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GEOLOGICAL ENVIRONMENTS OF SANDSTONE-TYPE URANIUM DEPOSITS

REPORT OF THE WORKING GROUP ON URANIUM GEOLOGY
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FOREWORD

The great surge of interest and activity in exploration for uranium deposits over the last decade has added significantly to our knowledge of uranium geology and the nature of uranium deposits. Much of the information that has been developed by government and industry programmes has not been widely available and in many cases has not had the benefit of systematic gathering, organization and publication. With the current cut-back in uranium exploration and research efforts there is a real danger that much of the knowledge gained will be lost and, with the anticipated resurgence of activities, will again have to be developed, with a consequent loss of time, money and effort. In an effort to gather together the most important information on the types of uranium deposits, a series of reports is being prepared, each covering a specific type of deposit. These reports are a product of the Agency's Working Group on Uranium Geology. This group, which has been active since 1970, has gathered and exchanged information on key questions of uranium geology and co-ordinated investigations on important geological questions. The projects of the Working Group on Uranium Geology and the project leaders are:

Sedimentary Basins and Sandstone Type Deposits – Warren Finch

Uranium Deposits in Proterozoic Quartz-Pebble Conglomerates – Desmond Pretorius

Vein Type Uranium Deposits – Helmut Fuchs

Proterozoic Unconformity and Stratabound Uranium Deposits – John Ferguson

Surficial Deposits – Dennis Toens

The success of the projects is due to the dedication and efforts of the project leaders and their organizations, and the active participation and contribution of world experts on the types of deposits involved. The Agency wishes to extend its thanks to all involved in the projects for their efforts. The reports constitute an important addition to the literature on uranium geology and as such are expected to have a warm reception by the Member States of the Agency and the uranium community, world-wide.

A special word of thanks is extended to Warren Finch for his work in organizing and guiding this project and for editing the text, and to Jim Davis for his participation in the editing of this report on sandstone type uranium deposits.

John A. Patterson
Scientific Secretary

CONTENTS

PREFACE

This Handbook on the "Geological Environments of Sandstone-type Uranium Deposits" was conceived at meetings of the Geology Working Group held in connection with the 26th International Geologic Congress, Paris, July 1980. The Project – Sedimentary Basins and Sandstone-type Uranium Deposits – had just finished a topical project (W.I. Finch, R.J. Wright, and H.H. Adler, editors, 1983) and had a membership of 21 members representing 12 nations. Part of this membership became the core of the present Project contributors to which new members were recruited. The success of this Handbook is the result of the fine co-operation and support of the individual Government and private company officials for whom the contributors work.

The geology of sandstone-type uranium deposits is the best understood of all types of deposits because they have been the chief source of uranium supply for the United States, where continuous scientific studies have been carried on for over 35 years with an estimate of over 10 000 man-years of scientific effort. The sandstone ores in the US as well as most in other countries are well described in the literature so that detailed descriptions of ores in this Handbook have been kept at a minimum. Thus, the main purpose of this Handbook is to summarize the key elements of the geologic setting of the sedimentary, tectonic, hydrologic, and geochemical environments of the uranium deposits in Phanerozoic sandstone formations in order to develop criteria to identify new areas for exploration, particularly in developing countries. At this time it seems most appropriate to summarize our state-of-the-art knowledge in anticipation of increased demand for uranium in the 1990's.

The scope of the Handbook is to report on at least one district in each country having sandstone-type uranium deposits. Most of those described are major producing or reserve areas, but some are of lesser importance. Every continent outside the polar regions is represented as is appropriate for a world-class type of deposit. Some important districts not described regionally are (1) host sandstones of Permian, Triassic, and Cretaceous ages, USA; (2) the Salt Wash Member, Morrison Formation, Colorado Plateau, USA; (3) Tertiary Sandstones of the Wyoming basins, USA; (4) Miocene basal deposits, British Columbia, Canada; and (5) Potwar district, Pakistan.

Members of the Project appreciated the guidance and support given by Geology Working Group Chairman Robert D. Nininger, Vice Chairman Lincoln R. Page, Secretariat Pedro Stipanicic, 1980–1982, and Secretariat John A. Patterson, 1982–1984.

Warren I. Finch and James F. Davis
Editors, Denver, Colorado, USA
May, 1984

PART I

GENERAL GEOLOGY

SANDSTONE-TYPE URANIUM DEPOSITS – AN INTRODUCTION

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Overview

World-class sandstone-type uranium deposits are defined as epigenetic concentrations of uranium minerals occurring as uneven impregnations and minor massive replacements primarily in fluvial, lacustrine, and deltaic sandstone formations. The typical sandstone host-rock sedimentary environments were 1) fluvial-lacustrine systems that formed molasse-like sequences on a wide foreland bordered by a magmatic-arc subduction zone on one side and an intracratonic sea on the other, 2) fluvial-lacustrine systems in intermontane basins formed by later tectonic adjustments in foreland regions, and 3) fluvial-shoreline systems of marginal marine plains. The two main uranium-deposit forms are tabular and roll-front, each related to a distinctive geochemical process of ground-water infiltration type of mineralization. The deposits in dominantly lacustrine fine-grained carbonaceous rocks are at least in part syngenetic. A few deposits are in volcanic lacustrine basinal rocks adjacent to hydrothermal mineralizing systems.

Nearly 90 percent of world uranium production from sandstone-type deposits through 1980 was from the United States, and most of the remainder was from Niger, France, Argentina, and Japan. Reasonably Assured Resources are also identified for Australia, Brazil, Mexico, South Africa, Spain, Turkey, and Yugoslavia. Exploration for sandstone-type uranium deposits has been extensive in continental sedimentary basins using models developed in the United States. Conventional open-pit and underground mining methods as well as in-situ leach are practiced. In the mill, the uranium is put into solution by either acid or alkaline leach and recovered by either ion-exchange or solvent extraction.

1. INTRODUCTION

Sandstone-type uranium deposits are truly world-class, for exploitable ones are known on every continent outside of the polar regions. They are the dominant domestic sources of uranium in Argentina, Japan, Niger, and the United States and are an important source in France. In addition, Reasonably Assured Resources have been identified in Australia, Brazil, Mexico, South Africa, Spain, Turkey, and Yugoslavia.

The main purpose of this introductory paper is to define, classify, and briefly introduce the reader to the general geologic setting for sandstone-type uranium deposits described in more detail in the regional descriptions.

2. DEFINITION

The term "sandstone-type uranium deposit" implies more than just uranium deposits hosted in sandstone. Most are surely recognized by their typical epigenetic form, geochemical character, and host-rock characteristics, regardless of the continent upon which they occur; others are less typical and have characteristics that resemble other types of deposits, such as syngenetic lacustrine or marine carbonaceous black shale, volcanogenic, and surficial deposits. Some primary uranium deposits in sandstone hosts have been modified by later secondary processes, such as deep tectonic deformation, hydrothermal action, and surficial oxidation, that may confuse their identification as sandstone-type. Quartz-pebble conglomerate, marine black shale, calcrete, and sandstone-hosted vein types of deposits are excluded. An important group excluded are the vein deposits hosted by the Franceville Sandstone in Gabon, Africa.

Typical sandstone-type uranium deposits are epigenetic concentrations of uranium occurring as uneven impregnations in sandstone and, in places, in conglomerate and finer grained interbeds. The host consists of fairly well-sorted, permeable, unmetamorphosed clastic sediment that ranges from mudstone to conglomerate, but the dominant hosts are fine- to medium-grained sandstones. The composition of the sandstone host ranges from quartzose through feldspathic to arkosic, and some hosts may contain varying amounts of acidic volcanic debris. The uranium minerals are most commonly very fine grained and occupy intergranular spaces and locally replace fossil wood. In such replacements, the uranium mineral is massive but still very fine grained. Rich concentrations of uranium minerals tend to follow bedding but locally, particularly near the edge of an ore body, they cut across the bedding, either irregularly or along sharply curved expressions called rolls. The overall form of many deposits may be best termed tabular. In other deposits the roll feature predominates, and in these roll-front deposits the geochemistry and the mechanism of emplacement are different from those described as tabular deposits, even though some tabular ones have local roll surfaces. In the San Juan Basin, New Mexico, U.S.A., many originally tabular ore bodies were redistributed by a much later roll-forming process so that both tabular and roll-front deposits occur in the same district.

Most sandstone-type deposits commonly have well-defined boundaries, but others grade out imperceptibly into the wall rock. The delineation of many deposits is difficult because ore bodies are connected by concentrations of low-grade uranium. Some tabular deposits seem to float within a sandstone layer with no obvious relation to mudstone interbeds and bounding mudstones, whereas others are related spacially to lithologic changes. Roll-front deposits, on the other hand, most always occupy a sandstone between bounding mudstones [1].

Associated with some typical sandstone-type deposits are syngenetic concentrations of uranium in carbonaceous siltstone and mudstone such as in the Date Creek Basin, Arizona, U.S.A. [2].

Some sandstone-type deposits occur in water-laid clastic sediments in small basins associated with volcanic centers where the deposits are satellitic to larger vein-like deposits, such as at McDermitt, Oregon, U.S.A.; at Pena Blanca, Chihuahua, Mexico; and near Rome, Italy [3]. The epigenetic form and precipitation of uranium in these deposits are similar to those of the sandstone-type, but the mineralizing solution was hydrothermal rather than low-temperature ground water, as indicated by intense kaolinization and rich iron-sulfide concentrations.

Another group of deposits that vary from typical sandstone-type are in sandstone formations that have been slightly metamorphosed. In these the uranium occurs in carbonaceous fine-grained rocks, where uranium, perhaps syngenetic in many deposits, has been redistributed and enriched in fractured rock, such as at Lodeve, France [4] and Eastern Europe [5].

3. CLASSIFICATION

Sandstone-type uranium deposits may be subdivided according to their geochemical environment and to the sedimentary environment of their host rocks. Such classifications are helpful in understanding relations between various deposits hosted by sandstones and between sandstone-type deposits and other types.

Most deposits are in fluvial and lacustrine sediments in either continental or marginal marine environments. Where lacustrine rocks dominate, very fine grained organic-rich hosts are more abundant, and the uranium deposits may be in part syngenetic. These deposits have been termed lacustrine deposits, as in Date Creek Basin, Arizona, U.S.A. [2]. A few deposits, particularly those in Miocene and younger channel sandstones that were deposited directly on igneous and metamorphic terrane have distinctive characteristics and have been termed basal-type uranium deposits, such as in British Columbia, Canada [6], and Japan [7].

The geochemical environment of mineralization determines the mineralogy and form of a deposit. The two main forms of deposits are tabular and roll-front types.

4. DISTRIBUTION

The wide geographic distribution of the deposits is shown on the index maps of each continent in this volume. The greatest known concentration of deposits is in the United States, but this may be due in part to intense exploration in the United States and the lack of exploration in other places.

Sandstone-type deposits are restricted to rocks of Silurian and younger ages, which is directly related to the time of the first development of vascular land plants. The largest resources are in Permian, Jurassic, and Tertiary sandstone formations. Tabular deposits are most common in Cretaceous and older rocks, whereas roll-front deposits are primarily in Upper Cretaceous and Tertiary rocks. Roll-front deposits do occur in older rocks, such as the Jurassic Morrison Formation in the San Juan Basin, but these deposits were formed by redistribution of originally tabular ore in Tertiary time.

5. SANDSTONE HOST-ROCK SEDIMENTARY ENVIRONMENTS

Typical sandstone host-rock sedimentary environments are fluvial-lacustrine systems that formed molasse-like (neomolasse) sequences on wide (500 km or more across) foreland basinal pediments bordered by a magmatic-arc subduction zone on one side and marginal marine plains of the intracratonic sea on the other [8]. Equally typical environments were fluvial-lacustrine systems in small intermontane basins a few tens of kilometers to a couple hundred of kilometers across that developed due to later tectonic events in the foreland regions and fluvial-shore-line systems at the edges of marginal marine plains. In the continental environments, deposition was subaerial and the basins had restricted outlets to the sea [9], which prevented wholesale oxidation and promoted reducing conditions during and after sedimentation. Tabular uranium deposits were generally formed in these reducing environments. Intermontane basins and marginal marine plains afforded topographic conditions favorable for the introduction of uranium-bearing oxidizing ground water into reduced host beds along exposed basin margins to produce roll-front deposits. In the continental forelands, the island arc provided uranium-rich volcanic debris for some sediments, whereas granite plutons in exposed basement rocks provided detritus for other host sediments. Both volcanic and granitic sources for uranium were possible. Some multicycle sediments were produced as well as single cycle so that metamorphic and preexisting sedimentary rocks were provenances for sediments in places.

The paleoclimatic conditions of the sedimentary environments for host sandstone rock units of Carboniferous and younger ages around the world were humid, subtropical to tropical [10] These conditions promoted the growth of abundant forests that provided the plant matter for later reducing conditions for uranium precipitation. These climatic conditions also existed in many sandstone units in which uranium deposits are unknown, so this feature is not a sole favorability factor.

The typical colors of the host sediments formed under reducing conditions are light-gray or green to white, whereas the colors of hosts modified by introduced oxidizing waters are light brown to red; these colors reflect the state of oxidation of iron minerals in tabular and roll-front ores, respectively.

Favorable hosts were characterized by high-water tables where anaerobic conditions below the ground-water level preserved fossil carbonized and pyritized wood and sulfate-reducing conditions that produced disseminated pyrite. Both of these permitted later, albeit very soon after sedimentation in many cases, precipitation of uranium minerals.

6. URANIUM MINERALIZATION

Mineralization of most tabular deposits seems to have begun shortly after sedimentation and burial of overlying sediments; indeed, some uranium could have been preconcentrated during deposition of overbank boggy mudstone (comparable to organic-rich surficial uranium deposits [11]. Gruner's [12] theory of multiple migration-accretion of uranium for tabular deposits is partly borne out by detailed isotopic age determinations of uranium minerals and studies of diagenesis of host rocks. Much mineralization appears to have accompanied diagenesis of the sediments. In the formation of roll-front deposits, uranium was introduced into the host rocks after diagenesis, particularly by oxidizing water.

Identifying the sources of the uranium and associated metals for the known deposits does not seem to be a problem because both internal host-rock and external sources are identifiable in most places. The main sources are igneous in nature, either uraniferous granite or volcanic ash. Debate abounds concerning these two sources, but the recognition of either is important both as a source and as criteria for assessing favorability for exploration.

Uranium was precipitated below the water table mainly by reduction and adsorption processes; in some, one of these was dominant [13]. Reduction was caused by in-place carbonaceous matter as plant remains, introduced humate-like matter, sulfide minerals, or infiltrating sulfidic gases. In some places, especially where evidence for carbon, sulfides, and gases are absent, a transient sulfite may have acted as a reductant [14]. Adsorption was by organic matter, iron-oxides, zeolites, clay, or TiO_2. Distinct types of ore developed where the quantity of these reductants and absorbents varied [13].

The nature and origin of mineralizing solutions have been investigated intensively. Tabular deposits seem to have been precipitated at chemical interfaces between a connate pore solution [9] and an infiltrating solution [11]. The stagnate pore solutions were probably briny in character and related to underlying saline sediments; and the infiltrating uranium-bearing solution apparently flowed above the pore solution, and uranium was precipitated at and near the contact. Roll-front deposits, on the other hand, were precipitated at a redox interface of a single extrinsic solution passing through reduced pyrite-bearing sandstone [13]. The extrinsic solutions were meteorically-derived oxidizing recharge waters that gained access to the host unit at its outcrop along the edges of the depositional basin, where the solutions were enriched with uranium from either a granite or volcanic terrane.

The chief primary uranium minerals are uraninite (pitchblende), coffinite, and urano-organic complexes; pyrite is the most common gangue mineral, and calcite is abundant in some. In the presence of phosphate, ningyoite is primary, as in the basal-subtype [6]. The kind of secondary minerals produced by weathering in the present-day surficial environment [15] depends a great deal upon the availability of key metals, such as vanadium and copper. In the absence of these metals, secondary uranium minerals are commonly uranophane and autunite; the presence of vanadium yields carnotite or tyuyamunite; copper yields cuprosklodowskite and torbernite.

In addition to vanadium and copper associated with uranium, which are commonly in minable grades exceeding that of uranium, there are locally fairly rich concentrations of trace metals of molybdenum (important in Karoo rocks; [16]), selenium, chromium, and naturally, radium. Zones that contain some of these metals outside the edges of uranium ore are common.

7. MODEL

Sandstone-type uranium deposits have the following diagnostic characteristics:

1) Host-rock unit is Silurian or younger in age.

2) Host-rock unit was deposited most commonly in fluvial and lacustrine environments in continental settings or in channel, lagoonal, and beach-bar settings on the marginal plains of marine basins.

3) Provenance for sedimentation was commonly granitic or acidic (felsic) volcanic terranes, either of which provided a plausible source for uranium.

4) Fossil carbonized plant matter or humic material is commonly present.

5) Uranium concentrations were controlled by sedimentary features rather than tectonic fracture structures.

6) The host-rock units are those with good regional transmissivity, and the deposits are localized where sandstone/mudstone ratios are near 1:1.

7) Low-temperature ground waters were the mineralizing solutions rather than high-temperature hypogene fluids.

8) The ore minerals are epigenetic even though mineralization was commonly part of diagenesis.

9) Mineralization took place in rocks having original low-angle basinward dips, and in most cases the deposits were preserved because of only slight increases in regional dip. More severe tectonic events have redistributed ore in some places.

8. PRODUCTION AND RESOURCES

In many ways, uranium production has had an unusual history relative to other metals. Particularly important to the future is the relatively recent discovery and development of high-grade unconformity-type vein deposits in Australia and Canada. For 30 years, production from the sandstones in the Western United States dominated the world uranium market, with ore grades continually dropping from more than 0.20 percent U in the 1950's to around 0.10 percent U in the early 1980's. It is likely that low-cost production of high-grade ores (0.25 percent to >1 percent U) from Australia and Canada will hold uranium prices in check, forcing old and new mines to either compete or go out of business. This probably means that new sandstone mines will have to be substantially higher grade than the 0.10 percent U mined in the last several years.

Sandstone-type uranium deposits yielded about 46 percent of World uranium production outside the Centrally Planned Economies Area from 1948 through 1980 [17]. Of the total of about 293,000 t uranium, about 89 percent came from the United States, 6 percent from Niger, 4.7 percent from France, and the remainder from Argentina and Japan. About 40 percent of the United States production came from the San Juan Basin, New Mexico [18]. Reasonably Assured Resources (RAR) at the cost category below \$80/kg U in sandstone totaled about 620,000 t U as of January 1, 1981 [17]. Of this, about 54 percent was in the United States, 26 percent in Niger, 8.4 percent in South Africa, 4 percent in France, 3 percent in Argentina, and the remaining 5 percent distributed in Australia, Brazil, Japan, Mexico, Spain, Turkey, and Yugoslavia. Estimated Additional Resources (EAR) at the cost category below \$80/kg U in sandstone totaled about 760,000 t U as of January 1, 1981. Of this about 81 percent was in the United States, 7 percent in Niger, 4.7 percent in Canada, 2.5 percent in South Africa, 1.9 percent in France, 1.6 percent in Yugoslavia, and less than 1 percent in Argentina, Australia, Brazil, and Portugal. Disparity in EAR estimates between the United States and other countries is due to the intensive national evaluation conducted during the National Uranium Resource Evaluation (NURE) Program in the United States.

9. EXPLORATION STRATEGY

Sandstones have yielded and will continue to yield high-grade and low-cost ores. The reports of this volume describe the geologic environment of some of the important productive areas of the world and potentially productive areas as well. Many other areas not yet identified undoubtedly exist. Despite the decline in production in the early 1980's, sandstone-hosted deposits will probably always maintain competitive importance, and in many countries constitute the primary exploration potential. The overall purpose of this volume then is to help set the stage for future exploration in the sandstone environment.

It is our opinion that the best strategy is direct exploration (surface and aerial-radiometric prospecting, geologic mapping and drilling) followed in importance by indirect exploration (geochemistry and non-radiometric geophysics). A study of case histories supports this approach.

Certainly a model is needed from the start, but it should begin as a simple one, based on empirical evidence from productive areas, and evolve as data are gathered on the area being explored. The initial model should be so broad that it encompasses background from several known areas--a multiple working hypothesis, in effect. As the program proceeds, the explorationist will subjectively identify what appears to be favorable evidence, such as pinkish-red staining, arkosic sandstone, radioactive siltstones adjacent to sandstones and braided stream deposits. As exploration proceeds it is important to objectively note those geologic features that could fit the critical parameters necessary for any ore deposit--source, solution movement, favorable host rock, concentration, and preservation, which together constitute an existence model [19].

It is, therefore, important that any exploration program be designed to be flexible so that modifications can be made as new data is gathered. Exploration success is usually dependent on many attempts, some creative thinking, and careful data gathering--not on a complex model derived soley from some distant region.

Exploration should begin with the simple surface and aerial-radiometric prospecting and geologic mapping, and then progress to more complex methods of drilling, geochemistry, and geophysics, but only as the need for more data is justified. A good geologic data base is essential to the meaningful interpretation of geochemical and geophysical data. Hydrogeochemical surveys have been quite useful in generally identifying specific areas of high potential within a larger favorable area.

The ultimate tool in sandstone uranium exploration is the drill rig. The relatively low cost ($3 to $10/m) of drilling provides the extremely important third dimension to the geologic picture. Sedimentary depositional patterns can be mapped, alteration trends traced, structural features identified, and, finally, the ore deposit characteristics outlined and evaluated. In exploration of potentially favorable sandstone areas, the drill hole and its geophysical log are unquestionably essential in order to adequately map regional stratigraphy, alteration features, and geochemical (radiometric) traces.

10. MINING AND MILLING

Mining of uranium from sandstone deposits has been about equally divided between underground and open-pit methods, and in-situ leaching has become more common in the 1980's, especially in Texas, U.S.A. Costs vary greatly, depending on such things as depth, ground-water conditions, ore grades, rock hardness, and overburden stability.

The open-pit mining of sandstone ores has been greatly facilitated by the utilization of large equipment that can rapidly and cheaply move waste from above the ore. This advantage diminished as mining depths increased and ore grades decreased, particularly in the United States. Consequently, present-day uranium mines in the sandstone environment in the United States were not competitive at the lower prices in the early 1980's. On the other hand, higher grade sandstone ores found at or near the outcrop in new areas might be produced at relatively low cost.

Milling of the ores is done by the acid leach process for low-lime ores and by carbonate (alkali) leach for calcareous ores. Uranium is extracted from the leach solutions by either ion-exchange or solvent extraction, and dried to produce the final yellowcake product. Costs of milling varied from $15 to $40 per metric ton for sandstone ore in 1983. A number of factors can affect recovery and cost, such as rock induration, ore mineralogy, associated elements (particularly vanadium, copper, and molybdenum), carbonates, and organic matter.

In-situ leaching has proven economic in some sandstone districts in the United States. Through properly spaced holes, either acid or carbonate solutions are pumped into the host unit, circulated through the ore, recovered from selected wells, and fed into a recovery plant. Most sandstone ores are permeable and the host beds are generally confined by impermeable layers, but even so considerable testing is necessary before in-situ leaching is contemplated.

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TECTONIC SETTINGS OF THE WORLD'S SANDSTONE-TYPE URANIUM DEPOSITS

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Abstract

The general relationships of global tectonic patterns and the occurrence of known sandstone-type uranium deposits around the world have been noted. The latter are generally in subduction-related tectonic settings, in back-arc compressive cratonic basins. Sandstone-type uranium deposits are found predominately in intermontane basins that developed on cratonic platforms. In general, they occur at least several hundred miles inland from the continental margins, although fluvial coastal environments of large river embayments also contain deposits.

The commercially important sandstone-type uranium deposits in the USA are all in intermontane basins on cratonic platforms, or in coastal embayment environments. In Asia, the deposits are over cratonic platforms, except for the intermontane basins of Japan which are in a volcanic belt at a continental boundary. In South America, the deposits are over stable shields or cratons, although in Argentina some are adjacent to the compressive folds and thrust zones of the Andean Belt. In Europe, these deposits are in a cover over Hercynian and Alpine tectonic zones, except for the Caledonian-related deposit in northern Scotland. Intermontane basins and craton platform cover environments generally characterize the sandstone uranium deposits of Africa and Australia-Oceania.

INTRODUCTION

In recent years, many geologists throughout the world have emphasized, in their research, the tectonic settings of specific mineral deposit types on a global scale. Typical examples are textbooks by A.H.G. Mitchell and M.S. Garson (1) and by C.S. Hutchison (2). The tectonic setting, in which a particular suite of rocks formed, has been defined as the location, relative to major features of the earth's crust, within which the rocks, including associated economic minerals of similar age were deposited, intruded, or formed by deformation and/or metamorphism. With specific reference to the world's uranium deposits in sandstone, the nature of the earth's major sedimentary successions, their geometry, thickness, composition, and detailed facies and associated formation of uranium deposits, are controlled by the tectonic setting.

Mitchell and Garson (1) have noted that essentially all of the world's mineral deposits have been formed in one of the following tectonic settings:

- Continental hot spots, rifts, and aulacogens,
- Passive continental margins and interior basins,
- Oceanic settings,
- Subduction - related settings,
- Collision - related settings, or
- Faults and lineaments in the continental crust.

Subduction-related settings are further divided into:

- Submarine trenches and outer arcs,
- Magmatic arcs,
- Outer-arc troughs,
- Back-arc magmatic belts and thrust belts,
- Back-arc compressive cratonic basins,
- Back-arc extensional cratonic basins, and
- Back-arc marginal basins and inter-arc troughs.

Mitchell and Garson (1) have related the world's sandstone uranium deposits to back-arc compressive cratonic basins. The relationship of such basins to other features of the subduction process are shown in Figure 1. These basins lie landward of the back-arc magmatic and thrust belt, on continental crust that is depressed in front of the thrust belt. They are equivalent to some of the "exogeosynclines" of ancient orogens. Some of the world's best examples are the large reserves of sandstone-type uranium ore being mined from a number of basins in a back-arc continental setting in Wyoming, USA (Fig. 2).

Another author, Charles S. Hutchison (2), states more generally that the world's strata-controlled epigenetic sandstone-type uranium deposits "are predominantly found in intermontane basins that developed on cratonic platforms. Generally, they occur well inland from the continental margins, but the fluvial coastal environment of large river embayments may also be important" (Fig. 3).

This paper is organized and written to correlate closely with the Definition and Classification of Sandstone-Type Uranium Deposits by W.I. Finch and J. F. Davis (3) and with the numerous other papers prepared for the 27th International Geological Congress on the geologic environments of sandstone-type uranium deposits. It relates to Finch's and Davis' compiled tables and maps for each continent, and is confined to tectonic settings, only, as indicated in the title. Descriptions of sedimentation, stratigraphy, ore controls, recognition criteria and other important geologic features of sandstone-type uranium deposits are to be found elsewhere. The variety of tectonic settings for these deposits is discussed by continent and by clusters of these deposits within continents, as set forth in the Finch/Davis tabulations and maps. The continents are considered in order of the quantity of currently identified ore reserves and the potential sandstone-type uranium resources in each.

NORTH AMERICA

Known sandstone-type uranium deposits in North America are virtually all in the United States of America (USA), with one small area in Canada and two

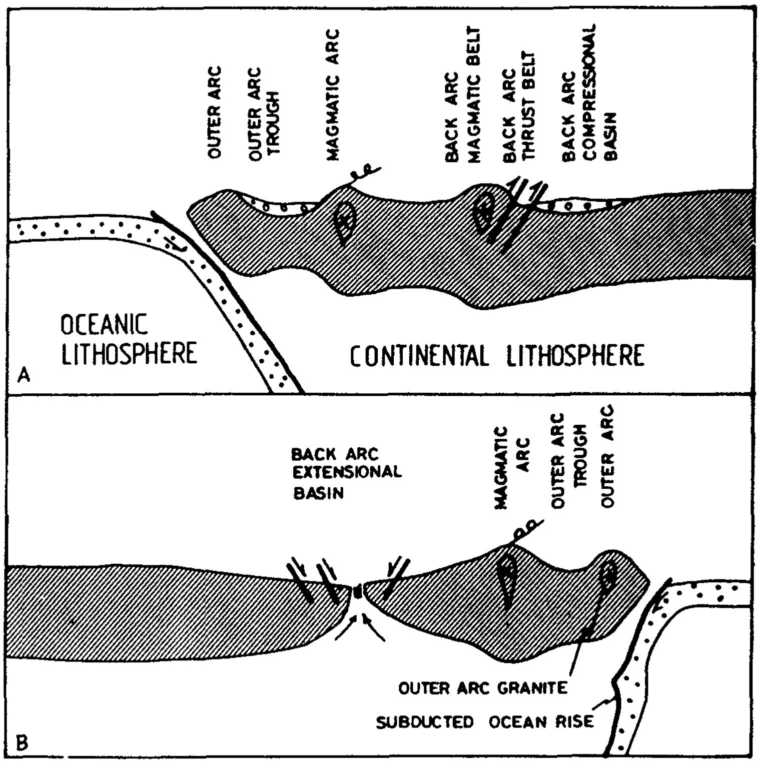

Figure 1. Schematic cross-sections through (A) west-facing continental margin arc and (B) east-facing incipient island arc system. From Mitchell and Garson (1).

