5 km.

(3) Evaluation of abyssal sections of deposits should be based on the alteration trends specific to the very geological conditions which were found by geological interpretation of VDR diagrams. It is recommended to take up the maximal lower mineralization limit of 4 km from the paleosurface at the ore formation moment and the maximal extent of mineralization of 3.5 km. The information on VDR and extent of uranium mineralization can be applied to the evaluation of depth of deposits bearing other metals of a similar environment.

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THE MINERAL COMPOSITION AND THE ORE TYPES OF THE URANIUM-VANADIUM DEPOSIT SREDNAYA PADMA (ONEGA REGION, RUSSIAN FEDERATION)

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Abstract

The deposit Srednaya Padma is the largest and best prospected of the uranium-vanadium deposits of the Onega region. There are abnormally high concentrations of gold, palladium, platinum, copper and molybdenum in the ores. The ore mineralization is located in the albite-mica-carbonate metasomatites upon the proterozoic aleorolites and schists. The ores are generally composed of albite, dolomite and micas. The main vanadium mineral is vanadian flogopite, the main uranium mineral is pitchblende. The proportions of the ore and ore-forming minerals are determined. The noble metal mineralization (which associates with selenides of lead, silver and bismuth) and the copper-molybdenum mineralization (represented by chalcopyrite and molybdenite) are spread extremely irregularly in the orebodies. The ores can be classified as carbonaceous by their composition. Four mineral ore types, with regard to the mineralization composition of the ore, are determined: pitchblende-flogopite, noble metal-pitchblende-flogopite, sulphide-flogopite and hypergene. The ores are classified in three technological ore types (uranium-vanadium; uranium-vanadium with Au, Pd, Pt; vanadium with Cu, Mo) and two technological ore sorts (by the acid inventory in processing). The correlation between the composition of the ore and the technological processing parameters are determined. The specifics of the various ore types distribution in the orebodies are discovered. A comparison with the other U-V deposits of the Onega region is made.

1. INTRODUCTION

After disintegration of the USSR 60% of all nuclear power station capacities and only 26% of prospected uranium resources were left on the territory of the Russian Federation. The demand of Russian nuclear power stations is basically met by accumulated uranium stocks. Beside the Streltovsk region, nowadays there are no more deposits in Russian ready for uranium production. This is why there is a problem of increasing demand for uranium resources Russia.

At the beginning of the 1980s a number of complex uranium-vanadium deposits with high concentrations of gold, platinum, paladium, copper and molybdenum were discovered by the geologists of the state concern "Geologorazvedka" on the northern shore of the Onega lake. They have considerable resources and can be evaluated as a perspective uranium-bearing region (Table I).

The ores of the deposits are known for their complex mineral composition and for an uneven distribution of both valuable components and various minerals affecting the technological characteristics. The insufficient information on the changeability of the material composition and technological properties of the ores was the reason for their mineralogical-technological mapping (MTM) [1]. It was conducted on the Srednaya Padma deposit — the largest and the best prospected of the uranium-vanadium deposits of the Onega region. The main task of this mapping was the interrelated studying of mineral composition and technological characteristics, determining of the mineral and technological ore types and singularities of their spatial location for the qualitative evaluation of the ore.

2. METHODOLOGY

The sampling method included the selecting of the drill core samples at the full thickness of the orebodies. They were formed from the separate core samples. The weight of the separate sample in the united sample was proportional to the length of each ore interval.

TABLE I. RESOURCES AND MEAN CONTENTS OF THE MAIN COMPONENTS OF THE ONEGA REGION URANIUM-VANADIUM DEPOSITS (DATA FROM CONCERN "GEOLOGORAZVEDKA")

Deposit	V_2O_5		U		Mo		Cu		Au		Pd		Pt	
	ths. tonn	aver C, %	ths. tonn	aver C, %	ths. tonn	aver C, %	ths. tonn	aver C, %	kg.	av.C ppm	kg.	av.C ppm	kg.	av.c ppm
Srednaya Padma *	107.7	2.35	3.10	0.07	1.0	0.02	2.0	0.04	1100	0.23	1300	0.29	70	0.02
Tsarevskoe**	78.7	2.33	2.20	0.07	3,3	0.07	12.1	0.24	210	0.04	1210	0.24	60	0.02
Vesenneye***	82.2	3.09	1.32	0.05	2.9	0.05	2.9	0.05	1040	0.18	460	0.31	50	0.02
Kosmozero***	69.3	4,22	2.10	0.13	2.2	0.13	13.8	0.84	380	0.24	580	0.36	50	0.02
Verhnaya Padma**	13.1	2.32	0.24	0.04	1.7	0.52	2.9	0.52	120	0.21	100	0.18	-	-
TOTAL:	351.0	2.89	8.96	0.08	11.1	0.14	33.7	0.48	2850	0.20	3650	0.28	230	0.02

* - category C-1 + C-2
** - category C-2
*** - category C-2 + P-1

There were 40 mineralogical-technological samples form the Srednaya Padma deposit in all (usually 1-2 samples at one section): 23 samples from the 1st orebody and 17 from the 2nd orebody. The laboratory study of the samples was provided with the wide spectrum of the special methods.

3. THE GEOLOGY AND MINERALOGY OF THE DEPOSIT

The U-V deposits of the Onega region have a similar geological structure and mineral composition as the uranium deposits of the Franceville region (Gabon), which correspond to the sandstone type according to the IAEA classification. But by some specific features we can consider them as an individual type [2].

The deposits are concentrated in the Onega epicratonnal trough, which is filled with the volcanic-sedimentary rocks of Lower Proterozoic age (schungite schists, sandstones, dolomites and tuffites prevail). The deposits are located in the zones of fold-fracture dislocations, which are presented by the systems of narrow (2–4 km) N–W oriented anticlines for the space of 30–90 km. The cores of anticlines are formed by dolomites and the wings by schists [3].

The orebodies are located along the by layers steeply dipping faults filled by the breccias and cataclasites and in the knots of their crossing with the dipping at low angle thrust-like faults [3]. The high grade ores are connected with the wedge-shaped cataclasm zones in aleurolites and at their contact with the schungite schists.

The Srednaya Padma deposit is 3 km long and consist of two orebodies with an echelon-like joint. The first one has a cigar-like configuration, wedge-shaped section and subgentle dip (Fig. 1). Its length is 1060 m, thickness 40–50 m, the average content of vanadium pentoxide is about 3% and 0.13% of uranium. The orebody 2 is situated in the steeply dipping fracture zone in aleurolites and in some wedge-shaped zones contiguous to the first one. Its length is 1840 m, the vertical size is 100–450 m, the average content of vanadium pentoxide is 2.4% and 0.11% of uranium. The 2nd orebody contains 63% of the total uranium and vanadium resources but differs from the 1st orebody by the lower ore grades.

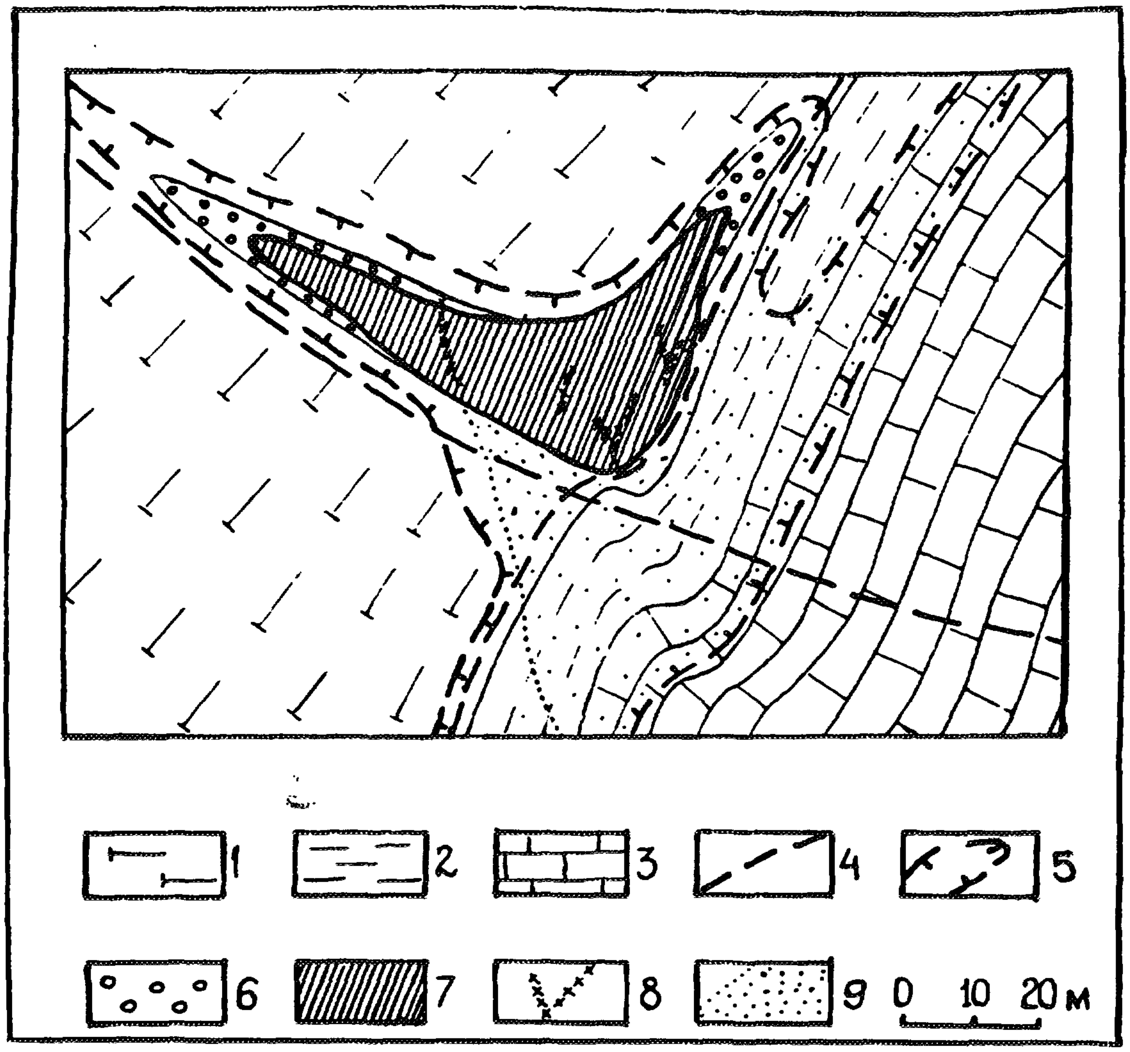
The U-V ore mineralization is situated in the zonal constructed aureoles of metasomatites upon the aleurolites and schists. There are the following aureole zones (from the periphery to the centre):

1) pyrite-dolomite-quartz-albite metasomatites,
2) albite-hamatite-mica metasomatites,
3) mica-carbonate metasomatites.

The albitites (1) usually do not contain ores. The glimmerites (2) are composed of low and middle grade ores. The main resources are connected with the mica-carbonate metasomatites.

3.1. Vanadium mineralization

The main vanadium mineral is vanadian flogopite (roscoelite). Fine-scaly aggregates of the brown flogopite usually form the even dissemination and closely associate with dolomite. The size of the flogopite scales is about 0.00n mm, up to the first mm. The chromian micas are represented by green chromphengite, which mainly form streaky and streaky-disseminated aggregates. The content of vanadium pentoxide changes in flogopite from 8 to 22%, in chromphengite is connected with forming of micas with intermediate composition, but nevertheless the isomorfism between Cr and V is not fixed.



1-schungite aleurolites, 2-arkose aleurolites and tuffaleurolites, 3-dolomites, 4-fracture zones, 5-volumetric cataclasm zones, 6-copper-molybdenum mineralization in albite metasomatites, 7-uranium-vanadium ore mineralization in carbonate-mica metasomatites, 8-carbonate streaks with noble metal mineralization 9-hematite zones.

FIG. 1. Schematic geological cross section of U-V deposit Srednaya Padma.

A small amount of vanadium ore mineralization is related to vanadium hematite (it contains 1-10% of V), to vanadian oxides (nolanite and karelianite), to admite and to uranium-vanadates (carnotite, calciocarnotite).

The balance of vanadium resources distribution in the minerals is the following: micas — about 90%, hematite — 7%, oxides and uranium-vanadites — 3%.

3.2. Uranium Ore Mineralization

The uranium ore mineralization has a streaky-nest-disseminated form, uneven distribution and is connected with the carbonate-mica metasomatites. The maximal uranium concentrations are in the carbonate veins and veinlets.

The main uranium mineral is pitchblende. Usually the aggregates of the broken down spherolites of pitchblende cement carbonate and mica grains. The aggregates of coffinite are spread rather widely. They form the separate fine dissemination in the low-grade uranium ores or present with pitchblende. The nets and streaks of various hypergene uranium minerals (hydrous uranates of the curite group, silicates of the urophane group, uranium-vanadites of the carnotite group) are wide spread in the oxidation zone. An insignificant part of uranium mineralization is connected with the bladed aggregates of uranium-titanates which have a heterogeneous structure. The uranium content in titanates is only about 5-10%.

The proportions of the uranium minerals in ores are the following: pitchblende: 65%, coffinite: 15%, hypergene uranium minerals: 20%, uranium-titanates: less than 5%. The part of the pitchblende increases in the high grade uranium ores and the part of coffinite and hypergene minerals increases in the low grade ores.

3.3. Noble metal mineralization

The extremely uneven distribution is typical for the noble metal mineralization. The maximal concentrations are connected with the mica-carbonate veins. It is often represented by the exotic minerals from the group of bismuthides and selenides, such as weibullite, frudite, polarite. The inclusions of the native gold, intermetal and sulphoselenides of palladium and bismuth were found in the grains of clausthalite and other selenides [4]. The geochemical association with Cu, Bi, Ag and Se is typical for the noble metals [3].

3.4. Copper-molybdenum mineralization

The copper-molybdenum mineralization is usually met at the edge parts of U-V orebodies with low-grade ores or out of them (Fig. 1). Its distribution is irregular. The ore minerals are represented by chalcopyrite, chalcosine and molybdenite, which associates with pyrite, marcasite, sphalerite and galenite.

3.5. Chemical and mineral composition of ores

The silicate analysis of the mineralogical-technological samples and their statistical calculation confirm that the composition of the ore is changeable. The composition of the 1st and 2nd orebody differs slightly. The content of vanadium pentoxide in probes is changing from 0.93 to 4.8% (the mean is 2.3%) and of uranium from 0.005 to 0.21% (the mean is 0.064%). The main ore-composing minerals are albite, mica and carbonates. They make up about 85% of all (Table II). Albite usually prevails over other minerals (the mean content is 37%). The concentrations of carbonates change from

TABLE II. THE CHEMICAL AND MINERAL COMPOSITION OF THE ORES OF THE SREDNAYA PADMA DEPOSIT

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO
Mean :	46.522	.708	11.963	5.276	1.011	7.203	7.096
Minimum :	33.270	.270	6.550	2.580	.090	1.150	4.710
Maximumm :	58.940	1.350	15.490	12.780	5.350	13.590	11.230

	Na_2O	K_2O	P_2O_5	los.ign.	H_2O	C	V_2O_5
Mean :	4.194	2.578	.194	11.366	2.106	2.572	2.306
Minimum :	1.580	1.140	.020	6.330	.110	.140	.930
Maximum :	7.200	4.400	1.110	21.220	20.100	5.940	4.800

	carbonates	albite	micas	chlorite	quartz	hematite
Mean :	19.7	37.8	26.0	3.5	9.1	3.4
Minimum :	1.1	13.9	10.4	0	0.8	1.0
Maximum :	44.5	61.0	57.2	14.9	31.3	7.9

6 to 44% (the mean content is 21%). The main carbonate is the ferriferous dolomite. Its content varies from 1 to 41%. The calcite and ankerite are met as an impurity. The mean content of micas in ores is 26%.

The concentrations of the rare earths in ores are slightly abnormally high and their industrial significance is unimportant.

4. THE INFLUENCE OF THE COMPOSITION OF THE ORE ON THE PARAMETERS OF TECHNOLOGICAL PROCESSING

The technological research carried out in the institute by S.A. Pirkovsky proved that the most complete vanadium recovery was reached only by sulfuric pressure leaching. It was also established that the ores of Srednaya Padma are refractory by the vanadium recovery, easily uranium-recovered, and that the effectiveness of vanadium recovery is determined firstly by the parameter of the acid discharge of the ore.

The statistical evaluation of the MTM data allowed to determine the relationship of technological parameters and the mineral composition. The considerable correlation coefficients for the acid discharge were obtained with the carbonates — 0.565, and with K_2O — 0.48 (as the index of micas presence). The absolute maximum correlation coefficients for acid discharge (up to 0.743) were obtained with the special parameter of the product of carbonates into K_2O (Fig. 2), which indicates the intensiveness of the carbonate-mica metasomatism.

All known vanadium and uranium minerals were discovered in the after leaching cakes. Their incomplete recovery is explained by the finally disseminated inclusions of minerals in the insoluble ore-forming minerals.

5. MINERAL AND TECHNOLOGICAL ORE TYPES

The important task of the mineralogical-technological mapping is the determination of mineral and technological ore types.

The mineral type represents spatially isolated ores with typical mineral composition and technological properties.

The technological type is represented by the ores which can be separately mined and processed according to a special technological principally devised for them. The technological types are subdivided into technological ore grades. They are to be treated in uniform circuits but differ in technological characteristics

5.1. Mineral ore types

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 content and the correlation of the main ore minerals.

According to the composition of the ore-bearing rocks the ores belong to the composition of the carbonaceous type. They are subdivided into two varieties: with medium (10–20%) and large (more than 20%) carbonate contents (Fig. 3).

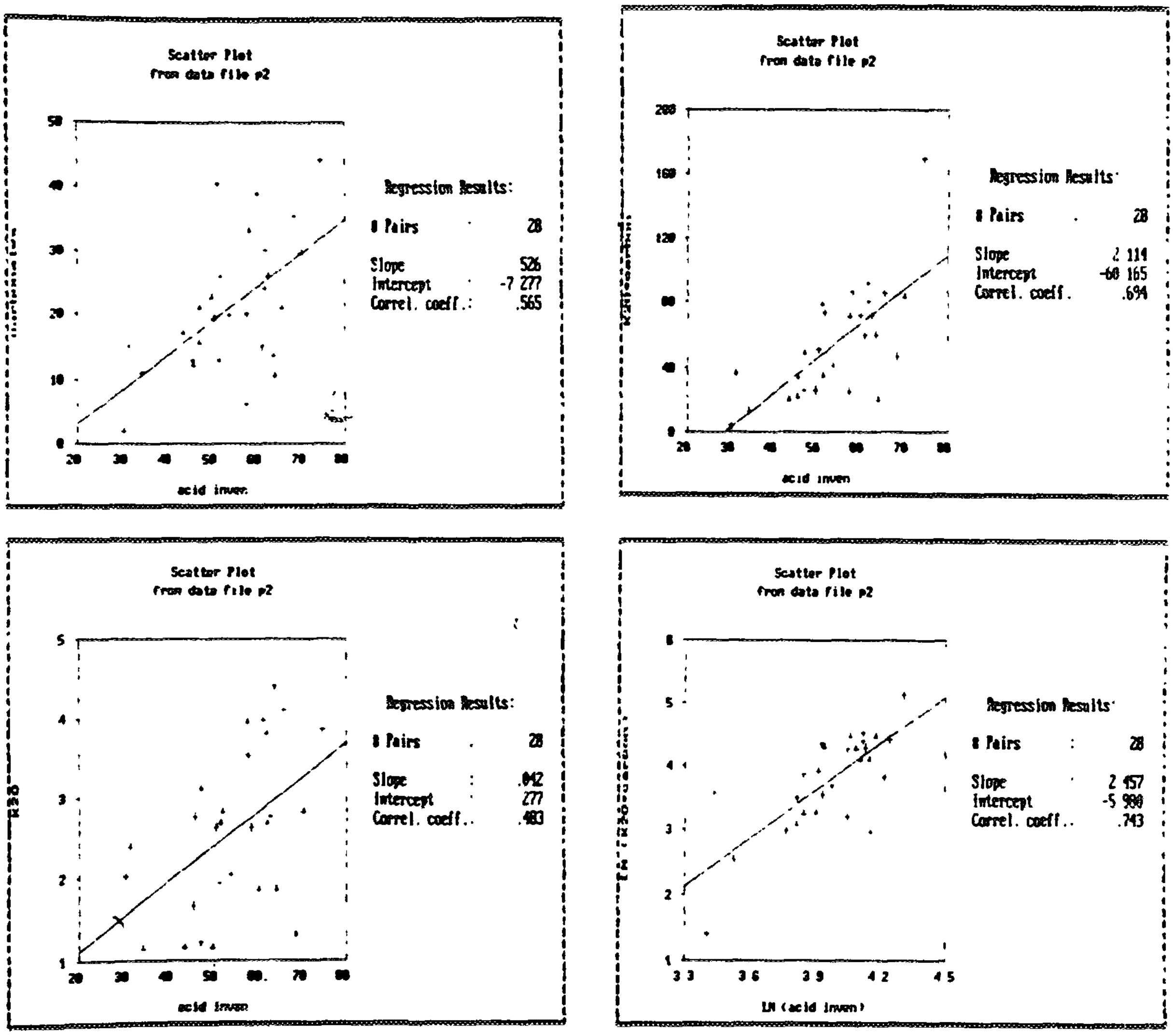


FIG. 2. The correlations between acid discharge and the mineral composition of the ores.

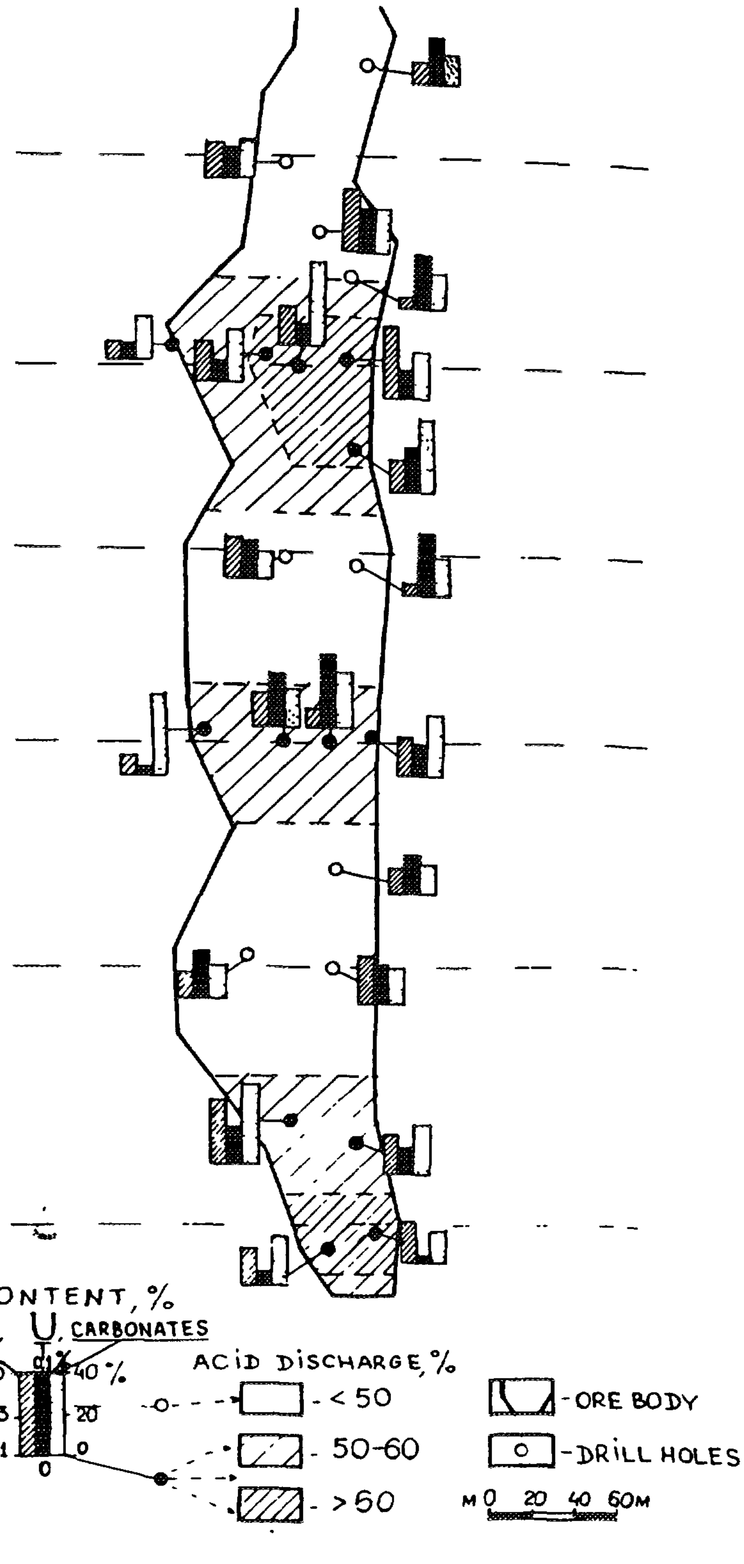


FIG. 3. *Projection of orebody 1 on horizontal plane. Some results of samples study.*

The main mineral type by the ore minerals correlation is the pitchblende-flogopite type, which forms most of the deposits resources with complex U-V ores. Other vanadium-containing and uranium minerals rarely prevail over V-flogopite and pitchblende respectively. Therefore, it is possible to single out only some mineralogical varieties of pitchblende-flogopite ores: with hematite, with chromphengite, with vanadium oxides, with coffinite, with uranium titanates.

Secondary U-V ores are spread along the fracture permeable zones. They are classified as a hypergeneous mineral type and favourable for leaching.

The presence of significant concentrations of by-components in ores made it possible to determine noble metal pitchblende-flogopite and sulphide-flogopite mineral types.

The delineation of ore types is not possible now under the existing rare sampling network.

5.2. Technological ore types

Technological ore types have been determined according to the contents of the main components and technological grades of ores — according to their acid discharge.

The main index determining the quality of the ores and technological scheme of processing is the contents of the value components and their spreading at the deposit. Delineation according to these features has been carried out by the geologists of "Geologorazvedka". These data show that the ores of the deposit are represented by the U-V technological type for which the technological scheme has been specially developed. The delineation of pure U or V ores into autonomous sites is presently impossible.

The ores with abnormally high concentrations of copper, molybdenum and nobel metals are classified as two separate technological types: uranium-vanadium type with gold, palladium and platinum, and vanadium type with copper and molybdenum. The development of the technological scheme for these ores is possible after their delineation on the stage of the detailed prospecting and taking of representative technological samples.

The ores of the deposit can be characterized as high in acid discharge (60%) of samples with acid discharge of more than 50%). Therefore two technological grades have been determined according to their acid discharge: acid-capacious (up to 50% of acid discharge) and high acid-capacious (above 50%) (Fig. 3).

6. THE PECULIARITIES OF THE OTHER U-V DEPOSITS

The mineralogical-technological studies have ben also carried out for 14 samples from the Kosmozero, Tzarevskoye and Vesenneye deposits, which, together with the Srednaya Padma deposit, can be considered as a single ore field (Table I).

6.1. Kosmozero Deposit

Several orebodies can be determined in the deposit. Orebody 1 is located in the breccia and cataclasm zone, in aleurolites and sandstones. Orebody 3 is in the cataclasm zone on the contact mica-carbonate and quartz-chlorite-carbonate schist with gabbro-diabase. The ore fragments are represented by albitized schists and glimmerites and the cement by quartz, carbonate and chlorite with sulphides.

6.2. Tzarevskoye Deposit

The deposit is situated in the anticline zone. The core of it is formed by terrigene-carbonate rocks and the wings by aleurolites. The rocks are intensively brecciated, mylonitizated and schisted. The tectonic activity was accompanied by hydrothermal-metasomatic and hypergenious processes. Two ore types are determined: carbonate in dolomites and silicate in aleurolites.

6.3. Vesenneye Deposit

Ores of the deposit are located in albite-carbonat-mica metasomatites and by the composition are similar to ores of the Srednaya Padma deposit. The exception are the ores of the third "non-uranium" orebody in the breccia zone on the contact of dolomites and the underlying terrigene-carbonate rocks. The vanadium micas are in the glimmerites and also in the breccia fractures and cement.

The research of the composition and technological qualities of ores of the Tzarevskoye, Vesenneye and Kosmozero deposits made it possible to find out that:

- the ores are mostly carbonaceous, ores in dolomites of the non-uranium 3rd body deposit Vesenneye belong to the high-carbonaceous type;
- the ores are mainly average grade by vanadium and low grade by uranium content, the main vanadium mineral is vanadian micas;
- high recovery of vanadium and uranium (97-99%) and high acid discharge was obtained for most samples;
- the high grade ores of the Kosmozero deposit with a considerable amount of vanadium oxides belong to the refractory grade by the technological properties.