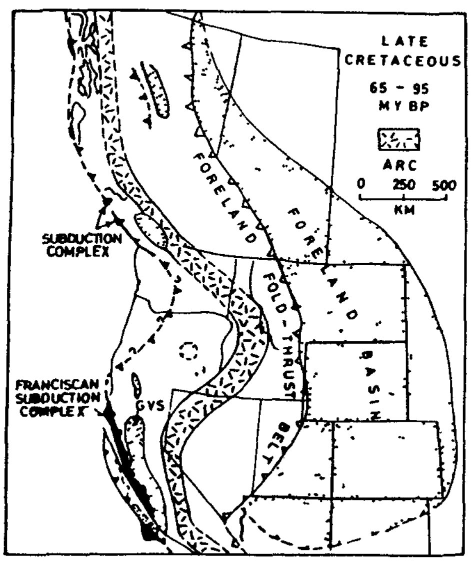

Figure 2. Back-arc compressive basin ("foreland basin") and back-arc thrust belt ("fold-thrust") in western Cordillera of North America. GVS—Great Valley Sequence (after Dickinson, 1976). From Mitchell and Garson (1).

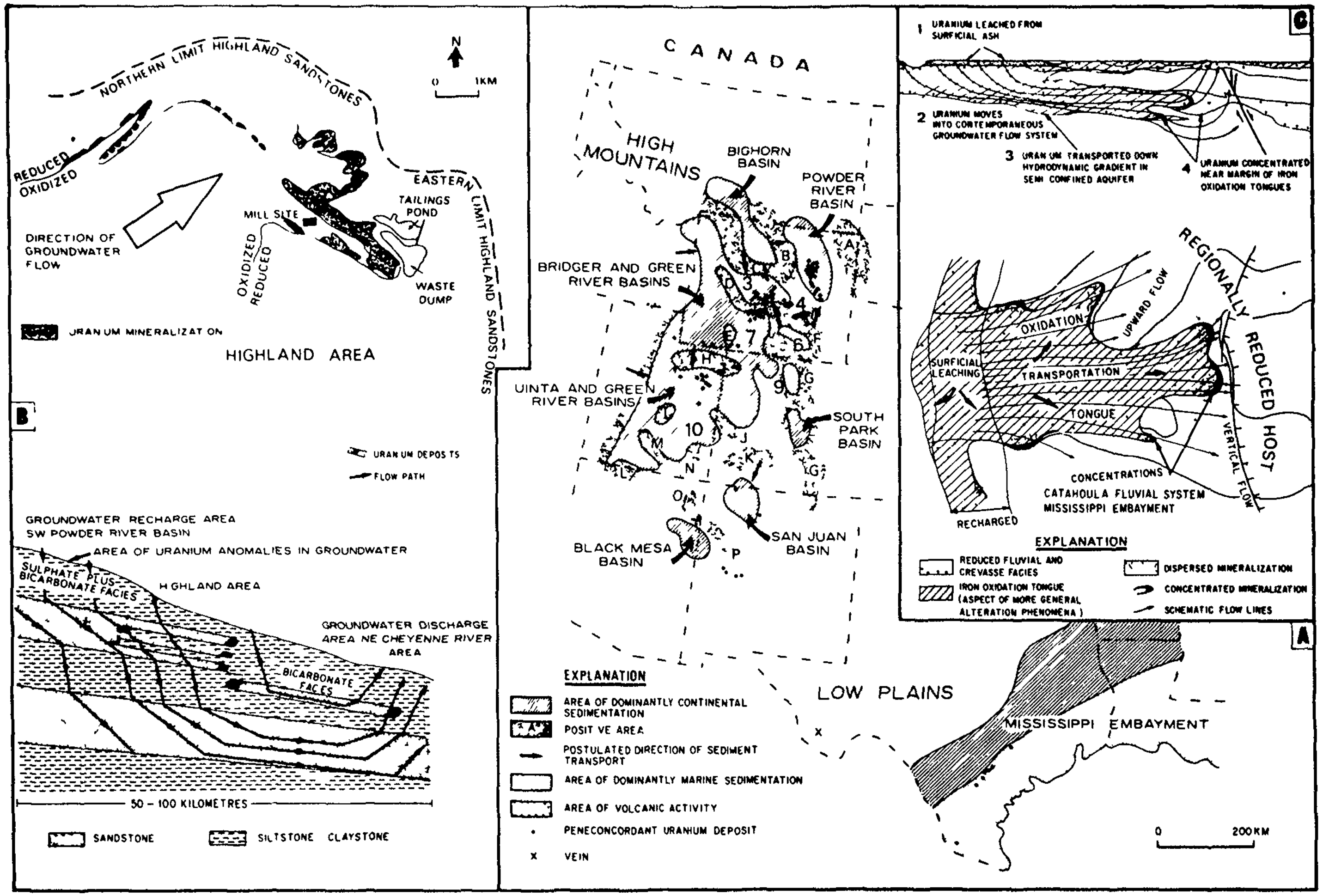

Figure 3. (A) Distribution of uranium deposits in sandstone of Eocene Age in Western USA (after Finch, 1967). *Positive areas:* A = Black Hills uplift; B = Bighorn Mountains; C = Owl Creek Mountains; D = Wind River Range; E = Rock Springs Uplift; F = Laramie Mountains; G = Front Range; H = Uinta Range; I = San Rafael Swell; J = Uncompaghre Up-warp; K = San Juan Mountains; L = Kaibab Up-warp; M = Circle Cliffs Up-warp; N = Monument Up-warp; O = Defiance Up-warp; P = Zuni Up-warp. *Basins:* 3 = Wind River Basin; 4 = Shirley Basin; 6 = Hanna Basin; 7 = Washakie Basin; 9 = North Park Basin; 10 = Green River Basin. (B) Plan (upper) and cross-section (lower) of the Highland area of the Powder River Basin (after Dahl and Hagmaier, 1974) to show how the deposits are formed by moving groundwater. (C) Cross-section (upper) and plan (lower) of the Mississippi Embayment deposits (after Galloway, 1978) to show their relationships to groundwater movement patterns. From Hutchison (3).

in Mexico, all lying near the USA borders (3). Within the USA, these deposits are, for the most part, located in the:

- Wyoming basins (and their extensions into the states of Colorado, South Dakota, and Nebraska)
- Grants district, New Mexico
- Coastal plain of Texasµ and
- The Colorado Plateau outside the Grants district.

Other occurrences have been recorded in sediments of Tertiary age in isolated basins in the states of Alaska, Washington, Oregon, California, Colorado, Idaho, Nebraska, and Arizona, in the west, and in sandstone of Devonian age in Pennsylvania.

WYOMING BASINS

The major roll-type deposits of uranium in sandstone of Tertiary age in these areas are in intermontane basins of the Rocky Mountain foldbelt that are filled with clastic sedimentary rocks several hundred miles from the margins of continental blocks (Fig. 4). The basin centers range from less than 20 to a few tens of miles from granitic cores of Precambrian age in the surrounding mountains. Tectonic processes were influential in basin formation and sediment filling, -- and therefore upon the nature of the host rocks for the uranium deposits. The basins are all products of the Laramide orogeny of late Cretaceous and Paleocene time. Intermittent subsidence, uplift, and displacement along faults at the margins of some basins continued throughout Tertiary time.

Two explanations for the orogenic forces that have produced this tectonism and magmatism several hundred miles from the continental margins have been advanced. Lipman and others (4) related it to a suspended subduction zone extending several hundred miles westward from the east front of the Rocky Mountains. In contrast, Gilluly (5) and Tweto (6)) emphasize vertical forces that are unrelated (at least directly) to a subduction zone.

GRANTS DISTRICT, NEW MEXICO

The area of the Grants district in the San Juan Basin (Fig. 5) has been subjected to recurrent differential vertical tectonic movement since late Paleozoic time. Three periods of deformation are recognized. First, broad shallow folds developed along east-west and north-south axes from late Jurassic to early Cretaceous time. Secondly, the San Juan Basin subsided and the surrounding uplifts were developed in early Cenozoic time. Finally, late Cenozoic deformation is reflected by fracturing along earlier northerly trends. Tectonic movements were vertical along the boundaries of basement blocks, and typical north and northwest-trending monoclinal flexures were developed. It is not clear why the tectonic movements in this part of the Colorado Plateau were dominantly vertical, whereas the district is surrounded by a stress field of regional horizontal compression.

There is a general tilt of the whole region to the northeast and this dip was a major controlling feature of the sedimentation of the Morrison Formation

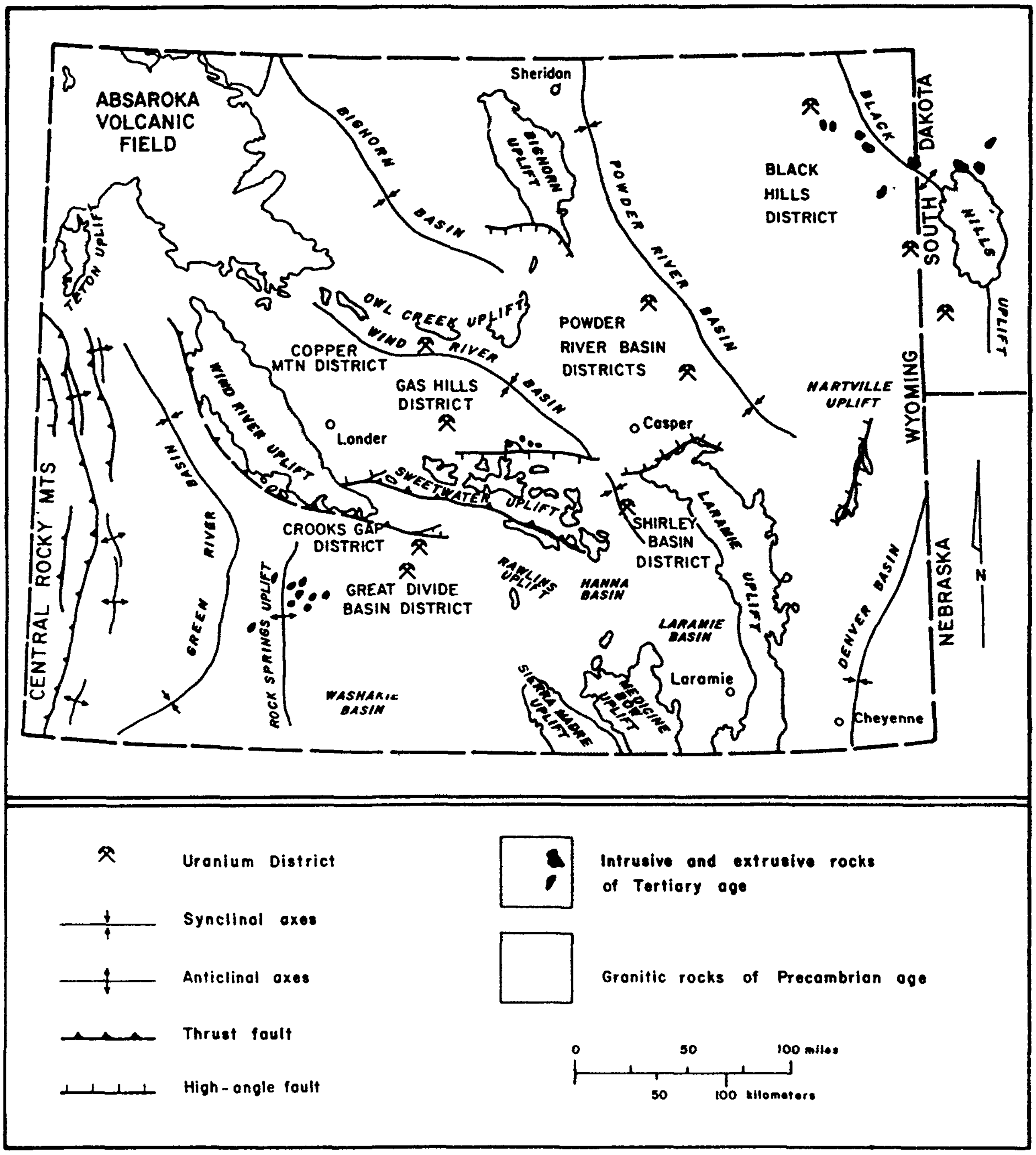

Figure 4. Location map and structural setting for the principal uranium districts in Wyoming.

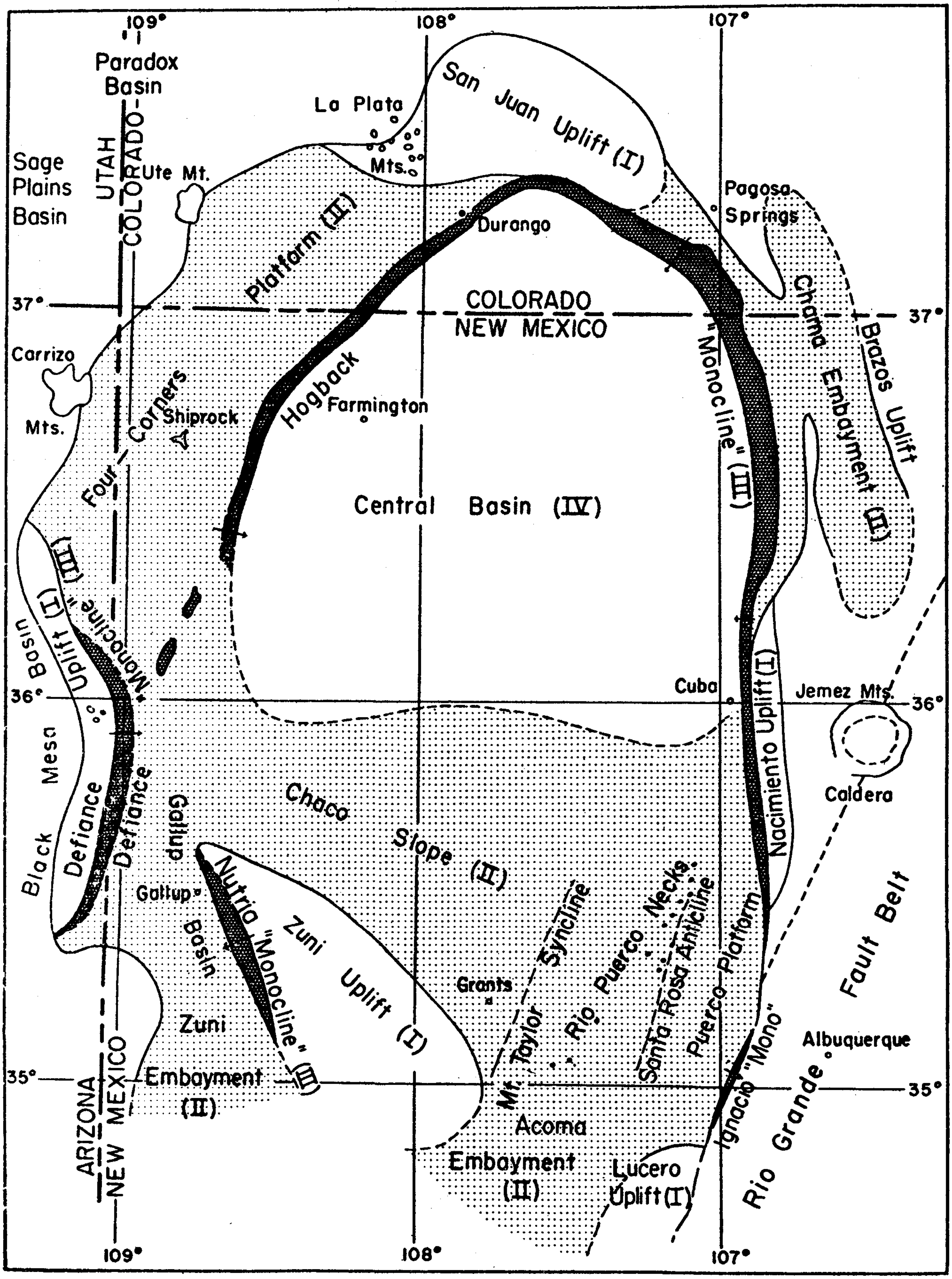

Figure 5. Structural elements of the San Juan Basin. From Kelley (8).

of late Jurassic age - the host rock for 98% of the uranium produced in the Grants uranium region according to Moench and Schlee (7).

TEXAS COASTAL PLAIN

The Texas coastal plain uranium district is in a sedimentary basin on the margin of a continental plate adjacent to a spreading ocean. It is also near a volcanic field occupying the Big Bend region and adjacent areas (Figs. 6 and 7). An apparent constant rate of subsidence has produced protracted sedimentation (40 to 60 million years) and favorable sedimentary and structural conditions for uranium ore formation. Sites have developed for the accumulation of host sediments, roll-front formation and preservation, and sources of uranium in the volcaniclastic sediments and groundwater. Relatively rapid and prolonged sedimentation has also produced πgrowth faults,π which reflect compaction and adjustment. These faults are tangential or parallel to the basin margins. Dip during sedimentation was 1 to 2 degrees toward the basin. It is increased to 3 to 5 degrees in places by compaction and growth faults.

COLORADO PLATEAU URANIUM PROVINCE

As early as 1955, V. C. Kelley (8), having undertaken a definitive, hallmark study of the regional tectonics of the Colorado Plateau and their relationship to the origin and distribution of uranium, concluded that πthere is no direct relationship between large tectonic features such as uplifts, anticlines, monoclines, or basins, and a concentration of uranium ore deposits.π More recently, Thamm, Kovschak, and Adams (9) have noted that πthe dominant feature of the geologic history of the Colorado Plateau has been its comparative structural stability since the close of Precambrian time. During most of Paleozoic and Mesozoic time, the Plateau was a stable shelf without major geosynclinal areas of deposition, except during Pennsylvanian time. The Laramide orogeny of late Cretaceous and early Tertiary time affected the Plateau only slightly, compared to the bordering areas. The nearly horizontal strata were gently flexed, producing uplifts and basins (Fig. 8). The spectacular monoclines of the region are interpreted to overlie basement faults. Epirogenic uplift in mid-Tertiary time raised the Plateau to its present structural position. So, of the possible tectonic settings in the Plateau in which a favorable sedimentary sequence might acummulate, broad intracratonic (continental interior) basins are by far the most favorable. This setting is followed in importance by intermontane basins, grabens, and finally by coastal plains.

In the Colorado Plateau, pre-existing and actively growing structures strongly affected the sedimentation within the Triassic Chinle and the Jurassic Morrison Formations. These formations are the hosts for most of the uranium deposits of the Colorado Plateau including those in the Grants district previously described. Recent detailed studies by Peterson (10) on the lower sequence of the Salt Wash Member of the Morrison Formation, the host for most of the deposits in the north central part of the Pleateau (Fig. 8), demonstrate that crustal deformation at the site of deposition may have considerably influenced braided-stream processes. Several of the large uplifts and basins in the Colorado Plateau, as well as some of the smaller folds within them, were actively moving during deposition of the lower sequence of the Salt Wash. Tectonic activity altered the stream gradients, which in turn governed sinuosity, flow, energy levels, and sediment distribution.

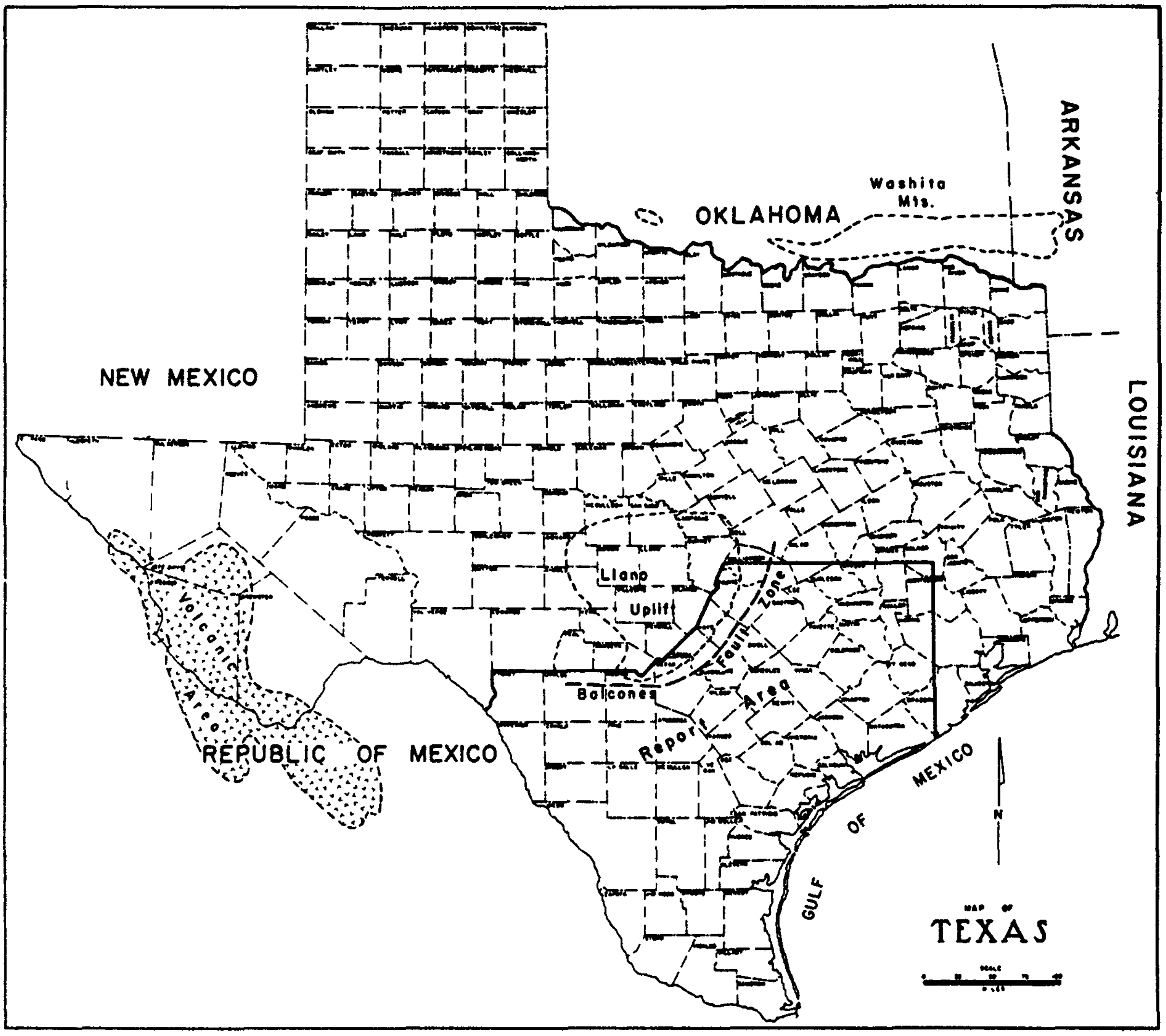

Figure 6. Location map for the South Texas Uranium Region and certain neighboring geologic provinces.

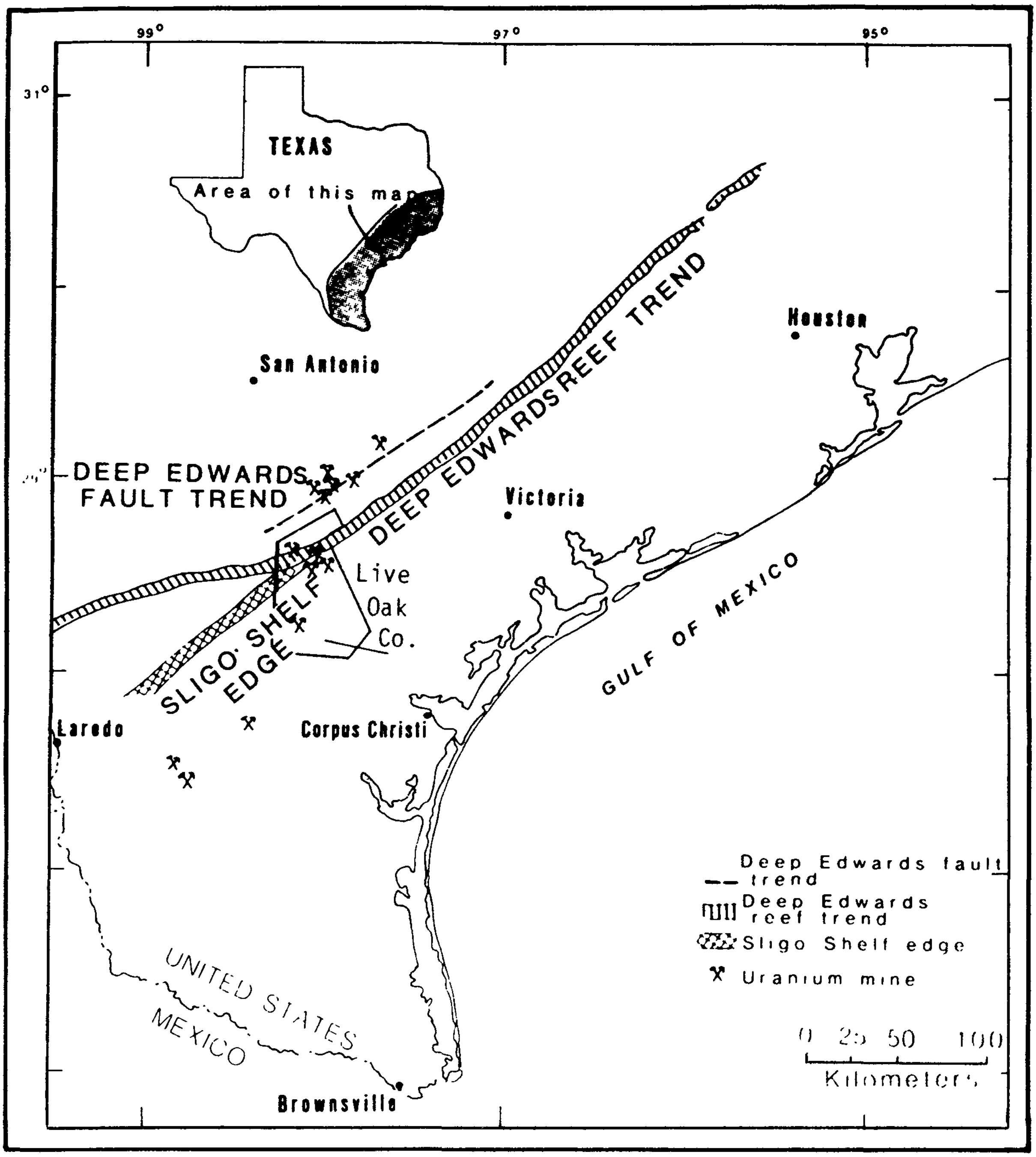

Figure 7. Simplified location map for uranium mines, the surface projection of the Cretaceous Edwards Carbonate Reef Trend and deep Edwards fault trend, and the Cretaceous Sligo shelf edge (modified from Goldhaber and Reynolds, 1979, U.S. Geological Survey Open-File Report 79-1696).

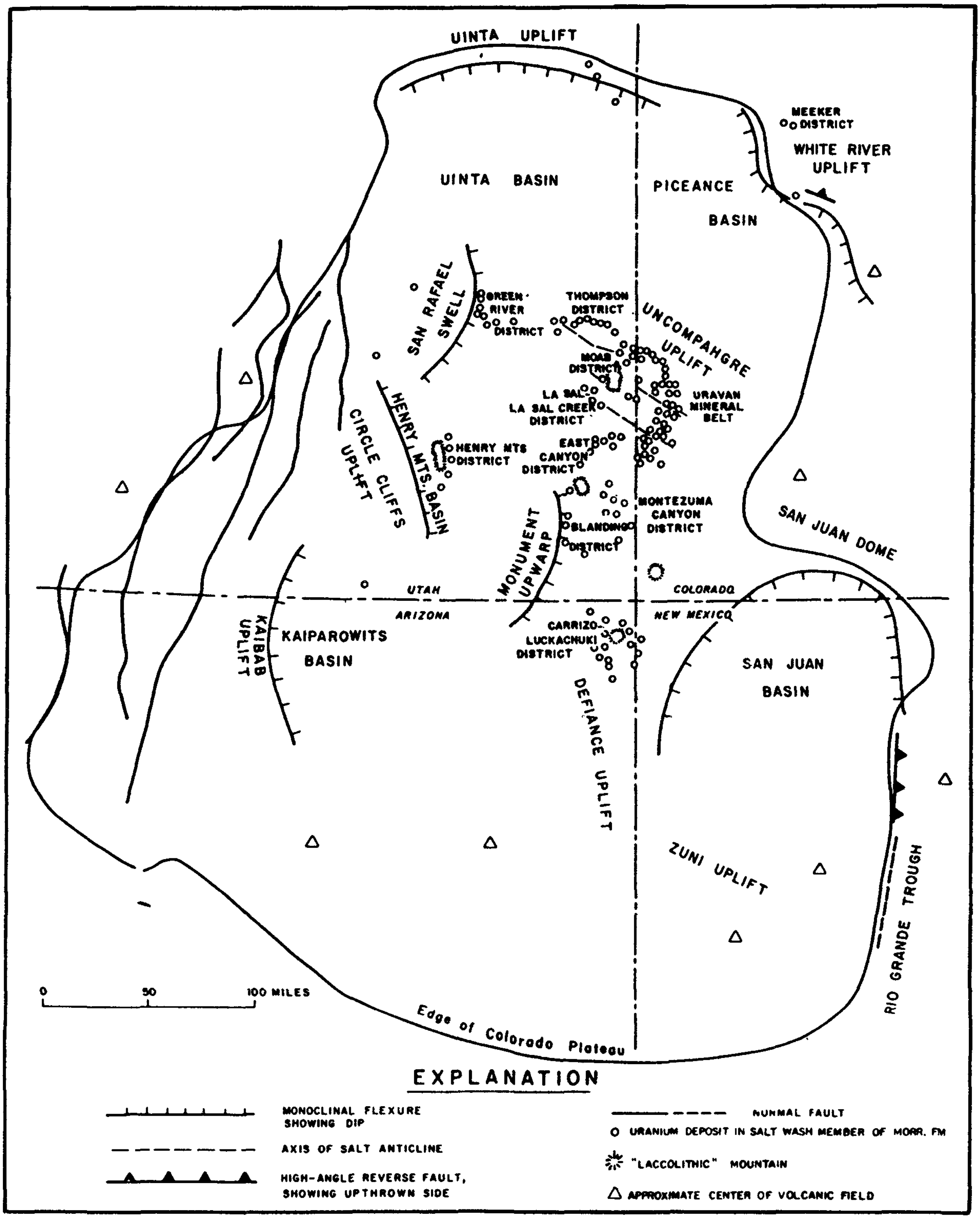

Figure 8. Location map of uranium deposits in the Salt Wash Member of the Morrison Formation and the principal structural and igneous features of the Colorado Plateau.

OTHER SANDSTONE-TYPE URANIUM DEPOSITS IN THE USA

The sandstone-type deposits that are located inland from the west coast of the USA, in Alaska, Washington, Oregon, California, Nevada, Idaho, Arizona, and central Colorado are all in isolated intermontone basins filled with continental, clastic sediments of Tertiary age. Tectonically anomalous uranium deposits near New Haven, Pennsylvania are associated with deltaic deposits of the Catskill Formation of Devonian age near the margin of the folded Appalachian Mountains.

CANADA

The Tyee and Blizzard deposits in the Okanagan Highlands of British Columbia are in fluival sediments of Miocene age in an intermontane basin of the Cordilleran Province of western Canada, near the western margin of the continent.

MEXICO

Two areas in Mexico are known to contain sandstone-type uranium deposits. The LaComa, Buenavista, and El Chapoto deposits in the La Sierrita area of Nuevo Leon are in sandstone of the Frio Formation of Oligocene age, a southerly extension of the coastal plain of Texas in the USA. The tectonic setting is the same.

The other uranium deposit, Las Margaritas, in the Pena Blanca Range of central Chihuahua, has also been assigned to the sandstone type. Actually, it occurs in sedimentary tuff breccia of Oligocene age, related to Tertiary volcanic rocks at the border of the Sierra Madre Oriental and the Meseta Central.

ASIA

Known sandstone-type uranium deposits in the huge continent of Asia are concentrated in isolated clusters in Turkey in the west, in the USSR, India, and Pakistan in central Asia, in Thailand, and in Japan, far to the east.

USSR

The Sa-Byr-Say and Uchkuduk uranium deposits in the Ferghana Basin of south central Russia occur in arkosic sandstone of Tertiary age. Tectonically, the basin is near the south edge of the great Siberian Platform, near its boundary with the Angara Syncline. These deposits are believed to be exogenic deposits of young platforms (Series D), epigenetic infiltration leposits (Class V) in the Classification of Uranium Deposits of the USSR (11). These are said to have been formed during the Cenozoic metallogenetic epoch, occuring in the weakly deformed sedimentary cover of the young platforms and intermontane basins.

INDIA

Three areas in India contain sandstone-type uranium deposits:

- Jammu and Hamirpur deposits, Beas-Sutlej Valley, in the Siwalik Formation of Mio-Pleistocene (Neogene) age
- The Meghalaya deposits on the Shillong Plateau, in the Mahadek Formation of Cretaceous age and

- The Bhawra-Satpura deposits in the Gondwana Basin, Madhya Pradesh, in the Motur and Bijori Formations of Permian age.

These are all on the Indian Shield or in basins from Permo-Carboniferous to Pleistocene in age, resting on the shield. When plotted on the structural lineament map of India, they appear to be associated with major deep-seated faults (Fig. 9).

TURKEY

In Turkey, the Alpine geosyncline is confined between the Arabian block to the south and the Russian platform to the north (Brinkman, 1976) (14). Four tectonic units paralleling the long east-west axis of Turkey from north to south are: 1) the Pontids along the Black Sea coast, 2) the Anatolids, 3) the Taurids, and 4) the Border Folds on the south boundaries with Syria and Iraq. Intermontane basins of Oligocene and Neogene age, filled with lagoonal and continental sediments, were formed at considerable distances away from the coast. These basin sediments are cut by vertical faults with displacements up to several thousand feet (Fig. 10).

Four sandstone-type uranium deposits occur in this general tectonic setting:

- The Kasar deposit is six kilometers north of Koprubasi in continental sediments that overlie, and were derived from, rocks of Paleozoic age in the North Menderes Massif

- The Takali deposit, which is in lacustrine beds of Neogene age

- The Kacarli deposit, which is in a small basin of Neogene age on a gneiss massif and

- The Eclinlitas and other small deposits in the Salihli-Koprubasi District, in fluvial and lacustrine sediments of Neogene age.

PAKISTAN

Sandstone-type uranium deposits have been studied and explored in the Siwalik Sandstone Formation of Miocene-Pleistocene age for more than 20 years. They are best known in the Dera Ghazi Khan in central Pakistan, but may occur throughout the Siwalik outcrop in the country, occupying Neogene foredeeps (transitional from unfolded forelands to marginal foldbelts) and Mesozoic-Paleogene paricratonic shelf formations (Fig. 11).

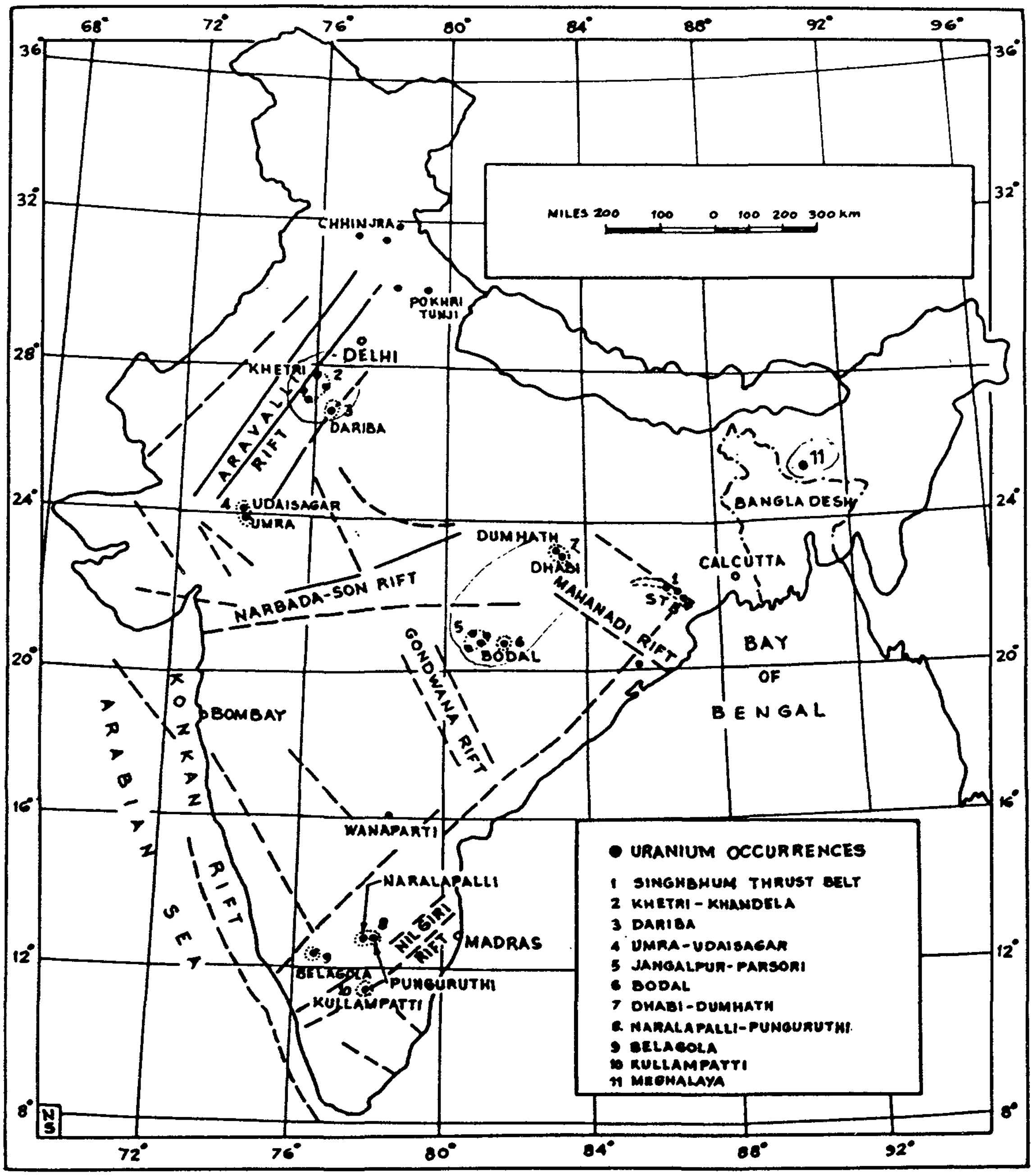

Figure 9. Tectonic lineament map of India showing uranium occurrences (after Nagabhushana et al., 1976, Exploration for uranium ore deposits, IAEA, Vienna, p.627).

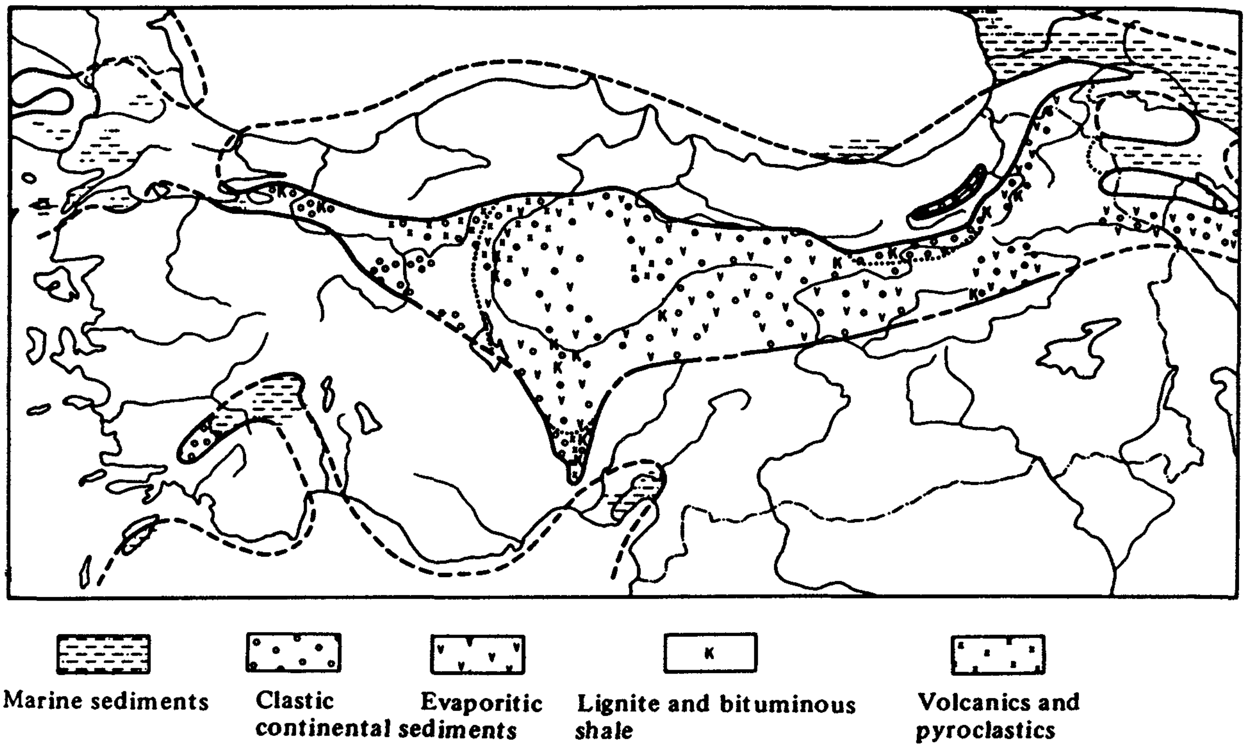

Figure 10a. Lithology and palaeogeography of the Oligocene in Turkey (after Brinkmann, 1976, Geology of Turkey, Verlag, Stuttgart, p.69).

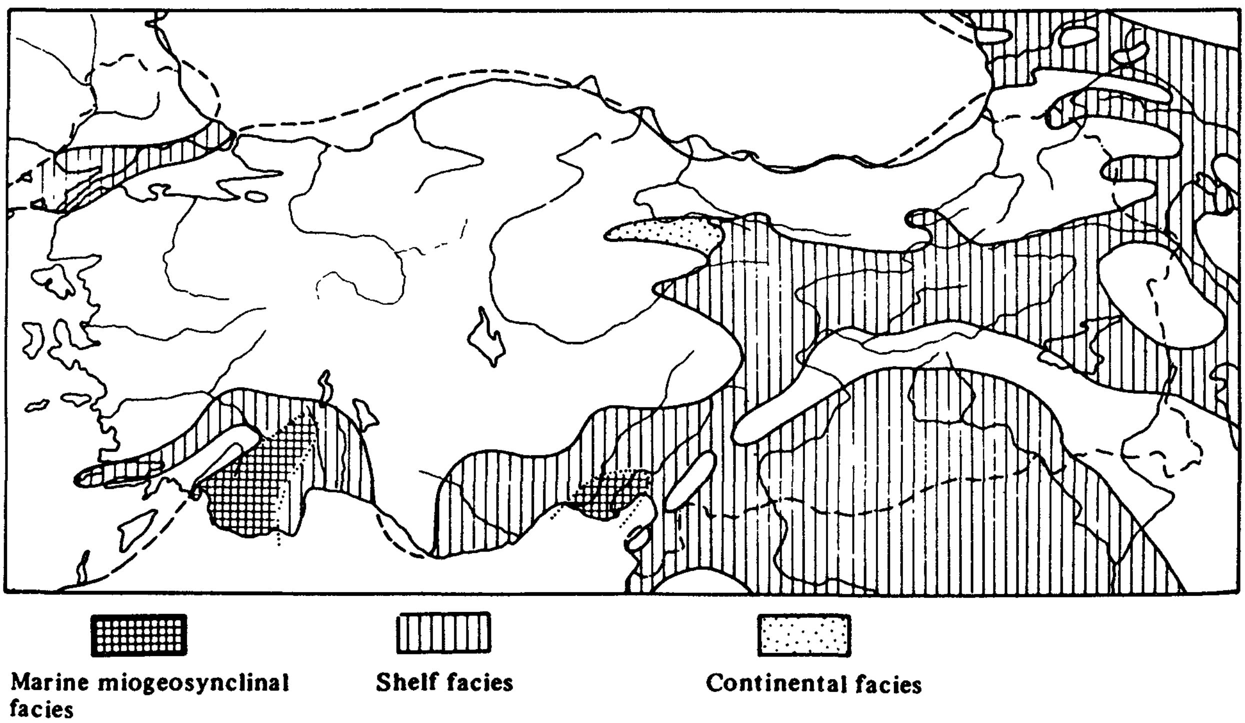

Figure 10b. Distribution, facies and palaeogeography of the Middle Miocene in Turkey (after Brinkmann, 1976, Geology of Turkey, Verlag, Stuttgart, p.71).

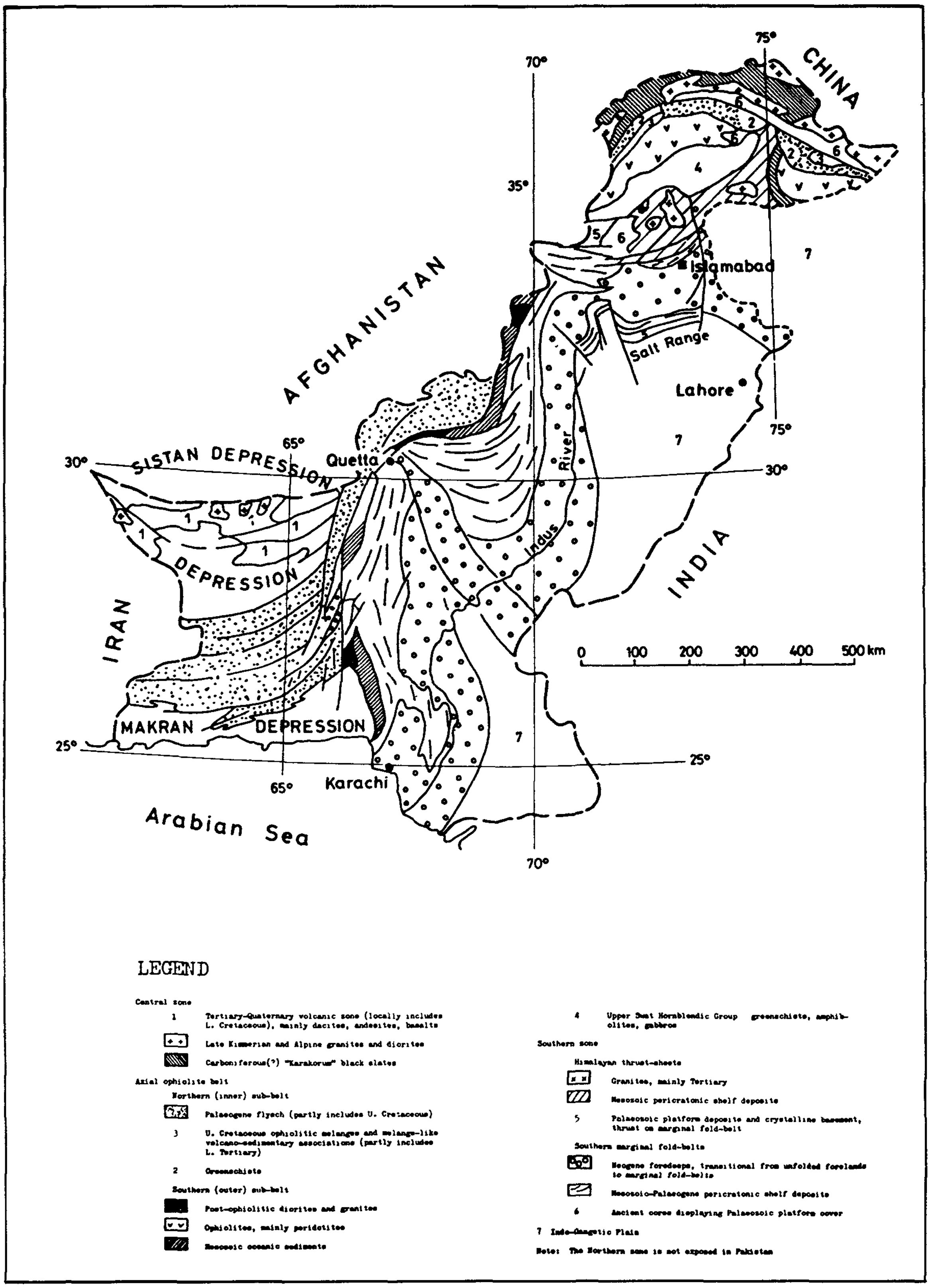

Figure 11. Tectonic map of Pakistan (after Stöcklin, 1977, Mémoire Hors Serie de la Société Géologique de France No. 8)

THAILAND

Uranium-copper deposits occur in the Phu Wieng Basin, near the northwestern edge of the Khorat Plateau, in the Sao Khua Formation (sandstone) of Jurassic age. This tectonic setting, on the edge of the Khorat Plateau, is consistent with other occurrences in the world on cratonic platforms (Fig. 12).

JAPAN

The three sandstone uranium deposits noted in Japan are all in conglomerate, arkose, siltstone, sandstone, and claystone of Miocene or Pliocene age, which occupy small Tertiary basins scattered the length of Japan. Tectonically, these basins occur in the belt of intense volcanism and faulting known as the πRing of Fireπ around the Pacific Ocean.

SOUTH AMERICA

Known sandstone-type uranium deposits in South America are confined to the Parana Basin and along the western edge of the Rio De La Plata and Patagonia Massifs of the southern part of the continent (between 15 degrees and 45 degrees south latitude) (Fig. 13). They occur in only three South American countries: Brazil, Uraguay, and Argentina.

Both Brazilian deposits are in the Parana Basin, where appreciable reserves have been identified. This basin is filled with sediments of Devonian to Cretaceous age and occupies 1.2 million square kilometers. The important uranium occurrences near Figueira are in the Rio Bonito sandstone and siltstone of Permo-Carboniferous age. The Amorinopolis deposit is in arkosic sandstone of Devonian age.

The Cerro Largo deposit in Uraguay is also in the Parana Basin, at the southern tip, and occurs in the San Gregorio-Tres Islas Formation of Permo-Carboniferous age.

The sandstone uranium deposits in Argentina occur in diverse settings, from Salta Province in the north to Chubut Province in the south. In the Tonco-Aumblay district in the north, uranium occurs in sediments of the Salta System of Upper Cretaceous age. These thick beds were deposited under continental and marginal marine conditions. Further south, the Rodolfo deposit is in a continental sedimentary sequence, of Eocene age, which lies discordantly over crystalline bed rock in the Cosquin district of Cordoba Province. The important uranium reserves in Mendoza province are in two different settings. The deposits in the Sierra Pintada District occur in cross-bedded sandstones and minor conglomerate of the Cochico Group of Permian age. They lie unconformably on sandstone and porphyritic extrusive and intrusive rocks of Lower Carboniferous age. Uranium in the deposits is thought to have been leached from the Carboniferous volcanics during Tertiary time, following orogeny. In the Malargue District, the uranium mineralization has occurred in conglomerate and sandstone of Upper Cretaceous age, and the source of uranium is thought to be igneous rocks of Triassic age. In Chubut Province, uranium deposits occur in continental sediments and tuffs of the Chubut Group of Cretaceous age in

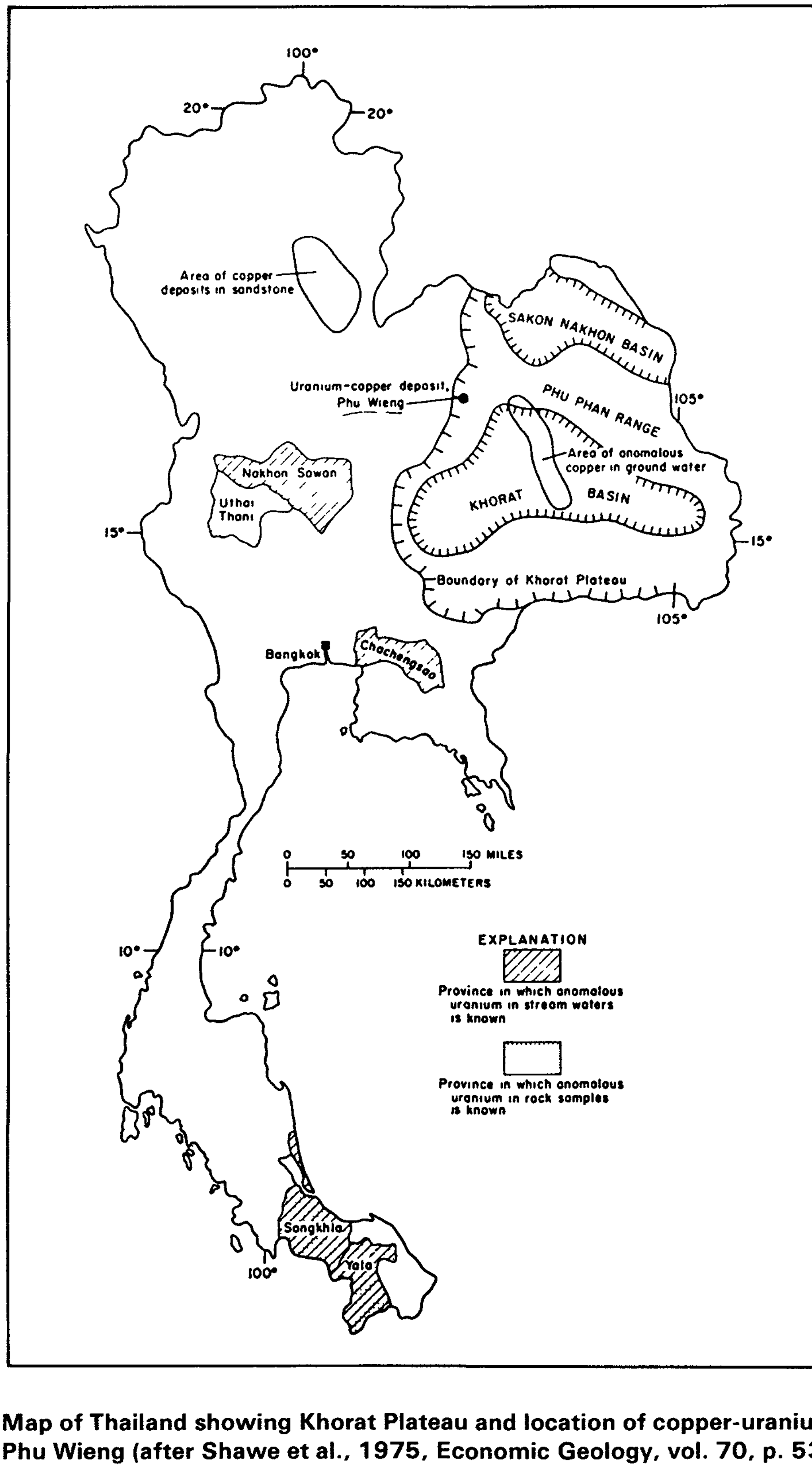

Figure 12. Map of Thailand showing Khorat Plateau and location of copper-uranium deposit at Phu Wieng (after Shawe et al., 1975, Economic Geology, vol. 70, p. 539).

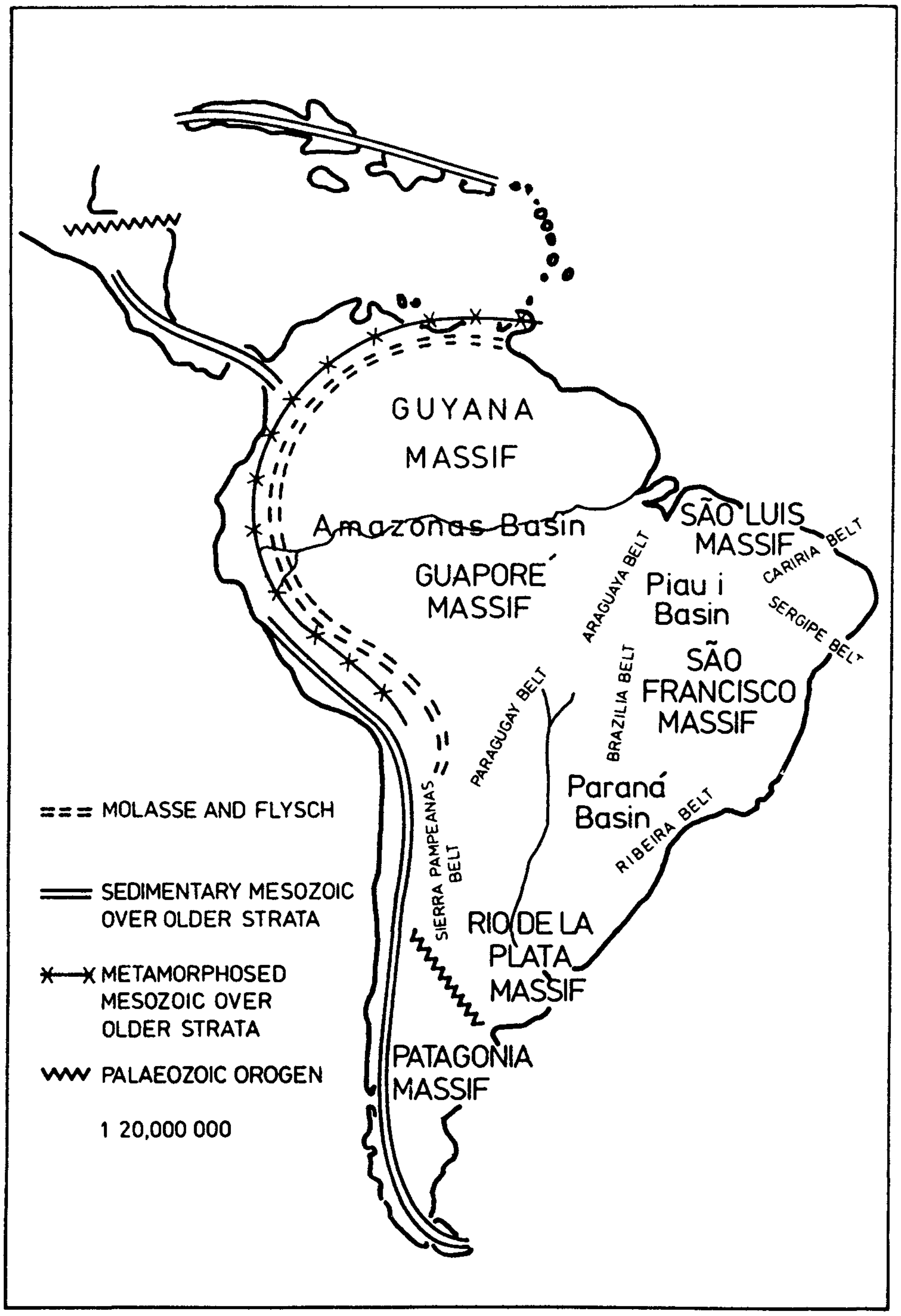

Figure 13. Main geologic features of South and Central America.

the Sierra Cuadrada, and in similar rocks of Jurassic and Tertiary age elsewhere. These deposits all lie at the south and southwest edge of the North Patagonian Mountain Massif (granite-monzonite intrusives and extrusives), and the uranium is believed to have been introduced into the host rocks during peneplanation of the mountains in mid-Tertiary time.