7. CONCLUSION

The data obtained on the distribution of various mineral and technological ore types is important for maximal and complex recovery of the components. They must be used on the next stages of exploration of deposits in order to create an optimal programme for its development and for designing and processing facilities.

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GENETIC TYPES OF URANIUM DEPOSITS OF UKRAINE

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Abstract

There are three genetic classes of uranium deposits in Ukraine. Eight types of uranium deposits are described with reference to their genesis, age and geological position. The attributes of uranium concentration in Precambrian and Proterozoic periods of activization are shown.

The territory of Ukraine differs exclusive diversity of geological conditions where uranium concentrations were formed. The convincing proofs in kinds of isotopic age of formation of uranium minerals accumulations during nearly all geological history of considered territory from Lower Proterozoic to Upper Neogene (Table I) are present.

TABLE I. THE EPOCHS OF URANIUM ORE FORMATION WITHIN UKRAINE

Limits (Ga)	Main geological processes which led to ore formation	Examples of deposits and occurrences
2.4–2.6	sedimentation and metamorphism	Nikolo-Kozelskoye; Yugok
2.1–2.2	hydrothermal metasomatism	Chabankovskoye, Nikolaevskoye, Novoselskoye, Sergeevskoye, Georgievskoye
1.9–2.1	postultrametamorphic hydrothermal processes	Yuzhnoye, Lozovatskoye, Kalinovskoye, Znamenskoye, Yubileynoye
1.55–1.85	hydrothermal metasomatism	Maloanastasyevskoye, Perzhanskoye, Anatovskoye, Vladymirovskoye, Gvoszdavskoye, Pavlovskoye, Tankovoye, Krasnogvardeyskoye, Tokovskoye
0.5–0.6	hydrothermal matasomatism	Kovshilovskoye, Gorodokskoye, Rozanovskoye, Kasperovskoye, Bekkerovskoye, Yuzhnobelozerskoye
0.3–0.4	hydrothermal metasomatism, epigenetic exogenic filtration	Nikolaevskoye, separate veins at Zheltorechenskoye deposit, Novosvetskoye
0.1-0.2	sedimentation, diagenesis, hydrothermal metasomatism	Adamovskoye, Markovskoye, Svatovskoye, Gorskoye, Chapaevskoye, Dombrovenskoye, Vorobyevskoye, Novoodeskoye, Yavornikovoye
0.002–0.025	Exogenic filtration of fracture waters of basement rocks through upper coaly sediments	Bratskoye deposit, Verbovetskoye occurrence

Known uranium occurrences relate to some seventeen genetic types of three genetic classes: exogenous (sedimentary, exodiagenetic, epigenetic infiltration), endogenous (magmatic, pegmatic, hydrothermal metasomatic and lodes) and metamorphic (sedimentary metamorphosed).

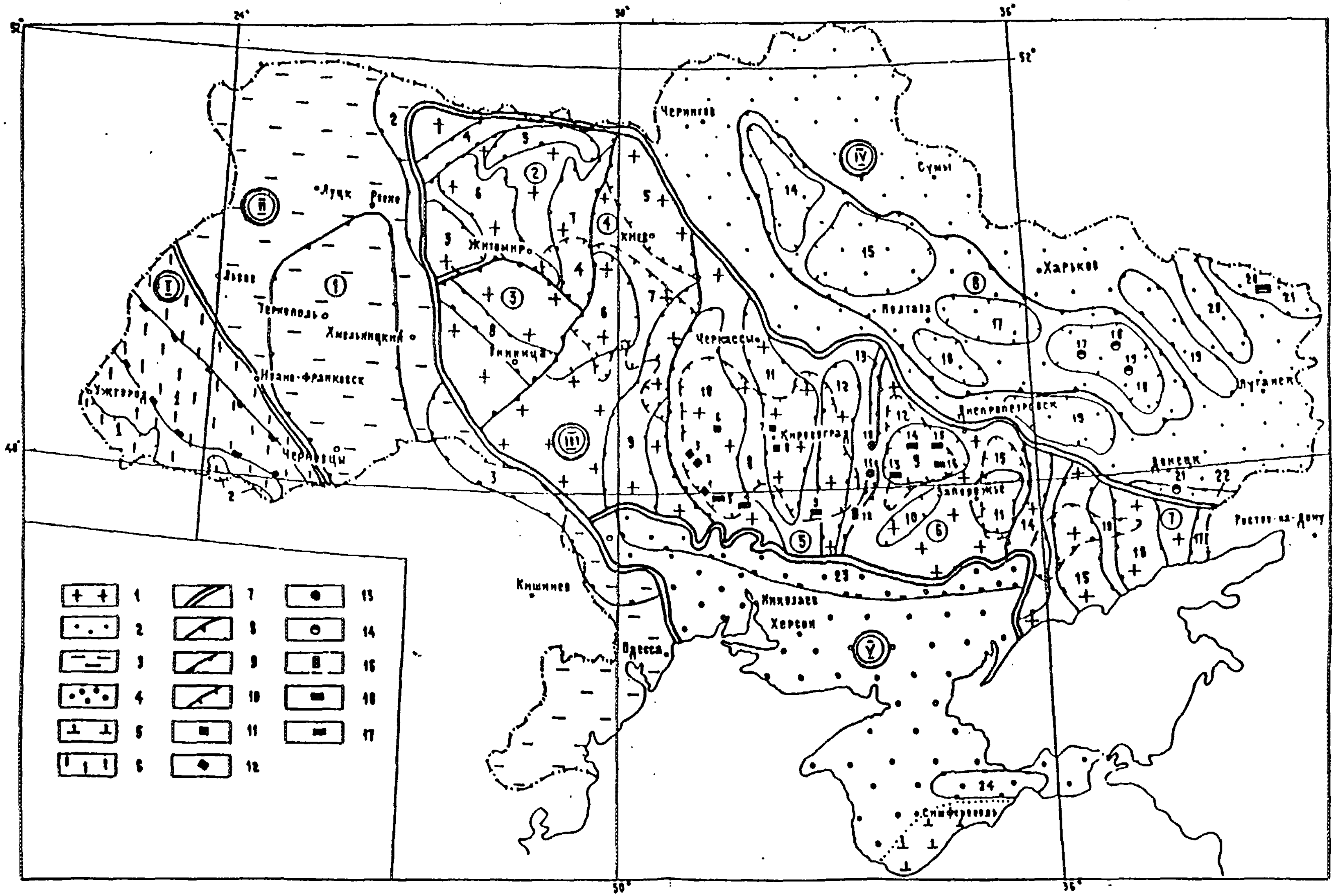

FIG. 1. Metallogenic scheme of the Ukrainian shield with respect to uranium.

Legend:

1-6 GEOLOGICAL REGIONS

1 Ukrainian shield
2 Don-Dnieper frough
3 Volin-Podolian plate
4 Black Sea maritime depression
5 Crimean mega-anticlinorium
6 Carpathian folded system

7-10 LIMITS OF METALLOGENIC DIVISIONS

7 province
8 region
9 zone
10 area

Limits of zones and areas within sedimentary cover of the Ukrainian shield are shown by a dotted line

11-17 GENETIC TYPES OF URANIUM DEPOSITS

11 hydrothermal-metasomatic deposits in carbonate-sodium metasomatites,
12 hydrothermal-metasomatic deposits in potassium metasomatites and pegmatoid granites,
13 hydrothermal deposits in mineralized zones of fracture basement rocks,
14 hydrothermal deposits in fracture zones of carbonate and terrigenous beds of depressions, cover of the shield and folded regions,
15 sedimentary metamorphic deposits in conglomerates and sandstones of crystalline basement,
16 sedimentary diagenetic deposits in coaly beds,
17 infiltration epigenetic deposits in particoloured terrigeous sediments associated with zones of oxidation-reduction

URANIUM DEPOSITS

1 Yuzhnoye
2 Kalinovskoye
3 Lozovatskoye
4 Bratskoye
5 Sadovo-Konstantinovskoye
6 Vatutinskoye
7 Severinskoye
8 Michurinskoye
9 Safonovskoye
10 Zheltorechenskoye
11 Pervomanskoye
12 Nikolo-Kozelskoye
13 Devladovskoye
14 Novoguryevskoye
15 Surskoye
16 Chernvonoyarskoye
17 Berekskoye
18 Krasnooskolskoye
19 Adamovskoye
20 Markovskoye
21 Nikolayesvskoye

METALLOGENIC (URANIUM-ORE) DIVISIONS

PROVINCES

I Carpathian
II Volin-Podolian
III Ukrainian shield
IV Don-Dnieper
V Crimean-Black Sea maritime

REGIONS

1 Ternopolskaya
2 Volinskaya
3 Podolskaya
4 Belotserkovskaya
5 Central Ukrainian (Kirovograd)
6 Dneprovskaya
7 Priazovsaya
8 Poltavskaya

ZONES

1 Samborsko-Yaremchenskaya
2 Sarnenskaya
3 Dnestrovskaya
4 Sushchano-Perzhanskaya
5 Ovruchskaya
6 Emilchinskaya
7 Radomishelskaya
8 Khmelnitskaya
9 Umanskaya
10 Brato-Zvenigorodskaya
11 Cherkasko-Kirovogradskaya
12 Zapadno-Inguletskaya
13 Krivorozhsko-Kremenchugskaya
14 Orehovo-Pavlogradskaya
15 Gulyaipolskaya
16 Maloonisolskaya
17 Elanchikskaya
18 Konkskaya
19 Lisichanskaya
20 Starobelskaya
21 Markovskaya
22 Volnovahskaya
23 Novoodesko-Molochanskaya
24 Kirovskaya

AREAS

1 Chop-Mukachsevsky
2 Rahovsko-Chivchinsky
3 Baranovsky
4 Khodorkovsky
5 Dimersky
6 Skvirsky
7 Tarashchansky
8 Vatutinsko-Alexandrisky
9 Sursko-Verhovtsevsky
10 Chertomliksky
11 Volnyansky
12 Devladovsky
13 Sinelnikovsky
14 Priluksky
15 Miragorodsky
16 Novosanzharsky
17 Karlovsky
18 Slavyansky
19 Pavlogradsky

Within Ukraine all three genetic classes are represented by uranium deposits of different ages and within various structures and lithological positions. According to genesis, age and geological position, the uranium deposits of Ukraine can be divided into eight types (Fig.):

1. Sedimentary metamorphosed deposits in sandstones and conglomerates associated with the initial stage of development of the Lower Proterozoic geosyncline in the central part of the Ukrainian shield.
   The isotopic age of ores is 2.4–2.6 Ga.
   Example: Nikolo-Kozelskoye deposit.

2. Hydrothermal-metasomatic deposits in pegmatoid granites associated with granitization during the finishing stage of the Lower Proterozoic geosynclinal cycle in the north-western, central and south-eastern parts of the Ukrainian shield.
   The age of ores is 1.9–2.0 Ga.
   Examples: Yuzhnoye, Lozovatskoye, Kalinovskoye deposits.

3. Hydrothermal-metasomatic deposits in albitites associated with the first Middle Proterozoic stage of tectonomagmatic activization following consolidation of Lower Proterozoic geosyncline in the central part of the Ukrainian shield.
   The isotopic age of ores is 1.55–1.8 Ga.
   Examples: Michurinskoye, Vatutinskoye, Severinskoye deposits.

4. Hydrothermal veins and impregnated deposits in tectonic breccias, as well as in folding, fracturing and layering zones in ferromagnesian and sodium metasomatites within Lower Proterozoic ferruginous quartzites and crystalline schists associated with the same period of the Middle Proterozoic tectonomagmatic activization.
   The age of the ores is 1.7–1.8 Ga.
   Examples: Pervomayskoye and Zheltorechenskoye deposits.

5. Hydrothermal subagree predominantly impregnated deposits in tectonic and altered sandstones of "white" Devonian connected with the intrusion of volcanic alkaline rocks within contact area between the folded Donets basin and the Ukrainian shield
   The isotopic age is 320 million years.
   Example: Nikolayevskoye deposit.

6. Sedimentary and exodiagenetic deposits in Lower Carbonic coaly sandstones, sometimes in limestones, aleurilites, argillites within the northern slope of the Dnieper-Donets depression. They are possibly processed with additional uranium intruding at Kimmeridgian time.
   The isotopic age of ores is 200 million years.
   Example: Markovskoye deposit.

7. Hydrothermal vein-impregnated deposits with subagree and crosscutting ore bodies in crushed and hydrothermal altered saturated by bitumens of petroleum series Upper Permian and Lower Triassic, seldom Carbonic, Lower Permian and Lower Jurassic sandstones directly within salt domes of Dnieper-Donets depression associated with Kimmeridgian tectonic activization.
   The age of ores is 180–200 million years.
   Examples: Adamovskoye, Krasnooskolskoye, Berekskoye deposits.

8. Epigenetic infiltration deposits in coaly Middle Paleogene sands filling tectonic depressions in the roof of Precambrian basement rocks of the Ukrainian shield associated with completion of Alpine orogenesis within the Mediterranean belt that has resulted in the formation of the Carpathian and Crimean mountains and in the rasing of the Ukrainian shield.
   The isotopic age of ores is 25 million years.
   Examples: Devladovskoye, Surskoye, Bratskoye, Safonovskoye deposits.

Taking into account the history of geological development of the earth's crust segment where Ukraine is located and known shows of uranium concentration, it is possible to assume that the prospects of discovery here new uranium deposits remain significant. Discovery of new deposits of all three genetic classes is possible.

Exogenic deposits of sedimentary, exodiagenetic and epigenetic infiltration types can be discovered in Carbonic coaly formation within the Donets basin, in Carbonic and Jurassic formations within the southern slope of the Dnieper-Donets depression, on the bottom of Lower Cretaceous formation within the southern slope of the Ukrainian shield, in Neogene formations in the Transcarpathian and Forecarpathian depressions, as well as in Paleogene-Neogene bitumen formations of the Carpathian and Crimean plain.

The genesis of new uranium deposits will be probably magmatic, pegmatitic and hydrothermal. As it is known, the first two of them have a practical significance only when uranium is in complex with other metals. The geological conditions answering to this requirement are observed in Ukraine.

Magmatic uranium deposits can be connected with the intrusions of Lower and Middle Proterozoic and Lower Paleozoic alkaline rocks including carbonatites in the eastern and south-western parts of the Ukrainian shield and within the contact area of the folded Donets basin and the Priazov block of the shield. Here uranium can associate with tantalum, niobium, zirconium, phosphorus.

Apparently pegmatitic and hydrothermal deposits in pegmatoid granites associate with intrusive and ultrametamorphic granitoids finishing the Early Proterozoic stage of the Ukrainian shield development. Therefore, they should be widespread in the central and north-western parts of the shield. Except for uranium these deposits can also contain thorium, rare earth elements, including the yttrium group and such rare metals as lithium, rubidium, tantalum.

The main prospects of increase of uranium resources in Ukraine must be connected with hydrothermal vein and vein-impregnated ores in fault zones which associate with five (three Precambrian and two Phanerozoic) periods of tectonic and tectono-magmatic activization. The attributes of uranium concentrations are already establish for all these periods.

The first of them with an age of ore formation of 2.1–2.2 Ga is stipulated by tectonic preparation to mass granitization of metamorphosed and folded rocks of Early Proterozoic geosynclines and to implantation of granite intrusions. The indicated process was widely displayed not only inside geosynclines but also in framing archeozoic formations — reflected activization. It was intensively developed in the western part of the Ukrainian shield.

The second period with an age of ore formation of 1.5–1.8 Ga is stipulated by large block-intrusions with complicated (from acid to basic) composition within formed Early Proterozoic geosynclines which are widespread in the central, north-western and south-western parts of the Ukrainian shield.

The third period with an age of ore formation of 0.8–1.2 Ga associates with formation and development of two avlakogenes within a consolidated platform. These avlakogenes set west, north-west and north-east limits of the present Ukrainian shield and provoked renewal of movements with intrusion of dykes and small-size intrusions through many faults in marginal parts and inside the shield.

Potential Phanerozoic uranium-ore periods of activization are connected with Hercynian and Kimmeridgian stages of tectonogenesis which took place in regions surrounding the Ukrainian shield. There are few attributes of uranium mineralization. Its perspective is defined by favourable geological conditions in the folded Donets basin, Carpathian mountains and Volin-Podolian plate. Numerous uranium occurrences of Kimmeridgian time (160–200 million years) are fixed in outcrops of old crystalline rocks of the Carpathian mountains, in various Upper Precambrian rocks and Lower Mesozoic rocks within the Dnieper-Donets depression and folded Donets basin.

The new deposits of metamorphic class, initially exogenic and endogenic, are most probably there where the structure of Lower Proterozoic geological formations has volcanogenic formations with acid and medium composition and where the metamorphic degree of these formations is minimal. The north-western part of the Ukrainian shield (teterevskaya series with novograd-volinskaya bed, leptite-clessovite of osnitskaya series) is equal to these conditions. The rocks of this region are thereto characterized by one of the highest uranium backgrounds in comparison to other regions of the Ukrainian shield.

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CLASSIFICATION SYSTEM OF THE MINERAL RESERVES AND RESOURCES OF UKRAINE

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Abstract

This paper describes the system used to classify the resources and reserves of all minerals and fuels in Ukraine. The classification system is part of an official procedure determined by the Ukrainian State Commission on Reserves. Following preparation of resource estimates the results are registered with the State, which maintains an official inventory of all mineral resources. This paper compares the Ukrainian system to, and finds it compatible with the United Nations International Framework of resource classification. The UN system is based on economics of production and mineability.

1. GENERAL CLAUSES

1.1. The classification defines the common principles of the calculation and state registration of the reserves and the estimation of mineral resources for the State Fund of Ukraine.

1.2. The prospected and preliminary estimates reserve of resources and also the perspective resources of oil and gas are calculated and registered in the State balance of the Ukrainian mineral resources based on the results of geological-exploration works (GEW). This includes all of test mining and drilling carried out during the process of commercial development of mineral deposits. The balanced and, conditionally balanced reserves and resources of solid, liquid and gas-like mineral resources are subjected, to state registration. These estimates underwent the examination and estimation of the Ukrainian State Commission on the reserves of mineral resources (SCR), and also the additional reserves discovered during deposit development. New deposits (fields) are added to the State balance according to the decisions of the State Commission of Reserves (SCR).

1.3. The perspective and prognosed estimated mineral resources are quantitatively estimated for the limits of all prospective areas based on the results of geological, geophysical, geochemical and other evaluation methods.

1.4. The reserves are calculated and registered, the resources are estimated separately for type of mineral resources and the direction of their commercial usage.

1.5 The reserves of the complex fields of the main and jointly bedded mineral resources and also the present useful components must undergo estimation and registration. The necessity of their commercial usage is established by the standards on mineral raw materials. The reserves of associated mineral resources and components are calculated and registered according to the "Demands of complex studying of the mineral resource deposits which are sent to the State examination estimation".

1.6. Quantitative estimation of prospective and prognosed resources is complex. For this aim the demands as to the quantity and quality of mineral resources and also the presence of useful components in them have been used. Is also necessary to take into consideration the standards of the known analogical deposits together with the possible changes of these demands in the nearest future.

1.7. Estimation and registration of the mineral reserves and the available useful commercial components are made in the case of their presence in the earth. Recoverable reserves of mineral resources are established according to the optimal system of development, which is substantiated by variational technical-economical calculations. These reserves include the losses during extraction, enrichment and processing of raw materials. The reserves of the associated useful components, which are accumulated during the processing of mineral raw materials in goods concentrates, products of metallurgical or another redistribution are calculated and registered so by the presence in the earth, as in the products and minerals which are extracted. For oil, gas-condensate, natural and dissolved gas and the other included useful components both the total and recoverable reserves are estimated and registered.

1.8 The estimation of the mineral resources quality is carried out according to the possible directions of their using correspondingly to the standards and demands of the acting standards and technical conditions and taking into consideration the technology for extracting and processing of the raw materials. At this point the composition of useful and harmful components, the forms of their location and the peculiarities of their distribution in the products of redistribution and waste materials of production are established.

1.9. Estimation and registration of the mass and volume of the reserves and quantitative evaluations of the mineral resources are made in the units of mass and volume. Exploitational reserves of underground waters are estimated and registered, and prognosed resources are evaluated in cubic metres per day. Steam-water mixture in tonnes per day. In industrial waters the quantity of components with commercial value (in tonnes) is established. These components may be obtained in the deposits during the calculation terms of its development without taking into consideration the losses during waters processing. By the deposits of heat-energetic waters, except the exploitational reserves, the heat-energetic power of the field is estimated (in gigajoule, megawatt, tonnes of conditional fuel).

1.10. The application of this classification for different kinds of mineral resources is regulated by the corresponding instructions of the Ukrainian State Commission on the reserves of mineral resources.

2. CLASSES OF MINERAL RESERVES AND RESOURCES BY THE DEGREE OF THEIR STUDYING AND TRUSTWORTHINESS

2.1. Mineral resources that are evaluated based on geological data studying in the areas of the earth, on the earth's surface, in the water and gas sources and on the bottom of water reservoirs as good for commercial exploitation by the conditions of bedding, quantity and quality compose the current mineral resources, and together with the accumulated production — the initial mineral resources of the objects of geological investigation.

2.2. Depending on their determination mineral resources are subdivided into the reserves of mineral resources of the discovered deposits (pools) and the mineral resources of the undiscovered deposits (pools) in the perspective areas of the earth.

2.3. Depending on the degree of geological study completed mineral resources are subdivided into two classes: prospected (proved) and preliminary estimated (probable).

2.4. Prospected (proved) reserves of mineral resources are the reserves with quantity, quality, technological properties, mining-geological, hydrogeological and other conditions of bedding were studied in the degree suitable for their commercial exploitation. The main parameters of the prospected reserves, which stipulate the project decisions as to the production and processing of raw materials and environment prospection, are established by the data of immediate measurements or investigations done by the uniform volumetrical network in the contours of the deposits with the limited extrapolation, based on the data of geological, geophysical, geochemical and other investigations. The main predestination of the prospected reserves is the projecting of the building of mining enterprises and the fields development.

2.5. The preliminary estimated (probable) reserves of the mineral resources are the reserves of which quantity, quality, technological properties, mining-geological, hydrogeological and other conditions of the bedding that have been studied to the degree suitable for the technical-economical evaluation for either commercial exploitation or test-commercial development. The main parameters of the preliminary estimated reserves of mineral resources, which influence the choice of methods of extracting and processing the war materials, are estimated mainly on the basis of the data extrapolation of measurements or investigations, located in the field limits by rare or uneven network. Extrapolation is grounded by the analogy with the prospected pools (deposits), and also by the data of geological, geophysical, geochemical studying bowels of the earth. The main purpose of the preliminary estimated reserves is the projecting of further prospecting of test-commercial development of the field and its preparation for the commercial exploitation.

2.6. Depending on the degree of geological study and reliability of the mineral resources of perspective underground deposits are subdivided into two classes: perspective and prognosed.

2.7. Perspective mineral resources are the resources of certain geological commercial type, quantitatively estimated based on results of geological study in the limits of productive regions with the known fields of mineral resources of the same geological-commercial type. Perspective resources take into consideration the possibility of discovering of the new deposits (pools) of mineral resources, the existence of which is stipulated by the positive evaluation of the established existance of mineral resources, geophysical, geochemical and other anomalies whose nature and perspectiveness are proven. Quantitative evaluations of the deposit (pool) parameters are determined on the basis of geological interpretation of geophysical and geochemical data or statistical analogy. The main use of the perspective resource estimation is planning prospecting and exploration.

2.8. Prognosed mineral resources are the resources that take into consideration the potential possibility of the fields forming of certain geological-commercial types, based on positive stratigraphical, paleographical, lithological, tectonical, mineraogenic and other preconditions, established in the limits of regional geological structures with undiscovered commercial fields. Quantitative evaluation of the prognosed resources is done on the basis of assumed similar parameters with the analogous geologic structures where discovered deposits of mineral resources of the same geological-commercial type. The main use of the prognosed resources is planning of regional and prognosing-geological works.

2.9. The instructions for using the classification for the deposits of separate kinds of mineral resources define the categories of explored deposits of the mineral resources in the limits of classes by the degree of geological studying and trustworthiness.

3. RESERVES AND RESOURCES GROUPS BY THE DEGREE OF THEIR PREINVESTMENT STUDY

3.1. Rational and effective geological study of the subsurface earth with the aim of discovering or prospecting the mineral resources deposits envisages the optimal succession of geological-exploration works (GEW). In order to determine the expediency of investing the next stage of geological-exploration works or the building of mining enterprise the geological-economical evaluation (GEE) of the objects of geological studying are done. Pre-investment studies of these objects envisage the establishing in detail of mining-geological, technological and technical-economical characteristics of the mineral resources deposits, and also the social, ecological, lawful and other conditions of the field development and the realization of raw materials or the products of their processing.

3.2. The primary geological-economical evaluation (GEE-I) is done for the basing of expediency of the investing the exploration-prospecting works in the earth's areas perspective for discovery of mineral resources. GEE-I is carried out on the grounds of qualitative evaluation of perspective resources and is given in the form of technical-economical suppositions (TESp) as to their possible commercial importance.

3.3. The preliminary geological-economical evaluation (GEE-II) is done with the aim of basing the expediency of commercial exploitation of the deposit (area) of mineral resources and the investing of successive prospecting and preparation for their development. GEE-II is done on the ground of the preliminary evaluated reserves of mineral resources and is given in the form of technical-economical report (TER) on the expediency of further prospecting or test-commercial development of the deposit (area).

3.4. The detailed geological-economical evaluation (GEE-III) is done with the aim of establishing the industrial activity effectiveness of the mining enterprise, which is created on the basis of prospected reserves of mineral resources and includes the technical-economical substantiation (TES) of the standards for their evaluation.

3.5. Thus the mineral reserves and resources by the degree of their preinvestment studying are divided into three groups:

- 3.5.1. To the first group the reserves of mineral resources are related reserves, on the basis of which the detailed geological-economical evaluation (GEE-III) is done of the effectiveness of commercial activity of mining enterprise which is projected for their development. The materials of GEE-III, including TES of stable standards for mineral raw materials, underwent the examination and were estimated by the Ukrainian State Commission on the reserves of mineral resources.

- 3.5.2. To the second group the reserves of mineral resources are related reserves on the basis of which the preliminary geological-economical evaluation (GEE-II) of their commercial importance is done. The TER materials on the expediency of the field further prospecting, including TES of temporary standards of mineral raw materials, underwent the examination and were approved by the Ukrainian State Commission on the reserves of mineral resources or by the client (investor) of the exploration works.

- 3.5.3. To the third group of the resources and reserves of mineral resources are related these, on the basis of which the primary geological-economical evaluation (GEE-I) of the possible commercial importance of the earth's perspective area is done. The TES materials on the expediency of further exploration works and the parameters of recommended standards for mineral raw materials underwent the examination and were approved by the client (investor) of exploration works or the Ukrainian State Commission on the reserves of mineral resources.

4. RESERVES GROUPS BY THEIR COMMERCIAL IMPORTANCE

The classes of mineral resources and useful components are divided into three groups: their commercial importance

- balanced,
- conditionally balanced,
- out of balance.

4.1. *Balanced* reserves are reserves that at the moment of evaluation accordingly to the technical-economical calculations *may be economically extracted and used with modern techniques and technology of production and processing* of the raw materials, which provide the keeping of demands of the rational using of the *bowels* and the protection of natural environment.

4.2. *Conditionally balanced* reserves are reserves the effectiveness and production and using of which at the moment of evaluation cannot be precisely established, and also the reserves that correspond to the demands for the balanced reserves, *but cannot be used because* of unsolved, unlawful, ecological and other questions.

4.3. Reserves out of balance are reserves the production and using of which at the moment of evaluation are not economically justified. However, in future they may become of commercial importance.

4.4. Only in their balance perspective and prognosed resources are evaluated on the basis of assumed parameters only in their balance part. Out of balance and conditionally balanced components of perspective and prognosed resources are not estimated.

5. GROUPS OF MINERAL RESOURCES DEPOSITS BY THE COMPLEXITY OF THEIR GEOLOGICAL STRUCTURE

5.1. By the complexity of geological structure the deposits of mineral resources or their areas, which are envisaged for the development by individual enterprises, are divided into four groups:

- 5.1.1. To the first group belong deposits (areas) of simple geological structures with undeformed or weakly deformed bedding of the deposit, consistent quantitative or qualitative parameters of the mineral resources pools, even distribution of the main useful and harmful components.

- 5.1.2. To the second group belong deposits (areas) of complex geological structure with inconsistent quantitative or qualitative parameters of the pools of mineral resources, uneven distribution of the main useful of harmful components.

- 5.1.3. To the third group belong deposits (areas) of very complex geological structure with changing quantitative of qualitative parameters of the reserves of mineral resources, very uneven distribution of the main useful or harmful components.

- 5.1.4. To the fourth group belong deposits of extremely complex geological structure with sharply changing quantitative or qualitative parameters of the deposit of mineral resources, with absolutely uneven distribution of the main useful or harmful components.

5.2. During the determination of the geological structure complexity in the field are used the indices of changing of the main deposit parameters which contain no less than 70% of the raw material reserves.

5.3. The instructions for using the classification for different kinds of mineral resources envisage the using of quantitative evaluations of changing of the mineral resources pools parameters and the indices of the raw materials quality for the establishing the groups of complexity of the field (area) geological structure.

6. PREPARATION OF THE MINERAL RESOURCES DEPOSITS (AREA) FOR COMMERCIAL EXPLOITATION

6.1. The state of preparation of mineral resources for commercial exploitation is determined by the decisions of the Ukrainian State Commission on the Reserves of Mineral Resources. The decision is made following examinations of the materials of geological-economical estimations of the deposits (areas) of mineral resources, taking into consideration the conclusions of the clients and performers of geological surveys, the investors of the mining facilities construction, which are projected on the basis of these reserves, and also the demands of the legislation of nature protection and the legislation on the earth's bowels.

6.2. The state of geological study of the reserves of the deposits (areas) mineral resources, which are prepared to the commercial exploitation and are transferred to the users of the bowels must correspond to the following conditions:

6.2.1. Balanced reserves of the main and jointly bedded mineral resources and the available in the adjoining useful components of commercial importance were estimated by the Ukrainian State Commission on the Reserves of Mineral Resources.

6.2.2. The volumes of total reserves and resources of the field (area) in its geological limits were established as to the degree of their geological studying, reserves and resources of the neighbouring undeveloped fields of mineral resources which are taken into consideration at the projecting of construction (reconstruction) the mining objects for the establishing of possible perspectives of the enterprise development, the bordering depth and the development area, the choice of the way of uncovering the pools' mineral resources, the places of laying of the mine shafts, the location of industrial constructions, access roads and so on.

6.2.3. The volumes of balance prospected and preliminary evaluated reserves of mineral resources were established which are used for the projecting of construction (reconstruction) of the mining objects, the possibility of these reserves development is substantiated without damage for the mineral resources pools which are left in the earth's bowels.

6.2.4. The quantity of the prospected reserves of the first class of geological studies provides the activity of mining objects for the period of returning of capital investments into prospecting and commercial exploitation of the field.

6.2.5. The dangerous ecological factors are established and estimated which influence or may influence the state of natural environment and human health during prospecting and development of the field, processing of raw materials, storage of industrial waste; the rational complex of the measures as to environment protection and the people's health is worked out; the background parameters of the environment state are established; preliminary consent are obtained for special use of plots of land with the aim of the mineral resources extraction according to the legislation.

6.2.6. The profitableness of industrial activity of mining object is grounded by technical-economical estimations which is projected on the basis of the reserves of mineral resources established by the State examination, taking into consideration the expenses for additional prospecting of mineral resources, the effectiveness of capital investments into the field (area) development is provided at the level of income average norm.

6.3. For the projecting of construction of mining and processing objects in the field of the first and second groups of the geological structure complexity the prospected reserves of mineral resources of the first class of geological studying are used; in the fields of the third and fourth groups of the geological structure complexity the prospected and preliminary estimated reserves of mineral resources of the first and second class of geological studying in the ratio which is determined by the instructions of the classification as to the separate kinds of mineral resources.

6.4. By the agreement of the interested users of the earth's bowels under conditions of economical risk the transfer of the preliminary estimated reserves of the deposits of mineral resources may be realized before their examination and estimation by the Ukrainian State Commission on the reserves of mineral resources with following obligatory estimation. In such cases the reserves studying, which are transferred to commercial exploitation, may not correspond to the demands of points 6.2 and 6.3 of this classification, on condition that geological studying provides the establishing

TABLE I. CORRELATIONS OF UKRAINIAN CLASSIFICATION OF RESERVES AND RESOURCES OF MINERAL RESOURCES WITH INTERNATIONAL FRAMEWORK FOR CLASSIFICATION OF RESERVES AND RESOURCES

UN International → Framework ↓		Detailed exploration	General exploration	Prospecting	Reconnaissance
	Ukrainian system	Class 1 explored	Class 2 preliminary estimated reserves (probable)	Class 3 prospective resources	Class 4 forecast resources
Feasibility study	detailed preinvestment estimation (TES)	1. (1.1.1) 2. (1.1.2) 3. (1.1.3)	usually do no		
Prefeasibility study	preliminary preinvestment estimation (TER)	1. (1.2.1) 2. (1.2.2. 3. (1.2.3)	1. (2.2.1) 2. (2.2.2) 3. (2.2.3)	singled out	
Geological study	primary preinvestment estimation (TESp)		1-3 (2.3.1-3)	1 (3.3.1)	1 (4.3.1)

Mineability

UN Framework

1. Economic
2. Marginally economic
3. Subeconomic

1-3. Economic-subeconomic

Commercial meaning

Ukrainian system

1. Balanced
2. Conditionally balanced
3. Out of balance

1-3. Indivisible balance and out of balance

(1.1.1) –
Figure indices of reserves and resources

and evaluation of harmful ecological factors connected with the deposit exploitation, according to point 6.2.5.

6.5. In the deposits which are brought into development the additional prospecting and exploitation prospecting are carried out.

6.5.1. The additional prospecting of the developed deposits is carried out in their insufficiently studied parts (flanks, deep or upper horizons, separated areas, etc.) and is done consequently according to the plans of productive works.

6.5.2. The exploitation prospecting which leaves behind the development of productive works, must specify the data on morphology, inner structure, conditions of the pools bedding and development and the quality of their mineral resources by data of drilling the additional wells and of hole-making of the mining-preparatory and other workings. The exploitation prospecting, which accompanies the productive works, must specify the quantitative and qualitative indices of the mineral resources pools by data of drilling and investigations in development and regime wells, investigations in the cleaning mining workings, etc.

6.5.3. In the result of carrying out the additional prospecting and exploitation prospecting of the deposits (areas) of the developed mineral resources the transferring of preliminary evaluated reserves into prospected ones, and also the calculation and registration of the established reserves are made.

6.6. In the developed deposits of mineral resources the uncovered, prepared, ready for extraction and also being present in the protecting pillows of mining-capital and mining-preparatory workings of the reserves of mineral resources are estimated and registered separately with their dividing into classes and groups according to the degree of geological studying and their commercial meaning.

6.7. The recalculation and the examination of the reserves of mineral resources are made by the State in the following cases:

- if in the result of mining or additional exploration works or the investigations as to the pool regime of mineral resources in the developed deposits the summary prospected balance reserves increases for more than 50% in comparison to the preliminary evaluated ones by the Ukrainian State Commission on the reserves of mineral resources, or if the written-off and envisaged for the writing off the prospected reserves as those that were not proved or inexpedient for production by technical-economical (mining-technical) reasons, exceed the norms established by legislation;

- if the revision of the standards demands and technical conditions as to the quality and quantity of mineral resources, the technology of their processing leads to decreasing of summary balance prospected reserves of the deposits of mineral resources of more than 20% or their increasing for more than 50%.

- if the exceeding of real terms of exploitation of the deposit (area) reserves of mineral resources over the adopted ones at heir State examination and evaluation is reached in the extent that leads to the reconstruction of mining objects in connection with the changing of exploitation conditions.

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EVOLUTION OF URANIUM FORMATION IN PRECAMBRIAN OF UKRAINE

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Abstract

The physical and chemical processes of uranium ore formation are used to describe the evolution of Precambrian age uranium deposits of the Ukraine. The processes controlling increasing migration of uranium in the environment are identified. These process are associated with two periods in the Precambrian: late Archean and early Proterozoic. Geochemical and isotopic evidence based on samples from uranium deposits are discussed.

The processes of increasing of uranium migration activity and changing of its partition coefficient between solid phase and fluid to favour of last are dated as late Archean, it connected with growth of water partial pressure. During this stage at temperatures of over 400°C chloride, phosphatic and hydratic complexes were dominated for uranium transportation. According to our experimental research, the most effective uranium transfer could be carried out by chloride complexes of iron as well as calcium and magnesium. On the inclusion data such fluids have been seen exocontact zones around field of late Archean granitization. Superfluous chemical elements were removed from those zones to form iron-magnesium metasomatites, iron ore deposits and plagiomigmatites in perpheral zones. At the Ukrainian Shield alike rock series most fully represented near the village of Petrovo (North Krivorozye), where uranium content in iron-magensium metasomatic rocks reaches $n \times 10^{-1}$ to 10^{-2}%. At the granites of Dneprovsky block many biotite lenses with uranium-containing monazite and xenotime were found. Regionally enumerated processes are connected with formation of thermal-cupola structures, which are framed by greenstone belts. Its isotopic age is 2900–2500 m. years.

The second stage of uranium regeneration was early Proterozoic. At that time at the Ukrainian Shield trough structures of different scale were born and developed. Krivorozsko-Kremenchugskaya belt is the best known example. Lower (arkosic-conglomerate) and upper (organic-enriched) rock benches of that belt are essentially uranium-bearing. Under metamorphism of those rocks uranium ore deposits with uranium content near 1% have been formed. Examples: some deposits of Zoltorechemskoye and ore deposit Thervony Shahtar. Their isotopic age is 2200–2000 m. years.

The most productive stage of uranium deposition in Ukraine is the stage of albitization. The isotopic age of ore deposits is 1750–1800 m. years. The albitization processes are connected with early Proterozoic microclinization processes, which have very wide development and are well-known at all Precambrian shields (so-called "potassium explosion"). We believe that they were a result of an applied endogenous wave which was born by increasing of upper mantle volume. All geological events caused by that wave in the upper beds of the earth's crust determine the division border Upper Archean-Lower Porterozoic. Natrium metasomatism processes separate from metapepsis processes in 250–300 m. years. Basification processes connected with enlargement in lower beds of earth crust were accompanied by removing of potassium from them. It spent for microclinite formation and natrium released from rocks spent for albitization. There was the evolution of polychronic system which had a large vertical stretch and where early chloride fluid changed by late carbonate solution.

Isotopic (S, C, O, H) study of the albitite uranium deposits of the Ukrainian Shield shows ore forming system polygenesis. At the natrium- carbonate metasomatism formation beside metamorphogeneous solution descending isotopically light oxygen meteoric water took part in fluid composition. The meteoric water role was increasing during the process. Carbon, sulfur and, in accordance with lead-isotopic research, uranium mainly took out from host rocks. At the same time there are evidences of sulphur and carbon entrance into tectonic-metasomatic zones by ascending depth emissions during diaphthoresis and especially at the period of ore formation. In temperature diapason 200–300°C isotopic balance at system: sightly ore albite of early association-water was established. Then it was broken when the productive (ore) mineral associations were formed. Probably it was due to the complexity of geological systems, exactly to combination of metamorphogenous-metasomatic surroundings, depth emissions, meteoric water, that ore-controlling geochemical barriers in tectonic-metasomatic zones appeared. Those barriers were fixed by isotopic data.

To solve this problem, isotopic-geochemical research was concentrated on the borders of representative sections of slightly eroded deposits where overlying ore, underlying and rooted parts of tectonic-metasomatic zones were revealed (Severinovskoye, Vatutinskoye and other ore deposits).

The sulphur, carbon and oxygen isotope distribution at minerals of uranium-containing metasomatites have fixed the presence of lateral and vertical isotopic-geochemical zonality.

Lateral zonality causes by position of natrium-carbonate metasomatite aureoles at tectonic-metasomatic zones and by changing of isotopic parameters from host rocks and diaphthorites to albitites and ore deposits. At all parts of zones the tendencies of isotopic parameter changing are stable. There are considerable sulfur and oxygen lightening and carbon getting heavy with simultaneous increasing of last quantity.

Vertical zonality is discovered under isotopic comparison of uranium-containing albitites at different levels. Extreme significances of isotopic characteristics as an indication of metasomatic process maximum intensity coincides with the most productive ore parts of zones. Over- and underlying parts isotopically are equal but carbonates with heavy (σ^{18}) > 16%) oxygen are present at the first and absent at the second. At the rooted parts of metasomatic zones the isotopic parameter changing is minimal. On the whole the changing curves of all isotopic parameters and linear productivity are identical.

The albitite ratio Fe_2O_3/FeO at the sections changes similarly, reaching the maximum (2.64–3.34) at the ore part levels and decreasing to 0.82–1.40 at the zone rooted parts. Thus the existence of reduced-oxidative geochemical barriers are confirmed. The localization of uranium ore deposits are determined by oxidation possibility of Fe-containing mineral iron. The process intensity depends on the degree of iron oxidation.

On the basis of isotopic zonality it is possible upon the extreme significances of isotopic characteristics to conclude about deposition depth of the most productive ore deposits (at the studying objects the depth is from 220–340 to 900–930 m). The comparison of isotopic parameters at the different zone parts also allows to conclude about levels of its erosion.

The question about combination of endogenous and exogenous factors of uranium ore deposits formation is still discussed. We concede the exogenous factor influences at rich ore formation, but at the same time suppose that such ore could form by endogenous way.

Thus uranium ore deposit formation in Precambrian Ukraine connected with the repeated uranium regeneration at the time interval Upper Archean-Lower Proterozoic. This regeneration caused to endogenous and exogenous processes, leading to earth crust differentiation: the entrance to crust of additional chemical elements which removed from the division sphere crust-upper mantle during rise of its border. Maximum element removing with their fixation at upper beds of earth crust was at the mantle projection exocontacts. On isotopic data mantle projection rise were polystage process and took place for a long time. Uranium regeneration and deposition to ore concentrates happened at some stages, the rich ore deposits formed at late stages. We suppose that the contrast rich ore deposits could form if late metasomatites laid on uranium-bearing albitites.

TWO MAIN TYPES OF URANIUM DEPOSIT WITHIN PHANEROZOIC FORMATIONS OF UKRAINE

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Abstract

The two main types of uranium deposits occurring within Phanerozoic formations of Ukraine are described. They consist of uraniferous bearing bitumen in the Upper Carboniferous to Lower Triassic red beds, and infiltration (roll front type) uranium ores, occurring in the sediments filling ancient Paleogene river valleys. The first deposit type include black to dark brown beds of disseminated to massive bitumen occurring respectively as ozyantraxolite and oxykerite. These beds include uranium, as well as other metals. This uranium mineralization is dated at 195 to 200 million years old. The second type includes infiltration deposits in Paleogene coal bearing sediments, with the uranium mineralization occurring in the upper part of the sequence. The sediments occur within paleovalleys eroded into the underlying crystalline basement of the Ukrainian shield and its weathered crust. The paleovalleys extend to a depth of 70 to 90 metres. The coal bearing sediments are overlain by sediments of younger age. Several uranium deposits of the second type are known, including a few identified as being of industrial grade.

1. INTRODUCTION

Phanerozoic deposits surround the Ukrainian shield. They form the platform mantle of the Volyno-Podolian plate, fill the Dnipro-Donets and the Nearblacksea depressions and participate in the structures of Donets, Dobrugia-Crimea and Carpathian folded areas (Fig. 1). Cenozoic deposits from a thin cover over the Ukrainian shield.

Several uranium deposits and numerous ore manifestations are known within sedimentary formations. Increased uranium concentrations within terrestrial deposits of the Middle Devonian and Lower Cretaceous appear near outcrops of the Pre-Cambrian crystalline rocks. There are the uraniferous coals in the Middle Carboniferous deposits on the south slope of Voronezh crystalline rock mass. The oil and gas-bearing Dnipro-Donets depression is characterized by widespread uraniferous bitumen deposits and smaller uraniferous manifestations. There are also commercial uranium deposits in the Eocene sedimentary rock of the shield cover. They are located in the Dnipro lignite basin.

Two main types of uranium deposits within the Phanerozoic formations are recognized by the importance of their uranium concentrations. There are uraniferous bitumen in the Upper Carboniferous to Lower Triassic red beds and infiltration uranium ores in the ancient Paleogene river valley.

2. URANIFEROUS BITUMEN DEPOSITS

The Adamovskoe deposit is typical representative of the uranium-bitumen deposits. It is part of the south-eastern Dnipro-Donets depression. That depression is filled by carboniferous, Lower Permian, Triassic, Jurassic, Cretaceous and Palogene sediments. They overlie the rift which is filled by thick Devonian terrigenous, saliferous and effusive formations.

The Devonian salt deposits which lies at the basis of anticlines and structural swells form numerous diapir and salt domes (Fig. 2). The uranium-bitumen mineralization is associated with these structures.

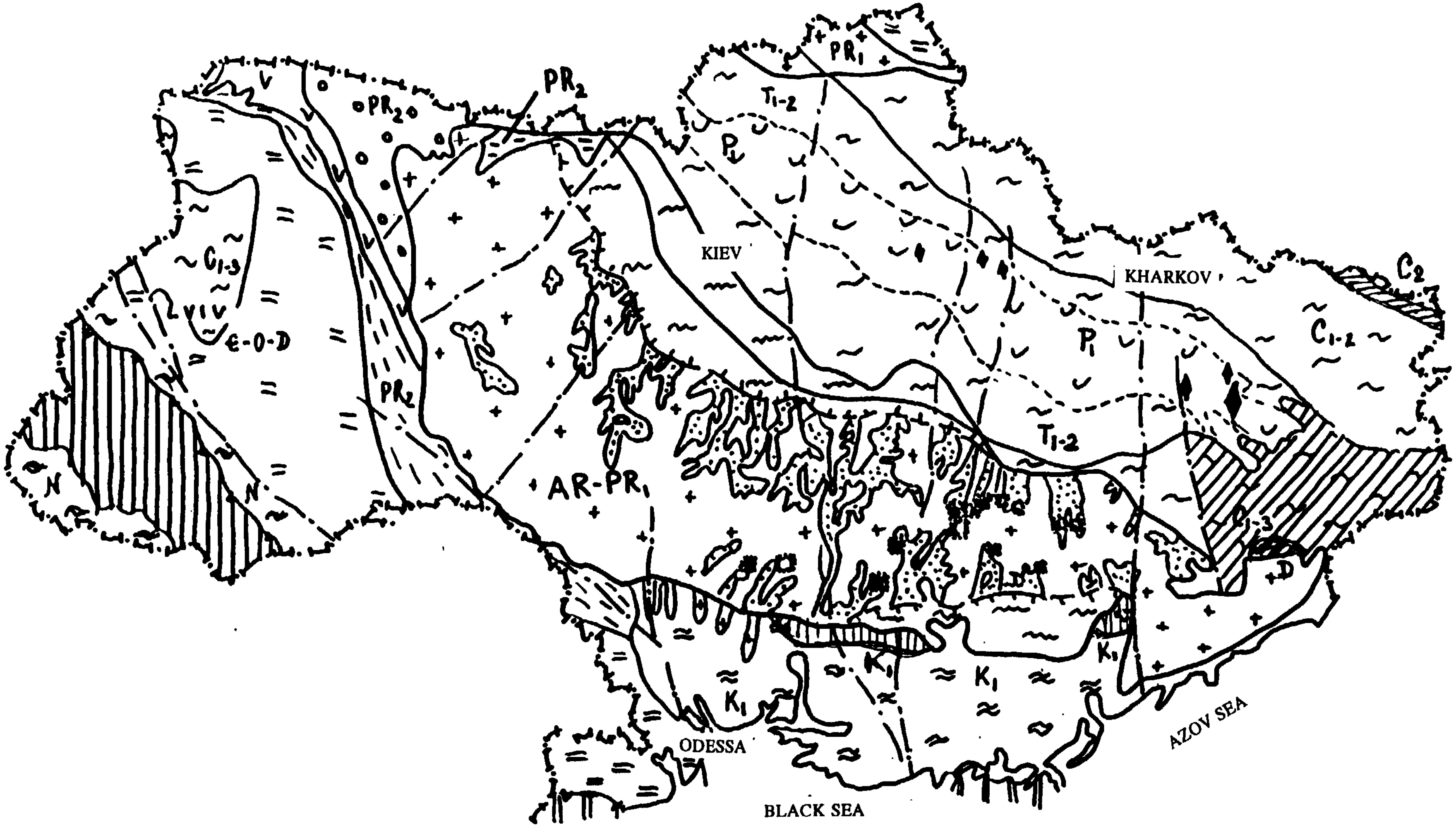

FIG. 1. Map of the uraniferous sedimentary structures in Ukraine and Moldova.

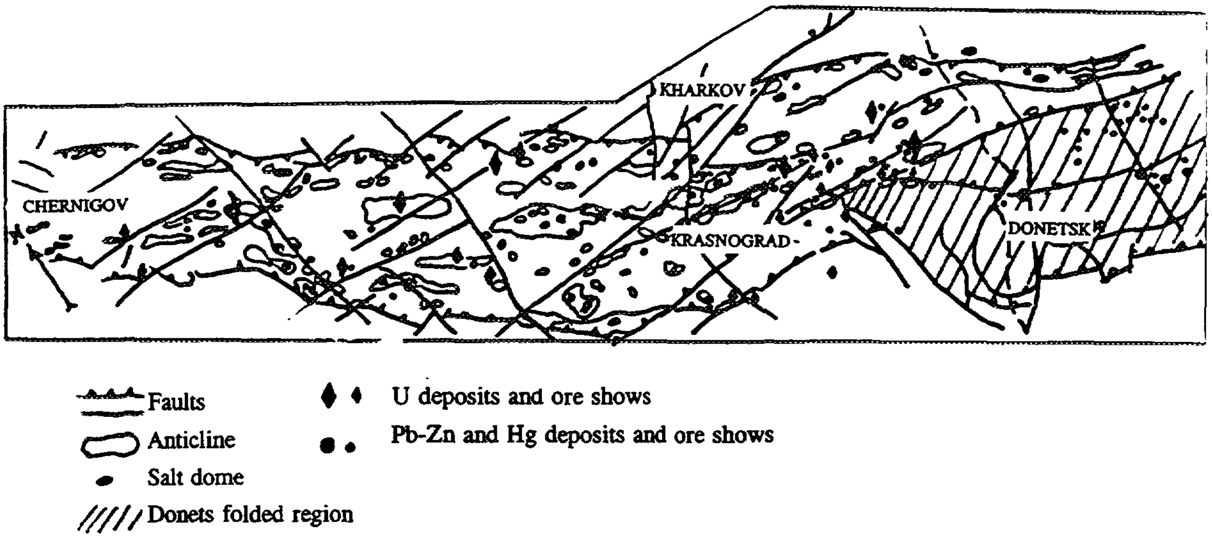

FIG. 2. The scheme of the uranium deposits distribution in the Dnipro-Donets depression.

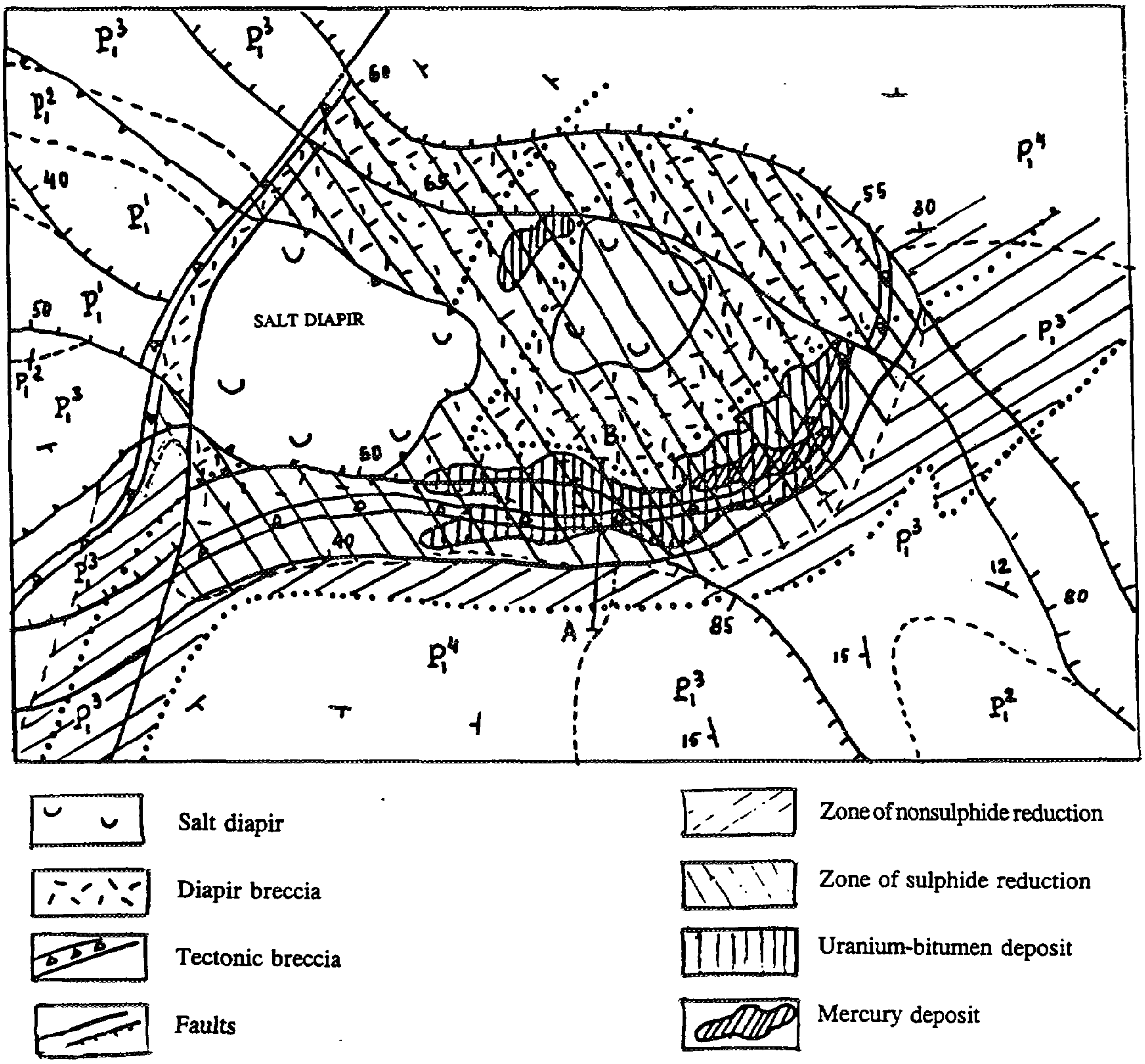

FIG. 3. Map of the ore-controlling epigenetic zoning of the Adamovskoe uranium-bitumen deposit,

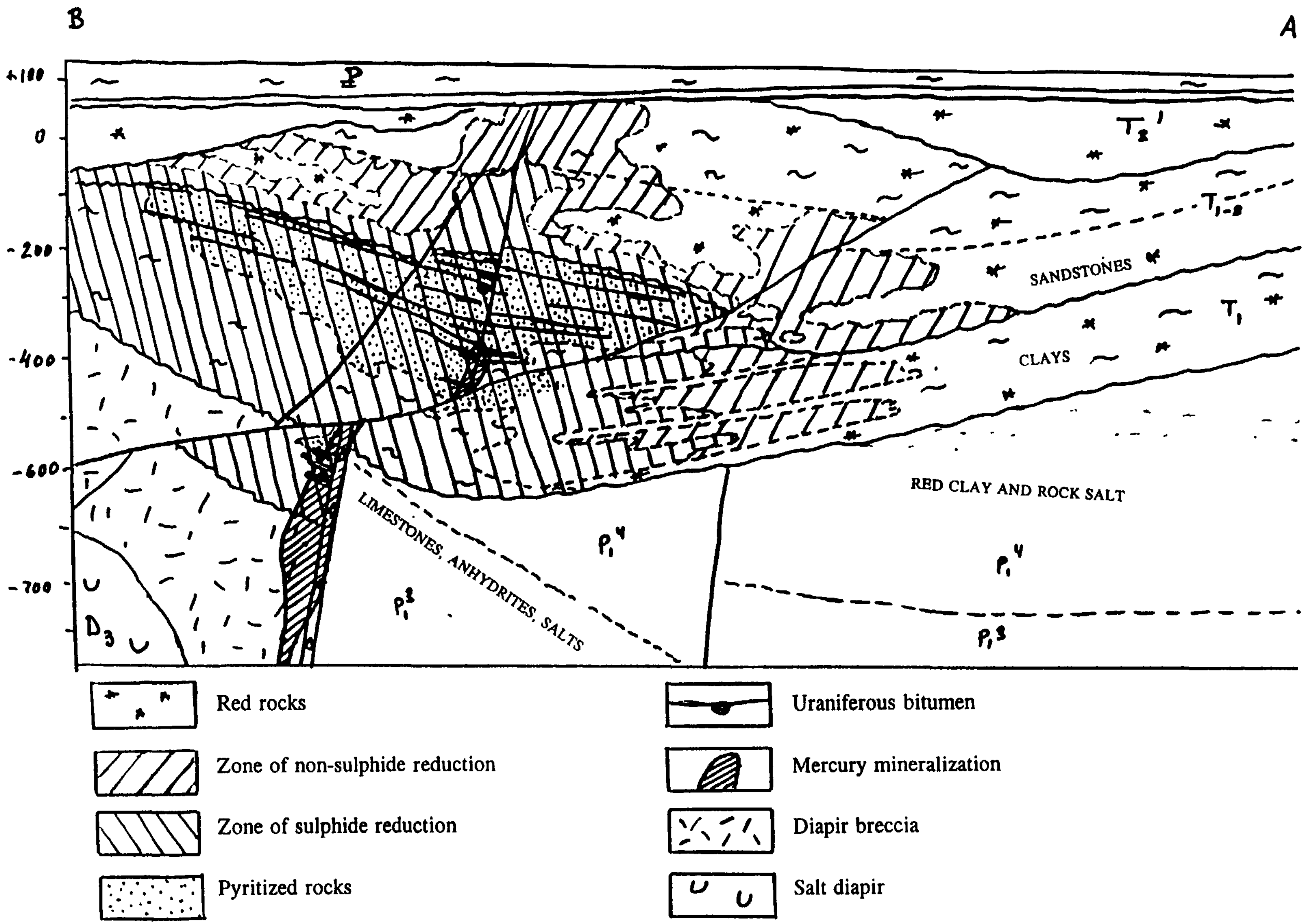

FIG. 4. The geological section A-B of Adamovskoe uranium-bitumen deposit.