EUROPE

Generalizations concerning the tectonic settings for the wide variety of sandstone-type uranium deposits identified in the relatively small continent of Europe require some audacity. Europe is very complex tectonically (Fig. 14), and 33 sandstone-type uranium deposits or districts occur scattered through 14 countries, from Portugal to Romania and from Scotland to southern Yugoslavia as shown on the index map of Europe. Ages of the host sandstones vary from Ordovician to Quaternary.

For the purposes of this paper, however, the European tectonic settings for sandstone-type uranium deposits are divided into four areas:

- The Ousdale occurrence in northern Scotland
- The occurrences in east central Europe, in East Germany, Poland, and Czechoslovakia
- The deposits in southeastern Europe, in southern West Germany (Federal Republic), Switzerland, Austria, Italy, Hungary, Yugoslavia, and Romania and
- The deposits in southern France, Spain, and Portugal (the Iberian Peninsula).

In the Orcadian Basin of Caithness in northeastern Scotland, the Old Red Sandstone (ORS) of Devonian age rests on a metamorphic Precambrian basement intruded by Caledonian granitoid rocks. The source of the sediments was the uplifted Caledonian orogen. Uranium occurs in arkose of the ORS.

In the German Democratic Republic, uranium occurs in sandstone and shale of Ordovician-Silurian age in the Gera-Ronneberg region, in sandstone of Permian age near Dresden, and in sandstone of Cretaceous age in the Elbtal district. These are mainly in post-Hercynian platform sediments. To the south, in Czechoslovakia, sandstone-type uranium deposits occur in both the sedimentary area of the Bohemian Massif and in the West Carpathian Mountains (geosyncline). They are in sandstone of Carboniferous age in the Sudetic Basin, in sandstone of Permian age in the Spis-Gemer Region, in sandstone of Cretaceous age in northern Bohemia, and in lignitic sandstone of Miocene age in the Sololov Basin. To the east, in Poland, uranium in sandstone occurs in the northern part of the Bohemian massif and a small part of the Carpathian Mountains, which are underlain by schist of Paleozoic age intruded by Hercynian granite.

In southeastern Europe, during Late Carboniferous and Early Permian time, conditions in some specific intermontane basins in southern Germany (FRG) and eastern France were favorable for the formation of uranium deposits. These

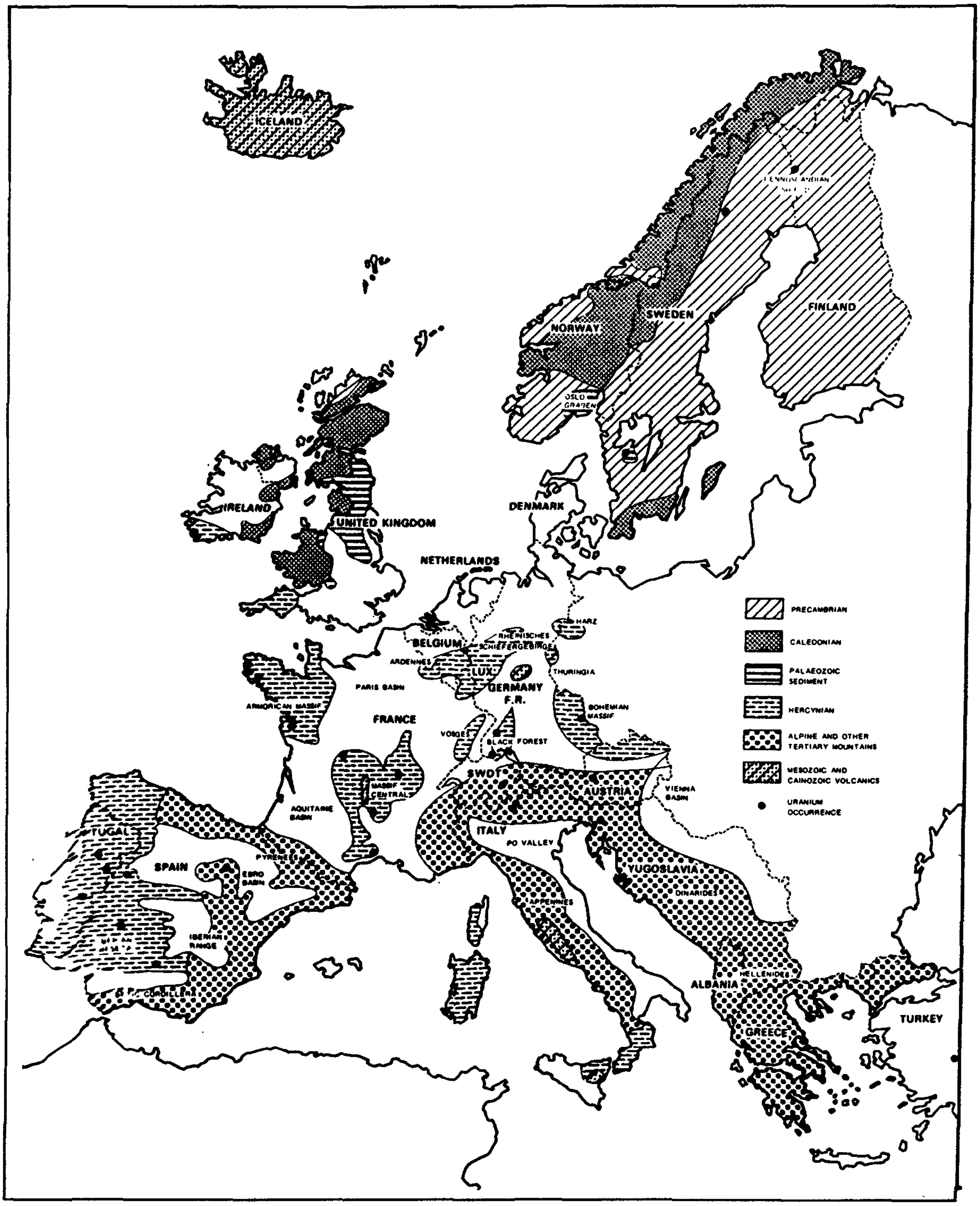

Figure 14. Map of Western Europe showing location of uranium deposits in relation to tectonic zones.

basins, in the Black Forest, northern Franconia, and the Saar-Nahe Trough in West Germany and in the Vosges area of France are fault-bounded and are adjacent to the Black Forest massif. To the south, in Switzerland, in the Ilanz area, uranium deposits in sandstone of Permian age have a similar setting, and farther east, in Austria at Forstau in the Northern Alps, quartzite and phyllite of Permian age also contain related urnaium deposits. In northermost Italy, in the Italian Alpine Range, favorable conditions for uranium deposits occurred in continental sediments of Permian age overlying the eroded Hercynian crystalline basement complexes. Felsic volcanic rocks of early Permian age were also part of a late Hercynian magmatic episode. In central Italy, at Latium, volcanic sediments of Quaternary age host anomalously young uranium deposits. They are believed to be related to magmatic exhalation of H_2S from Recent volcanism which precipitated uranium present in the ground water.

Farther east, in the Mecsek Mountains of Hungary, uranium deposits occur in gray arkosic sandstone of Upper Permian age. The arkose was derived principally from granitic rocks. To the south, in northwestern Yugoslavia, an important deposit at Zirovski vrh is on the southern flanks of the Yulian Alps. The uranium occurs in gray sandstone and conglomerate of the Groden Formation of Middle Permian age, and is believed to have come from a keratophyric basement source. A similar tectonic setting applies to the Stara Planina region in southeastern Yugoslavia, where small uraniferous lenses in a continental series of Lower Triassic age are developed. Finally, in the Banat district, Romania, uranium ore bodies are in terrigenous deposits of Permian age, part of a thick sequence of continental sediments that have been compressed into vertical folds. Granodiorite has been introduced into the sedimentary rocks along faults during early Tertiary time. At Brasov, Romania uranium also occurs in sandstone of Cenomanian (Late Cretaceous) age. All the mineralization is said to be Alpine in age.

In Southern France and the Iberian Peninsula, the ages of uranium host sandstones are grouped into the late Paleozoic/early Mesozoic and the Tertiary. In France, important uranium deposits are associated with detrital sedimentary (continental) formations of Permian age that have been preserved mainly in collapsed basins of the Moldanubian zone at its edge. For example, the Lodeve Basin is at the southern edge of France's Massif Central and the Cerrilly Basin is at its northern edge. In addition, uranium deposits also occur in sediments of the molassic type, of Paleogene (Early Tertiary) age, in the Moldanubian Zone (St. Pierre, Cantal), or outside it (Aquitaine Basin - Eocene).

In Spain, the principal uranium mineralization of sandstone that has been discovered is in the Iberian Range, in the east-central part of the country. This range has a Paleozoic basement including schist, quartzites, and carbonate rocks, metamorphosed during Hercynian time and affected by late volcanic activity. Continental sediments were deposited on this platform in Early Triassic and Early Cretaceous times, and in intermontane basins in Tertiary time. The entire range was affected by Alpine orogeny in the Oligocene-Miocene period. Uranium mineralization occurred in the sediments of all the ages cited above. In Portugal, sedimentation in the Mesozoic and Cenozoic periods was controlled by subsidence and uplift along a rift system located south and west of the Meseta and known as the Portuguese Depression. The principal episodes of continental deposition were lowermost Jurassic, Early Cretaceous, Miocene, and Pliocene. Uranium deposits in Portugal occur in sandstone of Tertiary age in the Tejo and Sodo Basins.

AFRICA

Africa, like South America and Asia, but in direct contrast to Europe, contains relatively few known sandstone-type uranium deposits, and they are clustered in just a few areas, widely scattered throughout the length of the second largest continent on earth.

In the northeast corner of Africa, uranium deposits at Gabel Quatrani, Egypt occur in the Quatrani sandstone formation of Oligocene age. The sands form a relatively thin veneer on the uplifted west block of the Great Rift System.

In Niger, in north central Africa, a large mountain mass of crystalline rocks, the Air-Massif, consists of Precambrian gneiss and granite, with some lavas, tuffs, and ash of Quaternary age. The Air-Massif separates several basins, one of which is the Agades Basin, to the west. This basin contains an assemblage of clastic rocks which were deposited on a relatively stable platform. The rocks range from Silurian to Upper Cretaceous in age. Uranium deposits occur in the Tarat and Guezoiman sandstones of Carboniferous age, the Tchirezrine sandstones of Jurassic age, and the Assaorias sandstone of Cretaceous age.

In the Republic of South Africa, north of the Cape of Good Hope, the Karoo Supergroup of sedimentary rocks covers more than half of the entire country (Fig. 15) and rests on a very large stable platform that forms the southern extremity of Africa. Uranium deposits are concentrated in the Lower

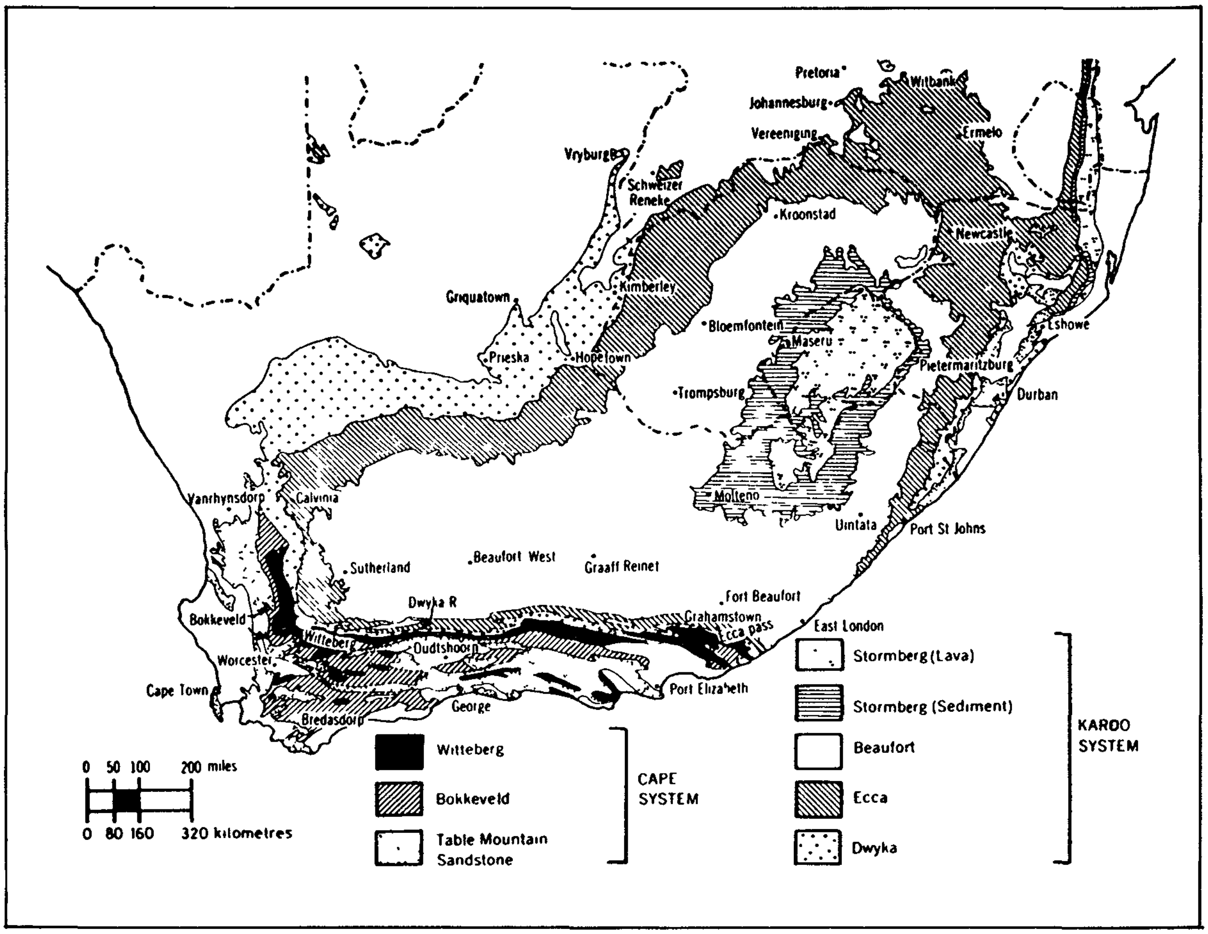

Figure 15. Map showing distribution of outcrops within the Type Karoo area (after S.H. Haughton, 1969, published by The Geological Society of South Africa, p. 350).

Beaufort Group of Upper Carboniferous-Jurassic (largely Permian) age. This group consists of alternating beds of sandstone and mudstone with a ratio of about 3:7. A uranium deposit of the sandstone-type occurs in the Dwyka Formation, lowermost of the Karoo Sequence, of Permian age, in the Engo Valley near the Skeleton Coast in the northwest corner of Namibia.

To the east, the complete cratonic stability of Madagascar was established about 450 million years ago (11) (page 134), and its separation from East Africa began about 300 million years ago. The transcratonic platform cover on Madagascar consists mostly of marine post-Karoo sediments along the coasts, and Oligocene and Plio-Pleistocene volcanics related to tensional faulting. A sandstone-type uranium deposit occcurs in Madagascar, near Antsirabe, in lacustrine clay and sand of Plio-Pleistocene age.

AUSTRALIA AND OCEANIA

In Australia, sandstone-type uranium deposits have been found in the Lake Frome Embayment, South Australia, in the Ngalia and Amadeus Basins of the Northern Territory near Maureen, Queensland and in the Victorian Desert.

The Lake Frome Embayment is part of a Mesozoic shallow marine basin developed on Precambrian and Paleozoic rocks during Late Jurassic and Cretaceous time. Terrestrial sediments of Tertiary and Quaternary age have filled the basin and faulting has uplifted the Flinders Range to the west. Uranium deposits occur in fluvial sandstone of Tertiary age near Beverly.

To the north, in the Northern Territory, the Ngalia Basin is a faulted and folded intercratonic basin within the Arunta Block. It is filled with sediments ranging in age from Paleozoic through Cenozoic. The Bigryli uranium deposit occurs in this basin in the Mt. Eclipis sandstone of Carboniferous age. In the nearby Amadeous Basin, to the south, the Angela uranium deposit occurs in a sandstone believed to correlate with the Mt. Eclipis Formation. In northeastern Australia, near Maureen, Queensland, a uranium deposit is in sandstone and siltstone formations of Permo-Carboniferous age which are part of the Trans-Australian Platform cover. A sandstone-type deposit has also been identified in the Tertiary sediments of the Victorian Desert, -- which are also part of Central Australian Platform cover.

Tectonically, New Zealand is located along a plate boundary of the continental crust. In the Hine Geosycline, rock units of Lower and Middle Paleozoic age were deposited, and then intruded by granite in Silurian-Devonian time. During Carboniferous-Jurassic time, volcanic/sedimentary rocks were deposited in the New Zealand Geosyncline, followed by the Rgitata Orogeny. Deposition of non-marine sediments occurred during Cretaceous time. Included is the Hawks Crag Formation in South New Zealand that contains a uranium deposit in Lower Buller Gorge.

CONCLUSIONS

The general tectonic models for sandstone-type uranium deposits, as set forth by Mitchell and Garson (1) and by Hutchison (2), are demonstrated to be valid in the detailed deposit-by-deposit consideration undertaken in this review. However, as stated by G. P. Landis (12) in a recent review of Mitchell and Garson's textbook, "(There is) a major leap required in traversing from a scale of global tectonics to that of the details of geologic and geochemical processes that ultimately determine the occurrence of mineral deposits. Tectonic settings define (only the) broad conditions of environment in which processes essential to mineral deposit formation operate."

The sandstone-type uranium deposits in North America are all in intermontane basins, over cratonic platforms, or in coastal embayment environments, except for the New Haven, Pennsylvania occurrence, adjacent to the Appalachian foldbelt. In Asia, the deposits are over cratonic platforms except for the intermontane basins of Japan which are in a volcanic belt at a continental boundary. In South America, the deposits are over stable shields or cratons, but in Argentina some of them are adjacent to the compressive folds and thrust zones of the Andean Belt. In the complex tectonics of Europe, the sandstone-type uranium deposits occupy sites affected by the Hercynian and Alpine tectonic events, except for the Caledonian-related deposit in northern Scotland. Intermontane basin and craton platform cover environments characterize all the deposits of Africa and Australia-Oceania, except Egyptian deposits near the Great Rift, and the New Zealand deposits near a continental plate boundary.

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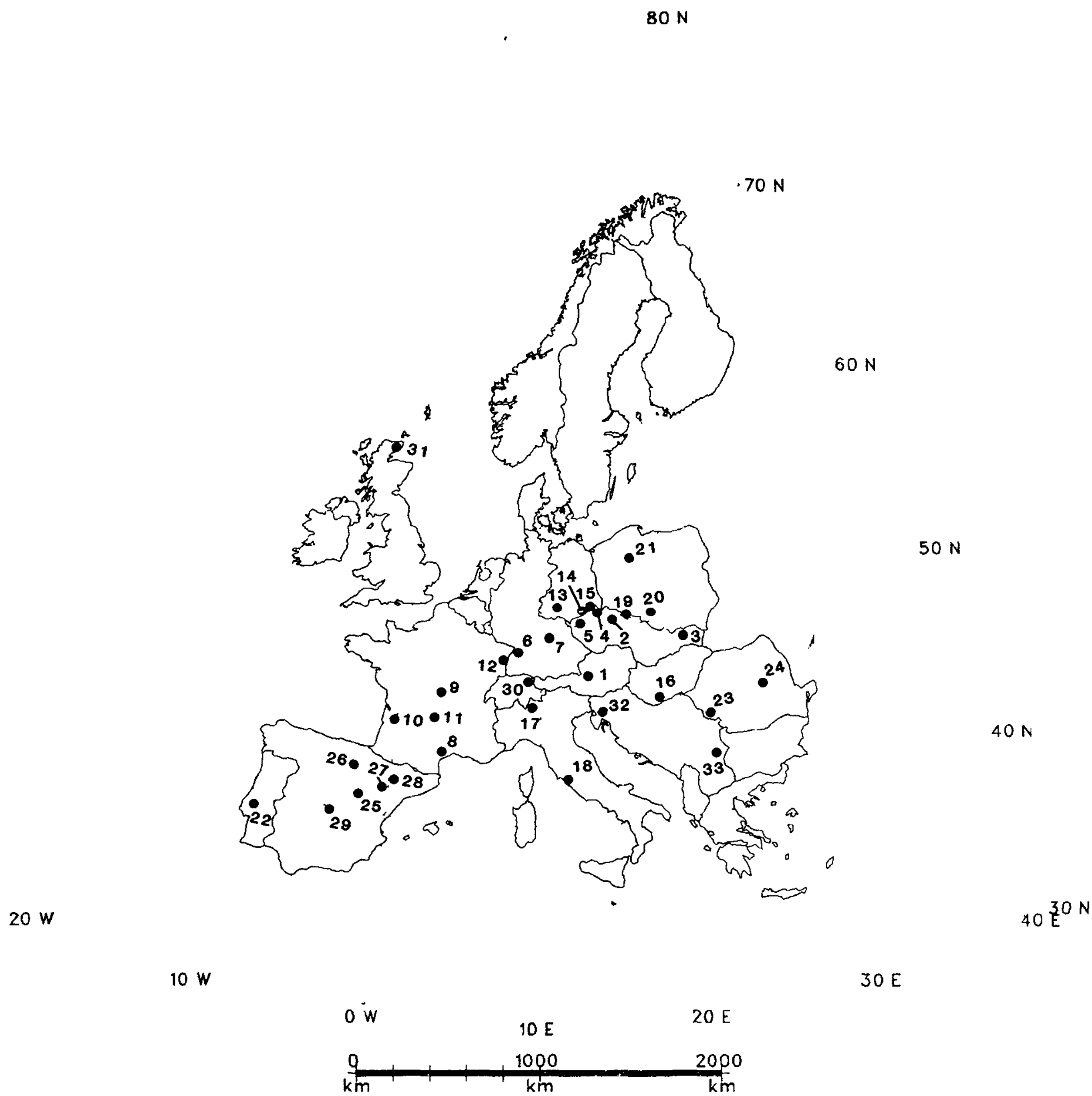
PART II

REGIONAL DESCRIPTIONS

EUROPE

MAP AND INDEX LIST FOR SANDSTONE-TYPE URANIUM DEPOSITS IN EUROPE



EUROPE

Austria:
1. Forstau, northern Alps, Permian quartzite and phyllite

Czechoslavkia:
2. Kladno-Rakovnik, Intra-Sudetic Basin, Carboniferous sandstone
3. Novoveska Huta, Muran, and Spis-Gemer region, Permian sandstone
4. Hamr and Teplice, northern Bohemia, Cretaceous sandstone
5. Cheb deposit, Sokolov Basin, Miocene lignitic sandstone

Federal Republic of Germany:
6. Mullenbach/Baden-Baden, northern Black Forest, Carboniferous sandstone and shale
7. Franconia, Triassic Keuper sandstone

France:
8. Mas Lavayre and Mas d' Alary, Lodeve/Herault, Permian shale
9. Allier, Cerilly Basin, Massif Central, Permian sandstone
10. Coutras and Gironde, Aquitaine Basin, Eocene sandstone
11. St. Pierre Basin, Cantal, Oligocene sandstone
12. St. Hippolyte, Vosges, Carboniferous sandstone

German Democratic Republic:
13. Gera-Ronneburg region, Ordovician-Silurian sandstone and shale
14. Freital-Dresden, Saxony, Permian coal and sandstone
15. Konigsstein-Pirna-Leupoldshain, Elbe, Cretaceous sandstone

Hungary:
16. Pecs, Mecsek Mountains, Permian sandstone

Italy:
17. Novazza, Val Seriana, Bergamo and Val Rendena, Permian sandstone
18. Latium, Quaternary volcanic sediments

Poland:
19. Nova Ruda, Intra-Sudetic Basin, Carboniferous sandstone and conglomerate
20. Upper Silesian Basin, Carboniferous coal and sandstone
21. Occurrences in Pomerian Trough, Triassic Bunter sandstone

Portugal:
22. Occurrences in Tejo and Sado Basins, Tertiary sandstone

Romania:
23. Banat district, Permian sandstone
24. Brasov, Cretaceous Cenomanian sandstone

Spain:
25. Mazarete, Guadalajara Province, Triassic Bunter sandstone
26. Burgos and Logona, Sierra de la Dalanda, Triassic arkose
27. Huesca, Montanuy, Permian sandstone
28. Ebro Basin, Tertiary lignite
29. Tajo Valley, Tertiary continental sediments

Switzerland:
30. Ilanz, Permian sandstone

United Kingdom:
31. Ousdale, South Caithness, Scotland, Devonian arkosic sandstone

Yugoslavia:
32. Zirovski vrh, Slovenia, Permian Groden sandstone
33. Dojkince, Stara Planina region, Triassic sandstone

SEDIMENTARY URANIUM OCCURRENCES IN EASTERN EUROPE WITH SPECIAL REFERENCE TO SANDSTONE FORMATIONS

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Abstract

Sedimentary uranium deposits, especially in sandstones, play an important role in uranium mining in Eastern Europe. The paper reviews recent publications on uranium occurrences in sandstone formations in the German Democratic Republic, Poland, CSSR, Hungary, Romania, Bulgaria and Albania. The uranium deposits in sandstones in Yugoslavia are described in a separate paper in this volume. Sandstone deposits of the USSR are not reviewed.

Uranium mineralizations occur in sandstones from Ordovician to Tertiary age. Major deposits are developed in Upper Carboniferous sandstones in association with coal (GDR, Poland), in Permian strata (CSSR, Hungary, Romania), in Cretaceous sandstones (GDR, CSSR), and in Tertiary sediments (CSSR). The Permian deposits can be compared with deposits of similar age in Northern Italy and Northern Yugoslavia. Roll-type orebodies are developed in some of the Cenomanian sandstones. Tertiary deposits are mainly associated with lignites. Uranium deposits in sandstones of Albania and Bulgaria are not described in the literature. Geologic similarities with sandstone basins in adjacent countries suggest the presence of uranium mineralizations in Permian, Lower Triassic, and Tertiary sandstones.

Introduction

The formation of uranium deposits in sandstones of various age was carefully studied in East European countries. The great amount of literature in some countries reflects the importance of these deposits for the uranium mining industry. The broadest information was available for Poland, CSSR, and Hungary, whereas from other countries only few papers are published. Secondary literature had to be used.

German Democratic Republic

A great variety of uranium deposits hosted in sedimentary rocks exist in the German Democratic Republic, but detailed information is difficult to obtain. Clearly, all sedimentary formations from the Lower Paleozoic to the Tertiary have been investigated at least on a reconnaissance scale with respect to their uranium potential. Exploration for sedimentary uranium deposits has become very important and has resulted in the discovery of mineable ore deposits.

Exploration for uranium in Ordovician and Silurian sediments dates back to the middle 1940's. Subsequently, mining started in Thuringia in 1951 in the area of Gera and Ronneburg (1). At that time, underground mining reached a depth of 300 m. The ore occured in bituminous shales of Upper Ordovician age and was processed for its V, Mo, and U.

The geology and genesis of these deposits are described by KRUPENNIKOW (2), who also discusses the various opinions on the formation of the uranium mineralization. Studies in the 1950's favoured a primary sedimentary origin subsequently affected by various metamorphic processes. Later studies tend towards a hydrothermal origin for the ore. The mineralizations occurs in slightly metamorphosed Ordovician shales with intercalations of calcareous sandstone, Silurian bituminous and cherty shales and Devonian limestones. The sedimentary formations are cut by Devonian diabase dykes. The mineralized sediments are part of the basal unit in the geosyncline and were intensively sheared and block-faulted by later structural movements.