The total thickness of the Phanerozoic formations near Adamovskoe deposit is estimated at 6.5 km by geophysical data. They form the large Slavyanskaya anticline. The north-western part of the anticline is broken by two Devonian salt diapirs. One of them is overlain by Triassic red beds, and the second is located under the Paleogene deposits.

The uranium-bitumen mineralization is located within the Triassic sediments. It is controlled by the old channels which surround the Adamovsky salt dome (Fig. 3). The old channels are filled with polimictic sandstones as shown in Fig. 4. In addition, the uranium-bitumen orebodies are controlled by the southern and northern faults, and also by the distribution of the epigenetically reduced, intensively argillized and pyritized Lower Triassic rocks. The orebodies (up to 11 units in the total of 100–200 m) are the black and dark brown beds of disseminated or massive bitumen. The black bitumen has the characteristics of oxyantraxolite, and the dark brown bitumen the characteristics of the oxykerite. Furthermore, there are many disseminated barren bitumens of the asphaltite and asphalt classes. The black bitumen is enriched by uranium (in excess of 1%) more than the brown bitumen (in tenths of one percent). the typical ore consists of a terrigenous quartz (69–80%), feldspars (1–3%), carbonates (1–10%), clay minerals (5–15%), iron sulphides (1–3%) biotite and chlorite (<1%). The uraniferous bitumen content varies from one to 85%.

The orebodies of the cross-cutting type are located near disjunctive dislocation and contain about 10% of total uranium reserves.

The solid bitumen also contains vanadium, molybdenum (up to 1%) and chromium (up to 0.1%). This bitumen is intimately associated with CR-bearing montmorillonite and calcite which formed at 180–190°C. Cinnabar is also present in the form of disseminations and veinlets along with uraniferous bitumen and iron disulphides. Galena, shpalerite, barite, celestite, fluorite occur in the calcite enriched rocks in the lower part of the Triassic in the southern fault zone. The sulphides and fluorite contain admixtures of mercury or diffuse cinnabar.

The argillitized rocks and the associated mercury and polymetallic mineralization extend within the Lower Permian and carboniferous deposits along the southern fault to a depth of more than 1000 m.

The content of lead ranges up to 1%, zinc — 10% and mercury — 0.3%. The uraniferous bitumen, V and Mo are not found beneath the Triassic deposits, despite the fact that the barren solid and liquid bitumen are widespread.

The age of uranium ores is from 200 $\pm$10 to 195 $\pm$5 mil. years according to U-Pb data (Lower-Middle Triassic). It is possible that the uranium ore was formed as the result of interaction between oxygen-bearing groundwaters and the hydrocarbon-bearing hydrothermal solutions which deposited the mercury-polymetallic mineralization.

3. INFILTRATION (ROLL-FRONT TYPE) DEPOSITS IN COAL BEARING SEDIMENTS

The second important type of uranium deposits are the infiltration deposits in the Paleogene coal-bearing sediments which fill the paleovalleys. The paleovalleys are cut in the crystalline rocks of the shield and its weathered crust to a depth of 70–90 m. The coal-bearing sediments are overlain by the Eocene and Oligocene marine deposits, or directly by Miocene littoral sands. The cover beds are usually 30–60 m thick.

The paleovalleys are formed by the rivers which ran off the Ukrainian shield to the north into the sea basin of the Dnipro-Donets depression, or to the south into the Tethys sea basin (Fig. 5). Some paleovalleys are filled completely by river sediments but others only partially. Those which are filled only partially are in the lower part of the Paleogene cover and are overlain by lagoonal or lacustrine marsh deposits.

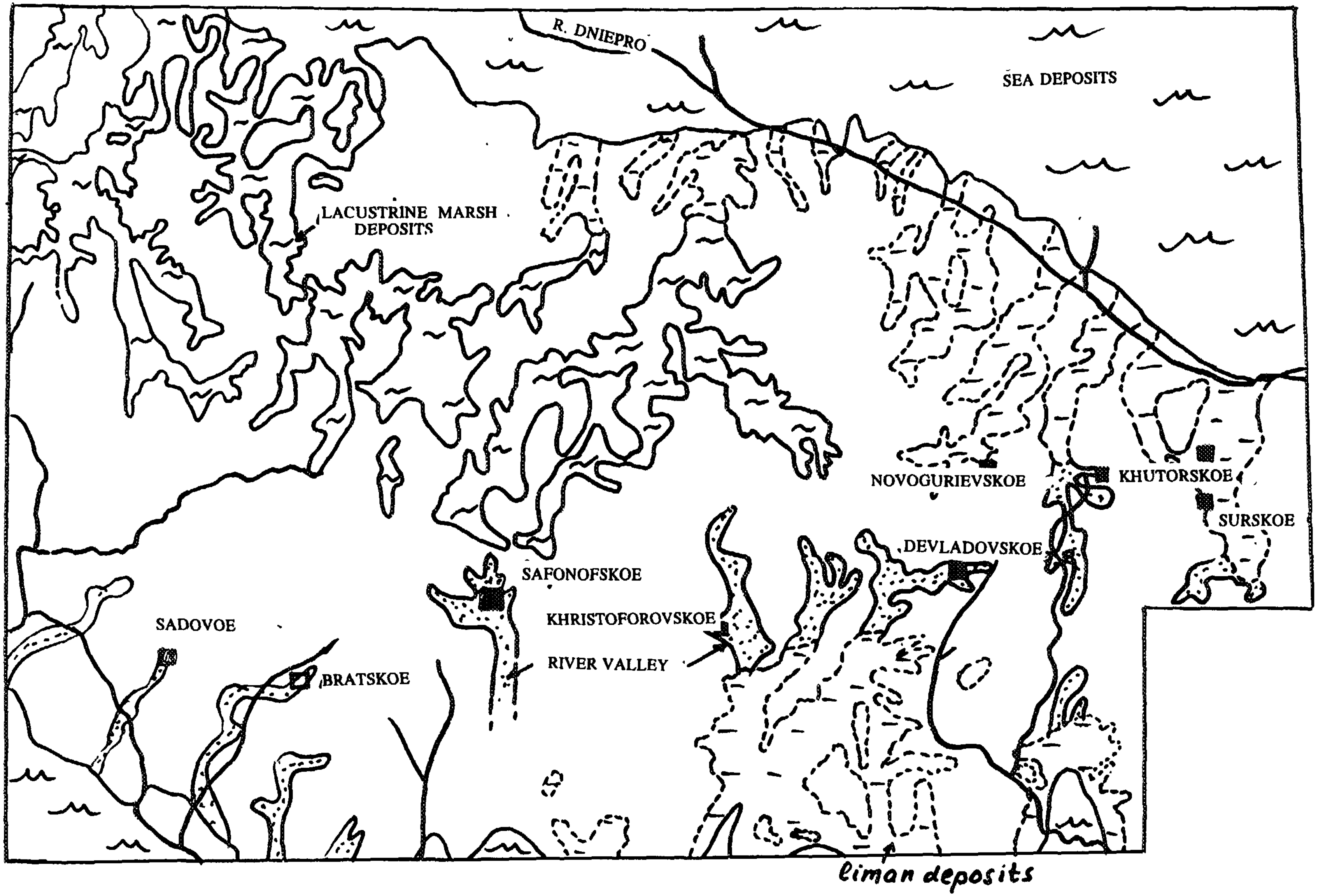

FIG. 5. Paleogeographical map of the western part of the Dnipro lignite basin, Middle Eocene.

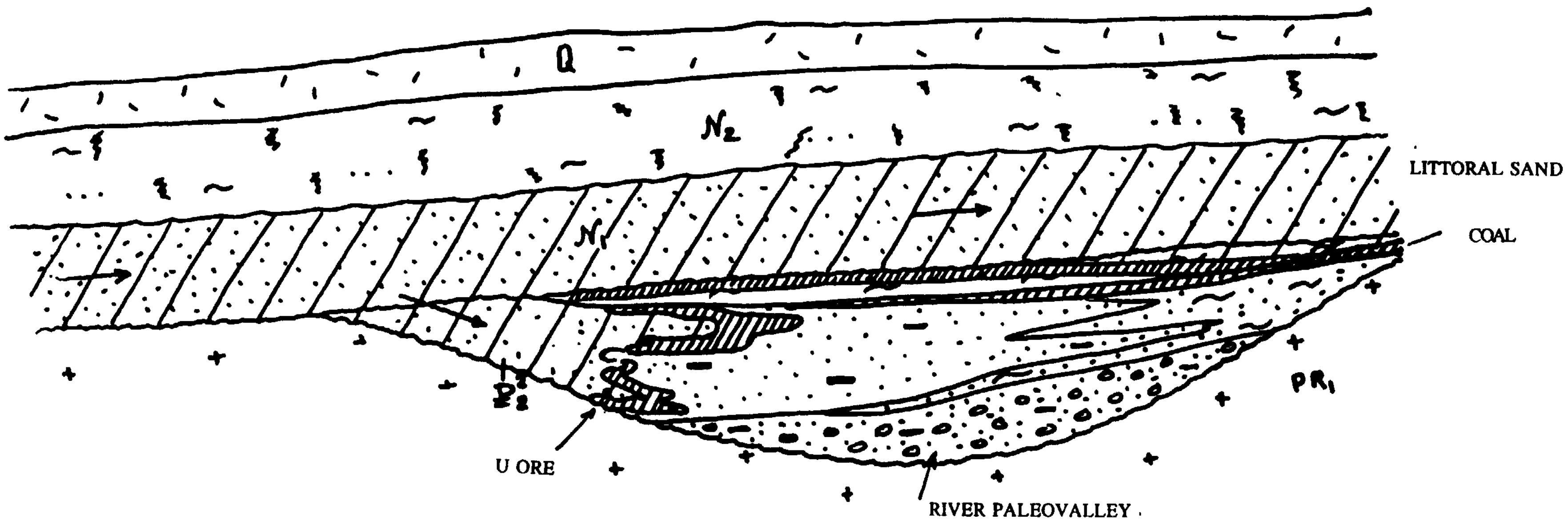

FIG. 6. Geological section of the Khutorskoe uranium manifestation.

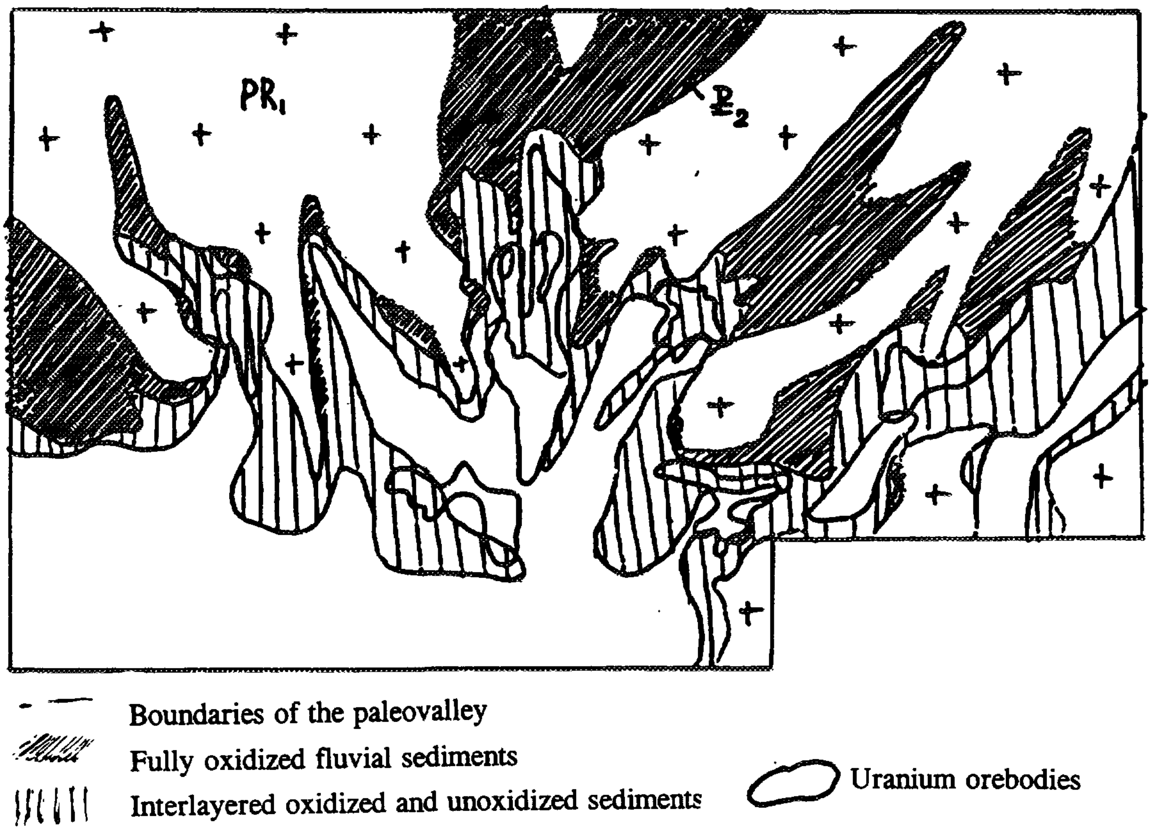

FIG. 7. Map of the epigenetic zoning of the Safonovskoe uranium deposit.

The main uranium deposits (Sadovoe, Bratskoe, Safonovskoe, Devladovskoe, Novogurievskoe) and manifestations (Khistoforovskoe, Khutorskoe and others) are associated with a river sedimentary complex at the south and central parts of Dnipro lignite basin (Fig. 5). The sheet uranium deposits of the valley type are distributed along nearly the entire width of the channel (Devladovskoe, Bratskoe, Novogurievskoe deposits). The uranium deposits of the near-slope type form narrow sinuous strips along paleovalley slopes (Sadovoe, Khutorskoe, Tashlykskoe and other deposits and manifestations) (Fig. 6). The localization of ore deposits depends on the development of the ore-controlling oxidizing zones which can develop downslope from the upper reaches of the river valley or from the sides of valleys (Fig. 7). Uranium bodies are distributed in all river sediments and also often in the upper part of the weathered Precambrian bedrock. The thickest and richest orebodies are located in lower and middle parts of river sands. Ore-bearing coaly sands predominate; clays and brown coals are less frequently ore-bearing.

The lagoonal facies are composed of coaly-clay sediments with rare small interbeds of fine-grained sand and sandstone. Thick coal deposits are characteristic of this complex. Two commercial uranium deposits (Surskoe, Chervonojarskoe) and numerous ore manifestations are in sediments of the complex. Uranium ores are mainly controlled by ground oxidizing zones. They are therefore located in the upper part of the Eocene coaly sediments. They are the ores of the ground-bed oxidizing zones which are present on slopes and in upper reaches of river valleys.

The locustrine marsh complex occupies a large area (Fig. 5). Its deposits consist of coaly siltstones, clays and thick beds of brown coal with sand interbeds. They fill a shallow (up to 20 m) gentle depression (40–50 × 20–30 km). These deposits are the least uraniferous of all. There are only small ore manifestations in the peripheral parts of locustrine marsh basins. Uranium concentrations are controlled by the ground oxidizing zones are located in the upper part of coal-bearing series (in coaly clays, brown coal).

Ore-controlling oxidizing zones in water-bearing horizons of Dnipro lignite basins were formed as a result of oxidation of iron sulphides and organic carbon by groundwaters. There are three main lithological types of uranium ores. In the Bratskoe deposits these are: coaly sands (63%), coaly clays (13%) and brown coal (16% of reserves). the reserves of uranium ore in the upper part of the weathered Precambrian crust are not more than 8% of the total. Uranium occurs mainly in coal-rich and clay-rich matter. Uranium hydroxides (~17%), uraniferous leucoxene (~5%) and iron hydroxides (~3%) are minor. The zone of uranium mineralization coincides with the zone of epigenetic reduction and hydrosulphuric and sorptive precipitation of some elements. An addition to iron disulphides there are bravoit, violarite, jordisite and sphalerite. High contents of Se, Mo and Re are present in some orebodies. Some deposits also have Zn, Co, Ni and Tl. The development of the river drainage and the zones of oxidation and the formation of uranium ores started between the early and late Pliocene and is continuing at the present time.

URANIUM DEPOSITS: MAIN TYPES AND CONCEPTS FOR DETECTION

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Abstract

This paper presents a classification of uranium deposits as a basis for developing an optimal exploration strategy for discovering deposits with favorable characteristics for low production cost. The classification is based on endogenic and exogenic sub-classes both of which are subdivided to syngenetic and epigenetic groups. The tectonic setting is also taken into consideration. Following description of the economic and geological types of deposits, the factors governing the formation of the deposits is given.

The recent uranium mineral resources in Russia are required to be essentially improved, both in quantitative and qualitative respects. In response to this statement, forecasting and prospecting works in the country should be aimed at the discovery of new large districts with a highly profitable uranium mineralization, which would be either rich or relatively poor, but at the same time adaptable to streamlined production. In order to enhance the efficiency of forecasting, concepts for the detection of uranium ore mineralization were worked out. They are based on the results of analysis, concerning the leading world types of uranium deposits, which are consistent with modern economic and technological requirements.

Extremely high mobility of uranium, especially at moderate and low temperature and pressure, causes a wide range of its natural concentrations. The intense prospecting and exploration, which were carried out during last decades all over the world, gave rise to the discovery of hundreds of uranium deposits of different type, dimension, ore quality, technological properties, and mode of processing.

Many classifications of uranium deposits exist; they are based on genetic features, tectonic setting, host rock composition, geological structure, morphology of orebodies, etc. (P. Kerr, 1955; D. Surazhskii, 1956; V. Ziegler, 1974; M. Shumilin, 1978; F. Dalkamp, 1989; N. Laverov, 1992 and others). The classification, proposed by the authors (Table I), involves all up-to-date known economic deposits — proven and potential — and has a genetic background. Endogenic and exogenic classes of ore concentrations are distinguished. Contrary to some investigators, the authors believe that the separation of a specific class of polygenic uranium deposits is inexpedient, because a genetic affinity of deposits would be more properly defined by the main type of productive process. All subsequent alterations, including those positively affect the ore quality, are of the second genetic importance. Each of the classes is subdivided into two groups of syngenetic and epigenetic deposits. The farther classification is issued from the tectonic setting of ore deposits (Table I).

In the *endogenic class* the objects of main interest are represented by epigenetic (hydrothermal) deposits from the areas of tectonomagmatic rejuvenation of shields, median masses and foldbelts. Above else, this are rich deposits, located in Precambrian tectonic and stratigraphic unconformities (Cigar Lake, Ranger), in exocontact zones of orogenic granitoids within median masses (Schlema-Alberoda) and in superimposed volcanotectonic structures of Mezozoic age (Streltsovskoe).

In the *exogenic class* the epigenetic (infiltrational) objects also play a leading role. They are located in platform forelands, epiplatform orogenic belts, and arches within shields and previously formed foldbelts. Large and intermediate deposits, related to zones of stratal oxidation in permeable rocks of sedimentary cover, are most important.

TABLE I. ECONOMIC AND GEOLOGICAL TYPES OF DEPOSITS

Genetic class	Genetic group	Tectonic setting	Economic type of deposit	Host rocks	Associated alteration	Main ore minerals	Orebody morphology	Scale of deposits, ore quality and technological properties	Examples of deposits
	Singenetic (magmatogenic)	Shield blocks affected by granitization	U and Th-U types formed at final stages of granitization	Alaskites, migmatites pegmatoid rocks	Quartz - K-feldspar	Uraninite, betafite, uranothorite, zircon, monazite, molybdenite	Bedlike and lenticular	Large and intermediate deposits of poor ore, well-dressed and easily broken down	Rossing, Charlebois, Yuzhnoe
		Rejuvenated Precambrian shields	U type in long-existed faults within areas of protorejuvenation	Gneisses, ferruginous quartzites, hornfels, migmatites, granites	Riebickite-aegirine and chlorite albitites, alkaline amphibole rocks, aegirinitites	Uraninite, brannerite, coffinite, pitchblende	Platelike loads, lenses, bodies of irregular shape	Large and intermediate deposits of ordinary ore, satisfactory dressed and easily (occasional satisfactory) broken down	Michurinskoe, Vatutinskoe, Novokonstantinovskoe Zheltorechenskoe
			Au-U type in long-existed faults within areas of Mesozoic teconomag-matic rejuvenation	Crystalline schists, migmatites, granites	Pyrite-carbonate-K-feldspar	Brannerite, Au-bearing pyrite	Platelike loads and lenses	Large and intermediate deposits of ordinary ore, well-dressed and easily broken down	Druzhnoe, Kurung Elkon, Snezhnoe
		Protoplatform depressions	U and Ni-U types in tectonic and stratigraphic unconformities	Crystalline schists and gneisses with intercalations of carbonaceous and carbonate rocks, sandstones and siltstones of sedimentary cover	Chlorite, illite,sericite, occasionally magnesite	Coffinite, uranium oxides, sulfides, arsenides, selenides, and tellurides	Flattened linear loads in unconformities, near-concordant and cross-cutting bodies in basement	Large and intermediate deposits mainly of rich ore, well-dressed and easily broken down	Cigar Lake, Rabbit Lake, Jabiluka, Ranger
Endogenic	Epigenetic (hydro-thermal)	Areas of tectonomag matic rejuvenation of foldbelts	U and P-U types in rifto-genic troughs	Quartz sandstones, carbonaceous shales, conglomerates, diabases, granites	Chlorite and ankerite albitites	Coffinite, brannerite, pitchblende, F-apatite	Pillarlike and lenticular loads	Large and intermediate deposits of ordinary ore, well-dressed and easily broken down	Grachevskoe, Kosachinskoe
			U type in exocontact zones of granitoids	Amphibolites, carbonaceous-siliceous schists	Albite-carbonate-chlorite	Pitchblende, Pb, Cu Mo sulfides	Veined and lenticular bodies	Large and intermediate deposits mainly of rich ore, well-dressed and easily broken down	Oberschlema, Niederschlema, Pribram
			U type in volcanogenic and terrigenous rocks in depressions	Chlorite-hydromica, rarely carbonaceous-siliceous schists, diabases, limestones	Hydromica	Coffinite, pitchblende, Fe, Zn, Cu sulfides, occasionally Ni arsenides	Lenticular and bedlike loads, rarely veined bodies	Large and intermediate deposits of rich and ordinary ore, mainly well-dressed and easily broken down	Schmirhau, Roist, Beerwalde
			F-Mo-U type in superimposed paleovolcanic depressions	Acidic, intermediate basic volcanics, tuffaceous sandstones, metamorphosed limestones and granitoids of basement	Quartz-hydromica, quartz-kaolinite-montmorillonite ankerite-chlorite-albite	Pitchblende, coffinite, brannerite, jordisite, fluorite	Flattened stockworks, steeply dipping lenticular and veinlike bodies bedlike loads	Large and intermediate deposits of rich and ordinary ore, mainly well-dressed and easily broken down	Streltsovskoe, Tulukuevskoe, Argunskoe, Chauli
			U type in highly radioactive granitoid plutons	Leucogranites	Albite, chlorite-mica, occasionally montmorillonite-zeolite	Pitchblende, Fe sulfides, occasionally -uranotil	Veined and lenticular bodies	Intermediate deposits of ordinary and rich ore, well-dressed and easily broken down, occasionally suited to underground leaching (UL)	Limusin, Gornoe

Genetic class	Genetic group	Tectonic setting	Economic type of deposit	Host rocks	Associated alteration	Main ore minerals	Orebody morphology	Scale of deposits, quality and technological properties of ore	Examples of deposits
	Singenetic (sedimentary, sedimentary-diagenetic)	Sedimentary cover of young platforms	Uranium - rare metal sulfide - phosphorus type at shelf - deep-water basin joints	Grey-colored clay with bone detritus		Rare metal-, U-, and Re-bearing bone phosphate with Ni, Co, Cu, Pb, Mo, etc., Fe disulfides	Beds, splitted and stratal-lenticular bodies	Large, deposits of well-dressed poor ore, intermediate and small deposits are less common	Melovoe, Tomak, Stepnoe
		Precambrian protoplatform depressions	U and Au-U types in Proterozoic conglomera-tes	Conglomerates with quartz pebbles		Uraninite, native gold	Beds	Large deposits of poor ore	Blind River, Witwatersrand
		Marginal parts of young platforms affected by orogeny	U (with Se, Mo, Re, V) type in basins and graben-synclines	Grey-colored sands, sandstones, gravels and gritstones	Stratal limonite (hydrohematite is less common), reduction (bleaching)	Pitchblende, coffinite, uranium black, native selenium, jordisite	Ore rolls, lenses, ribbonlike loads	Large deposits of poor ore, suitable for UL, intermediate and small deposits are less common	Uchkuduk, Karamurun, Inkai, Shirly Basin, Gas Hills
			U and Zr-U types in graben-synclines	Grey-colored sandstones	Stratal limonite, kaolinite, and hydromica	Pitchblende, coffinite	Lenses, ribbonlike loads, ore rolls are less common	Large and intermediate deposits of poor and ordinary ore, partly suitable for UL	Hamr, Konigstein
Exogenic		Marginal parts of ancient platforms affected by orogeny	U and V-U types in basins and aulacogens, including downfall pipes	Red- and grey-colored sandstones	Bitumen, reduction (bleaching), kaolinite and hydromica	Pitchblende, coffinite	Lenses, pocket- and ribbonlike loads, ore rolls are less common	Intermediate and small deposits of ordinary, rarely of rich ore	Ambrosia Lake, Jeckpile, Adamovskoe, Arizona-1
	Epigenetic (infiltrational)	Arches at shields and in previously formed foldbelts	U type in erosional paleovalleys	Grey-colored sands and gravels, including carboniferous rocks, sandstones are less common	Ground and stratal limonite, reduction (bleaching), kaolinite and hydromica are less common	Pitchblende, coffinite	Lenses, ribbon- and cloaklike loads, ore rolls are less common	Intermediate and small deposits of poor ore, suitable for UL, large deposits are less common	Devladovskoe, Sanarskoe, Chiagda, Semizbai
			Vanadate-uranium type n erosional paleovalleys	Calcretes, hypocretes, and silcretes in paleovalleys	Near-surface carbonates, hypsum and silica	Carnotite	Cloaklike bodies, lenses	Intermediate and large deposits of ordinary ore	Jeelirne
		Orogenic belts superimposed upon platforms	Uranium - coal type in intermontane grabens and graben-synclines	Brown coal, carboniferous sandstones are less common	Ground and stratal hydrohematite, reducnon (bleaching)	Pitchblende, hydronasturan coffinite, molybdenite	Ribbon- and bedlike loads	Large, intermediate, and small deposits of poor and ordinary ore	Nizhne-Iliiskoe, Koi dzhat, Turakavak, Mengqiguer
			U type in intermontane grabens and graben-synclines	Grey-colored sandstones, gritstones, conglomerates are less common	Ground and stratal limonite, hydrohematite, kaolinite, zeolite	Pitchblende, coffinite, jordisite	Ribbon- and bedlike loads	Large, intermediate, and small deposits of poor and ordinary ore, occasionally situable for UL	Ima, Kharat, Suluchek

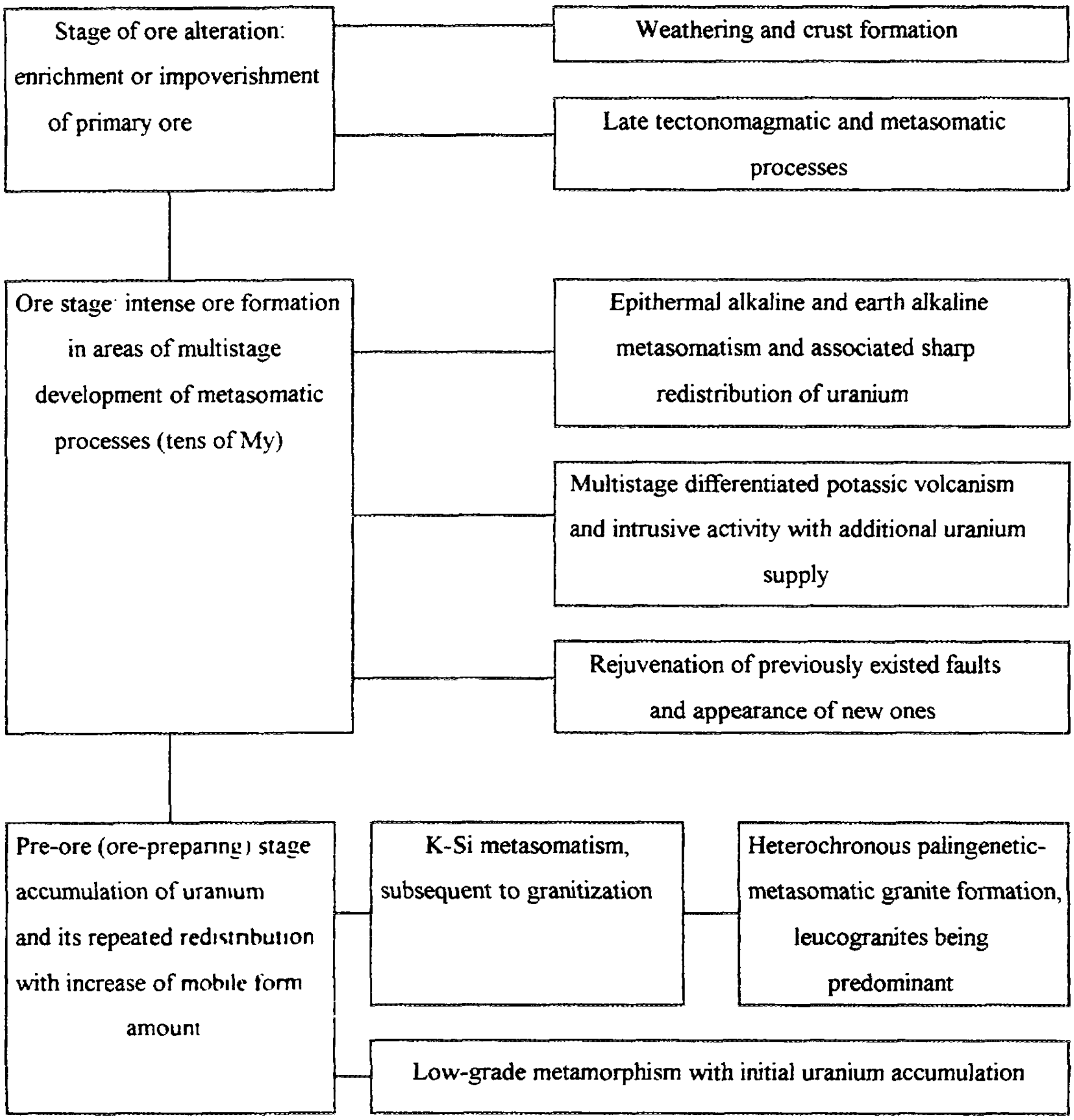

FIG. 1. Evolutionary geological model of endogenic uranium deposits formation.

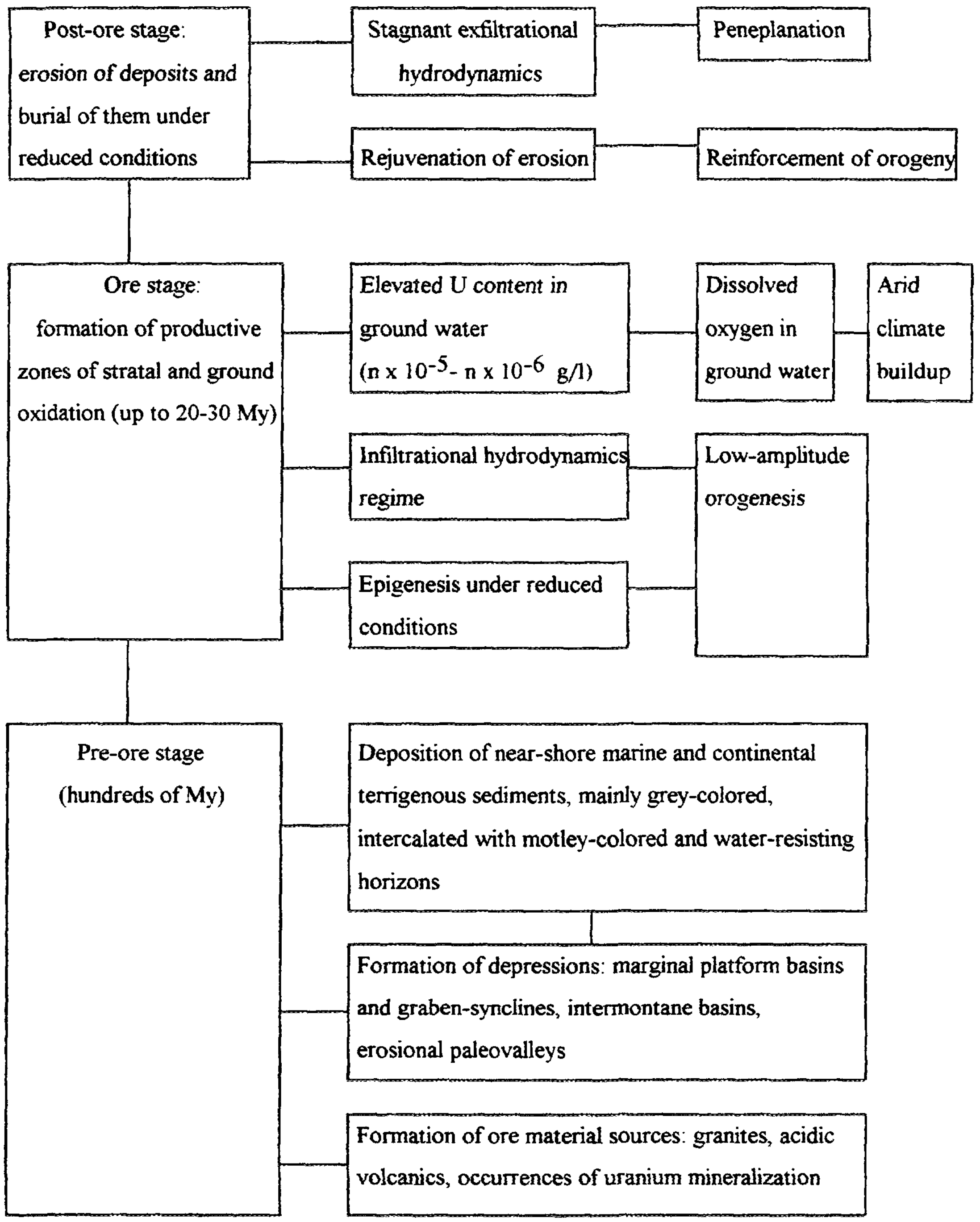

FIG. 2. Evolutionary geological model of exogenic epigenetic uranium deposits formation.

A comparison of geological and genetic features of economic deposits led to the conclusion that all large uranium deposits appear as a final event in the sequence of prolonged interrelated geological processes that induce a directional uranium migration and accumulation, resulted in the formation of potential sources of ore. Two models of geological evolution during uranium ore formation are suggested: endogenic epigenetic (hydrothermal) and exogenic epigenetic (infiltrational) ones (Figs 1 and 2). Both models involve successive ore-preparing, ore-forming and ore-transforming processes. Large ore deposits appear under conditions, which provide the superposition of all main ore-forming processes within a limited geological space.

A model of endogenic uranium ore formation allocates the most important role to ore-preparing processes, which occurred well in advance to the ore mineralization proper and caused a widespread multistage granitization and K-Si metasomatism. These processes were most intense within long-evolved granite gneiss cupolas. The migration of a great body of uranium, thorium and other metals into the upper crust associated with such processes, gave rise to potential sources of ore materials.

The granitized blocks were subsequently affected by intense pre-ore tectonomagmatic and tectonic processes, which induced a rejuvenation of previously existed deep-seated zones and the appearance of new ones, both being highly permeable for magmatic melts and postmagmatic hydrothermal solutions. These processes favored an additional gain of uranium and redistribution of the metal, which had been previously contained within granitized complexes. In the course of this, the role of mobile uranium increased.

The pre-ore rejuvenation stage was followed by ore-forming processes that were related to the interaction between ascending carbonate and sulfide-carbonate thermal solutions and the host rocks, enriched in radioactive elements. As a result, rich uranium and complex mineralization was formed at degassing geochemical barriers.

Late-ore and post-ore processes could transform the primary ore mineralization, inducing its secondary impoverishment or enrichment. Occasionally these processes may be rather important.

A model of exogenic-epigenetic uranium ore production envisages the formation at the early ore-preparing stage the following geological objects:

- sources of ore materials (U-rich igneous and metamorphic rocks, uranium occurrences);
- various depressions (platform basins and graben-synclines, intermontane basins, erosional paleovalleys);
- grey-colored bedded sandstone-carbonate-claystone sequences.

The ore-forming stage is characterized by a low-amplitude orogenesis, arid climate buildup and provides the infiltrational hydrodynamic regime, downward penetration of oxygen- and U-bearing solutions along with local upward epigenesis. A combination of these interconnected processes gives rise to the formation of productive zones of ground and stratal oxidation with high uranium concentrations at the pinches.

If orogenesis and erosion are enhanced, a partial destruction and alteration of deposits are possible at the post-ore stage. On the contrary, the burial and conservation take place under stable tectonic conditions, favorable for the peneplanation and sluggish hydrodynamics.

Evolutionary geological models, worked out by the authors, allowed to define general conditions of formation and localization of large uranium deposits and to establish two groups of main prerequisites for the formation of them (Table II). These favorable prerequisites can be used for a forecasting evaluation of vast areas, including poorly studied regions, with the aim of discovery of high-productive uranium mineralization of various nature.

TABLE II. FACTORS GOVERNING THE URANIUM ORE FORMATION

Ore objects		Prerequisites of mineralization formation
Exogenic hydro-thermal	Ore districts	1. Continental blocks of early consolidation and prolonged emergence, affected by heterochronous tectonomagmatic rejuvenation. 2. Regional tectonic mobile structures of increased transcrustal permeability. 3. Prevailing development of low-grade sialic rocks in crystalline basement with predominance of mobile uranium forms. 4. Large structures of central type with intense development of multistage granitization. 5. Widespread K-Si alteration, greisen, skarnoid rocks, formed subsequently to granitization that produces U, Th occurrences and disseminated radioactive mineralization. 6. Multistage differentiated subalkaline volcanism and intrusive activity related to tectonomagmatic rejuvenation with predominance of mantle-derived basic rocks at initial and final stages.
	Ore fields	7. Joints of long-existed deep-seated faults with superposition of igneous activity of different age. 8. Linear deep-seated zones of dilatation and geophysical fields with contrasted gradients. 9. Areas of differentiated radioactive element distribution with U-deficient haloes against a normal or elevated radiochemical background. 10. Development of various alkaline and earth alkaline (Mg, Ca, Na) alterations, superimposed onto the early K-Si alteration. 11. Tectonic and stratigraphic unconformities and other contrasted inhomogeneities of host rocks. 12. Endogenic occurrences of fluorite, chalcophile and rare elements.
Exogenic epigenetic	Ore districts	1. Continental blocks with widespread sialic rocks of crystalline basement, approached the aeration zone. 2. Areas of moderate emergence at margins of platforms (forelands), at shields, in epiplatform and epigeosyncline orogenic belts. 3. Regional tectonic mobile structures of increased transcrustal permeability. 4. Weakly lithified, mainly arkose (continental or shelf) platform and orogenic sediments. 5. Active infiltrational hydrodynamics regime in artesian systems as well as ground water basins, existed at the time of ore formation. 6. Predominance of arid or moderately wet climate at the epochs of reinforcement of orogenic processes.
	Ore fields	7. Marginal basins and systems of graben-synclines at platforms; intermontane basins within orogenic belts; erosional paleochannels. 8. Horizons and units of permeable grey-colored sands, sandstones, gritstones, and conglomerates, including lignite- and coal-bearing rocks. 9. Zones of stratal and ground oxidation of primary grey-colored rocks, including zones of secondary reduction (bleaching). 10. U-rich rocks, uranium ore occurrences, and geochemical haloes of mobile uranium forms in areas of ground- water recharge . 11. Elevated uranium ($> n \times 10^{-5}$ g/l) and dissolved oxygen contents in infiltrational stratal and ground water. 12. Pre- and sin-ore reducing epigenesis in aquifers that reinforces the ore deposition in sedimentary rocks and enhances the contrast of reducing barrier.

The existence of early consolidated blocks and prolonged emergence with associated low-grade metamorphism of sialic rocks, containing mobile forms of U, are regarded as main prerequisites for the appearance of large endogenic uranium concentrations. Large uranium ore districts at rejuvenated ancient shields (Alligator Rivers in Australia, eastern Athabaska in Canada, Aldan in southern Yakutiya, Krivoi Rog — Kirovograd in Ukraine) are consistent with these conditions as well as districts within median masses in foldbelts (Streltsovskii in southeastern Transbaikalians, northern Kazakhstan, Erzgebirge, etc.). Multistage granitization and associated subsequent K-Si metasomatism, producing disseminated radioactive mineralization and U and Th occurrences, play the most important ore-preparing role. Differentiated subalkaline volcanism and intrusive activity, including initial and final basic rocks of mantle origin, are also important at the stage of rejuvenation. The differentiated radioactive element distribution with deficient U haloes against the background of normal or elevated radiochemical field is of essential significance. Alkali earth and alkaline alteration, superimposed upon early K-Si metasomatism in local structure, as well as structural and stratigraphic unconformities and other contrast heterogeneities of host rocks are also noteworthy.

The most substantial prerequisites for the large exogenic epigenetic uranium concentrations include: (1) continental blocks of the Earth's crust with widespread sialic basement, approached the aeration zone; (2) areas of moderate uplift at marginal parts of platforms, shields, and orogenic belts; (3) depressions, mainly filled by weakly lithified sediments of Mesozoic-Cenozoic age; (4) favorable paleohydrogeological and paleoclimatic factors. Attention should be also drawn to (1) permeable grey-colored horizons and units in sedimentary cover; (2) zones of stratal and ground oxidation; (3) U-bearing rocks and uranium occurrences in regions of alimentation for ground water; (4) elevated U contents ($>5\ 10^{-6}$ g/l) and enrichment in dissolved oxygen of recent stratal and ground water.

The largest exogenic epigenetic deposits are controlled by zones of stratal oxidation within sedimentary cover of ancient and young platforms, which were affected by a moderate mountain building, associated with the Alpine orogeny in adjacent mobile belts. Host structures are represented by marginal platform depressions and graben-synclines, transformed into foredeeps.

A combination of above-mentioned prerequisites in a certain geological space allows to set off the areas, prospective for large uranium accumulations of economic importance. Geological and mineral types of them are determined by a local geological structure, lithology and geochemistry of host rocks.

The leading prerequisites of uranium ore formation determine the basic concepts of geological and genetic forecasting that envisage the successive analysis of potentially prospective regions in the range from a small scale (1:2 500 000–1:500 000) to the evaluation of discovered deposits.

The early stage of endogenic deposit forecasting (1:1 000 000–1:500 000) involves the compilation of schemes, which represent (1) basement structure; (2) deep-seated structure of potentially prospective blocks; (3) composition and abundance of products of tectonomagmatic rejuvenation; (4) radioactive element contents in rocks of different age. Additional field studies in specific areas are scheduled.

At the following stage (1:200 000–1:50 000) the scheme of altered rock and ore localization should be prepared in addition to above-mentioned data. A complex analysis of prerequisites for ore formation allows to set off areas, prospective for exploration.

The forecasting for exogenic epigenetic deposits has to be performed by the same way. The forecasting investigations under consideration do not replace the compilation of forecasting and metallogenic maps, but allow to provide an express evaluation of large geological blocks, based on main factors of uranium ore formation, expensive geological exploration being applied only to a limited extent.

The evaluation of revealed ore objects includes the determination of mineralization type, its technological and geotechnological properties and the forecast for environmental consequences of exploration and mining. The detailed works at an object are completed by a preliminary geological and economic estimation of advantages for further development.

URANIUM MINING AND PRODUCTION OF CONCENTRATES IN INDIA

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Abstract

In order to meet the uranium requirements for the atomic power programme of the country, uranium deposits were explored, mined and concentrates were produced indigenously. The geology of the areas, mode of entries and the various extraction methods deployed in different mines with their constraints are described. The various equipments used in mining and processing activities are elaborated. The flow sheets for processing the uranium ore and that of the effluent treatment plant are given in detail. The future plans of the company for undertaking the new projects to meet the demand of uranium requirement for the increasing nuclear power programme are given.

1. INTRODUCTION

With the formulation of the Atomic Power Programme in the context of power requirements of the country with regard to the availability of various types of energy resources, the importance of uranium assumed a considerable significance. During the first phase of the nuclear power programme, natural uranium was selected as the fuel. Thus, there was an imperative need to locate the uranium deposits in the country so that the requirement of the strategic mineral could be met indigenously.

The Atomic Minerals Division under the Department of Atomic Energy undertakes the exploration programme of various radioactive minerals by various geophysical and geochemical methods. In the promising areas, they also undertake exploratory mining. Once a deposit of sufficient tonnage and grade is proved, the deposit is handed over to Uranium Corporation of India Ltd. (UCIL) for commercial mining and production of uranium concentrates.

Presently the Corporation is having three deposits under commercial exploitation, i.e. Jaduguda, Bhatin and Narwapahar. All these deposits are in the Singhbhum Trust Belt in Bihar State in Eastern India.

The occurrence of uranium-bearing minerals in Singhbhum Thrust Belt has been known since 1937. In 1950 a team of geologists was appointed with the specific task of closely examining the 160 km long Singhbhum Copper Belt to locate the presence of uranium mineralization and other radioactive minerals. The team located several anomalous radioactive areas in Singhbhum Thrust Belt of which Jaduguda, Bhatin, Narwapahar, Turamdih and Bagjata were a few. During the leastfour decades, some of these mineral occurrences have become major uranium producing mines.

UCIL was established on 16 October 1967 as a Public Sector Enterprise with its registered office in Jaduguda with the specific objective of mining and processing of uranium ore.

UCIL has a number of operating units, among them there are three mines at Jaduguda, Bhatin and Narwapahar, three uranium recovery plants to recover uranium from copper tailings, a by-product recovery plant to recover copper and molybdenum sulphide concentrates and a magnetite plant to recover magnetite present in the uranium ore.

2. JADUGUDA MINE

2.1. Geology

The original geology of Singhbhum Thrust Belt (STB) has been the subject matte of intense study for many geologists for the past 50 years. The pioneering work in this region was done by Dr. Dunn and Dr. Dey. They divided the entire area into two broad divisions, north and south of the thrust belt. On the northern side of the thrust belt, there are rocks of Chaibasa and Iton Ore series while on the southern side the rocks of Iron Ore and Dhanjori stages and Singhbhum granites have been described. The thrust zone is developed between Chaibasa and Iron Ore stage rocks.

In the Jaduguda Mine, there are two orebodies, one the Footwall Lode (FWL) and the other is called Hangingwall Lode (HWL), both are separated from each other by a distance of about 60–100 m. The FWL extends over a length of about 800 m in SE and NW direction. The HWL has only 200–300 m of length and is confined to the eastern part of the deposit only. The average width of he lodes is about 3–4 m, though at certain places in the mine the lodes are as thick as 20–25 m. The FWL is better mineralized and contains copper, nickel and molybdenum sulphide minerals in addition to uranium. Both of these lodes have an average dip of about 40–45°. The orebody in Jaduguda has been prospected up to a depth of about 800 m below ground level, and it is expected that it would continue further in depth.

2.2. Mode of entry

The main entry to the mine is through a circular concrete lined shaft of 5 m diameter. The shaft has been sunk to a depth of 640 m in two stages: one from surface to 315 m and the second from 315 to 640 m. The shaft is equipped with two tower mounted multi-rope friction winders. The Cage winder is a 280 KW D.C. winder, and the skip winder is a 360 KW AC winder. The cage and skip winders are balanced by counter-weights and tail ropes. A double deck cage is used for lowering and hoisting of men and material and for hoisting waste rock. The skip with a payload of 5 tonnes is used for hoisting ore from 605 m level. The shaft is also equipped with pipe columns for compressed air, water mains, drilling and drinking water and power and control cables.

2.3. Mine layout

The main levels are at vertical interval of 65 m, the last level being at 555 m.

During exploratory mining, 5 adits are driven to meet the lodes. The ground level (0 m.l.) and -30 m.l. were developed and connected by raises and winzes. Subsequently, levels at 50 m, 100 m and 165 m depth were developed from the principal winzes sunk from 0 m.l. and later connected to shaft and ore-pass. Development of lower levels at 230 m, 295 m, 370 m, 434 m , 495 m and 555 m depth was done from the shaft. Crushing and loading stations are located at 580 m.l. and 605 m.l. respectively.

2.4. Mine development

The mine development work involves development of winzes, raises, cross-cuts and drifts in ore and waste rock.

2.4.1. Drives

Drives in the main levels are generally 2.4 m × 2.5 m in size with a 610 mm gauge track fitted in them. Drilling is done by Jack hammer drills with Burn cut pattern. The blasted rock is cleared by pneumatic loaders (EIMCO 12 B/21) loading into side tipping tubs. These tubs are hauled by diesel locomotive for either dumping in grizzley (ore), or hoisting to surface by the cage. The ventilation in the drives and cross-cuts is provided by auxiliary fans with metal and flexible ducts.

2.4.2. Raising

Raising is a key job in the development programme of any mine. Raises are developed from bottom to top level for ventilation, ladder-ways, ore transfer etc. To bring the mine to its targeted production and efficiency, speedy raising methods are necessary. Constant efforts are made to improve the raising methods with regard to safety, speed and economy. There are three ways of raising. They are:

(i) *Open raising*

This is the simplest and most commonly used method where persons on a platform of timber planks, supported on standard rail clamps drill the face. Before each round is blasted the platform is dismantled. Access to the face is made by rope ladders etc. This method is well suited for short raises of 6–15 m and inclinations of 40°–60°.

(ii) *Compartment raising*

In this system a timber partition separates the raises in two compartments, major cross section is used by broken rock and the rest for placing of pipes and ladder for access to the face. At times the broken rock reserves as platform for performing drilling etc. The ladder-way compartment is covered with wooden planks at the time of blasting.

(iii) *Alimak raising*

Raising by Alimak Raise Climber is essentially a self powered rugged manoeuvrable platform for a limited height and angle, moving on a rail guide anchored to the roof of the raise to carry men and material. The guides are anchored to the walls by retractable expansion bolts.

Jaduguda was the first mine in India to use Alimak Raise Climbers in 1967. The ore-pass raises and ventilation raises in the I- stage and subsequently raises in II-stage shaft deepening work were all done by Alimak Raise Climber.

2.5. Stoping

The method of stoping deployed in a mine depends on the nature, shape and size of the orebody and strength of the wall rocks.

In Jaduguda the "Cut & Fill" stoping method is applied, using deslimed mill tailings as backfill. The broken ore is mechanically handled using Load Haul Dump (LHD) machines. The broken ore is transferred to the foot-wall ore-transfer passes. At the bottom of the ore-pass, the ore is loaded into 3.5 tonne capacity Granby Cars. These mine cars are hauled by diesel locomotives for automatic dumping into the main ore-pass system. The main tramming drive in each level is developed on the foot-wall side of the ore drive. By this way no ore is left in pillars. In the "Cut & Fill" method, the percentage of recovery of ore is approximately 80% and is ideally suited for the Jaduguda Mine.

Earlier the horizontal holes were drilled with the help of jack-legs standing on the muck pile and the broken ore was handled by LHD. This was changed to drilling uppers. Lately the drilling operation has been mechanized by drilling horizontal holes by hydraulic drifters and the broken ore is handled by 1 cu.yd. LHD. The filling in this case is done close to the back leaving a gap of about 1 metre. This has improved the productivity tremendously. Until the 3rd stage is ready, a decline is also being constructed to the two levels below 555 m.l.

2.6. Backfilling

The deslimed mill tailings are transported hydraulically to underground through 3" diameter (75 mm) diamond drill boreholes drilled from surface to underground. There are three boreholes located in the west, central and eastern parts of the deposit, and are connected to 100 m.l., 165 m.l. and 230 m.l. drives. The tailings are tapped from the bottom of these boreholes, and are conveyed to different stopes through 90 m High Density Polyethelene (HDPE) pipes. Boreholes are also drilled from level to level to transport the tailings for deeper working levels.

2.7. III-stage of shaft sinking

An auxiliary shaft is under construction for mining ore lying below 555 m.l. to a depth of 900 m. The location of this shaft is about 580 m north of the main shaft. The winders will be installed at 495 m.l., and between 555 m.l. and 495 m.l. the excavation is 7.5 , diameter, similar to the tower arrangement above ground level in the first stage. The ore bin and ore transfer pockets are excavated in the rock. The new levels at 620, 685, 750, 815 and 880 m.l. will be opened up. The crushing station and skip loading station would be opened at 835 and 865 metres depth respectively.

Drilling in the shaft is done in two halves, the benches differ in elevation by about a meter, thus giving two free faces for blasting, to restrict the throw and avoid damage to sollars, ladders and pipes. Spiral pattern of drilling is followed. For mucking a cactus grab of 0.6 m^3 capacity in conjunction with two 1.5 m^3 capacity buckets is used.

For ventilation two fans of 15 HP each in series are installed near the shaft top with metal ductings of 50 cm in diameter and flexible terelene ductings are used below the metal ductings and are extended to about 20 m from the shaft bottom. The shaft lining will be done by slipform method. After lining, the shaft will be equipped with buntons, rails, rope guides, pipe columns, power and control cables, etc. The cage and its counter weight will then be installed.

2.8. Ventilation

P.V. 160 Aerofoil fans with a capacity of 3000 m^3/min each at 75 mm water gauge are located at Adits No. 2 and No. 5, at the western and eastern ends of the mine.

Ventilation doors have been installed underground to prevent short circuits, and to allow fresh air to ventilate the working places from the deepest level. Air is split at alternate working levels to provide fresh air to the working stopes.

3. BHATIN MINE

Bhatin Mine is an extension of Jaduguda, located at a distance of about 4 km from it. IN between Jaduguda and Bhatin, there is a big upthrow fault whereby the Jaduguda lode has been upthrown. A separate mine is in operation at Bhatin. The orebody width varies from about 2 m to 10 m, having a gradient of about 30–40°. The deposit has an almost similar geology as at Jaduguda with the same country rock as chlorite biotite schist. Because of the low reserves the deposit is developed by adits and incline shafts and the main mining method is cut and fill. The ore is transported by dumpers to Jaduguda Mill for beneficiation.