Uranium mineralization of Lower Permian age has been reported to occur in the Freital coal basin near Dresden (3). Extraction of uranium from the coal was started as early as 1954. The coal from Freital is irregularly mineralized with U, Sn, Ge, Mo, Fe, Zn, Pb and Cu; the ore minerals form fine disseminations and fissure fillings in the combustible shales. The uranium content of the coal is not known. The ash has been reported to contain between 0.12 to 1 % U. No information is available on the uranium content in the sandstones associated with the coal seams. Thus, no comparisons can be made between this type of uranium mineralization and those reported from Silesia (see Poland) or those in the Federal Republic of Germany (4,5).

The uranium content of the Permian Kupferschiefer in Central Europe is well documented (6). BARTHEL (4) gives a description of the uranium distribution in the Kupferschiefer and associated Permian sandstones in the GDR.

Other uranium mineralizations in the post-Variscan platform rocks are mainly confined to the sedimentary formations of the Upper Permian, Lower Triassic and Upper Cretaceous (7). No detailed information is available on these occurrences, except on the Cretaceous roll-type uranium deposits in sandstones.

Geologically favourable conditions for the formation of uranium deposits are developed in the Rotliegende sandstones (Upper Permian). No information is available on the existence of such deposits.

The lithostratigraphy of the Triassic Buntsandstein of the GDR is similar to that in the neighbouring countries, the Federal Republic of Germany (FRG) and Poland. In the FRG and Poland, uranium enrichments of uneconomic grade and size occur in dark shales within a grey sandstone sequence. We assume that the uranium potential of the Buntsandstein in the GDR has been investigated and found to be uneconomic.

Important uranium ore deposits are reported from the Cretaceous basin which extends into the southeastern part of the GDR, northern Czechoslovakia (CSSR), and western Poland. The deposits in Cenomanian sandstones in the CSSR are described by RUZICKA (7) (see section on Czechoslovakia). Similar mineralizations are developed in the Elbsandsteingebirge (Elbe Sandstone Mountains) in the GDR. A detailed description of the Cenomanian sandstones of this area is given by MIBUS (8), however, their uranium content is not given. The stratigraphic sequence in the Elbsand-sandsteingebirge is very similar to that of the Hamr district in the CSSR, where the main uranium-bearing horizons occur in fresh-water sediments of Lower Cenomanian age. The Cenomanian sandstones in the GDR were deposited in depressions formed in the Variscan basement, which is composed of granites and meta-sediments. The basement rock were deeply weathered prior to the deposition of the Cretaceous sediments. The Cenomanian starts with a fluviatile basal conglomerate, which is overlain by a sequence of sandstones with intercalations of clay containing plant remains. The sandstones are grey in color, and commonly medium to fine grained. Locally, intercalations of coarser material are developed. The sandstone contains pyrite in nests a few mm across, irregularly distributed clusters of bleached bio-tite, as well as kaolinized feldspar grains. The argillaceous material occurs in lenses of black or dark grey colour, locally associated with small coal seams.

The beds of the freshwater sandstone in the Lower Cenomanian reach thicknesses of 20 to 40 m. They are generally flat lying, with a maximum dip of 5°. The sediment of the sandstones, as well as the uranium, was derived from the surrounding terrain, which consisted mostly of granitic and metasedimentary rocks (Lusatian Massif). The material was transported by rivers over a distance of 40 to 130 km prior to deposition. The uranium was precipitated in layers containing organic material, clay and sulfides. The uranium-bearing horizons are developed in the basal part of the sandstone sequence. The ore occurs in many isolated orebodies, which vary in size and uranium content. The mineralization in the Cenomanian sandstones is comparable with the roll-type deposits in Wyoming, USA.

Uranium mining is centered around Königstein and Pirna. Indivi-dual orebodies were previously mined by conventional techniques at depths of up to 150 m. Later, underground leaching techniques were developed, primarily for the extraction of low-grade ores. Similar techniques are used in the Hamr district in Czechoslova-kia (see CSSR).

Poland

Exploration for sedimentary uranium deposits has been carried out for many years, focussed on various types of rocks of diffe-rent ages. It is clear from the literature available that the main targets were sedimentary rocks of Ordovician, Silurian, Carboniferous, Triassic, and Cretaceous age, but no indication was found as to whether the exploration was successful in fin-ding mineable orebodies.

The oldest rocks with known uranium concentrations are of Lower Ordovician and Silurian age (7, 9, 10, 11). See GDR and CSSR. BAREJA (9), describes the results of geochemical investigations in the Podlasie depression, where the concentration of U, V, and Mo in Lower Ordovician sandstones, black shales and phosphatic shales were studied. Uranium shows enrichments of up to 80 ppm in black shales, as also for V and Mo. In the Sudeten Mts.

(Kaczawa Mts. and Bardo Mts.) black shales of Lower Silurian age contain several 100 ppm uranium (10). The general stratigraphic setting is comparable with that in Thuringia (GDR) were uranium is mined. However, no information is available as to wheter this is also the case in Poland. The authors (op. cit.) also describe phosphatic nodules with 200 ppm U in black shales of Lower Silurian age.

The uranium content of the Carboniferous sediments in the coal basins of Upper and Lower Silesian has been studied in great detail (12,13,14,15). The Upper Silesia Coal Basin is characterized by its paralic setting, whereas the Lower Silesian Basin is typically intermontane. According to observations by SALDAN (15), the distribution of uranium in the Upper Silesian Basin is not uniform, neither in the vertical sense nor horizontally along the strike.25 % of the uranium occurrences are in Namurian beds, whereas 75 % are found in rocks of Westphalian age. Study of the areal distribution of uranium shows a concentration of occurrences in the eastern part of the basin.The mineralizations are usually confined to the vicinity of faults. The richest concentrations are observed in the coal itself (up to 2660 ppm U) forming irregular lenses. The sandstones and sandy shales adjacent to the coal have a lower uranium content. SALDAN states that the uranium content of the sandstones in the eastern part of the basin is much lower than in other parts. The uranium in the coal shows the reverse trend. It can be suggested that uranium was removed from the sandstones and concentrated in the coal by postdepositional infiltration. This is supported by the fact that the top parts of the coal seams are enriched in uranium. In boreholes, a significant decrease of radioactivity was observed with depth.

A study on the geochemistry of uranium and other elements in different coals was carried out by JECZALIK (13) in order to investigate the processes involved in the concentration of the metals. The coals from the Lower Silesian Basin are rich in uranium, whereas the Upper Silesian coals are generally very low grade. The degree of uranium enrichment shows a positive correlation with the degree of oxidation of the organic components. The maximum uranium content was observed in coals with a density of 1.7 to 2.0(uranium enriched by a factor of 2 to 4).

A maximum concentration of 0.8 % U (dry matter) was found. The uranium is randomly distributed in the organic material and does not form distinct minerals. Fe- or Al-minerals and aluminasilica gels are not responsible for the accumulation of uranium. Uranium was concentrated by sorption, the same process also being responsible for concentration of V and P. The uranium can be leached using 2 % sulphuric acid.

Uranium enrichments in Permian sediments (Lower Rotliegendes) of the Intrasudetic Basin in Lower Silesia are epigenetic in origin (12). During weathering and oxidation of Permian arkoses and greywackes under humid conditions, U, Zn, Pb,and Cu were leached and U concentrated. The leaching occured in the zone of direct oxidation, transforming sulfides into sulfates. Where no sulfides were present, alkaline carbonate and bicarbonate solutions were formed. By migrating downwards into an acid environment, the pH of the alkaline solutions changed, causing an additional enrichment in heavy metals. By reaction with the carbonate, the solutions became neutral, and elements were precipitated as pitchblende at a pH of 4.2; followed by Zn at pH 5.2, Cu at pH 5.4, and finally Pb at a pH of 6.0. The deposits formed under these conditions were covered by later formations. In mineralized parts of the Permian, the uranium content varies in the range 100 to 300 ppm. In some cases enrichments of 500 to 800 ppm were observed in drill cores from depths of between 120 and 290 m.

Uranium mineralizations of the sandstone type is reported by BAREJA (14) from Upper Carboniferous rocks (Westphalian C and D and Stephanian in the Intrasudetic Basin near Nowa Ruda. The uranium mineralization occurs in the clay and clay-carbonate cement of sandstones and polymict conglomerates. The most important uranium mineralization is concentrated in the middle part of this sequence, in which the uranium content increases towards the lower part of the unit.

Stephanian sediments are reported to contain uranium mineralization consisting of pitchblende und uranium sulfates in the cement of flaggy sandstones and the basal conglomerate. The paragenetic association of pitchblende, pyrite, chalcopyrite, sphalerite and galena is typical of this type of mineralization in the Intra-sudetic depression. It is comparable with the mineralizations reported by DEPCIUCH (12) from the Lower Rotliegendes.

The uranium content of the Triassic Buntsandstein (Bunter sediments) has been investigated by SALDAN (15) in Northern Poland (Pomerania trough and Peribaltic syneclise) and in the western part of the country (Fore-Sudetic monocline and Zary pericline). Uranium mineralizations occur in grey-green sandstone, conglomerate and mudstone of the Middle and Upper Bunter.

In the Fore-Sudetic monocline, limestones are mineralized. The uranium-bearing strata in the Middle Bunter are in the same stratigraphic position in all the occurrences. The thickness of the Lower and Middle Bunter can reach approximately 1200 m in the central part of the basin. In the Fore-Sudetic monocline and the Zary pericline, the uranium mineralization is bound to a 70 to 180 m thick sequence of red-grey sandstone with intercalations of limestone and claystone. Within this sequence, individual layers several m thick are mineralized. The uranium is bound in carbonates (calcite, dolomite, and to a lesser extent ankerite and siderite). A second, epigenetic type of uranium accumulation is associated with sulfide, which may have acted as a reducing agent. The uranium content shows considerable variation, which is controlled by the lithology and chemical composition. The highest uranium concentration (ca. 100 ppm) was observed in grey-coloured claystone and mudstone.The elements V, Mo, Se, Zn and Pb show a positive correlation with uranium. The maximum concentration of uranium of over 1000 ppm is encountered in layers a few tens of cm thick.

In the Peribaltic syneclise, three uranium-bearing horizons were observed. The uranium enrichments occur in green-grey claystones with intercalations of grey sandy mudstone, in the lower member, and in grey sandstone with coaly material and pyrite in the middle member;the richest mineralizations (above 1000 ppm) occur in layers 0.5 to 1 m thick. Uranium minerals (sooty pitchblende and coffinite) occur as cement in the sandstone, and V,Mo and Se are enriched in the same layers. The uranium mineralization shows similarities with deposits of the sandstone type elsewhere in the world (16).

Features similar to those of the Peribaltic syneclise are observed in the Pomeranian trough. In the limestones, uranium was concentrated mainly by diagenetic processes, the enrichments in claystones are attributed to syngenetic processes, and epigenenetic concentrations are observed in the sandstones and conglomerates.

Economic prospects are not given. The depth, thickness, and grade of the uranium-bearing horizons may be limiting factors.

The uranium potential in Cretaceous rocks in the North and Central Sudetic Basins was investigated and found to be negative (17). In the northern and northwestern part of the Bohemian Cretaceous Basin, Cenomanian sandstones contain mineable uranium deposits in the German Democratic Republic and in the CSSR. In the Polish part, the uranium-bearing facies is represented in small portions of the basin, or it merges laterally into unsuitable lithologies. The outcrops and boreholes checked showed low radioactivity.

Czechoslovakia

In Czechoslovakia, uranium mineralizations occur in sedimentary rocks in the Silurian, Permo-Carboniferous, Mesozoic and Tertiary.

In the Permo-Carboniferous platform cover of the Bohemian Massif, uranium accumulations are associated with both carbonaceous sediments and sandstones. The Permo-Carboniferous sediments are of fluviatile and lacustrine origin and are composed of conglomerates, sandstones, arkose, shale and mudstone, either with coal seams or enriched in organic matter. Uranium mineralization is developed in some high ash coal-bearing sequences, and argillaceous or sandstone horizons with organic remnants (Lower Silesian Basin, Kladno-Rakovnik Basin, Plzen Basin). In the first two basins, an elevated uranium content was observed in paleochannels intersecting the coal measures (18).

The uranium and vanadium concentrations in rocks of Stephanian and Autunian age in the Lower Silesian Basin are the products of selective precipitation from solutions circulating through the sediments after deposition (19). LEPKA (20) came to similar conclusions for the Kladno-Rakovnik Basin. The uranium was precipitated from groundwaters containing 2 - 8 ppb.

Some extensive horizons with relatively high uranium contents are known from the Permo-Carboniferous (Stephanian and Lower Permian conglomerate, sandstone, shale, with local coal seams) of the Sub-Krkonose region and the Bskovice Furrow. Agglomerates and tuffaceous conglomerates with uranium minerals occur in the Lower Permian of the Lower Silesian Basin (18). Uranium mineralization is represented by sooty pitchblende in coalified remnants of plants, accompanied by pyrite, marcasite and small amounts of galena, sphalerite and chalcopyrite.

The epigenetic type of mineralization occuring in the Permo-Carboniferous in the Intrasudetic Basin in Czechoslovakia is also found in the Polish part of the basin (see section on Poland).

In the Upper Permian (Verrucano) of the West Carpathians (Spis-Gemer region),stratiform, mixed sedimentary and volcanic uranium mineralizations occur at Novoveska Huta and Muran. The ore-bearing sediments comprise conglomerate (tuffaceous) sandstone, shale and quartz porphyry. The mineralization (U, Cu, Mo) is syngenetically associated with th

Carpathians is the Lower Tatra. The area is underlain by Permian to Lower Triassic rocks. Uranium mineralization occurs in Permian sandstones of continental to lagoonal origin containing carbonized plant remains. These sandstone beds are overlain by Lower Triassic volcanic rocks. Beside uranium mineralization, which occurs mainly as torbernite, other minerals such as pyrite, chalcopyrite and galena are present. The uranium-copper mineralization associated with the carbonaceous sandstones, is apparently epigenetic. The uranium deposits and occurrences are located at Cierny Vah, Kravany and Stiavnik (7).

Uranium occurrences (Hamr deposit, Brevniste deposit) of the subconcordant type are found in sandstones of Cenomanian age near the northern margin of the so-called Czech Upper Cretaceous Table in northern Bohemia (7, 18, 23, 24, 25).

The mineralization is associated with the freshwater Cenomanian sediments and the basal part of the marine Cenomanian.The freshwater deposits which usually do not exceed 10 m in thickness, but may reach up to 27 m, occur only in local depressions in the pre-Cretaceous basement, which is composed of Permo-Carboniferous (?) granitoids or metasediments. The transgression of the marine Cenomanian began with the deposition of unsorted sediments on an erosion surface. These are followed by siliceous sandstone with interbedded conglomerate. They are in turn overlain by Lower Turonian marlstones and Middle Turonian sandstones. During the Tertiary, basaltic rocks were emplaced along faults. The uranium mineralization is confined to several tabular or lens-like bodies. In some cases a typical roll structure can be observed, as well as the influence of paleochannels. The most important orebodies are confined to the basal beds, 2-5 m thick, of the marine Cenomanian, and are associated with greyish sandstones with a high content of argillaceous material, coal detritus and pyrite. At locations where the Cenomanian rocks transgressed directly onto the underlying basement, the ore mineralization penetrated the strongly weathered (kaolinized) metamorphic and igneous rocks. Where Tertiary basalts intersect the ore-bearing horizons, mineralization is found in volcanic breccia.

Distinct alteration appears above the orebodies; it is characterized by bleaching and partial limonitization of the sandstones.

The predominant minerals are uraninite, coffinite, hydrozircon, ningyoite, brockite, iron sulphides and crandallite. Galena, sphalerite chalcopyrite, bravoite and other accessory sulphides are rare (26, 27). The uranium mineralization is believed to belong to the low-temperature epigenetic type and is geochemically characterized by an unusual association of the elements U, Zr, P and Ti. The mineralization mostly occurs as a fine dispersion in the cement of the sediment. The source rocks of the uranium are the acidic igneous rocks of the Lusatian granite massif and its country rocks.

The Teplice area, where uranium mineralization occurs in Cretaceous sediments, is geologically similar to the Hamr area. CADEK et al. (28) reported the low-temperature mineralization as an example of a sub-recent ore-forming process. Unlike the Hamr area however, the mineralization is present within the Cenomanian and also within the Turonian. The mineralization consists of sooty pitchblende, galena, pyrite, sphalerite, quartz, fluorite and barite.

Uranium mineralizations within the Tertiary occur in the Sokolov and Cheb Basins of the Krusne Hory (Erzgebirge) Graben. The freshwater sediments consists of sandstone and mudstone containing organic matter, coal seams and some tuffaceous rocks (7). The basement is composed of deeply weathered Variscan granite, migmatite and gneiss. Tectonic movements have separated the basins into several blocks (18). The sediments of the Sokolov Basin, which overlie the Karlovy Vary crystalline massif, are subdivided as follows:

Miocene
- Cypris Claystone (mainly kaolinitic clay, coaly clay, claystone and sandy layers)
- Main-seam Formation (mainly coal)
- Volcanogenic Series (tuffite, tuff, agglomerate)
- Josef-seam Formation (mainly coal)

Oligocene Basal clastics.

The uranium deposits are located within those parts of the basin which overlie the granite basement. The second important feature is their position within the stratigraphical sequence. Most of the deposits occur within the lignitic and/or bentonitic beds of the Volcanogenic Series and the Main-seam Formation. The third feature of significance was the existence of favourable hydrogeological conditions.

In the Sokolov Basin, the following types of mineralization occur:

-- Uranium-bearing lignites (Oder deposit), where U occurs together with Ge.

-- Uranium-bearing lignitic-bentonitic beds (Hajek and Ruprechtov deposits), where U occurs in association with Be.

-- Uranium-bearing accumulations in sandy sediments (Domino deposit).

The mineralization is represented by uraninite, uranium humates, secondary uranium minerals, sulphides, hematite, and hydrated iron oxides. The origin of the mineralization is epigenetic. Low temperature uranium-bearing solutions migrated from the weathered basement rocks through permeable sediments that contained carbonaceous or tuffaceous material; these caused uranium ions to be precipitated or adsorbed.

In the northwest of the Cheb Basin, the uranium mineralization occurs in basal conglomerate and sandstone overlying the granitoids of the Variscan Smrciny (Fichtelgebirge) Massif. Uraninite and pitchblende are associated with iron oxides and hydroxides cementing the clastic sediments. Organic matter is absent in the mineralized strata (29).

Uranium mineralization in the Tertiary is less extensive than in the Cenomanian.

Hungary

The only information on uranium deposits in sandstones is reported from Permian sediments occurring in the Permian-Triassic anticline of the Mecsek Mountains (7). They occur in a 500 m thick sequence of Upper Permian fluviatile sandstones. The Upper Permian beds are composed of mainly grey arkosic sandstone and siltstone with siliceous and calcareaous cement, containing lenticular claystone intercalations. The uranium mineralization occurs in the green Köragoszöllös Sandstone, between the grey and red sandstones (4, 30, 31).

The productive formation represents the deposition in a fluviatile to swampy environment under semi-arid conditions. The lenticular from of the mineralized beds derives from the original sedimentation of fine grained material rich in organic matter. The detritus has derived from the erosion of granitic rocks enriched in Bi, Co and Ni. The sedimentary basin has gradually widened during Upper Permian time (32). At the margins of the basin, flood-deposited sediments were developed, whereas in the central parts mainly river-bed sediments were accumulated. The pressure imposed on the Permian sediments during Late Cretaceous was about 1500 atm and the temperature may have exceeded 150° C. The area was uplifted in the Late Cretaceous, forming an open pericline dissected by faulting.

The complex process of uranium mineralization started during sedimentation. The surface waters during Late Permian time had favourable pH and Eh values for migration of uranium and associated elements (mainly Cu, V and Cr). During flood periods, the elements were precipitated from waters percolating lateraly and downwards. The best conditions were present in abandoned channels, ox bows, ox-bow lakes and swamps. In these parts grey sediments rich in organic matter are deposited. In the central part of the basin, under oxidizing conditions, red sandstones were developed. Between these a green sandstone sequence was deposited. In some parts, uranium was dissolved by oxidation processes during later stages of deposition. Overburden pressure caused the uranium to migrate towards the margins of the basin. On reaching reducing sediments, the uranium would be precipitated and gradually become enriched, resulting in the formation of commercial concentrations of uranium. The largest accumulations of uranium are associated with intertonguing of red, green and grey sandstones. The uranium occurs as stratiform, disseminated and transveral enrichments. Uranium oxides, coffinite and sooty pitchblende were formed (31), associated with pyrite, marcasite, galena, chalcopyrite, sphalerite and arsenopyrite. Clausthalite and bravoite are present in minor quantities. The textural pattern of the ore mineralization is described as a matrix type (31). The matrix of the sandstone is composed of carbonate minerals (dolomite, ankerite, calcite), hydromicas (Cr-hydromuscocovite, Cr-illite, common hydromuscovite, illite, V-illite) and ore minerals. A partial replacement of the rock-forming components by the ore minerals was observed as well as the replacement of the carbonate matrix. VINCZE (33) concludes that the mineralization processes occurred after deposition of the sediments. Replacement of both the matrix and the rock-forming minerals by the ore indicates a sedimentary, possibly polygenetic mode of origin. The hydromicas and coalified plant material may have played an important role by sorption and reduction.

Romania

In recent publications on the geology and mineral deposits of Romania no information is given on the presence of uranium deposits in sandstone formations (34, 35).

In 1974, however, a paper by KORNICUK (36) was published on the lithological features and facies of uranium deposits in terrigenous sediments of Late Carboniferous and Permian age. The names of the deposits are not given. From the literature cited, one can assume that the deposit (or deposits) are in the Banat district. Further information is contained in a paper by NITU (37).

The sedimentary sequence starts with grey conglomerates of Late Carboniferous age unconformably overlying the crystalline basement. The Upper Carboniferous (several 100 m) is overlain by red and grey Permian conglomerates, sandstones, silts and clays (650-1000 m). Uranium mineralization is developed in both formations, preferantially in the Permian. The ore deposits occur in sandstones and conglomerates of grey to greyish-green color.

Lithologically,five multicolored horizons can be distinguished. Each is a cyclothem, starting with a basal conglomerate and ending with fine-grained material (mostly silt). The uranium mineralization is bound to three horizons. The first horizon consists of 20 to 25 microrhythmic cycles, each composed of conglomerate, sandstone and bituminous silt. The conglomerates are derived from the metamorphic basement. The detritus of the sandstone is of similar composition. The sandstones are grey in color due to the high amount of mica and clay. The barren horizons are well sorted conglomerates and sandstones. Their detritus consists mainly of volcanic material.

In each of the mineralized horizons, three to four different cycles are observed, each constisting of conglomerate, sandstone and silt.Cross-bedding is a common feature of these grey layers. In the upper part, dark limestones and marls together with claystones are observed.Normally the uranium mineralization is found in lenses of grey, mica-rich intercalations in red sandstones.In horizon I,tabular bodies are closely associated with organic material.In horizon IV, columnar orebodies are the main feature. The uranium mineralization is bound to bituminous material,which may replace the cement of the sandstone or forms fillings of fissures. In horizon V, the uranium mineralization occurs in the carbonate matrix of medium- to finegrained sandstones. The orebodies are tabular or lense-like. The ore occurs also in nests or coatings of sedimentary structures.

The uranium mineralization is controlled by a change of coarse- to fine-grained sediments. The porosity of each microrhythm is an important factor for the emplacement of uranium. Sandstones with high porosity are more richly mineralized than others.Later structural displacement was an important mechanism for the concentration of uranium, especially in deposits with higher grades. They occur mainly in the apices of anticlines.

According to mineralogical studies, both syngenetic and epigenetic types of mineralization are present. The syngenetic mineralizations are located in bituminous and coal-bearing layers in Upper Carboniferous and Lower Permian deposits. Epigenetic mineralizations have been formed by migration of the bituminous material into the Permian sediments above the synge- syngenetic deposits. Only the epigenetic deposits are of economic interest.

The uranium bearing bituminous matter (up to 15 % U, mainly as sooty pitchblende) replaces the matrix of the sandstones and occasionally also sandstone grains. A positive correlation between the uranium content and the degree of oxidation of the bituminous matter was observed. The bituminous matter migrated into the sandstone and was oxidized and polymerized together with the formation of uranium mineralization. During a later phase, hydrothermal influences may have mobilized the mineralization or even introcuced new uranium. This type is limited to fault zones.

Another type of sandstone uranium mineralization may be present in Cretaceous sandstones. STEFANESCU (38) described the Bogata Sandstone (Vraconien = Cenomanian) of the Baraolt Mountains north of Brasov in the external part of the East Carpathians.

The sandstones were deposited under continental conditions, they are compared with calcareous sandstones of Bohemia (CSSR) and Saxonia (GDR) where uranium deposits occur. In the Baraolt Mountains, a sandy-calcareous and a conglomeratic facies can be distinguished. No specific information is given for their uranium content.

Bulgaria

In the literature reviewed, no reference was found to uranium mineralizations in sandstone formations. An elevated uranium content is reported from phosphate-bearing marine sandstone of Mesozoic age.

Although no publications on uranium deposits are available, one might speculate on their existence in favourable environments. These conditions were developed during the Carboniferous, Permian, Liassic, and Early Tertiary in different parts of Bulgaria (39, 40). The corresponding rocks are mainly found on the Moesian platform, N of the Balkan Mts. (Stara Planina), and at the edges of the platform.

Sandstones of continental facies containing anthracite are reported from the Stara Planina. Permian continental sandstones with intercalations of tuff and red argillites, and coal, were deposited in the western part of the country (41). Theoretically, these sandstones may have been deposited under conditions favourable for the formation of uranium accumulations, similar to these reported from other countries of the Balkan Peninsula (see sections on Hungary and Romania). According to the description given by YANEV (41) the Lower Permian in the Balkanides shows some similarity with the Lodeve basin in Southern France. In the adjacent part of the Stara Planina in Yugoslavia, a small uranium occurrence was found at Dojkince in the colored series of Early Triassic age (42) in which pitchblende mineralization (0.02 to 0.06 % U) is associated with carbonaceous matter, and some chalcopyrite and galena. The mineralization occurs in lenses about 0.5 m thick. According to FOOSE (39) Lower Triassic consisting of sandstones, red quartzites, and conglomerates are present in the Stara Planina. These are described as a mixed sequence of red sandstones of continental origin, followed by marine limestones (43). Liassic sandstones may also be favorable since they were deposited under shallow-water or deltaic conditions. During Early Tertiary time (Paleocene), sandy shallow-water sandstones were deposited in various parts. In Paleocene basins in NW Bulgaria, coal seams are associated with the sandstones.

Albania

Recent geologic literature on mineral deposits other than chromium, nickeliferous iron ore and copper is scant. No information is available on the existence of uranium deposits or on exploration for radioactive minerals in Albania. Older publications reviewed do not contain any reference to the presence of uranium mineralizations in any of the rock formations in the country.

Albania constitutes part of the Dinarian orogenic belt, which covers much of the Western Balkan Peninsula and stretches from Northern Yugoslavia and Albania into Greece and Creta. Within this zone, sedimentary basins were formed which, lithologically, show many similarities. In particular, the sedimentation in the Upper Paleozoic and Mesozoic intramontane basins was of comparable character.

NOWACK (44) decribes a sequence of reddish-green sandstones forming intercalations in shales and conglomerates near the Drin river in Northeastern Albania. These sediments were deposited on Upper Paleozoic rocks and are overlain by Triassic sediments. The shale, sandstone, conglomerate and limestone can be compared with the Permian Verrucano Formation. The Verrucano is the host rock of uranium mineralizations in Northern Italy and Northern Yugoslavia. From the description of the sediments in Albania, no conclusion can be drawn whether uranium mineralization might be present or not.

Permo-Triassic conglomerates of Verrucano facies are also developed in the Korab and Mirdita zones (internal Albanides) (45). The same author mentions Permian and Lower Triassic ferrugenous formations in the Albanian Alps.

Most of the detrital sediments of Mesozoic age are of marine origin and therefore may be not favourable for uranium enrichments.

During Tertiary time, many small lignite deposits were formed, pointing to a limnic or deltaic environment of deposition. These basins contain flysch sediments. The detritus was possibly derived from igenous rocks of intermediate to basic composition (46). Their favorability for the enrichment of uranium is regarded as low.

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GEOLOGICAL ENVIRONMENT OF THE URANIUM DEPOSITS IN THE PERMIAN OF LODEVE BASIN, FRANCE

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Abstract

The Permian rocks of the Lodeve Basin are characterized by a biorhexistasic cycle which produced fine alternating sequences of organic-rich sedimentary deposits in a basin ranging from lacustrine to a confined briny lagoon. The erosion of the Hercynian massifs, source for the sediments, along with the constant arrival of volcanic ash, provided metallic ions, particularly uranium. A continual subsidence permited a regular influx of sediments and a burial compatible with a genesis of hydrocarbons.