4. NARWAPAHAR

The uranium deposit at Narwapahar is one of the many economic deposits in the Sighbhum Thrust Belt (STB). The orebodies are monomineratic — the uranium occurring as uraninite and the host rock is chlorite quartz schist containing some magnetide. The underlying schist is of similar composition but with increased magnetic content. The ore-bearing chlorite quartz-schist is overlain by a quartz chlorite schist. At their maximum extent the orebodies have a strike length of about 2100 m and extend to a vertical depth of 600 m. There are 6 uranium-bearing beds/lodes which are:

(1) Main Band I
(2) Main Band II
(3) Band No. 3
(4) HW Lode West of Fault
(5) Khundungri I
(6) Khundungri II

The average dip of the orebody is 30°-35° towards the north-east and occurs sa tabular lenticular horizons. The thickness of orebodies varies from 2.5 m to 20 m.

4.1. Mode of entry

The deposit is planned to be developed by one vertical shaft to a depth of 350 m and a 7° access decline suitable for trackless mining,

The shaft is presently being sunk and it has reached a depth of 200 m. It will have two ground mounted multi-rope friction winders — one for the cage and the other for the skip. These winders are also under installation. Once the sinking and equipping are completed, the temporary headframe will be replaced by a permanent structure and other facilities like orebin, wastebin, belt conveyor etc. will be constructed.

The 7° access decline is excavated by deploying twin boom hydraulic drill jumbos, LHDs of 1.78 m^3 and 2.8 m^3 capacities, LPDTs — 13 and 23 tonne capacities and the relevant service equipments like passenger carriers, supply trucks, service-cum-lube trucks, motor equipments which enter the mine directly from surface through the access decline. Where the orebody is narrow, it is proposed to deploy the "room and pillar" method with steps using decline as the main entry and ramps for entry to the stopes. The main haulage drives are in the foot-wall with the cross-cuts at pre-determined levels. Where the orebody is wider, the cut and fill method will be used with post pillars.

Presently when the mine is under construction, the ore is brought to surface through the decline and transported to Jaduguda Mill by road. As soon as the shaft is commissioned, the ore will be hoisted to surface by skip and then transported to Jaduguda by road.

Since most of the equipments are used for the first time in the country, great care is taken for the training for the engineers, supervisors, operators and maintenance staff, and for the adequate service backup and spare parts management. Arrangements are also made for training of the engineers aborad, posting of foreign commissioning engineers along with foreign engineers.

4.2. Use of high pressure and high capacity main and auxiliary fans

Because of the large scale use of big diesel equipments, ventilation requirements for the mine are high. The ventilation system has been designed with the help of computers. In the long run, for total mine ventilation, three fans with a capacity of 75 m^3/sec at 1.7 KPa (about 7" WG) each with 250 KW electric motors will be used for main ventilation. Provision has been kept for the installation of one additional fan in case ventilation problems are faced in the future. The total circulating quantity of air of about 200 m^3/sec is equivalent to about 0.18 m^3/sec per tonne of ore mined for rated capacity production plus an allowance of 10% additional waste. This large quantity of air required to control heat, dust and diesel emissions is also sufficient to control the radon content in mine air. Two fans Model VF-2000 supplied by M/s Voltas have already been installed in parallel at the western ventilation shaft.

5. RADIATION HAZARDS

In a uranium mine the workers are exposed to the hazards of radiation in addition to the other hazards of underground mining operations. Two main sources of health hazards are inhalation of radon gas and airborne dust. To minimize the effects of radon, the mine must have a good ventilation system, so that all radon gas generated is flushed out of the mine and the working places are well ventilated. With this in view, powerful ventilation fans are installed and are kept running. Auxiliary fans are installed wherever thy are necessary.

For suppressing dust, all operations in the mine where there are chances of raising dust are made wet operations with sprinkling of water. All drilling operations in the mine are wet and in all places where ore is handled, water is sprinkled to keep the dust down.

Monitoring of radiation, radon and dust is done by the Health Physics Group of the Bhabha Group of Bhabha Atomic Research Laboratory at Jaduguda. Members of this laboratory take samples from the mine and mill sites at periodic intervals and keep a watch on all aspects of radiation. The results of the investigation conducted at Environmental Survey Laboratory at Jaduguda show that the exposure to radiation is below the permissible limits of 5 rem per year.

6. JADUGUDA MILL

Uranium ore produced from Jaduguda, Bhatin and Narwapahar mines and uranium mineral concentrates transported from uranium recovery plants are processed in the mill located at Jaduguda. The mill has an installed capacity of 1370 tonnes of ore per day. It is now being expanded to process 200 tonnes per day.

6.1. Crushing

The uranium ore from Jaduguda is transported by conveyor belt to the crushing section while the ore from Bhatin and Narwapahar mines is fed via ground hopper for crushing and grinding. In two stage crushing — 200 mm ore is screened on — 125 mm opening scalper. Oversize is crushed in primary jaw crusher. This is screened on a triple deck screen with openings of 113 mm, 65 mm and 25 mm, -25 mm size is collected as fine ore and -113 mm +65 mm as pebbles, and the rest is recycled back for secondary crushing.

6.2. Grinding

This is followed by two stage wet grinding with a primary rod mill and secondary pebble mill to get ground material of the size of 60% passing through 200 mesh. This slurry is thickened and filtered to remove water for proper solution balance and the cake is repulped with secondary filtrate from downstream to 60% solid slurry. This was mechanical preparation of slurry.

6.3. Leaching

This slurry is pumped for leaching in leaching pachucas, which are essentially air agitated tanks. In leaching tetravalent form of uranium is oxidized to hexavalent from which is soluble in acidic medium. For this sulfuric acid and pyrolusite i.e. MnO_2 is added to maintain 1.6–1.7 pH and -480 mv emf, temp. around 36–38°C. The reaction time is 12 hrs. There are 13 Nos of pachucas, 9 in line. The slurry overflows from one pachuca to another and by the time it comes out from the last pachuca, the slurry has been retained for 12 hrs and around 95% of uranium is leached out.

6.4. Filtration

The leached slurry is filtered in two stages employing string discharge vacuum drum filters. The primary filtrate so received contains 100–500 ppm slimes. This is clarified on precoat filter to get a clear liquor of less than 8–10 ppm suspension.

At this stage the liquor contains 0.5–0.6 gm/lit of U_3O_8, ferrous and ferric sulphate, dissolved manganese, free acid and other impurities. This is concentrated and purified by the ion exchange system, strong base an ion exchange resin is used in a two column system. The complexes of uranyl sulphate, ferric sulphate and sulphate ions get absorbed which are eluted by one normal salt solution. The strong eluate contains around 5–6 gm/l U_3O_8.

This eluate is treated with lime to increase pH to 3.8, ferric sulphate and gypsum get precipitated. This is thickened and filtered. As along with iron some of the uranium complexes also get precipitated hence this is sent ahead of leaching to recover this uranium.

6.5. Precipitation

The overflow is treated with magnesia to get magnesium di-uranate or yellow cake, which is thickened, washed, filtered, dried and packed in drums. The U_3O_8 content in yellow cake is around 74% U_3O_8.

During the process of recovery of uranium, two types of wastes are generated — barren cake from filter section and barren liquor from ion exchange system. Barren liquor is neutralized to pH 10.5 to precipitate dissolved manganese etc. The barren cake slurry is sent to the magnetite plant where magnetite is recovered, then this is mixed with neutralized barren liquor. This is classified by hydrocyclone. Coarser sand is sent to mines for backfilling and finer size is sent to a tailings pond where solid and precipitates settle and clear liquor is decanted off.

6.6. Effluent treatment

The decanted liquor of the tailings pond occasionally used to have higher manganese and radium values than the prescribed limits. The final combined effluent, however, used to be within the limit due to dilution by other streams. Recently the mill has been expanded to increase its capacity needing higher water requirements, which could have been met only by water reclamation. This would have resulted in less water available for dilution and values of radium etc. would have increased in the final effluent.

Therefore a combined scheme of water reclamation and retreatment of tailings pond effluent was implemented. This has been commissioned in March 1990. This has resulted not only in a reduction of fresh water requirement, but has also resulted in the purity of the final effluent.

6.7. Scheme

The main consideration in formulating the scheme was that mine water, magnetite pit water and tailings pond water cannot be used ahead of ion exchange due to its chloride content. The scheme has been shown in a diagram and shows the different streams:

(i) The compressor water and excess vacuum seal water is collected and recycled back to the industrial water reservoir at the water treatment plant for reuse.

(ii) The mine water and magnetite pit water contains fines and hence is pumped to the thickener, the overflow is collected in a water reservoir in the mill. This water is used for secondary cake repulping and for the magnetite plant, all downstreams to ion exchange. The underflow is pumped to tailings pond.

(iii) The tailings pond overflow is brought to the water treatment plant area by gravity drain and is pumped to raw effluent thickener. The clarified effluent is stored in a tank and supplied to the mill as per requirement. Extra effluent is treated for radium and Mn removal before the same is discharged to the environment.

6.8. Treatment scheme

The re-treatment plant capacity is 100 m^3/h. The clarified effluent at controlled rate is pumped to the barium reaction tank. Barium chloride solution is dosed @ 25 mg/l of effluent to precipitate radium as barium radium sulphate, the reaction time being half an hour. This is then neutralized by lime to pH 10 to precipitate Mn, the reaction time in this case is 1 hour.

The resultant precipitate is thickened in treated effluent thickener, the settled precipitate is pumped to the tailings plant, where it is mixed with fresh tailings before pumping to the tailings pond. This is required as the barium radium sulphate precipitate is quite concentrated and is difficult to settle if pumped alone.

The overflow of this thickener, i.e. treated effluent is brought to normal pH by dosing sulfuric acid before the same is discharged to the atmosphere.

6.9. Recovery of uranium from copper tailings

The copper ores of Singhbhum Thrust Belt contain small amounts of uranium minerals which are recovered as by-products. UCIL has set up 3 uranium recovery plants at Rakha, Surda and Mosaboni, near the Copper Concentrators. Tailings after the extraction of copper are sent to UCIL plants for recovery of uranium. The uranium content of copper tailings is of the order o 0.01% U_3O_8. The copper tailings are recovered. These uranium mineral concentrates from all three plants are transported to Jaduguda Mill by road for further processing. All these plants contribute about 150 tonnes of uranium mineral concentrates per day.

6.10. By-product recovery

Uranium ores of Jaduguda, Bhatin and Narwapahar contain small quantities of sulphide minerals of copper, nickel and molybdenum. These are recovered as by-products. Sulphide minerals of Cu, Ni and Mo are recovered by floatation. The combined concentrate of copper and nickel, containing about 20% CuS, are sold to Hindustan Copper Ltd., Ghatsila for smelting and recovery of copper metal. The sulphide concentrate of molybdenum is converted into ferromoly which is used in Ordinance Factories.

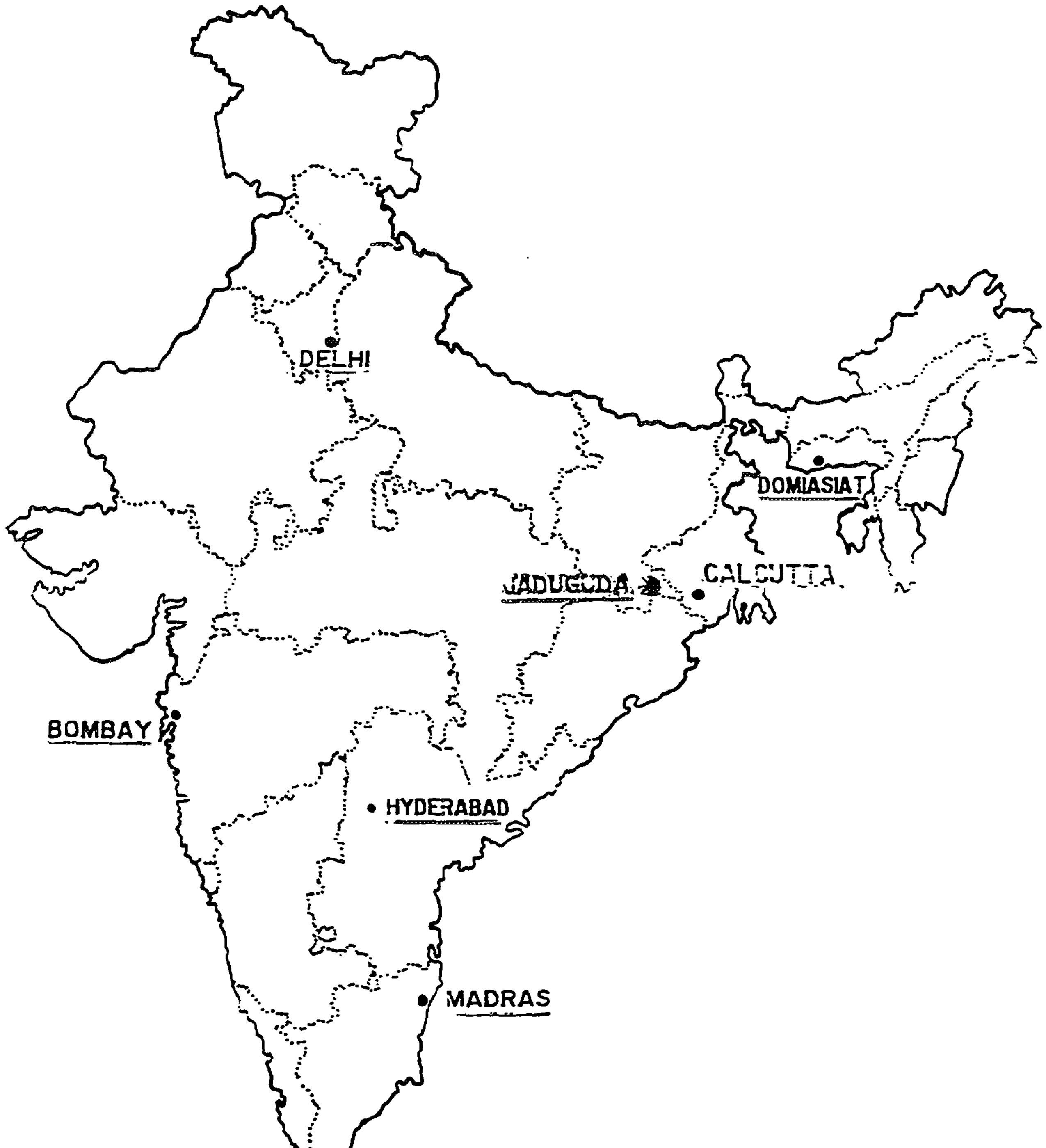

FIG. 1. Location map of Jaduguda in India.

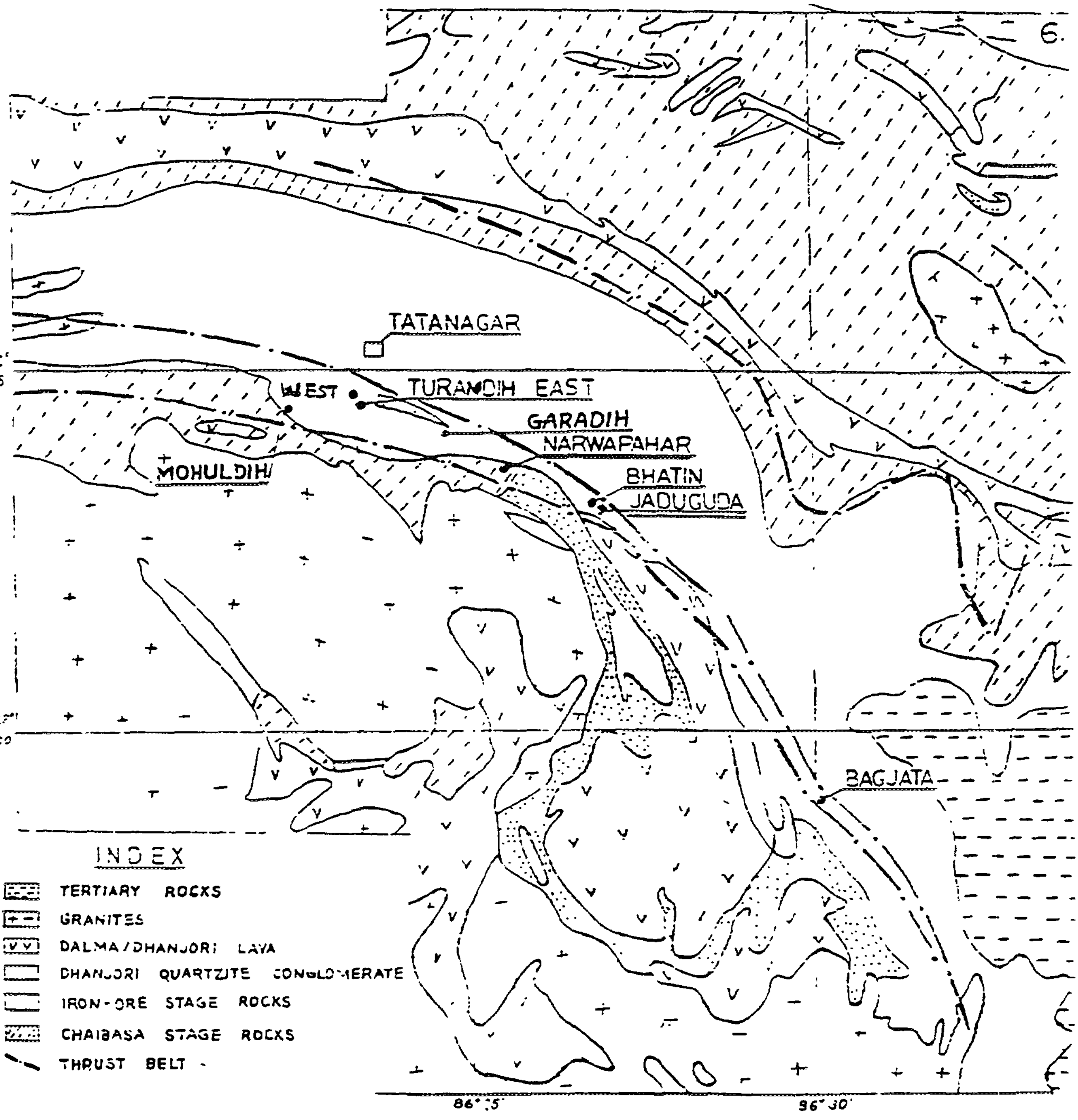

FIG. 2. Geological map of Singhbhum Thrust Belt.

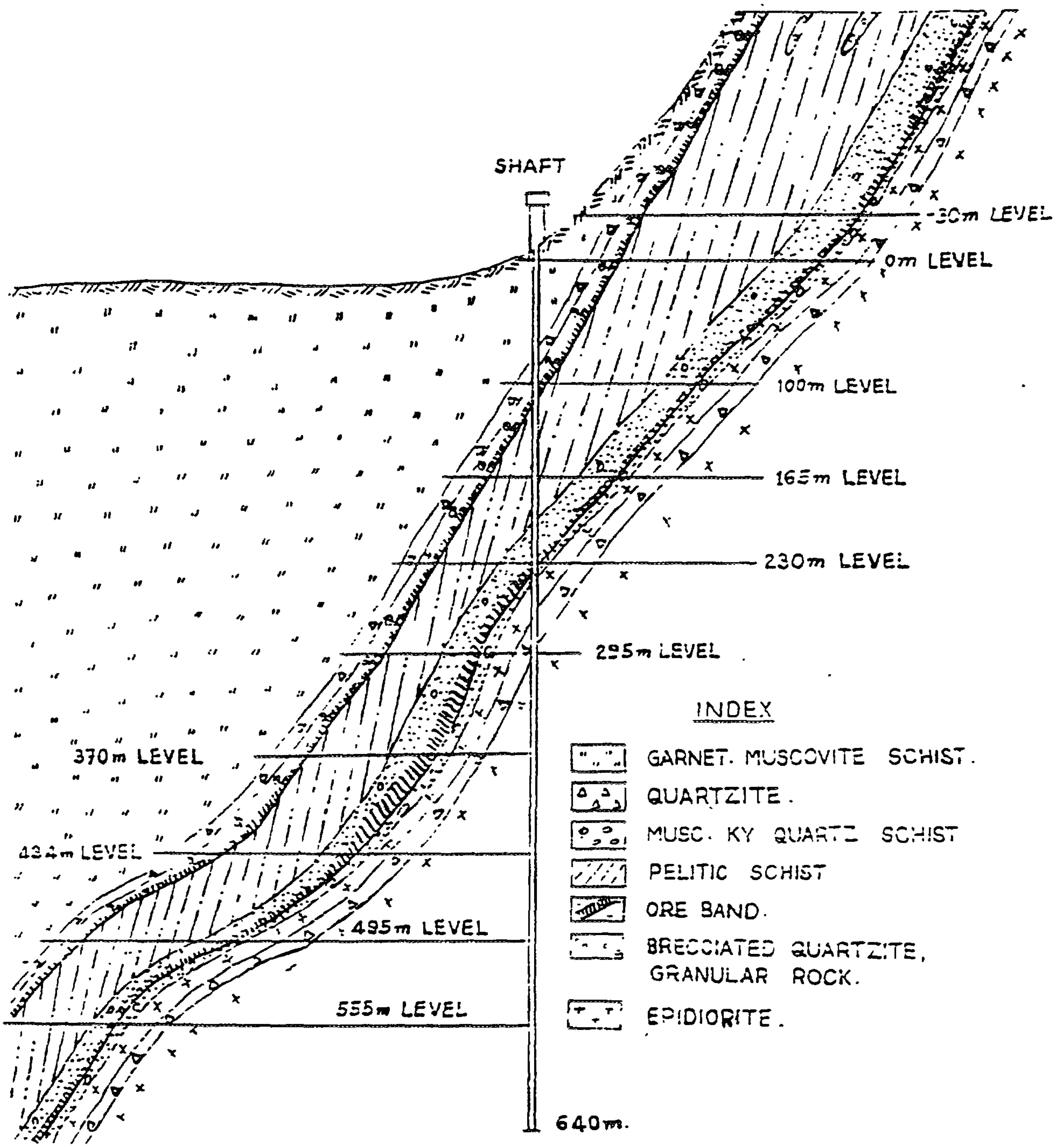

FIG. 3. Transverse section across Jaduguda Hill. Scale: 1:4000.

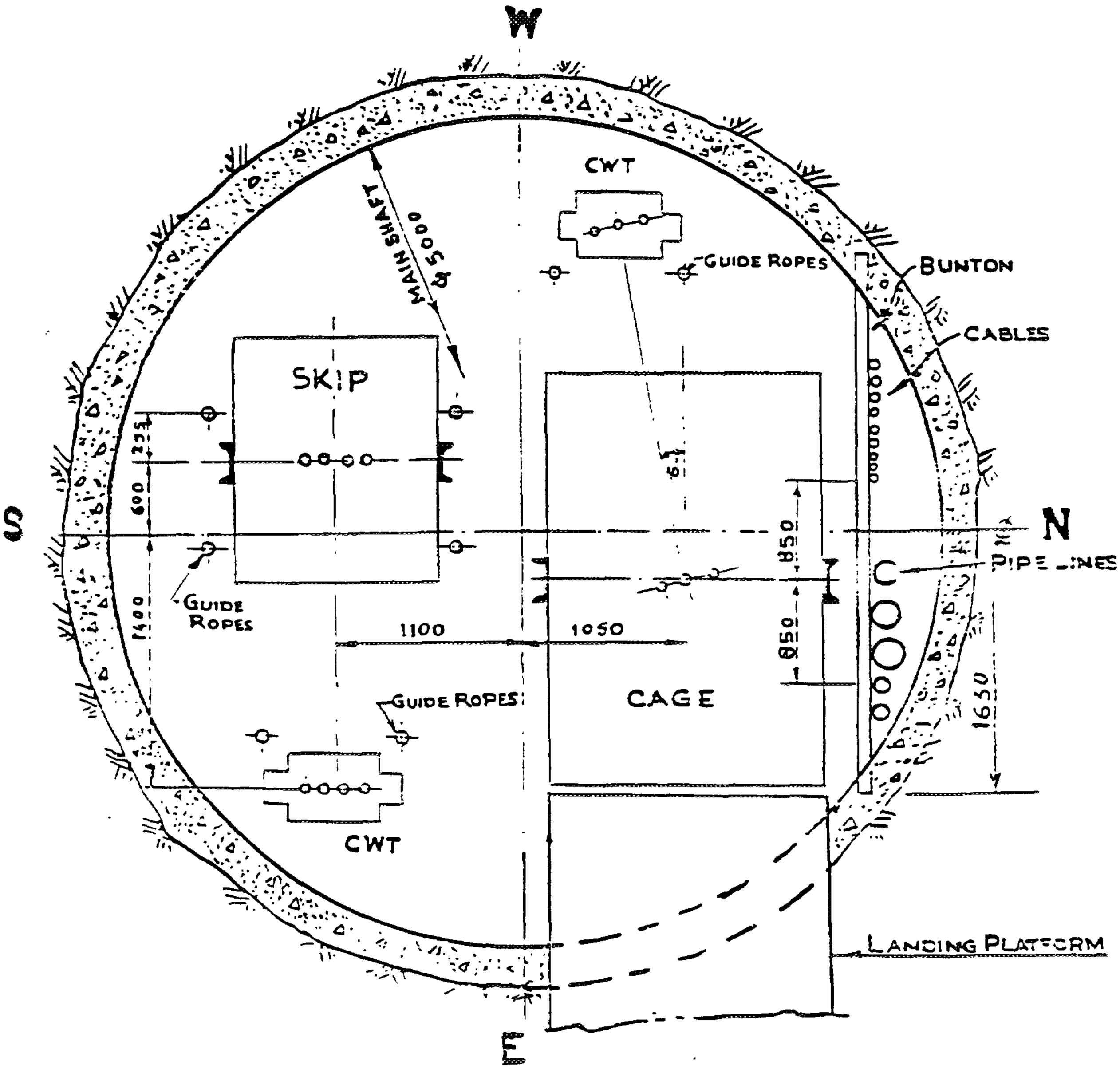

FIG. 4. Shaft plan.

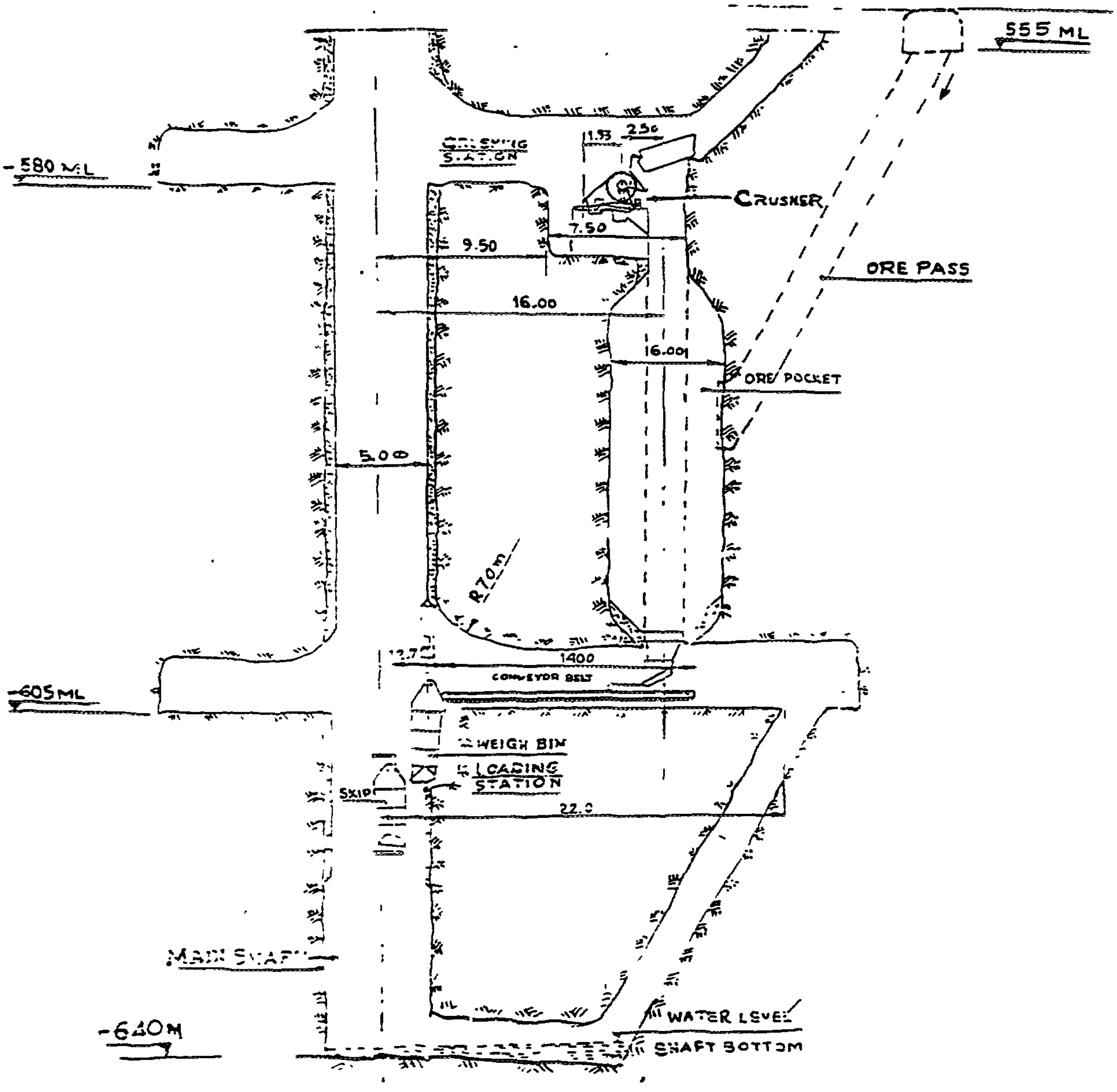

FIG. 5. Crushing and hoisting station.

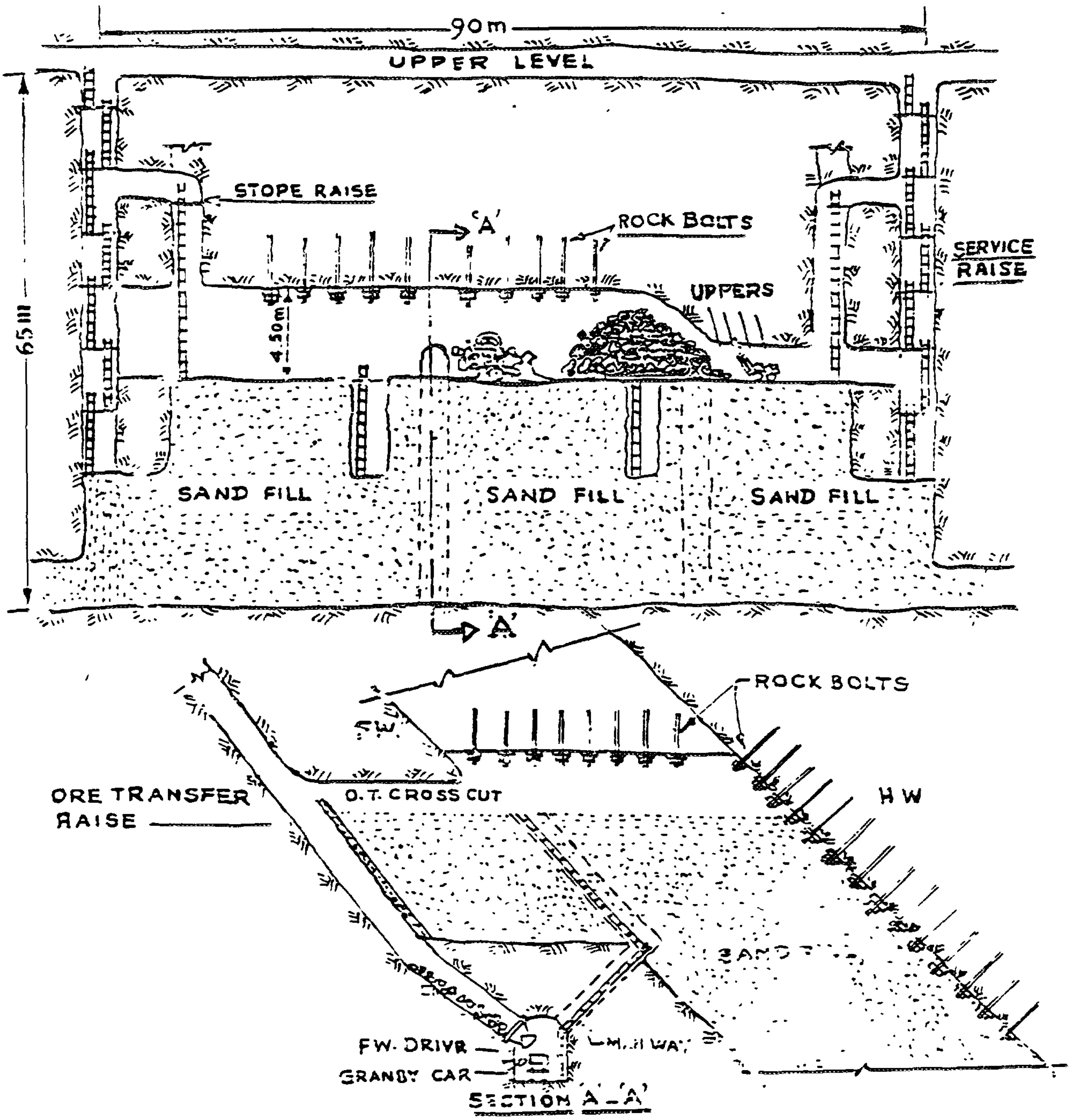

FIG. 6. Cut and fill stope at Jaduguda.

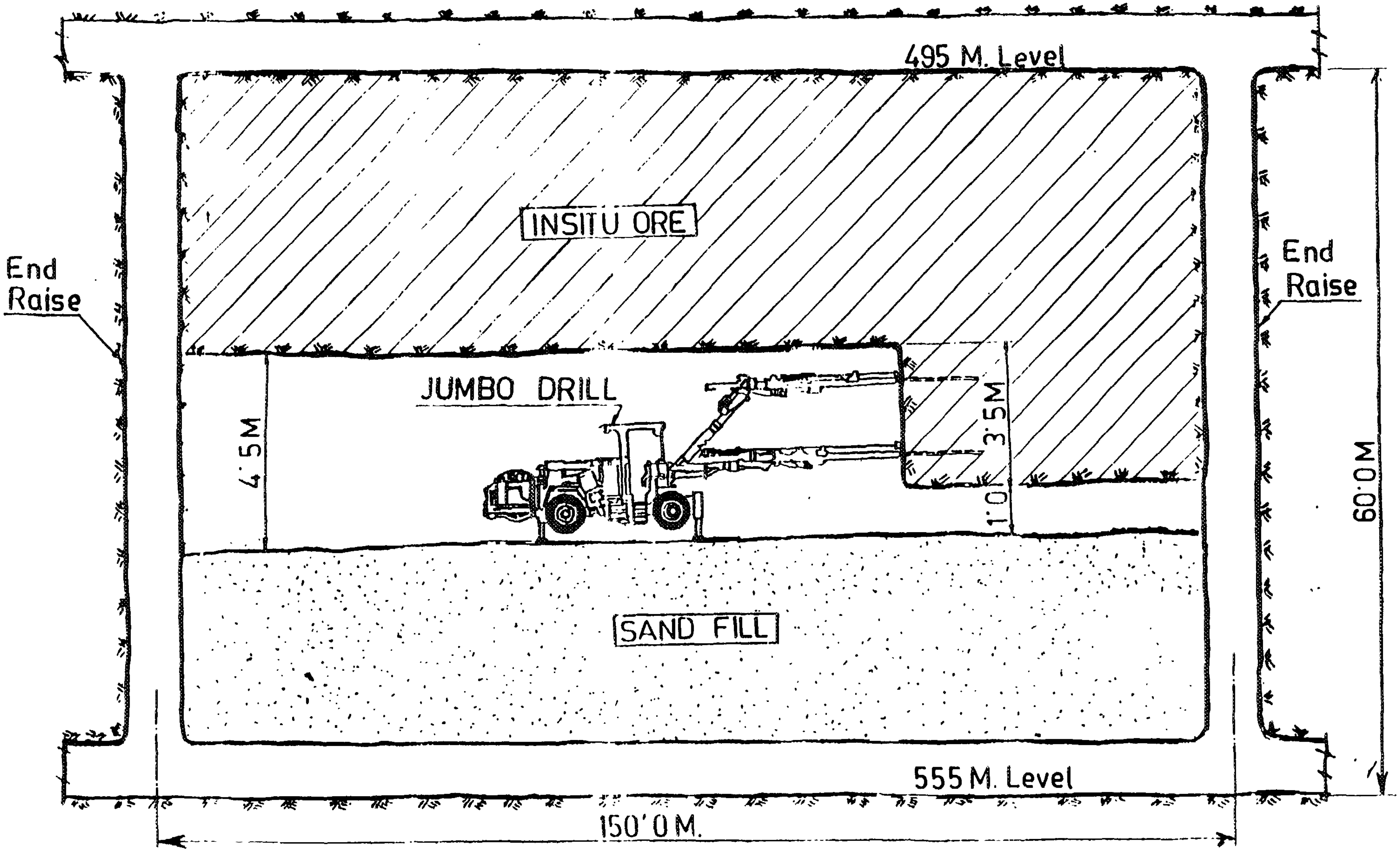

FIG. 7. Vertical longitudinal section; mechanized EO-W5 stope.

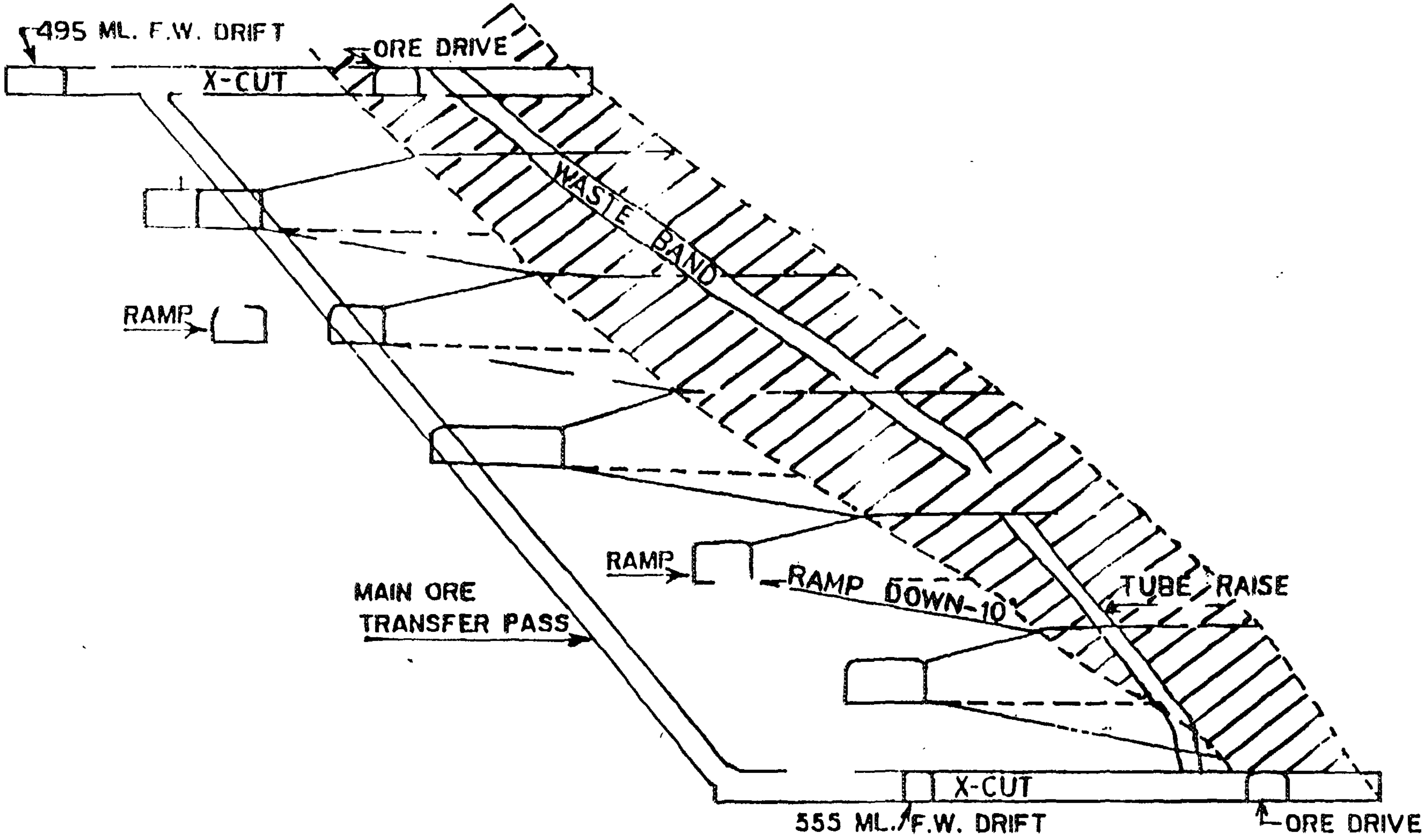

FIG. 8. Transverse section showing the general arrangement of HCF stoping.

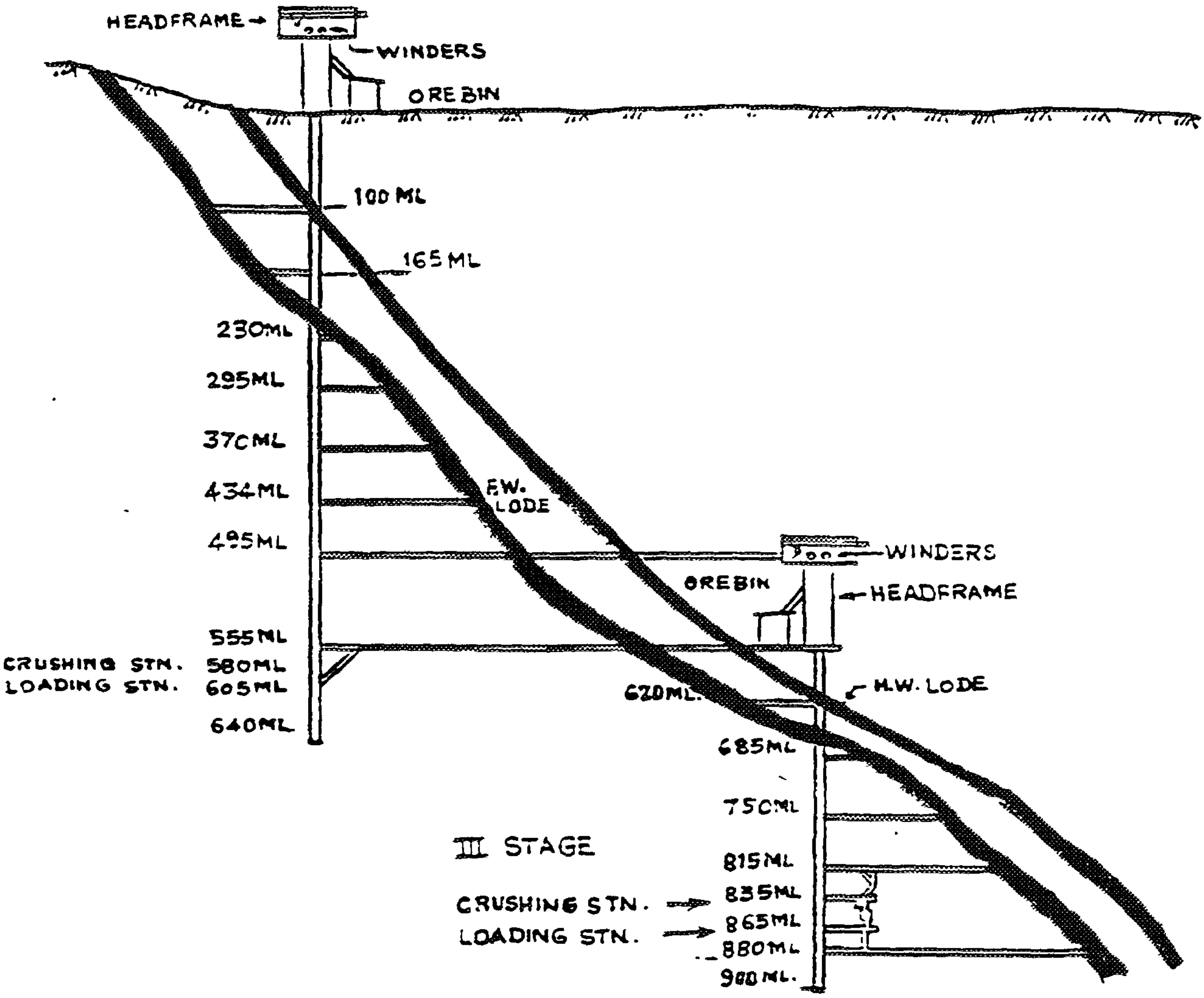

FIG. 9. III-stage shaft sinking.

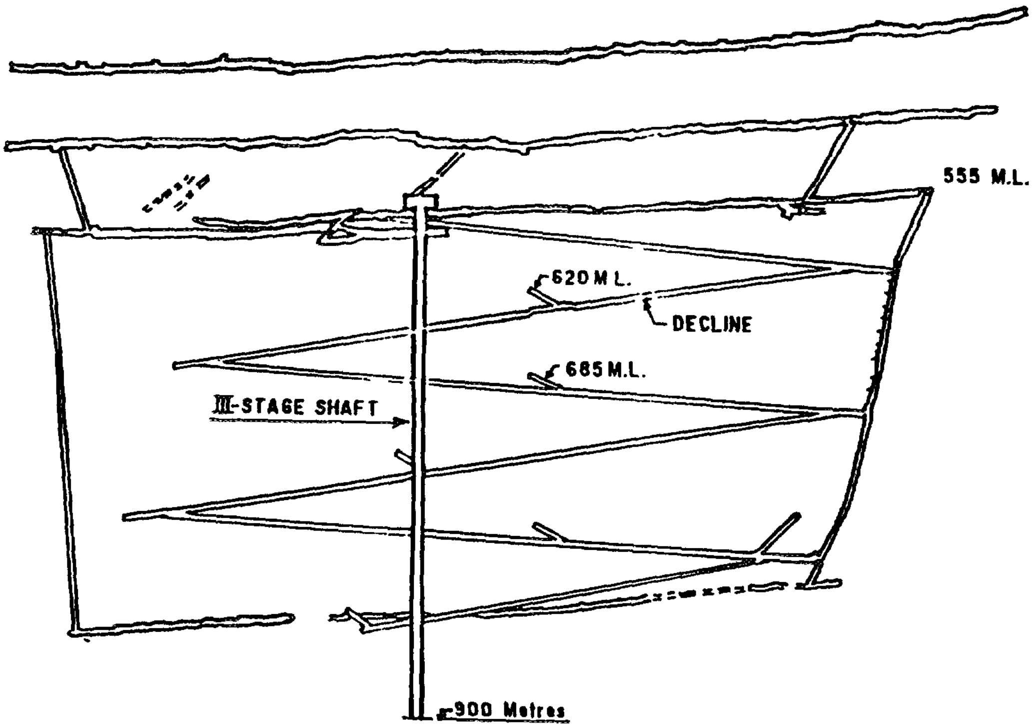

FIG. 10. Development below 555 m.l.

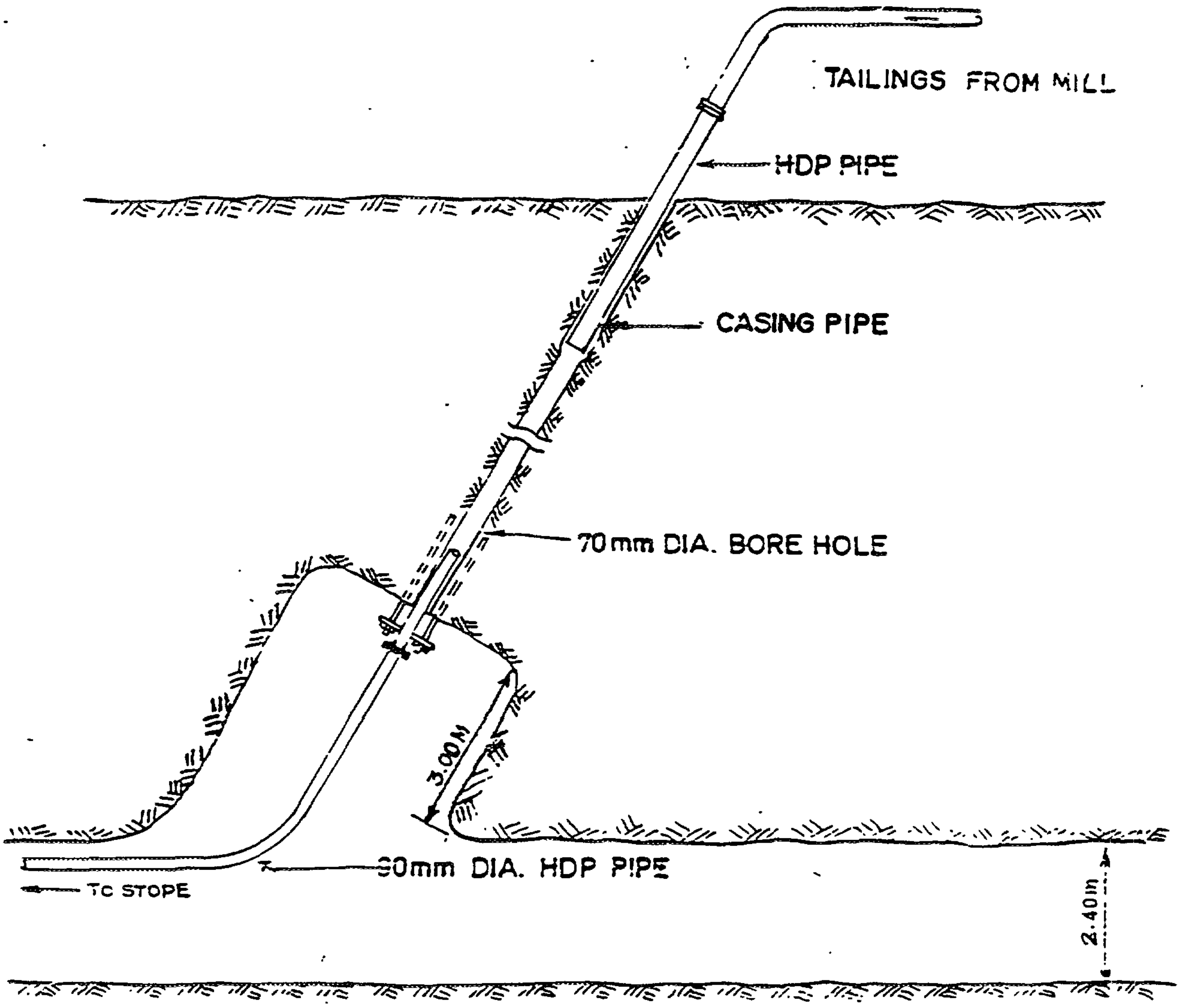

FIG. 11. Sand stowing borehole.

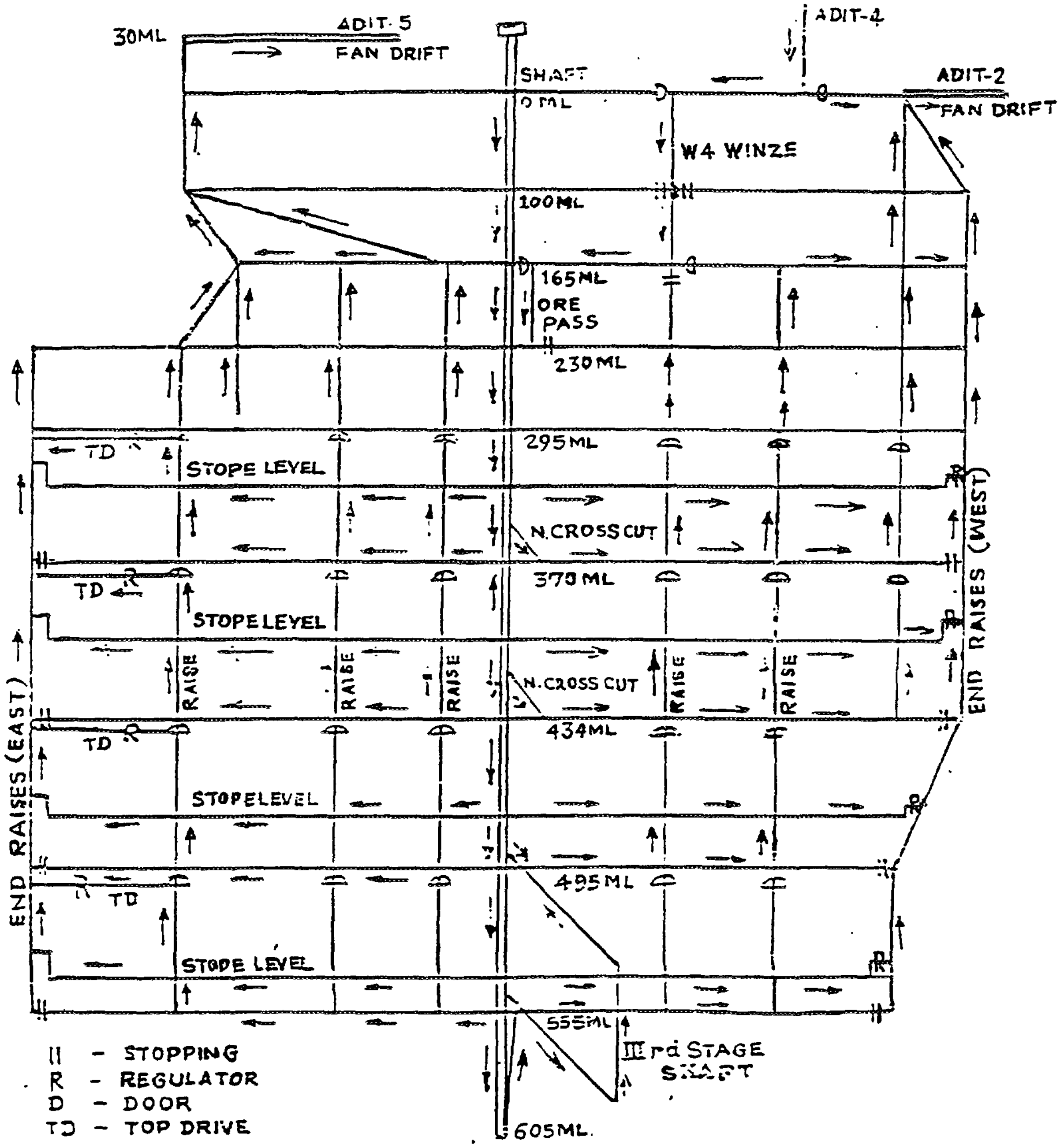

FIG. 12. Schematic diagram of proposed ventilation network of Jaduguda mine.

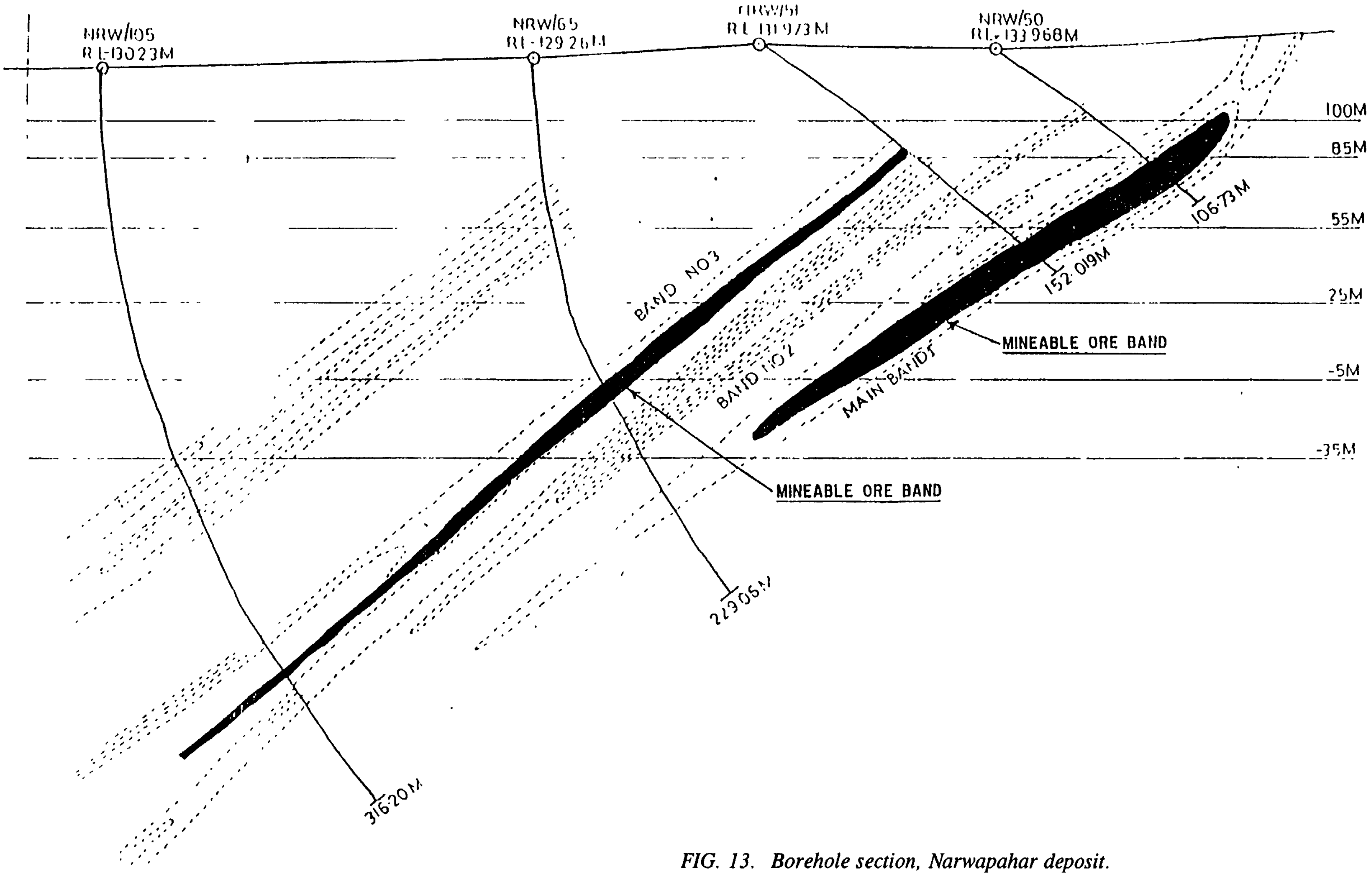

FIG. 13. Borehole section, Narwapahar deposit.