Post-sedimentary tectonic extension as well as the fine bedding of certain layers, created permeable zones that facilitated the circulation of fluids : the oils migrated, concentrated in petroleum-type traps formed by fault zones and the finely bedded layers. The interstitial waters flushed by compaction were carriers of metallic ions in solution. They used the same permeable zones as the oil, and the uranium was precipitated in the hydrocarbon traps which were strong reducing agents.

During diagenesis, an important physical and mineralogical evolution affected the surroundings and certainly played a role of prime importance in the "recycling" and precipitation of the uranium.

In the meantime, oxidizing and carbonate-bearing meteoric water rose within the rock formations along the principal faults, flushing and transporting uranium to the traps, developping a complementary accretion process.

Classified into three principal types, the mineralizations developed within the framework of a dynamic basin system in which several factors - sedimentary, tectonic and diagenetic - operated.

1. GEOGRAPHICAL SITUATION - CLIMATE

The Permian Lodeve Basin is located in the south of France, 45 km northwest of Montpellier. It is more or less ellipsoidal in form with a major axis 26 km long oriented in an ENE-WSW direction and a minor axis 10 km in length. The total surface area is 150 km2. It appears as an eroded depression surface, dominated on all sides by limestone formations.

It has a typical Mediterranean climate, where vineyards, olive, holm-oak, and low, sparse vegetation grow.

2. ACTUAL GEOLOGICAL SETTING

2.1. Regional context

The Lodeve Basin is one of the most southern of a series of Permo-Carboniferous basins located south of the Central Massif on the western edge of the Causses (fig. 1) (1). It is bordered by three large, contrasting geologic and geographic

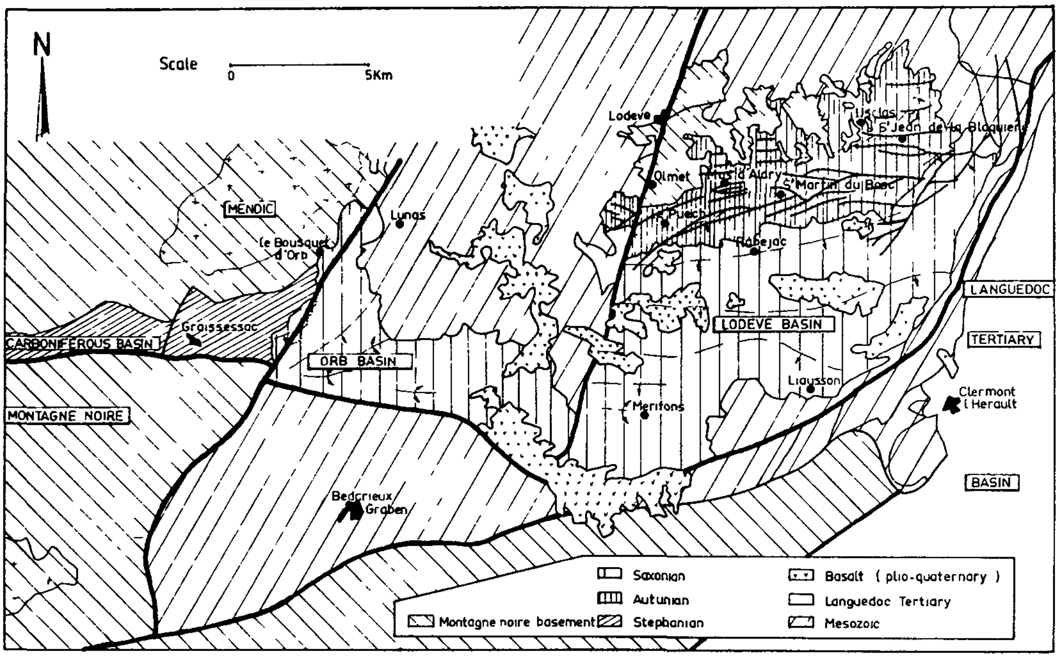


fig 1 Geologic Sketch of Lodeve Basin

terranes : the Montagne Noire, the Causse and the Languedoc Plain. The underlying bedrock is composed of divers geological formations : gneiss, granite intrusions, Cambrian schists and dolomites. The basin is continued westward by a Stephanian depression : the Graissessac Basin. To the southwest Triassic-Jurassic beds cover the series of Permo-Carboniferous basins. The Lodeve Basin forms the southern border of the Causse, while the downdropped Tertiary Plain of Languedoc lies to the east an south. Finally, throughout the region are plateaus formed by Quaternary basaltic flows.

2.2. General structure of the basin

The Lodeve Basin is formed by a monoclinal structure gently dipping (10° to 15°) towards the south (2) (3) (Fig. 2). Major faults run in an E-W and NNE-SSW direction along the western, southern and eastern boundaries of the basin while towards

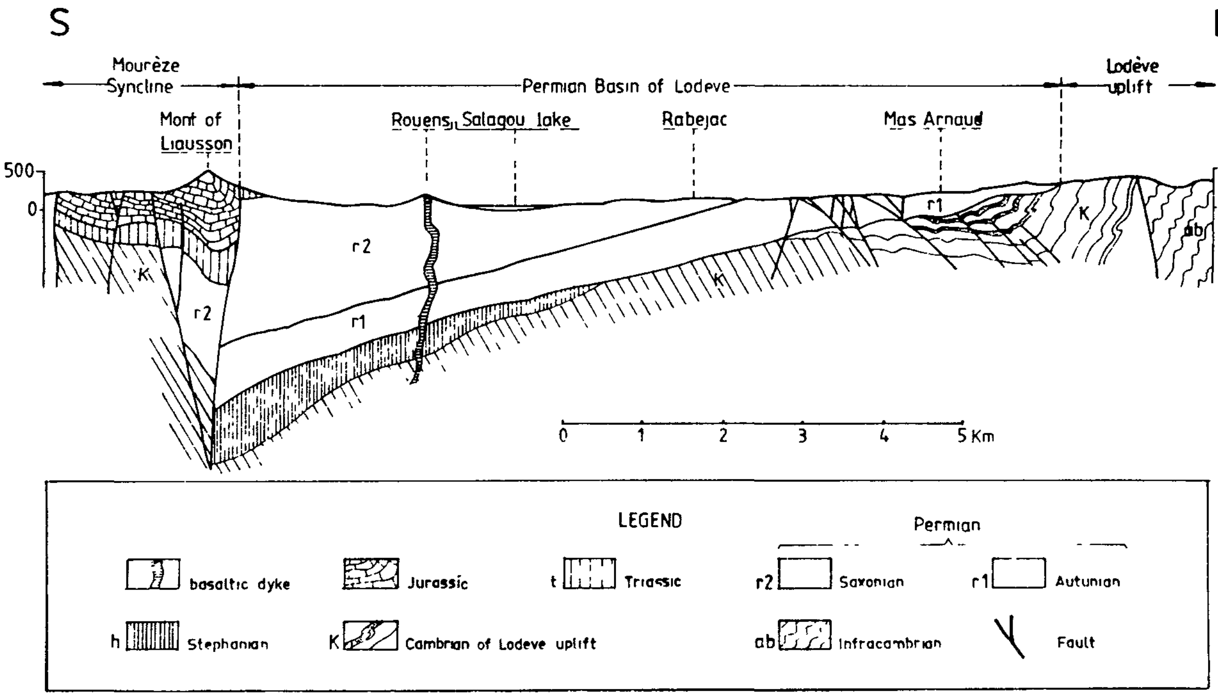


fig 2 Cross section of the Permian Basin of Lodève

the north, the basin lies discordantly on the Cambrian dolomitic bedrock of the Lodeve uplift. The NNE-SSW Olmet fault divides the basin into a downdropped western half and uplifted eastern half. The Permian rocks are crossed by a network of normal E-W faults with a geometry of "wedges and strips". These faults play an important role in the distribution of the uranium deposits.

2.3. Stratigraphy

The Permian rocks are of the classical succession of the European Hercynian period. Stephanian coal beds are overlain by deposits of the Autunian, and then the Saxonian series. These series largely trangress and overlap the older coal stratum (4)(5)(6).

2.3.1. Autunian

The Autunian contains almost all of the uranium deposits. With a maximum thickness of 650 m, the Autunian stratum is composed of four units :

- at the base, a conglomerate (0 to 80 m) of dolomitic clasts, irregulary deposited along the paleovalleys,
- a grey unit (150 m),
- an alterning red, green end grey unit (150 m),
- a red unit (300 m) nearest the top.

The three upper units are composed of a succession of elementary sequences of variable thickness and color, but whose three principal lithologies are identical : the base is sandstone, followed by a bituminous layer, and by pelite at the top (7). The sandstone is very fine grained with a silty matrix. Its cement is generally carbonate. Grey or red sandstone is in regular beds but may be found locally slightly chanelled within the red units. The bituminous layer, called "couche" alternates between very fine beds of carbonated sandstone and carbonate clay rich in organic matter, often passing near the summit towards dolomitic levels. The "couche" is grey or black. The upper portions show numerous signs of emergence or shallow water marks : mud cracks "premammalian" tracks (8, 9) and traces of rain drops. The pelite is consolidated argillite. It can be red, green or grey and contains varying amounts of carbonate and sand.
The thickness of each bed varies from 1 to 15 m. The sequence may be incomplete by the absence of either pelite or sandstone (or both).

The Autunian is composed of about fifty such sequences which differ only in thickness, color and the relative importance of their three principal lithologies, but are remarkably widespread throughout the basin. Thirteen ash beds (cinerites), from centimeters to decimeters thick, are interbedded among the sedimentary sequences and form excellent markers throughout the entire basin.

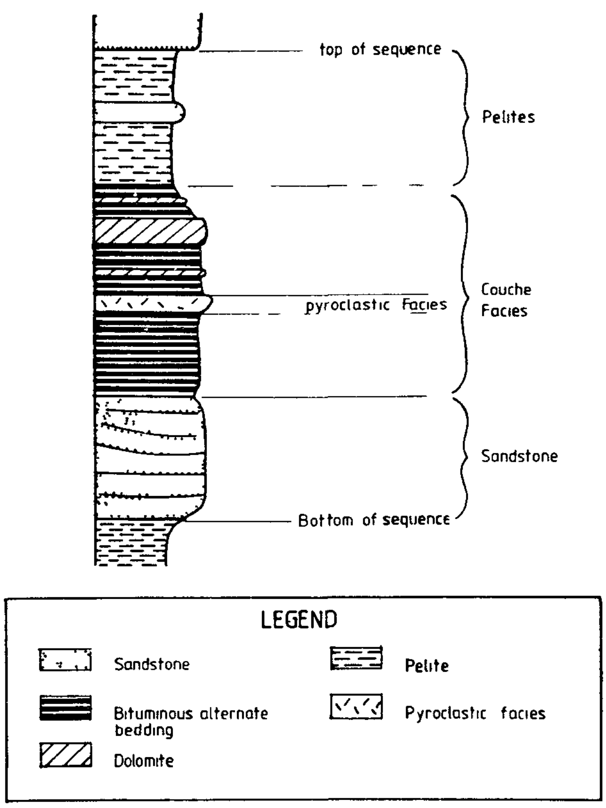


fig 3 Autunian type sequence

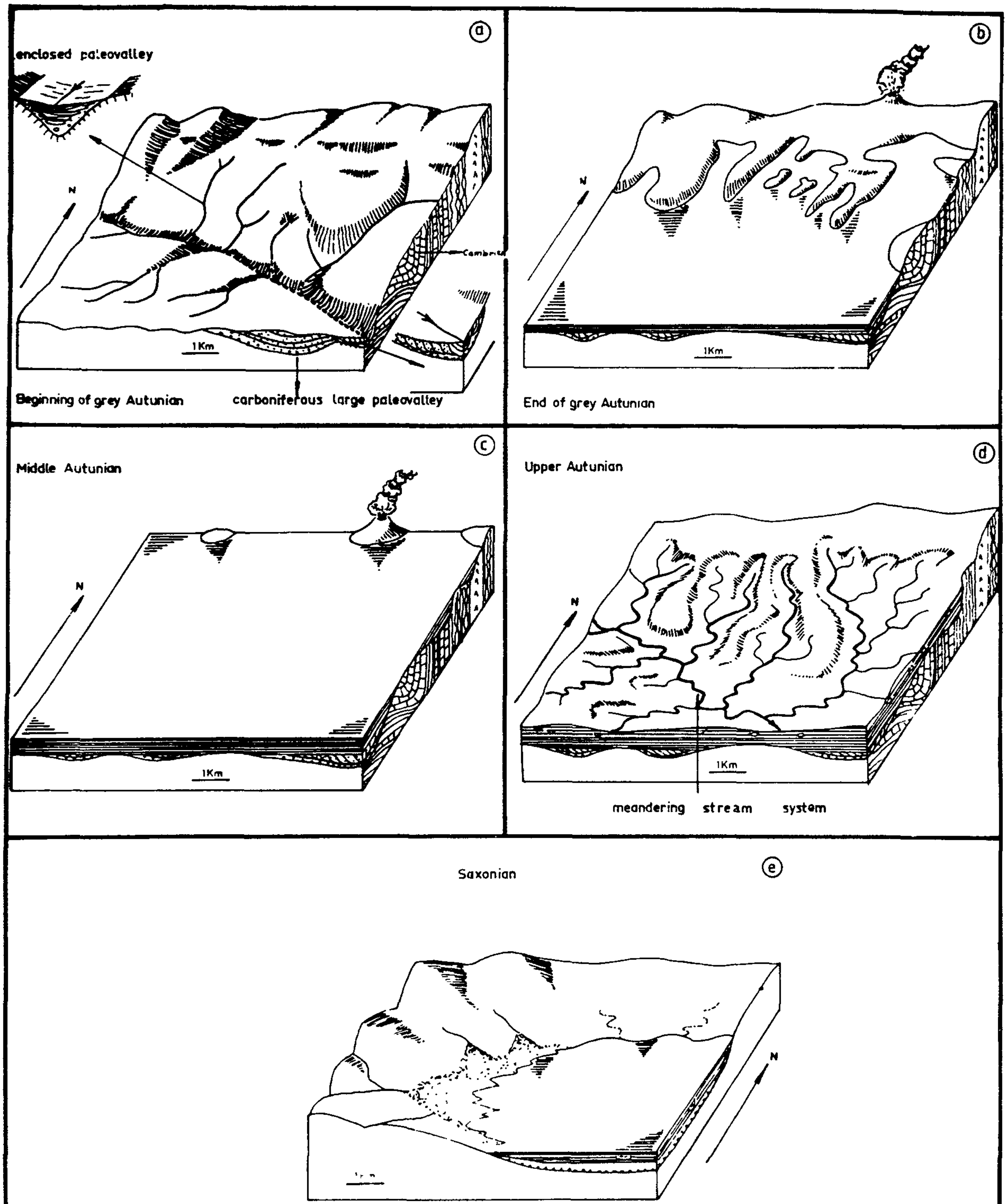


fig.4. Basin of Lodève : Permian Paléogeography

2.3.2. Saxonian

The Saxonian stratum overlies the Autunian with slight regional discordance and is a uniform unit more than 1500 m thick. Its base is usually a thin conglomerate that is overlain by a 50 to 100 m thick series of fine-grained sandstones. The uppermost part is composed mainly of claystone, occasionally carbonate-rich and some interbeds of carbonate-cemented sandstone with large lateral continuity. The Saxonian is brick red with some greenish layers at the top and has numerous traces of "premammalian" (8, 9), mud cracks as well as other evidence of emergence.

The Saxonian is overlain by discordant Triassic formations.

2.4. Hydrogeology

The principal aquifer is composed of a karstified shisto-dolomitic Cambrian bedrock and of the Autunian basal conglomerate. It is supplied by seepage of meteoric water through the basin's northern outcrops, where the aquifer is exposed. Towards the south the aquifer is buried by the Autunian rocks whose permeability is low.

Secondary aquifers are located in the Autunian stratum. This multilayer formation does not lend itself lithologically to the development of important aquifers. However, small pockets of subsurface water may be induced by the joints of stratification, the presence of sandy units and the existence of fractures. This is due particulary to artesian water invading up from the conglomerate or to limited percolation from meteoric water.

Hydrochemically speaking, the basin water can be divided into three large groups (10) :

- in the west, a sodium to calcium bicarbonate water of a hydrothermal character,
- in the east, sodium-sulfate water,
- in the central region, sodium-chloride water.

3. SEDIMENTOLOGY AND DIAGENETIC EVOLUTION OF THE AUTUNIAN

3.1. Environment of deposition of the Autunian series

The sedimentary record of the Permian of Lodeve can be roughly sketched as follows (fig. 4).

At the beginning of Permian deposition, the relief was uneven with abrupt valleys oriented north-south, branching into a large WNW-ESE paleovalley of a less pronounced relief (11). With the start of the Autunian Period the renewed erosion was marked by a very coarse polygenic conglomerate filling the paleovalleys, topped by progressively finer grained sandstone layers as the filling proceeded (fig. 4-a). At the end of the grey Autunian, the paleorelief was subdued for the most part, and a eutrophic-type lake (12) or saltwater lagoon developed. The sedimentation was in calm shallow water, probably alternating with sporadic marine incursions throughout the Autunian period (fig. 4-b). During the mid-Autunian period (alternating grey-red), the sequences became more laterally continuous, the proportion of clay increased while the sources of coarse detritus receded. Meanwhile there was a corresponding rhytmic extension of the sedimentary basin, as well as a diminution of the confinement and organic reducing potential (fig. 4-c) During the Upper Autunian period (red), the number of channel-like structures filled with sandstone-pelite increased while the horizontal regularity lessens. The environment was no longer confined and the sediments were deposited under oxidizing conditions : this could have been a flood plain, periodically immersed (fig. 4-c).

All during the Autunian period intensive volcanic activity deposited ashes and pyroclastic debris. The ash bed (cinerite) markers indicate definite volcanism though the exact location of the volcanos of this period remains unknown.

An entire single sequence represents an upward fining sedimentary cycle corresponding to a progressive reduction in energy and water depth. There was a change from detrital sandstone deposition to chemical and evaporitic sedimentation (dolomites, sulfates) with emergence (animal traces, mud cracks) by way of a permanent, calm and enclosed seasonal lake regime ("couche"). The pelites found towards the top of the sequence indicate an increased depth in water within a currentless environment initiating the next sequence.

During the Saxonian a sharp contrast between the eastern and western parts of the basin existed. The east was characterized by a shallow lake that periodically dried up while the west was of a more vigorous relief with a more dynamic sedimentation (fig. 4-e).

A biorhexistasic hypothesis permits the reconstruction of the sedimentary process that led to the deposition of repetitive sequences. The subsidence that simultaneously affected the entire basin was the cause of these rhythmical deposits. The feeble amplitude of the movement maintained the basin in a low energy state, while the water depth remained minimal, evidence of emergence are ubiquitous.

3.2. Origin, nature and diagenetic evolution of the sediments

The entire basal conglomerate was produced by the erosion of the Cambrian dolomites with a very limited transport of the eroded material. With the abrupt decrease in the basin's energy, the conglomerate gives way to fine-grained sandstone and simultaneously, to the first "couche" facies as well as to clay. The composition of the series varies according to the nature of sediments : sandstone, pelite or "couche" but also in function of their stratigraphical position within the series. The original nature of the sediments is often obscured by the products of diagenesis. One can, however, point out certain general characteristics. The feldspars are dominant (45 to 55 % within the sandstones, the "couches" and the cinerites, 20 to 30 % within the pelites). They range from more or less potassic at the base to a sodic towards the top. The detrital potash feldspars are found in greatest quantity in the grey Autunian where they have best resisted the salt brine produced by compaction, while the sodium has been leached. Newly formed albite, present throughout the series, becomes dominant in the red layers while the potash feldspars disappear. The quartz is scarce (15 to 20 % in the sandstones and cinerites where it is authigenic ; 2 to 10 % in the pelites and "couches").

Argillaceous minerals (from 10 % in the sandstones to 65 % in the pelites) evolved similarly to the feldspars : the montmorillonite dominates in the upper portion and gives way, as one descends, to an illite-montmorillonite. A diagenetic illite then becomes the only argillaceous mineral present in the lower portion of the Autunian. The kaolinite is confined to the red facies (11).

Carbonates are abondant (20 % in the sandstone and "couches", 5 % in the pelites). Calcite dominates throughout the flood plain sediments (red Autunian) while the lagoon sediments (grey) are dolomitic. Within the grey Autunian, one may observe numerous evidence of crystallized sulfates, epigenetized in carbonates by bacterial action (11).

The ash beds are composed of 20 % authigenic quartz, 10 % clay, 15 % dolomite and 55 % feldspar. As with the other units, they change from potassic (sanidine and microcline) to sodic (albite, analcite) towards the top of the series.

The original composition of these rocks has undergone numerous modifications during the diagenesis. The sanidine in the basal part has been partially transformed to microcline, whereas near the top the sanidine associated with plagioclase has been entirely albitized (14). The volcanic globulites and shards have been largely devitrified. The ferromagnesian minerals have been reduced to a phantom state. Quartz, albite, apatite and analcite are neoformed. The upper levels have been invaded by the carbonates. During diagenesis the original texture of these marker ash beds have been completely destroyed. Because of this, diagenesis appears to be very important in the Autunian.

3.3. Organic matter

The organic matter of the Lodeve Basin consists of lignite, sapropelite, and mixtures of the two (26 % lignite, 38 % mixed and 36 % sapropelite in average). It is erratically distributed throughout the series and, often, even within the same layer (15). There is no variation in the composition between the uraniferous and barren horizons (16).

The Autunian shales have matured to the point of oil generation by burial and thus are excellent source rocks (16). The migration of hydrocarbons, from the shales into reservoir horizons (breccia faults, sandstones and dolomites) (17), occurred, creating a reducing environment in the facies originally unfavorable to uranium. These liquid hydrocarbons evolved into almost insoluble solid bitumen (18). Though little is known about this transformation, it could have been caused by the effect of radiation from the uranium (dehydrogenation of the organic matter and destruction of the ammo acids) (18, 19, 20) or rather (certain bitumen being barren) by bacterial decay related to either meteoric water (aerobic bacteria) or connate salt water (anaerobic bacteria) (21).

3.4. Compaction - Permeability - Porosity

Compaction is very important in such a fine detrital sequence as the Permian of Lodeve. Compaction ratios are estimated as 1 to 3 for the sandstone and as much as 1 to 50 for the pelites or the "couches" (4). Circulating fluids and soluble elements moved along the basin following the more favorable permeable zones, such as thickened detrital-rich zones (such as paleovalleys), faults, and sedimentary joints, playing an important role in the formation of mineral concentrations.

Porosity and permeability are very poor because of the fine grained material, but also because of clogging due to later diagenetic phenomena : carbonation and especially albitization.

The claystone and sandstone are almost totally impermeable. Only the "couche" facies, thanks to its fine bedding, has kept some permeability (4) and allowed for ciculation of the meteoric and compaction water (16).

A post-diagenetic dissolution within the base of the Autunian and the Cambrian developed a karst and cellular dolomite formation where the hydrocarbons are frequently found.

3.5. Oxidation and reduction - Rock colors

The color is essentially linked to the stratigraphy and sedimentology. The red color results from a diagenetic alteration of iron-rich minerals in an oxidizing environment and appears to have been unaffected by the climate (22).

The grey colored layers of sediment of the Lodeve Basin draw their color from two factors : the presence of a sufficient amount of organic matter to preserve their reducing power during the diagenesis, and their comparatively rapid burial, this being the case for the lower levels and certain layers of the Mid-Autunian.

Certain local variations of a later date should be noted : reddening by relief inversion and the seepage of meteoric water in the Mas d'Alary valley ; reddening "per descensum" along the pre-Triassic faults or along the interface of the Triassic upon the Permian (4).

Inversely, certain initially red sediments were later reduced by reducing fluids circulating "per ascensum" along the fractures. These belated oxidations and reductions have not played an important part in uraniferous concentrations, remaining confined to the zones where they were formed.

4. TECTONICS

4.1. The late Hercynian structures

The Lodeve Basin is located in a collapsed zone bordered on the east, south and west by late Hercynian transversal faults linked to a NW-SE compression, while to the north the sediments of the basin overlie in discordance upon Cambrian bedrock. The basin thus appeared at a very early stage as an individual half-graben, and formed a weaker zone favourable to subsidence phenomena. These faults are recurrent from Stephanian to present times, influencing the nature and distribution of sedimentary rocks.

Lastly, deformations during the Saalian and Palatinian phases witness a stress regime in submeridian extension which later influenced all syn- and post-diagenetic structures.

4.1.1. Syn-diagenetic deformation

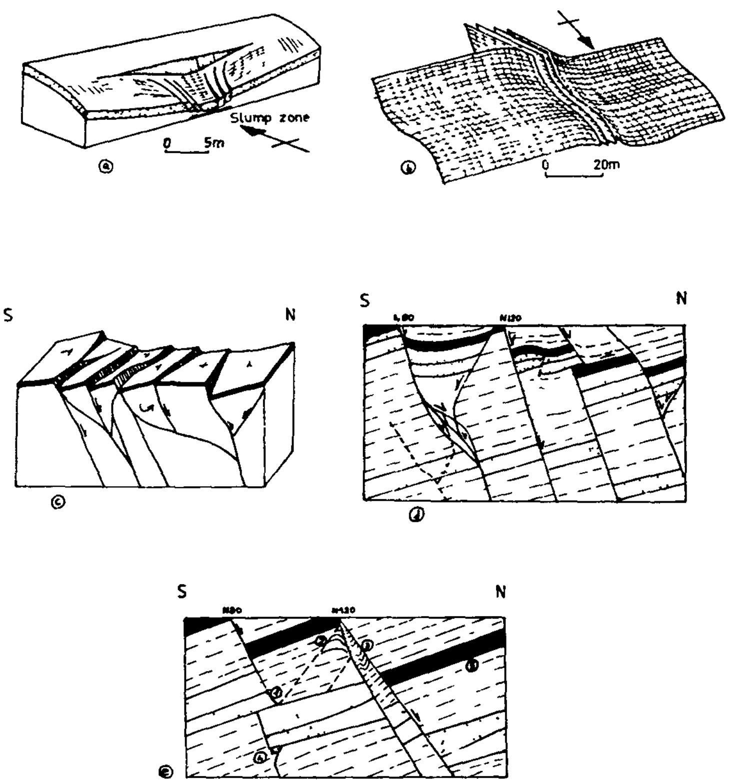
Related to paleorelief, subsidence and differential compaction, syn-diagenetic deformation is characterized by slumping phenomena, bending and stretching of strata, tension joints and packing faults (fig. 5-a) (20).

4.1.2. Late to post diagnetic deformation

This deformation affected already lithified material and is characterized by collapsing and tilting (25) The principal faults are generally orientated N80 to N120, dip north from 45° to 75° and sometimes south 75° to 90° with a normal throw of 10 to 100 m to which is associated a dextral component, and cut the rocks into WSW elongated slivers and blocks. These surfaces, ranging from a few meters to kilometers, are warped in a horizontal and vertical plane. Near these bends and dips the quantity of fractures and thus, the permeability of the rock increase (fig. 5-b) (24).

The normal fault network generated loose wedges and strips with downdropping and often associated with a weak dextral component, downdropping and rotation along an east-west axis, and drowndropping, rotation and downbending along a meridian axis (fig. 5-c) (24).

The kinematics and progressive placement of these different tectonic elements generated recurrent movement of faults and slumps, appearence of folds within certain blocks, presence of prism-like readjustments, and signs of local compression (reverse faults, zig-zag folds) (fig. 5-d).



① Strike slipping of preexistant fault
②③④ Stuffing and folding
⑤ Layer to layer slipping

fig 5 Tectonics

4.2. Late structures

Submeridional compression associated with the Eocene North Pyrenean compression phase modified the principal structures formed during the extension period. It is recognizable by its zig-zag folds, stuffing folds, layer to layer slippage (from the south towards the north) and strike-slip movement along pre-existing faults (26).

The last apparent evidence of large-scale submeridian movement along the basin dates from this epoch. The latest movements may be related to Pliocene to Quaternary basaltic volcanism and associated N-S extension.

5. MINERALIZATIONS

5.1. Characteristics of ore deposits

One may class the Lodeve mineralizations into three types (fig. 6) :
1. "couche" type mineralizations, 2. mineralizations centered upon coupled "couche"/ faults, and 3. mineralizations linked to large fractures.