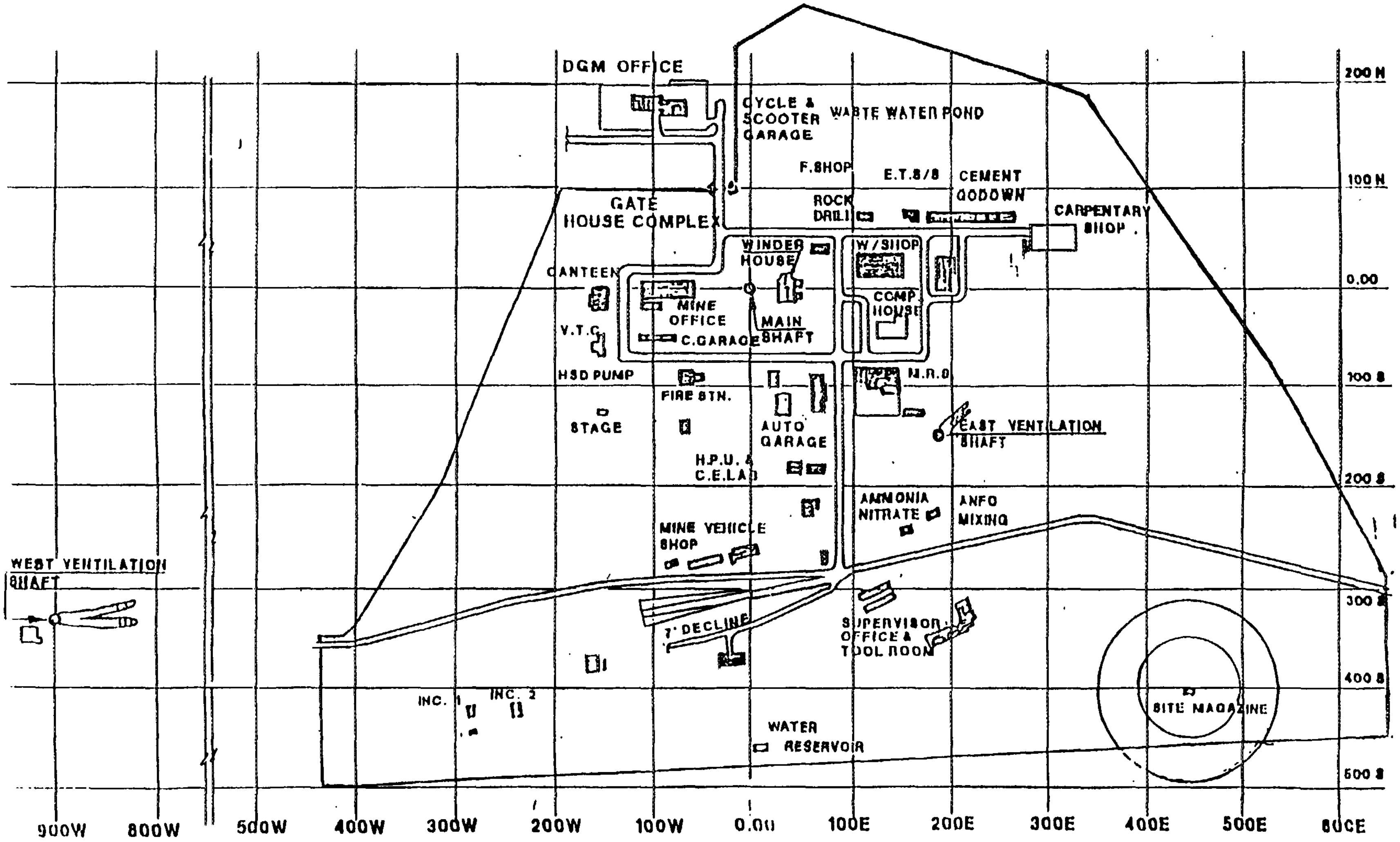

FIG. 14. Narwapahar mining project; surface plan.

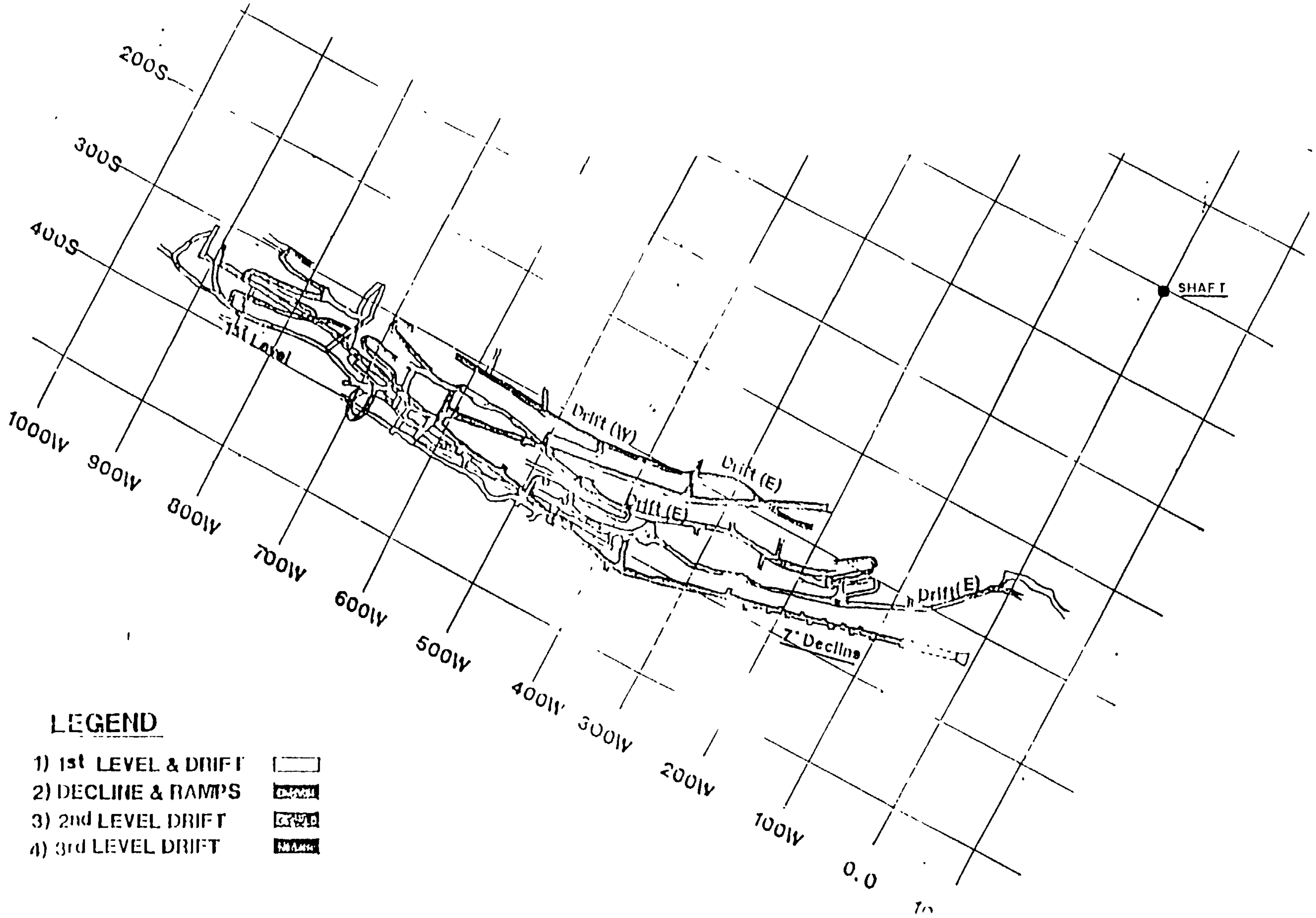

FIG. 15. Narwapahar mining project; underground plan showing present development through decline.

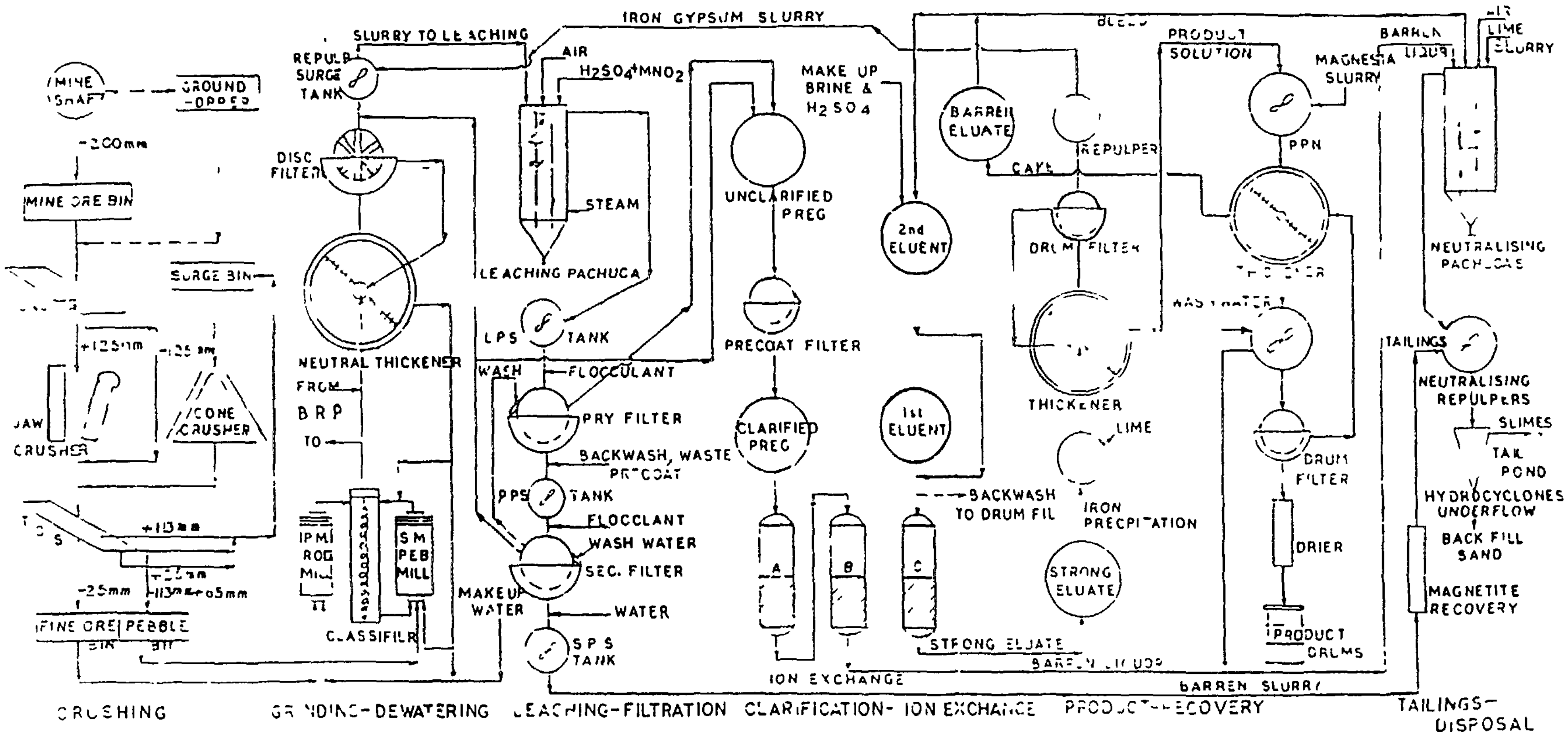

FIG 16 Uranium ore processing flowsheet.

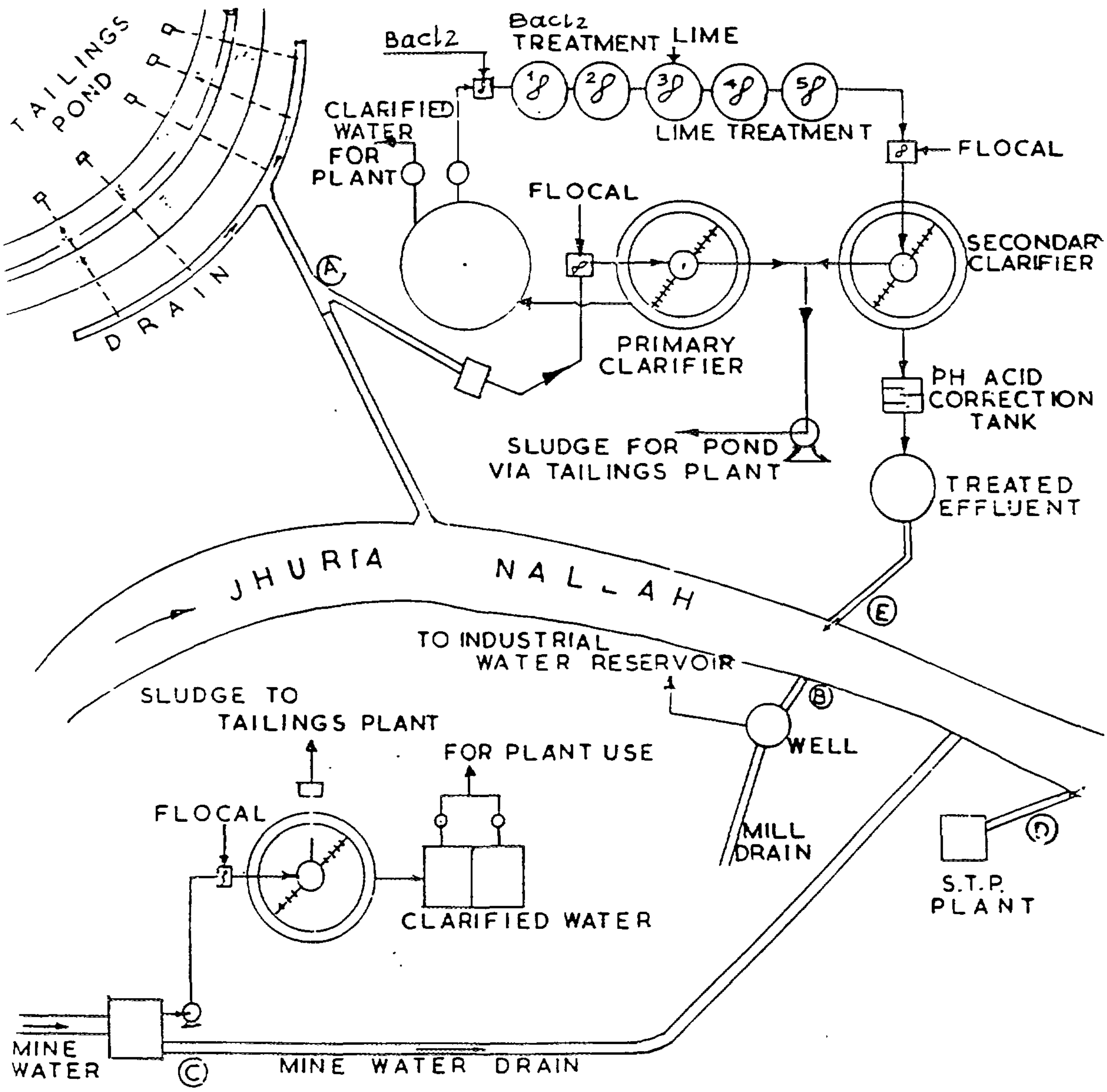

FIG. 17. Flowsheet of effluent treatment plant

	FLOW		Ra (Bq/M3)		Mn (gm/M3)	
	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTET
INDUSTRIAL EFFLT.	6360	600	700	80	3.0	0.2
S.T.P. EFFLUENT	3000	3000	50	50	—	—
TOTAL EFFLUENT	9360	3600	500	55	2.0	<0.1

FIG. 18. Anticipated results in lean period, i.e. mid-October to mid-June

6.11. Magnetite recovery

The uranium ores of Singhbhum contain about 3% magnetite minerals. These are separated after the recovery of sulphide minerals and uranium by electromagnetic separation. It is ground to 90% -300 mesh. The magnetite produced is 95% magnetics and find its use in coal washeries.

7. FUTURE PLANS

To meet the ever increasing requirement of uranium for the nuclear power programme, there is a constant search for viable uranium deposits in the country. One such deposit has been located at Domiasiat in Meghalaya state in the north-eastern part of the country. This was the result of extensive drilling and exploratory mining. The estimated ore reserve is expected to be 9.22 million tonnes with an average grade of 0.1% U_3O_8. The ore occurs at shallow depth of 45 m from the surface. The ratio of ore to ore burden is 1: 6.7 which makes the deposit amenable to exploitation by open cast mining method. The only difficulty is the remoteness of the area whereby the heavy open cast mining machinery will have to be transported. The mill will have to be installed at site to process the mined ore. The raw materials required for processing will have to be supplied constantly and all this will add to the cost of the finished product.

THE CURRENT SITUATION OF URANIUM MINING IN HUNGARY

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Abstract

The paper describes the history of uranium production in Hungary. It focuses on the Mecsek Ore Mining Company, now known as Mecsekuran Limited, and its relationship with the Hungarian Government. From the start of uranium production in 1963 until May 1989 all production was exported to the Soviet Union under an bilateral contract. In exchange the Soviet Union agreed to provide fabricated fuel for the future Hungarian nuclear power plant. In May 1989 the Government of Hungary announced closure of its uranium mining operations because of the high cost of production. The paper describes the history of events since 1989, as well as the current plans to terminate all uranium production by 31 December 1997. The Mecsek Mountains lie in the southern part of Hungary, west from the Danube, about 30 km from the former Yugoslavian border, and north from the city of Pécs. Its eastern side is built up from medieval limestone and dolomites, while the western part is from sandstone and clay from the geological Paleozoic. In the eastern part high quality cokeable coal has been mined for more than 200 years, east from the city of Pécs; and in the western part uranium ore was discovered and the mining began only a few decades ago.

HISTORY OF THE HUNGARIAN URANIUM EXPLORATION AN MINING

The work began with Soviet participation in 1952, by examining the materials of different Hungarian Coal mines. Exploration started in 1953 in the Western Mecsek, with the deposit discovered in 1954. With surface trenching and shallow borings the presence and orientation of uraniferous lenses were documented. Based on this knowledge, the mine-purpose exploration speeded up and the development of the first mine began. In 1956, the previously Soviet-Hungarian Joint Venture for Uranium exploration went into Hungarian ownership and the Uranium mining started in the same year.

In the next years the production increased very fast, and had a steady level for many years. Three mines were producing continuously and as the Mine No I. and later the No II. were expected to be depleted, mines No IV. and V. were commissioned.

The construction of the Processing Plant was finished in 1963, and since then the Company has not exported raw ore, but uranium concentrate. The export was directed solely to the Soviet Union, under an interstate contract. This contract ensured that the future Hungarian power plant or plants would be supplied by the Soviet Union with fuel elements.

Production continued without any problem until May 1989, but it needed a very high state subsidy, as the production costs soared, and this was not followed by the price fixed in the interstate contract. In the meantime the world market price of the uranium had a sharp decline. In the last years, the subsidy reached the 30–40 million US$/year. In May 1989, the Hungarian Government of that time, with economical explanation but with political consideration announced the closure of Hungarian uranium mining.

The governmental decision left only the possibility to the Company for surviving to find a new market or a new partner while the decommissioning work began. This concession was verified by the fact that the deposit had a huge amount of proven reserves at that time, the newest mine built from central sources was commissioned, and the enlarging of the Paks Nuclear Power Plant was in the Hungarian energy policy. Social policy played also a role in the consideration, as unemployment rose, and large crisis areas developed in Hungary, mainly because of the drastic reduction in the (heavy) industry.

With this concession, the Mecsek Ore Mines started to search for partners. In the meantime radical measures were taken to reduce the production costs, and redundancy was also reduced by using the government workforce policy measures which was given especially for the uranium mining. The area of the company activities were also reduced, which meant to get rid of the auxiliary activities, to reduce the number of departments, transform the production structure, revaluate the geological reserves and to some extent also transform the technology.

The main issues of the programme were as follows:

- To wind up all unprofitable works and units. Drastic decrease in central administration.

- Cleaning the profile, i.e. to separate auxiliary activities from the main one.

- To organize economical associations from activities enables to self-supporting.

- To acquire governmental level help for discharged staff not employed in new associations and companies.

- To seek foreign partners.

In 1990-1991 the Mecsek Ore Mining Company closed two of its plants, the Geological Surveying and the Research Automatization. It further dissolved 8 departments and sub-departments. 17 (seventeen) economical associations were formed from the auxiliary activities, of which a few are mentioned below:

- boring and hydrogeological survey
- trade and supply of materials
- production and trade of explosives
- foundary
- transportation
- fabrication of steel structures
- manufacturing of nuclear and electronic instruments
- managing of guest houses and holiday resorts
- timber yard, etc.

By organizing the main activity, it became evident that it could bear not more than about 2000 men, and the self-supporting other companies about another 5-600. As for the redundant 5000, we had to take care of them in a way that no new "crisis belt" could develop in a country trying to change into market economy and struggling with serious economical difficulties of the startup.

The Uranium Company is located not far from the third biggest city of Hungary which also has another big industrial facility characterizing the city: a coal mine, which is also in serious recession.

In 1990-1991, nearly 5000 men left the Company, provided with subsistence, without problems and they did not increase the unemployment rate in the area.

Fuel supply of the nuclear power plant providing approximately 50% of the national electrical energy production is not solely an economical but also a political issue. Above that, the Government took into account the previously performed and outlined measures and the foreign partner's wish for joining. Based on these facts, the Government decided to produce the fuel for Paks NPP from Hungarian uranium, if its price is not too far from the international praxis.

Five years ago the company produced 1 kg U for more than 100 US$, and this cost was reduced by more than 40%.

In 1991, the Company formed 5 units instead of the previous 9. These are:

- mine (with 3 shafts)
- mill
- operational auxiliary plant (energy supply, ore transport)
- head office (management, control and enterprising, business)
- human and recultivation department.

On 1 of April 1992, the State Property Agency assented devaluating of the Affiliate's estates, based on market value judgement, and by this to form a new Limited, the MECSEKURAN.

The MECSEKURAN Ltd disposes of all underground and surface facilities needed for mining and processing (within the existing mining areas), with a workforce of 1850, and of three smaller but important affiliates: Trade and material supply, manufacture of explosives and fabrication of steel structures.

The ore reserves of the mining property are owned by the state, but concession rights are kept by the Limited Company, even if it should be privatized and a foreigner acquire the majority share. The ore reserves were revaluated and categorized. The basis of revaluation — in the present market environment — is profitability, and for the re-categorization of the recommendations of the IAEA.

The MECSEKURAN Ltd was the first company to perform its structural change, and did it from its own sources. As a supplier of the national nuclear power plant, it enjoys some protection against market effects, but real assurance of its survival is the setting its performances and costs to the real market.

During the last years the MECSEKURAN was the only supplier of the Hungarian NPP. The production was in 1992 430 tonnes, in 1993 380 tonnes and in 1 994 it will be 413 tonnes. Between October 1992 and August 1993 the company could utilize only one shaft from the two deep units due to serious accident that occurred in shaft No 4 in October 1992.

The high costs of the renovation the state of the uncertainty and the absence of the developing works created altogether a very serious situation at the beginning of the recent year, both from the point of view of production and financially.

In this situation the former (springtime of 1994) Hungarian Government had worked out a programme for the consolidation of uranium mining. This programme consists of decreasing production parallel to a gradual closing down of certain mine areas. It further comprises the expenditures of required developing works. The programme includes the human costs and the costs of necessary environmental rehabilitation.

As a consequence of the absence of developing works, the ore reserves were diminished drastically. Firstly in category RAT.

On 01.01.1993 the declared uranium resources were as follows:

RAR	Reasonably Assured Resources 1132 tonnes U
EAR I.	Additional Resources 16 661 tonnes U

on 01.01.1995:

RAR	672 tonnes U

EAR I. 15 644 tonnes U

As it appears form these figures, the RAR resources are sufficient for a production of 3 years on the reduced level. At the same time the deposit has considerable resources for about 20 years.

The problem of the absence of developing works comes from the financial situation. In 1991 the Hungarian Government declared the price of domestic uranium in US$60/kg. Since that time inflation has increased by about 120% but the devaluation of the HUF was about 80% only.

Under these conditions the company is forced to consume the existing RAR resources and the future.

The change of the Government in last May is delaying the decision. The new Hungarian Government declared the closing of Hungarian uranium mining on 23.12.1994. The closing means that the end of production will be on 31.12.1997. After this time the company will continue the closing of mines and begin the environmental rehabilitation works.

THE CURRENT SITUATION

Some data about the Hungarian uranium centre:

Name of the production centre:	MECSEKURAN LLC	
Operational status:	existing	
Startup date:	1956	
Deposit type:	sandstone	
Type of the mining operation:	UG	
Size (tonnes ore/day):	2500	
Average mining recovery:	50 to 60%	
Type of the mill:	IX/AL (+ heap leaching)	
Size (tonnes ore/day):	1500	
Average processing ore recovery:	90%	
Nominal production capacity (t U/year):	650	
Employment:	1300, at the end of 1995:	1200
Historical U production (t):		
to 1992:	16 718	
1993:	380	
1994:	413	
1995 and later:	210–200/year until 1998	

During the last years the MECSEKURAN was the only supplier of the Hungarian NPP. In 1995 the MECSEKURAN reduced its production the further demand of NPP is coming from Russia.

THE OPTION OF THE DEPOSIT OF RADIOACTIVE WASTE

In the near vicinity of the Mecsek Uranium deposit, to the west, and in the deep footwall of the "productive" complex, in the Lower Permian aleurolit (a claystone) could be of major importance in the future.

Hungary is not a very extensive country, and most of its area is overlain by Tertiary-Quaternary sediments, therefore the deposition of the different kinds of toxic and radioactive wastes causes anxiety. Presently the high activity radioactive waste — the spent fuel elements — are delivered to the Soviet Union, within the framework of an interstate contract, but the deposition of the middle, low and high activity wastes is a continuing problem.

The above mentioned geological formation is extremely large extensive, about 140 km^2, and has a thickness of 600–800 m. Its homogeneity, water-tightness makes it quite suitable for final deposition of any kind of dangerous waste, radioactive waste included.

The experts of Mecsek, knowing well the importance of the geological sealing of waste deposits, began the detailed surveying of the area.

As the area in question is not far from the western flank of our deposit, the idea emerged that with the help of an exhaust of the mine which could be taken out of the mine activities and is 1000 m deep, will we can access the formation, and the shaft could be used for the deposition in 1100 m depth. The formation in the area is free from faults, is tight, and even the quality of its material excludes the possibility of water migration, therefore the dangerous wastes could be separated from the environment with total safety.

The research is in progress, and as a matter of course the economical calculations too, both national and foreign companies and authorities, scientific institutions are involved, the interest is very intensive.

According to the present concept, the planned depository even in the first phase could receive about 30 000 m^3 waste per year.

The whole surveying and research work on the waste deposit is performed according to international standards. Within the framework of a National Project and using technical assistance of the Canadian AECL, the Mecsek Ore Mining Co. and the MECSEKURAN LTD. excavated about 300 m drift and drilled about 800 m boreholes for the prospection of the claystone.

The programme is expected to continue in the next years.

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