5.1.1. "Couche" type mineralizations (type 1, fig. 6) :

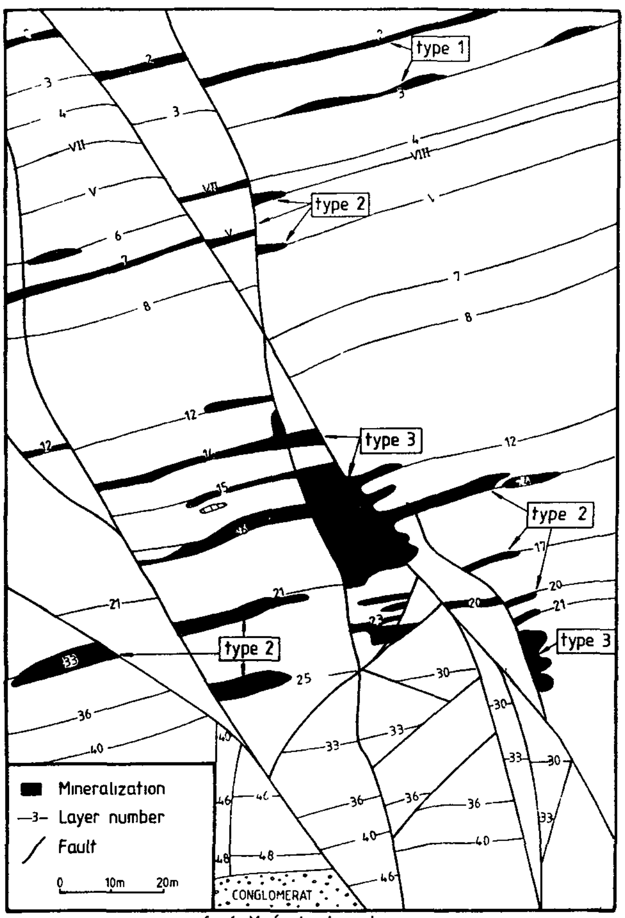


fig 6 Minéralization types

These are contained in alternating organic-rich layers of bitumen and sandstone. The uranium was deposited syn-genetically, then during diagenesis, concentrated through successive accretions. The uranium grade is locally as much as 0.2 % U. This type of mineralization is particularly common in the upper "couches" where the oxidized environment accentuated this phenomenon by liberating most of the available uranium.

5.1.2. Mineralizations centered upon coupled "couche"/faults (type 2, fig. 6) :

This type is characterized by enriched layers close to the faults. These latter form an oil type trap and augment the rock fractures. The uranium grade is extremely variable and may range as high as 1 to 2 % U.

This type of mineralization prevails in most of the Lodeve ore deposits where there is a development of a "wedge and strip" tectonics. This includes most of the smaller shallow ore deposits ranging from hundreds to thousands of tonnes (Les Mares, Mas d'Alary, Tréviels, etc) with an average grade ranging from 0.1 to 0.2 % U, as well as the larger part of the underground ore deposits of the Mas Lavayre.

5.1.3. Mineralizations linked to large fractures (type 3, fig. 6)

Near the larger faults, an intense fracturing develops at all levels with the formation of cataclastic breccia. The bitumens were trapped within the interstices. The uranium mineralization spreads widely beyond the "couches" to form an almost continuous mineralized accumulation over an area ranging from several meters to several tens of meters. Such is the case of the heart of the Mas Lavayre ore deposit which is located at the junction of two large converging faults known as the St Julien and Riviéral faults. The uranium grade can locally attain several percent.

Smaller mineralizations, in association with the bitumen within the fractures, are known to exist in the Saxonian formation (Rabejac) and in the Cambrian dolomites.

Although separated into three categories, these mineralizations are formed by reduction in oil type traps. The uranium is not directly related to the bitumen but they are associated through the reducing environment which the bitumen created.

The essential uranium minerals are pitchblende and coffinite, which are associated with pyrite, sphalerite and galena. Moreover, molybdenum can be found within the upper portion of the Autunian while zirconium may occur in the lower part.

The ore of Mas Lavayre heart totals about 4000 tonnes of uranium at 0.34 % U. The total reserves of the basin, before exploitation, were about 18000 tonnes of uranium at an average grade of 0.22 % U.

5.2. The origin of uranium - Formation of mineral deposits

Two factors combined during sedimentation to form the uranium deposits of the basin : the leaching caused by the desintegration of the Hercynian substratum of the Massif Central producing terrigenous sediments, together with the important contribution by volcanic sediment deposits (apparent or not) throughout the entire series. In the beginning, the presence of sapropelic ooze formed in the basin provoked a syn-sedimentary trapping of uranium (2) (7), creating a preconcentration within the "couches".

At the time of the compaction, due to subsidence and burial, organic matter matured and generated hydrocarbon. These oils migrated along permeable zones consisting of the "couche" facies and the extension zones created by the syn- and post-sedimentary tectonics. The oils are trapped in the most porous rock reservoir, that is to say the fractured and brecciated tectonic zones, as well as the "couche" facies. Some uranium was transported in the form of organo-metallic complexes (27).

The uraniferous fluids contained within the sediments were also expelled (28) and followed the same paths as the oil though slightly shifted (18).

The precipitation of uranium favoured by certain conditions found in the oil traps : open space zones near the faults, a lowering of pressure, and a strong reducing environment.

This phenomenon was further accentuated by a process of concentration through repetitive accretion cycles. These were caused by oxidation-reduction phenomena due to the maturation of organic matter and, in the permeable zones, by fluids squeezed by compaction (connate water) or water that rose along the faults through the bedrock (meteoric water).

These ascending waters, rich in CO_2, were also carriers of important quantities of uranium in solution, originally released by leaching of the bedrock and contributed to the enrichment of the ore deposits (11). Moreover studies of the lead isotopes in the galena of the Autunian stratum confirm that a part of the metals contained in the Autunian originated in Hercynian granitoids from the Massif Central (29).

5.3. Dating

Recent U235-Pb207 dating indicates an age 173 ± 6 My for uranium mineralizations with a slight remobilization at 108 ± 5 My (29). This concurs with previous studies that attributed the mineralization to the Mid-Jurassic. An identical age has been found for the enclosing rock from illite dating in the Saxonian pelites of the Lodeve Basin (30) as well as in the Stephanian-Permian basin of Brousse-Broquies, located 60 km northwest of Lodeve (31). Moreover Mid-Jurassic extension in this area is related to the opening of the Tethys sea (25).

The crystallinity index of illites as well as the presence of associated analcite-quartz (32) indicate a burial metamorphism with temperatures not exceeding 200° (30). The correspondence of dates may be related to a thermo-epirogenic event during which the sediments exceeded 100°C, the temperature at which begins the diffusion of the argon in illites, which defeats the dating system. For the present time, the total loss of any mineralogical record prior to 173 My prevents confirmation by dating methods of any further hypothesis about the formation of uranium.

6. CONCLUSION

The uraniferous ore deposits of the Permian Basin of Lodeve result from the following features.

Fine-grained rocks were confined to lake regimes rich in organic matter ranging from mixed land plants/sapropelite to sapropelite. In addition coarse-grained terrigenous and volcanic detritus with abundant uranium and other metals was deposited. Concurrent tectonics favoured the basin's subsidence and then a later tectonic extension created open zones and oil-type traps. During diagenesis the rocks matured to the point of hydrocarbon generation. The oil migrated and became trapped in stratigraphic and fault reservoirs. Compaction liberated ore-forming fluids that followed the same zones.

Liberated uranium precipitated in the strong reducing environment created by the hydrocarbons. Finally, the meteoric waters from the aquifers enriched the ore deposits through accretion.

Important diagenetic transformations also ocurred in the enclosing sediments causing the disappearance and formation of new constituent minerals.

As shown for other ore deposits (33) the physico-chemical environment of these transformations is fundamental. This is why work is underway to try to integrate the uranium mineralizations in a paragenetic succession, probably multiphased, permitting a better understanding of the mineralizing process.

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GEOLOGIC ENVIRONMENTS OF URANIUM DEPOSITS IN QUATERNARY VOLCANO-SEDIMENTARY BASINS IN CENTRAL ITALY

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Abstract

High U and Th values have been measured in the volcanites belonging to the Roman Comagmatic Province, which consists of a perpotassic magmatic suite. This volcanic province was formed during the Quaternary along the coastal plain between the Tyrrheniam Sea and the Apenninc Range, as extensional tectonic features which were connected by the collapse of the Tyrrhenian Basin.

Continental volcano-sedimentary formations were deposited at the borders of the volcanic belt against the walls of the enclosing graben system and peneconcordant layers of uranium deposits have been detected in the formations. Uranium is disseminated in beds of kaolinezed tuffites associated with iron sulphide.

The genetic interpretation is that the U mobilized from the volcanic rocks and concentrated in the ground water in the volcano-sedimentary basins. Along faults limiting the basins, H_2S exhalation occurred, and the gases, dissolved in the ground waters, caused the precipitation of the uranium. The ore-forming control was due to the structural evolution of the volcano-sedimentary basins and to the hydrodynamic conditions of the ground waters.

1. INTRODUCTION

The Quaternary volcanic province that extends along the coastal plain between the Apenninic Range and the Tyrrheniam Sea has very high uranium and thorium contents. Even the most primitive basanites display several ppm of U, whereas the most evoluted trachy-phonolites attain mean values of 50 ppm U. The petrochemistry of the province is perpotassic with a very characteristic positive anomaly in the concentration of incompatible elements. The clastic, volcanogenic continental sediments that accumulated laterally to the volcanic belt contain uranium reconcentrations in the form of supergenic stratiform deposits.

The alkaline volcanic belt is considered as an uraniferous province because of the high uranium concentration in the volcanites and the existence of uraniferous deposits. This province is very young and still in evolution, both in volcanic and in metallogenic processes. It has therefore been considered as a suitable test area for studying the origin of uraniferous provinces associated with alkaline rocks.

The Appenninic perpotassic volcanic province represents partial melts of the mantle, and its high content in incompatbile elements is due to particular processes of mantle metasomatism. The geologic evolution of the area enclosing this volcanic belt (Tyrrheniam Basin and Apennines) was connected to the evolution of a mantle-dome. In order to make a proper description of the geologic environment of this uraniferous province, the regional evolution is outlined first, and then the evolution of the areas connected with the uraniferous mineralizations is outlined. In doing so, I present some information about the control of primary processes of uranium concentration in the Earth's crust and the control of secondary reconcentration processes.

2. REGIONAL GEOLOGIC EVOLUTION

The Quaternary volcanic belt was emplaced upon, sedimentary formations which were subjected to compressional tectonics during most of Miocene time, and to extensional tectonics from Messiniam time to the present (fig.I).

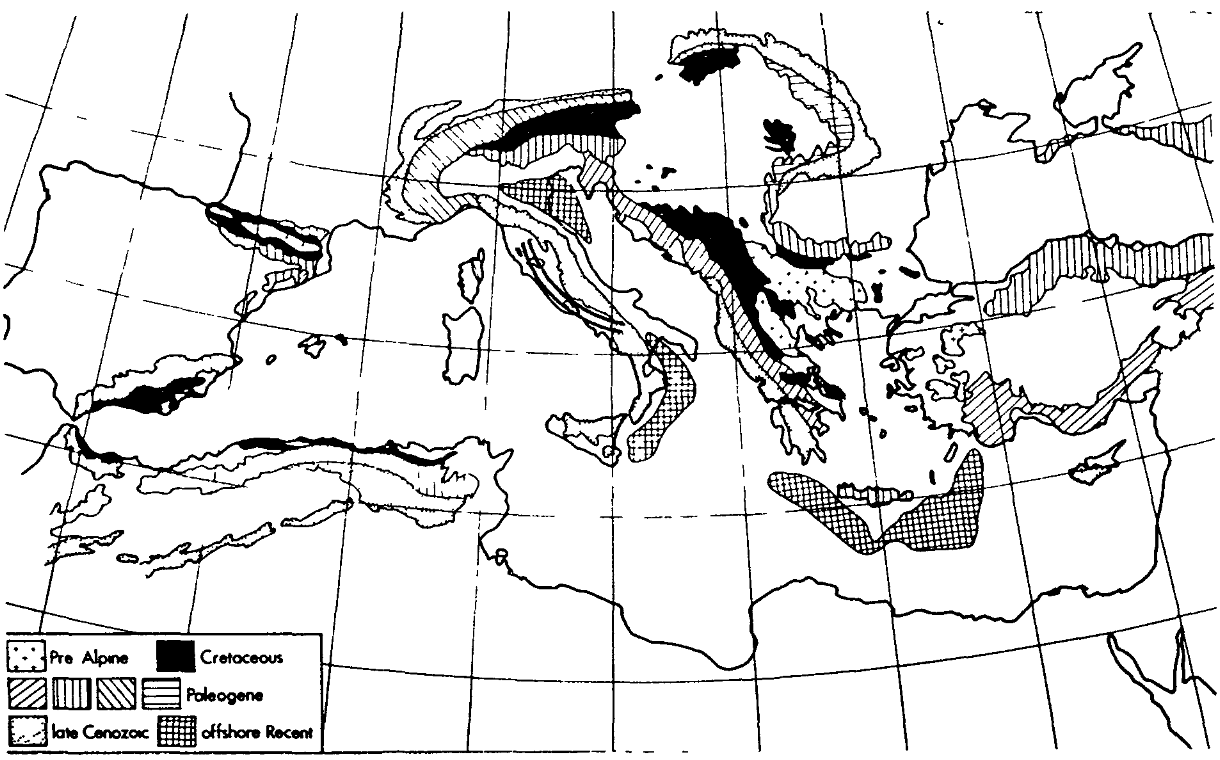

Fig. I. Distribution and approximate age of folding in the Alpine system (from (I), modified). The Apenninc Quaternary perpotassic belt is represented by the double line.

This Neogene-Quaternary tectonic phase was a later one in respect to the well known Upper Cretaceous-Eocene "Alpine" phase, that is interpreted as a result of collision between the African and the

Euroasiatic plates. From Oligocene on, no important relative movements between the two plates were recorded (2), and instead of horizontal movements, vertical movements of the mantle set in. Mantle-domes rose in several areas, and basins formed in correspondence of the mantle uplifts with oceanization of the former orogenetic crust. This was the main cause of the origin of part of the Mediterranean Basin (3, 4), which formed inside the Alpine orogenetic system during the Neogenic phase of mainly vertical tectonics.

There were several distinct mantle uplifts in the Western and Central Mediterranean (4). Between the mantle domes, the sectors with normal lithospheric thickness underwent counterclockwise rotation. This kind of tectonics controlled the last part of the Apennines evolution and the formation of the Tyrrhenian Basin. Rotational tectonics was preceeded by rifting and grabening in the Tyrrhenian area about 10 Ma ago, and both are still going on.

The present setting of crust-upper mantle-asthenosphere boundary, as measured by geophysicists, is represented in fig. 2.

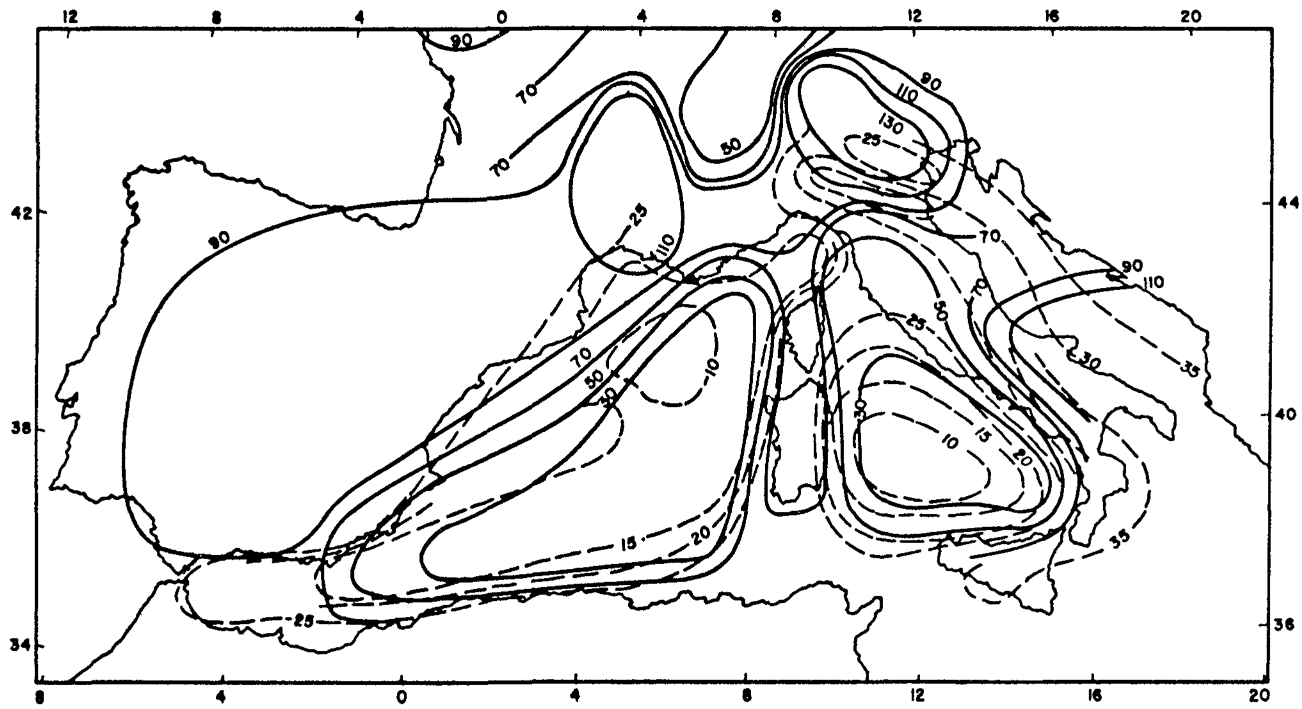

Fig. 2. Lithospheric (solid line) and crustal (broken line) tickness in Western-Central Mediterranean area (from (5)).

The cause of mantle uplifts inside an orogenic region are important. From the compositions of the mantle derived magmas it is known that some mantle regions in the Tyrrhenian are have been enriched in incompatible elements by fluids of deep origin and metasomatic products (6). The addition of heat and matter through fluids rising from dephth may account for the volume increase of the upper astenosphere and for its doming (7).

This origin of these mantle fluids (mostly hypercritic solutions of H_2O and CO_2) is still debated. They could have been derived from Earth's degassing processes, which are the very causes of the volcanism. If one consider that the normal Earth's degassing was inhibited in the Alpine Range by lithospheric plate collisions that lasted about 100 Ma, it becomes evident that some reaction was to be expected when the compressional regimes finished. The mantle should have reached an isostatic equilibrium according to the new tectonic conditions, and expecially the most volatile mantle components, which are the watery, CO_2 saturated fluids. On the other hand, one cannot deny subduction on deepening of the lithosphere during the Alpine orogenesis. The fluids could have represented the dehydration products of the lithosphere in the deep mantle. Whatever their origin, the important mineralogenetic principle is that fluids during their ascent into the mantle are able to bring into solution those elements that for their large ionic size and strong electric charge are not strictly linked to the crystal lattices. These elements are incompatible ones, such as U, Th and LREE, that are so highly enriched in the mantle-derived magmas of the Apennines.

The perpotassic volcanic belt formed about I Ma ago after the beginning of the collapse of the Tyrrhenian Basin and developed successively through volcanic pulses that correspond to pulses of extensional tectonics in the Tyrrhenian (3). New arcuate extensional fault systems formed on the western continental slope of the Apennines, and along the Apennines perpotassic volcanism occurred (fig. 3). This volcanism represented the most volatile rich and fluid part of the melts that accumulated on top of the metasomatized mantle dome and successively drained along the new extensional features (6). From that period on, magmas were continuously supplied to the surface.

In conclusion, the geodynamic factors which controlled the genesis of the highly uraniferous melts were:

- Mantle uplifts in an orogenic area after the major compressional phases;
- Supply of hypercritical watery, CO_2-saturated fluids of mantle origin, addition of heat and incompatible elements to the upper asthenosphere, enhancement of the mantle doming and the partial melting of the metasomatized mantle;
- Accumulation of fluids caused a density drop in the upper layer of the astenosphere and consequent differential movements of the more fluidized part (tectonics of subcrustal transfer);
- Plastic flow in the upper astenospheric domes involved the overlying lithosphere, which resulted in the tectonic denudation of lithosphere on top of the asthenospheric dome and lithospheric accumulation on its flanks, which gave origin to the Apenninic Range.
- In the areas of tectonic denudation, tholeiitic volcanism occurred accompanied by extensional tectonics, while in the zones corresponding to the front of the asthenospheric flowing mass the volcanics which were erupted are perpotassic and uranium-rich.

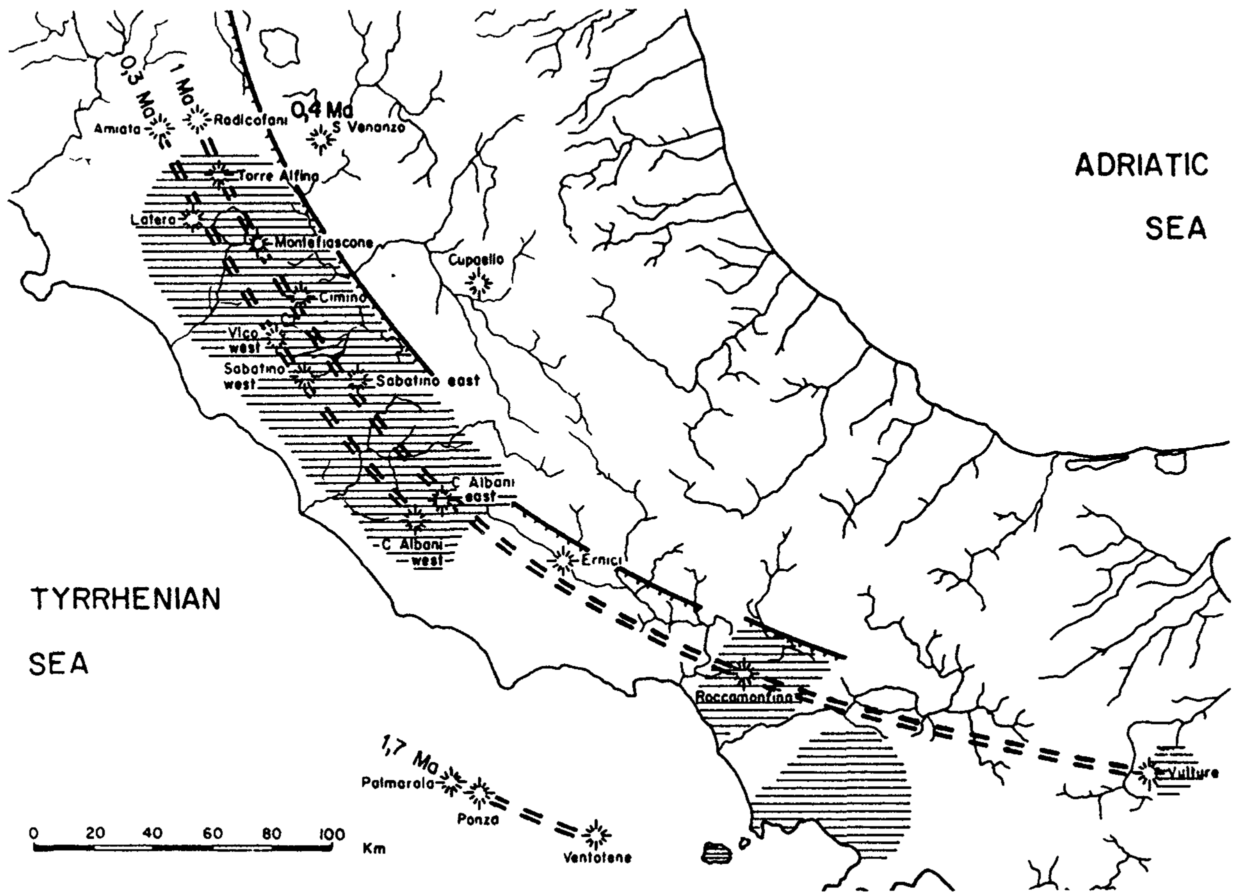

Fig. 3. Central volcanoes with similar age of initial eruptions are located along arcs which are elongated according to the new extensional features. The oroghaphy of this sector of the Peninsula has been impressed during this volcano-tectonic phase. Main volcanic areas are dashed (From (3)).

3. LOCAL GEOLOGICAL EVOLUTION

The perpotassic volcanic belt is composed of several volcanic groups but only the northernmost and the southernmost of which have been investigated for uranium reconcentrations. These groups have been selected for uranium exploration because they showed the best development of volcano-sedimentary basins around them. The idea, actually, was the explore the basins that could collect the uranium mobilized from the uraniferous volcanic rocks. In both groups supergenic uranium reconcentrations have been detected. The northermost group, corresponding to the Vulsini volcanoes, where most of the exploration work has been performed, will be described here.

Beginning from Messiniam times, with a maximum during Pliocene, a series of very elongate basins formed on the folded, allochtonous terrains along the western side of the Apenninc Range (fig. 4).

These basins are roughly parallel, but in places intersect the previously compressional structures. Marine clays fill the depressions, which total about 1.000 m in thickness. These negative fan-shaped forms, which occur in the Northern Apennine, are believed to represent crustal stretching in consequence of the northeastward oriented subcrustal mass transfer.

During Middle-Upper Pliocene, the western sector of this horst-graben-like structure uplifted long a coastal belt from Southern Tuscany to Northern Latium ("Etruscan swell") and corresponds to a volcano-tectonic horst. Along this belt intrusive-effusive activity of acidic crustal anatectic magmas occurred in Upper Pliocene.

During the Quaternary, a graben structure formed east of the "Etruscan swell", cutting the Pliocenic sediments, and in this new graben the perpotassic volcanic groups of Vulsini, Vico and Sabatini were formed. The external outlines of the graben stretch parallel to the structures of the former Pliocene basin (NW-SE). Superficial expressions of these new graben systems are calderas and volcano-tectonic depressions (like the Bolsena structure).

The volcanoes are very flat because they developed during subsidence. The buried morphology is, on the contrary, very steep according to the step-like collapse structures. The volcanic pile reaches 1.000 m thickness in the central parts and diminishes at the edges, with a shape of an inverted cone. The eastern and the southern parts of the Vulsini volcanic group represent an exception to this morphology because of thick volcano-sedimentary accumulations against the faults bordering the graben. These faults are cut mustly into Plio-Pleistocene clays and into Mesozoic-Eocene flysch which behave as impervious formations.

So, in general, it can be said that volcanism developed in a subsiding through composed of impervious rock series. The negative movements first developed as a consequence of regional crustal stretching, more recently as collapse zone related to the foundering of the Tyrrhenian Basin, and finally as volcano-tectonic grabens.

Before the volcanic activity the area was subjected to uplift during Lower Pleistocene (even more that 1.000 m) along the Apennine direction and the successive graben-in-the-graben formation occurred very rapidly in the same belt, but was controlled by transverse NE-SW directed strike-slip faults. The volcanic activity lasted until some tens of thousand years ago, and afterwards the area was subjected to uplift. This unusual feature is probably due to a post-magmatic geothermal system.

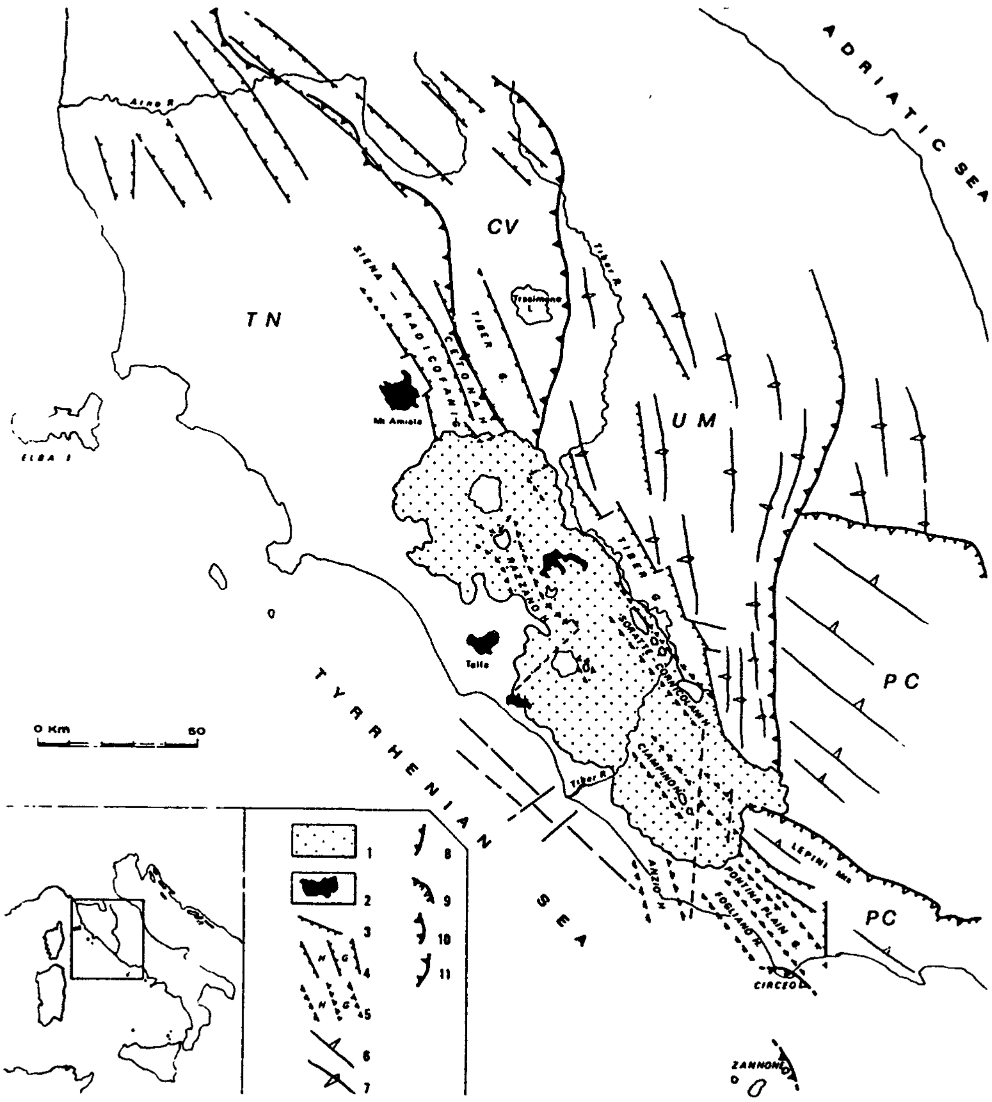

Fig. 4. Main regional tectonic lines of Central Italy (from (8)).
I: Latiam perpotassic volcanics (Pleistocene). 2: Acid volcanics (Upper Pliocene-Pleistocene). 3: Normal faults (dashes indicate the downthrown side). 4: Graben (G) and Horst (H) (Pliocene-Pleistocene). 5: idem, beneath the volcanic cover. 6: Norhteastward-dipping monoclines of the Panormide Complex. 7: Fold axes generally overturned east-or northeastward. 8: Overthrust of the Umbria-Marche-Sabina Complex. 9: Fronts of the Panormide Complex (Uppermost Miocene). 10: Front of the Cervarola napple (Middle Miocene). II: Front of the Tuscan nappe (Middle Miocene).
PC = PANORMIDE COMPLEX (Carbonatic shelf sequences).
UM = UMBRIA-MARCHE-SABINA BASIC COMPLEX (Pelagic sequence).
TN = TUSCAN NAPPE
CV = Mt. CERVAROLA NAPPE.

4. THE VOLCANISM

The volcanism which occur in the uraniferous volcano-sedimentary basin belong mostly to the potassic "Meditteranean" magmatic suite. It has to be noted, however, that just before the beginning of this phase of mantle-derived volcanic activity, a volcano of crustal anatectic, "Tuscan" type (Cimino volcano) erupted between the Vulsini and the Vico groups (fig. 5).

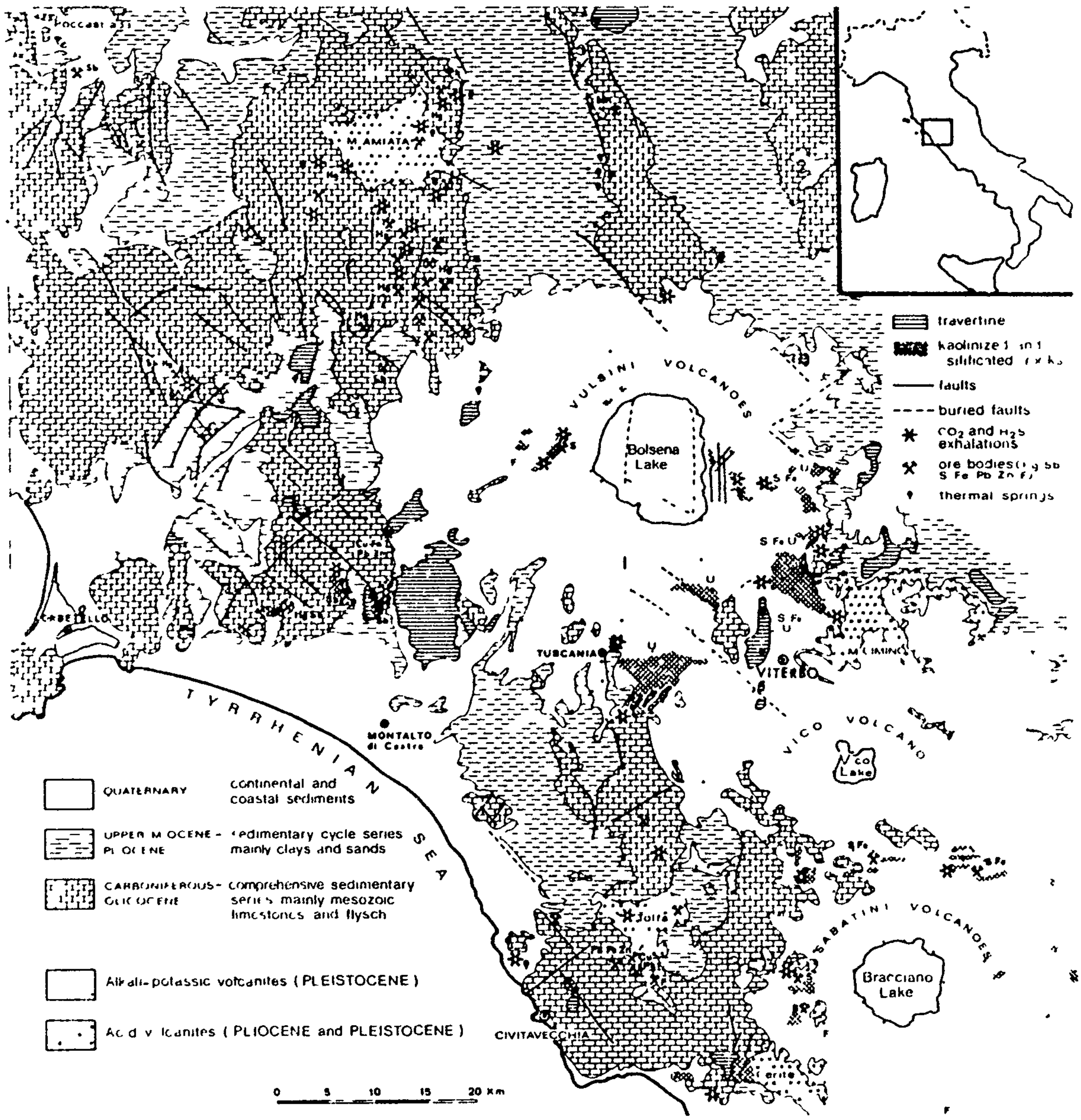

Fig. 5. Geological map of the mineralized area (from (9)).

The Cimino volcano shows an uncommon magmatic evolution from acidic anatectic products to final potassic olivine-latitic melts, which are very similar to the "Mediterranean" suite. This volcano is believed to have been derived from partial melting of the crust due to the upward migration of the geotherms accompanying the uplift of the mantle-derived magmas.

In the Vulsini group the volcanism began about I ma ago, and the most ancient deposits are represented by epivolcanites derived by erosion of a primordial volcanic center. The epivolcanites accumulated in an eastern area of the Vulsini group where basins were subsiding rapidly. The volcanism shifted in time towards the west, and this shifting was accompanied by structural adjustment. About 0,4 Ma ago the area of volcano-clastic accumulation began to uplift, while the area which fed the basins (corresponding in part to the present Bolsena Lake area) began to sink. These differential movements were marked by fissial eruptions of lavas and pyroclastic flows. About 0,3 Ma ago the volcanism shifted further to the west and formed the big Latera central volcano. About 0,1 Ma ago a very strong extensional tectonic phase effected the whole volcanic region, and this phase was characterized by very widespread phreatomagmatic volcanic activity.

The majority of the primary volcanic products are represetend by lava flows, pyroclastic flows and cinder cones.

5. THE VOLCANO-SEDIMENTARY BASINS

Epivolcanic debris and lacustrine sediments alternative with primary volcanic rocks through a thickness of 50-150 m against walls formed by step faults that bound the volcanic area.

The depositional environments were always lacustrine and fluviatile. The succession of reworked tuffs, diatomitic beds, paleosoils was often interrupted by the volcanic formations that filled the basin, such as fluid lava flows, pyroclastic flows, air-fall ashes, lapilli and pumice. The reworked tuffs are composed mainly by unconsolidated material of more or less sandy and pumiceous ground mass. The series is generally pervious, the less pervious strata are represented by diatomitic beds, ash layers and compact lava flows.

These basins developed for about 50 km to the east and south-east of the volcanic group, and have a mean width of 5 km. In the innermost parts of the primary volcanics, the basins loose their sedimentary character. This system, described as a whole, is composed by several basins which are connected by zones of less thick sedimentary series.

The volcanoclastic and diatomitic sediments crop out very rarely because they are covered by ignimbritic and lava sheets. These sheets were erupted from fissures at the end of the subsiding phase of the basin, and a relief inversion occurred. The volcanic cover extends over the step-fault system limiting the graben, masks in part the tectonic structure, and contributes to the flat morphology of the volcanoes.

6. MAGMATIC COMPOSITION AND URANIUM DISTRIBUTION

As usual in highly potassic provinces elsewhere in the world, the range of chemical composition is very large. From the series near to the saturation in silica, or even slightly oversatured, the rock change to a leucititic series, or sometimes the series tends to be the carbonatitic one. The quantitatively more represented petrographic association are: the basanite-tephrite-phonolite and the olivine basalt-latite-trachyte to quartz trachyte.

In general, the uranium content increases in the more alkaline suites. But even the less evolved of the low-alkaline association have anomalous uranium contents with respect to other known potassic series and even with respect to the similar suites in other parts of the same volcanic belt. From initial values of 5-10 ppm U, values of about 20-50 ppm U are reached through crystal fractionation, which corresponds to a normal fourfold increase in the differentiation series.

What is abnormal is that very commonly the degree of uranium enrichment does not reflect the degree of magmatic differentiation. For istance the mean uranium value of the most represented rock type (trachyphonolite) in the volcanic groups north of Rome is 27 ppm U. Formations that are similar, in chemical and mineralogical composition and from the same volcano show a bimodality in uranium distribution, with a peak of 27 ppm and another peak of 55 ppm (fig.6). Furthermore, similar thrachyphonolites of other volcanic groups, such as the Flegrean Fields in Campania, contain much lower uranium values (about 17 ppm for the Campanian ignimbrite).

The different magmatic series, essentially silica undersatured and enriched in incompatible elements, could correspond to different degrees of partial melting of mantle regions, which have been previously more or less intensely metasomatized. This accounts for part of the uranium enrichment of the rocks. Actually, in order to explain why volcanic products that are similar and from the same vent have different uranium contents, of why similar volcanic products vary in their uranium content relative to their geographic position, some additional mechanism or uranium enrichment should be considered.

There are indications that U, Ra, Th, Sb, Pb and radiogenic Sr can be added not only to the mantle regions that deliver the magma, but also to magma already stored in the upper crust. These elements were transported in a very mobile fluid phase. This supply was variable in time (from the same volcano, similar products have different uranium contents) and selectively distributed in space (variation of uranium content in similar products belonging to different volcanic groups). Evidence of the activity of these fluids come from radiometric analyses of historical sample of the Vesuvius (11). The lava erupts with a Ra content which, instead of measuring around zero, is ten time the value of that when in equilibrium. Ra, Th and U were added to the magma from mantle fluids just before the eruption, as demonstrated by these radioactive elements isotopic equilibria measured on mantle material from the 1944 eruption of Vesuvius. The mantle region from which the fluids came is much larger than the one that delivered the magma. An other indication comes from the series of the Volcano Cimino (12). The crustal anatectic rocks, whose major elements composition is so different from the one of the mantle-derived olivine latites that erupted during the late stages, have on the contrary similar contents of the incompatible trace elements. This is probably because the anatexis was enhanced by the same mantle metasomatic fluids, carrying incompatible elements in solution, that provoked the partial melting in the mantle.

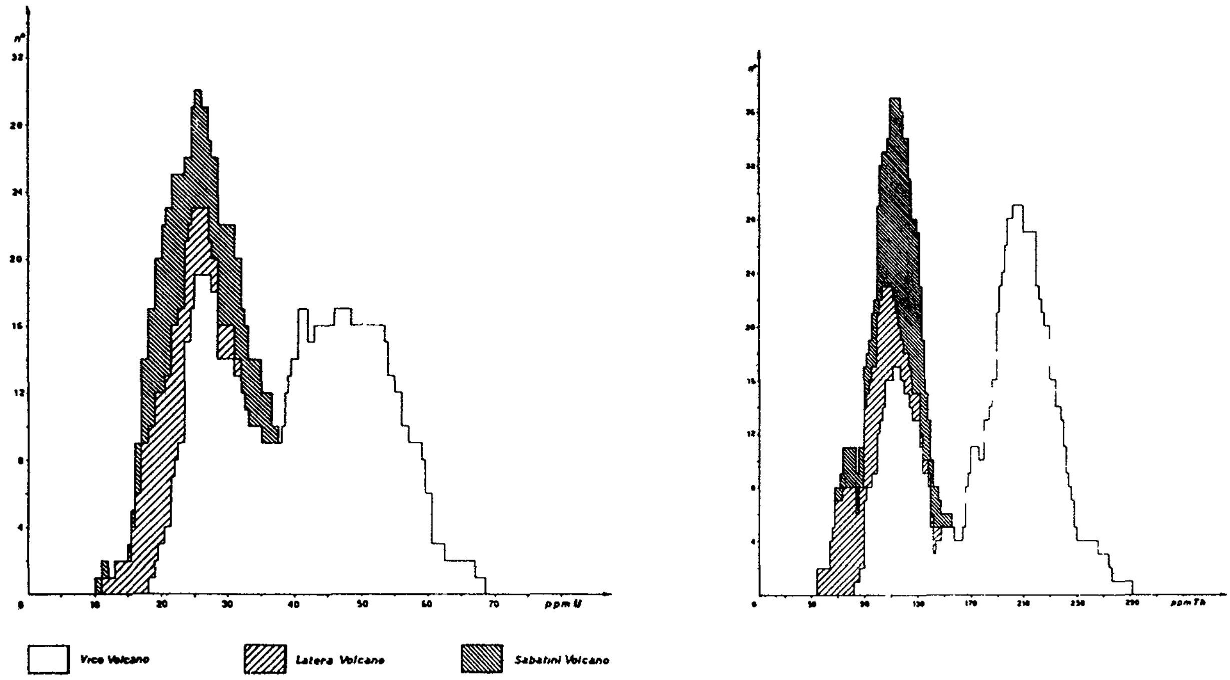

Fig. 6. Distribution of U and Th in the trachyphonolitic ignimbrites (from (10)).

7. REGIONAL MINERALIZATIONS

In the subject volcanic belt there are three main mineralogenetic associations:

- pitchblende and marcasite (restricted to the alkaline volcanic belt)
- fluorite with minor barite, calcite and marcasite (in the alkaline volcanic belt and in flysch associated with Pliocene magmatism of crustal anatectic origin, which border the alkaline volcanics to the west)
- cinnabar and stibnite (even more peripheral to the alkaline belt, only on the western side, apparently associated with Quaternary effusives of crustal anatectic origin).

To be noted that the cinnabar mineralizations represent one of the largest in Europe, and that the fluorite deposits are one of the largest in the world.

Uranium oxides and marcasite, as discussed in the next paragraph, are of supergene origin. Fluorite, barite and calcite were transported in a hydrothermal solution and precipitated in lacustrine sediments, in veins in the sedimentary basement, or as impregnations in alkaline volcanic pipes. Cinnabar an stibnite were mostly precipitated at the contact between flysch formation and the Pliocene marine cover rocks, as well as inside the acidic volcanites.

The distribution of this mineralogenetic association is rather selective:
uranium in the western hemisphere of the Vulsini volcanoes, fluorine on the eastern hemisphere, cinnabar-stibnite in the sedimentary horst limted to the west by the main graben infilled with tha alkalic volcanoes (fig.5).

Nevertheless , there should be a genetic link between the different kinds of regional mineralizations because:

- they always occur in association with CO_2 and H_2S exhalations
- isotopic analyses of sulphur give the same values whatever the geological and structural situation, or distance from the alkalic or crustal anatectic magmatic bodies.
- Hg, Sb, Ba, U which form economic deposits are anomalously concentrated in the alkaline volcanic rocks.
- Travertinization and CO_2 + H_2S exhalations is widespread and very common in all of the region, independent of the kind of volcanism and structural setting.
- In the same region, from the Tyrrhenian coast to the Tiber Valley, strong positive heat-flow anomalies esist, whose distribution was controlled by major tectonic features rather then by the distribution of magmatic bodies.

These tectonic features are the extensional ones which formed in Pleistocene time as a consequence of the collapse of the Tyrrhenian Basin. On the same tectonic lines magmas of crustal anatexis and of mantle partial melting were emplaced. The geothermal anomalies and the mineralizations were part of the first-order geodynamic process which, during Neogene-Quaternary times, controlled the evolution of the Tyrrhenian Basin and of the Apennines.

The mantle degassing processes, which were responsible of mantle metasomatism, uplifts and of the particular magmatic composition played an apparent role even in the kind of mineralizations and on the heat-flow anomaly distribution.

8. THE URANIUM MINERALIZATIONS

Inside the volcano-sedimentary series uranium occurs as oxides disseminated into peneconcordant layers of kaolinized and iron-sulfide impregnated rocks (fig. 7).

In the mineralized areas some cold gas exhalations of CO_2 with minor H_2S occur, bur fossil traces of such manifestations (silification) are very common. In association with uranium and iron only vanadium is contained in anomalous concentration: carnotite is a common secondary mineral in the area. No minerals indicating a higher temperature of formation have been detected.

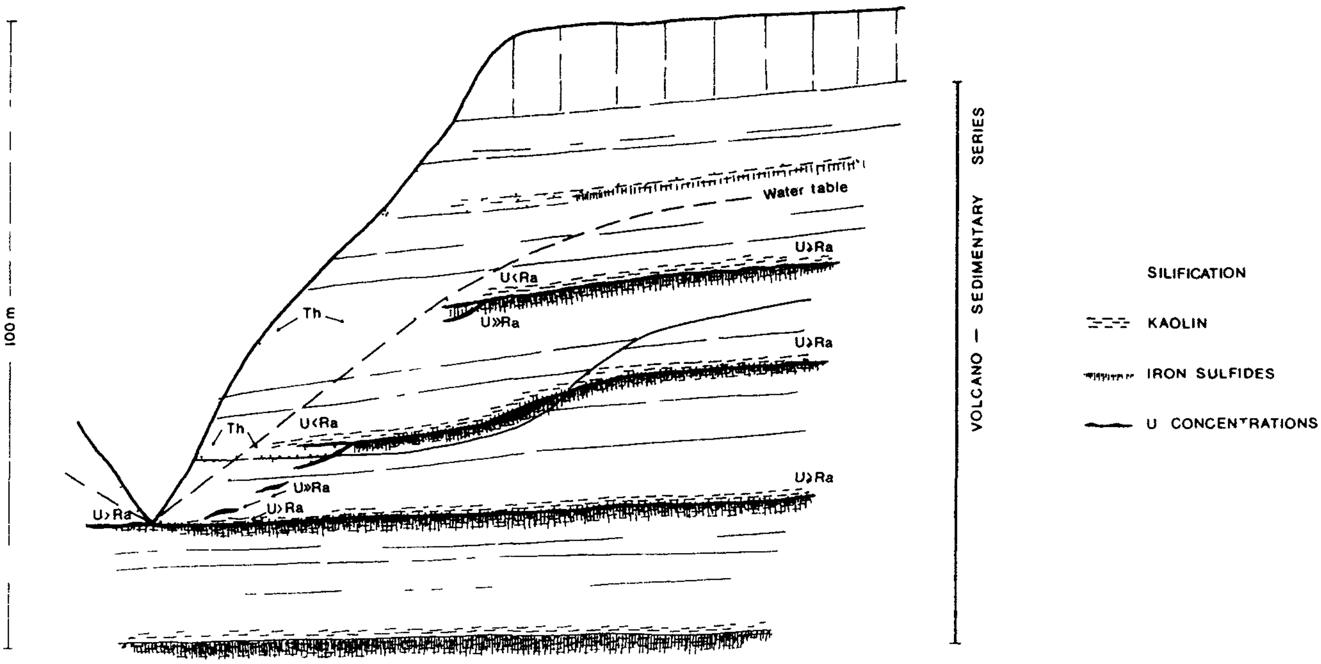

Fig. 7. Section of the volcano-sedimentary formation and composition of the uraniferous beds (from (13)).

Uranium mineralizations are mostly concentrated in the areas of convergence of the faults systems which border the basin (fig. 8). The same areas correspond to the maximum erosion of the basin wall and form the thresholds of the aquifer. It is interesting to note that the uraniferous beds lie up to a few meters higher than the level of the local groundwater thresholds, and that the succession of uraniferous layers is always contained in the mobile part of the present groundwater system. Furthermore, the attitude of the mineralized beds follows an hydrostatic level and not a stratigraphic horizon. The presence of uranium deposits is therefore clearly related to the distribution of the present aquifer.

In correspondence of the principal thresholds of the aquifer the uranium mineralizations extend rather regurarly on some square km. The most regular mineralizations (from 30 to 100 cm thick with a grade from 300 to 600 ppm U) correspond to the present water table level.

The water table level of the aquifer contained in the volcano-sedimentary series is lowering from north (420 m) to south (260 m). In the same direction the grade of the mineralization increase until values of more the 0.1% on levels of 5 m are reached.

This can be interpreted as if the quantity of uranium deposited would be proportional to the quantity of ground water which passed through. The traps are given by the tectonic horsts bounding the basin, through which CO_2 and H_2S exhalations occurred.

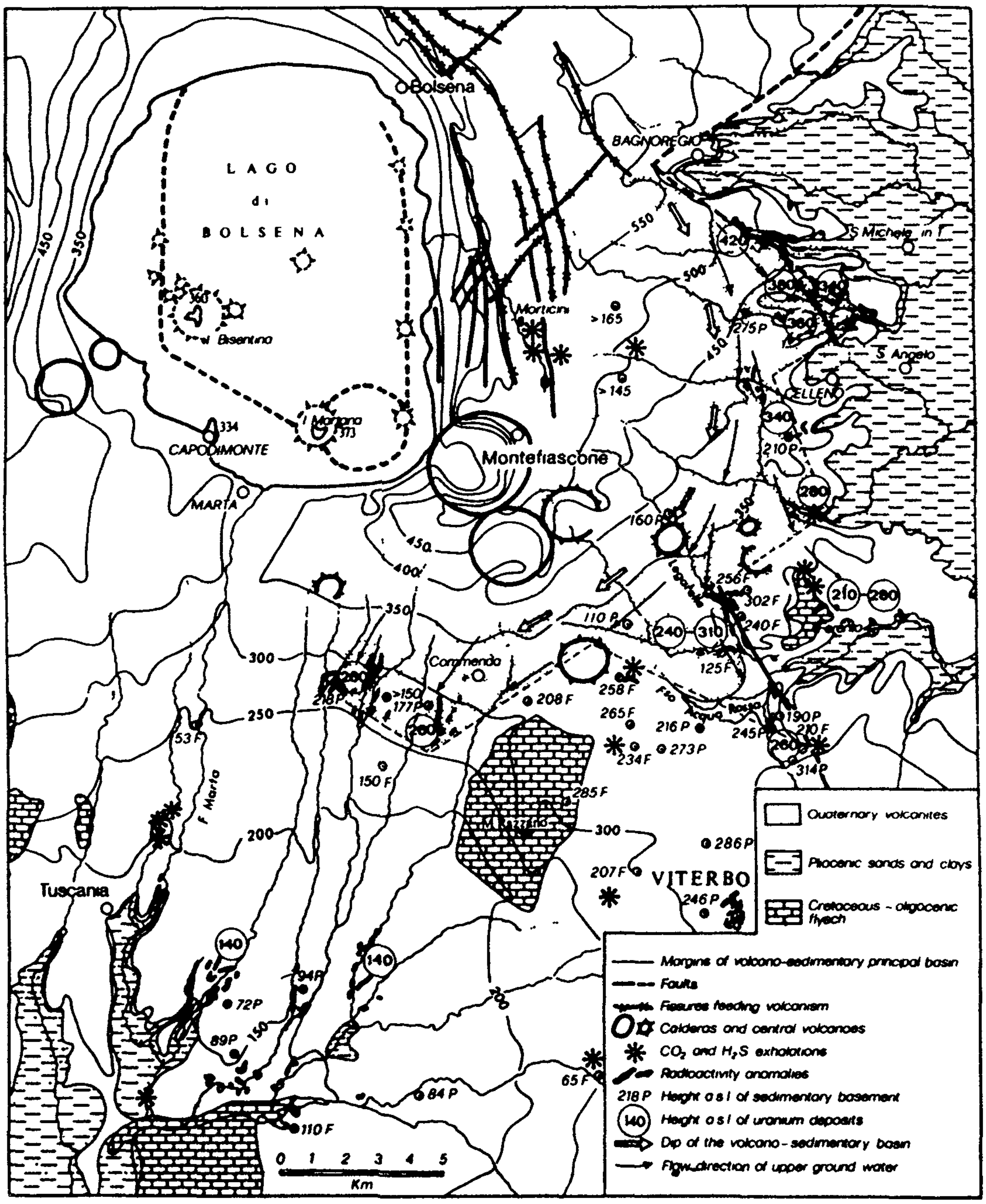

Fig. 8. The volcano-sedimentary basin (stippled area) in the Vulsini Volcanoes (from (9)).

These gases are percolating the ground water, and it is self explanatory that in the oxygenated upper part of the aquifer, oxidation of sulphur causes pH and Eh variations that induce iron to precipitate as marcasite and uranium to precipitate as oxide. In the same oxidation zone of the water table, the oxidation products of H_2S alters the host rock into kaolinic products (metahalloysite). This mechanism explains the observed concurrence of uranium oxide and marcasite disseminations in kaolinized beds.

The area is presently undergoing uplift, and the succession in the volcano-sedimentary series of several mineralized beds corresponds to several stages of water table equilibria.

The uplift is not a steady process but a pulsatory one, and the phases of quiescence were long enough to trigger the formation of regular mineralizations at the water table level. A successive uplift brings this level into the oxidation zone; sulfuric acid liberated from the marcasite leaches the rock, tranforming it in residual silica with some alumina. Uranium is transported per descensum and reprecipitated in the new water table level. Radioactive disequilibria, marked by Ra excess in the upper levels and Ra deficency in the lowest ones, are coherent with the proposed mechanism. An other demonstration comes from the uranium content in waters. The normal uranium content of several ppb falls to less than one ppb in the uraniferous basin where, actually, precipitation of uranium occurs.

The source of uranium has never been considered to be a problem, because the mineralization is distributed in an environment of very uraniferous volcanic rocks. Devitrification and alteration processes should supply to the ground water the quantity of uranium that we find concentrated in the supergenic layers. The most important uranium mobilization process seem to have been the zeolitization of the volcanic glass. Some ignimbritic formations, representing several cubic km of magma, lost 30% of their uranium content during complete zeolitization and mobilized about 20,000 t U/km^3.

Conclusion

Deep mantle degassing processes enhance mantle domings, rifting, and the formation of uraniferous magmas. The mantle derived fluids were mostly represented by hypercritic water and CO_2 (with minor H_2S) keeping in solution high charge and large ion elements ("incompatible" elements like U, Th, K, Ba, Sb, F, etc.). These elements were therefore highly concentrated in the mantle-derived melts.

The magmatic activity developed in grabens during their subsidence. Volcano-sedimentary basins formed laterally to the volcanic edifices and against the tectonic walls which border the graben. In these continental, clastic sediments, stratiform layers of uraniferous deposits alternates with barren rocks.

The formation of the uraniferous levels corresponded to the evolution of the ground water system during the recent uplifting of the area. Mineralizations were controlled by CO_2 + H_2S exhalating from the tectonic blocks which dammed the basins. On the oxigenated water table the reactions leading to the kaolinization of the host rock, and to the precipitation of iron sulfide and of uranium oxides occurred. Only the mobile part of the ground water gave mineralizations of some economic interest.

The fact that in a relatively short time (some 100.000 years) about 10,000 tons of uranium have been precipitated is related to the structural situation of the basins and with the high uranium content of the volcanics. The basins were closed by clayey, impervious basement rocks, and in the same areas H_2S acted as an efficient precipitant.

In the same province, besides U, other mineralizations occurred of other elements (F, Ba, Hg, Sb) whose concentration characterize this alkaline magmatism.

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GENETIC CHARACTERISTICS OF THE URANIUM DEPOSIT ŽIROVSKI VRH, YUGOSLAVIA

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Abstract

Pseudomorphs of pitchblende and coffinite after plant remains, a wide range of $\delta^{34}S$ values, and enrichment of sulfide sulfur with light isotope indicate formation during diagenesis of the uranium deposit Žirovski vrh in the reducing environment of Gröden sandstones.

Due to subsidence from Upper Permian to Cretaceous the deposit was buried 6000 m deep. Dissolution and precipitation of minerals occurred during epigenesis at higher temperatures. In the orebearing horizon rock minerals and sulfides were remobilized, but not pitchblende and coffinite.

Movements of the Miocene Rhodanian orogenic phase, to which the beginning of retrograde epigenesis is attached, uplifted the orebearing beds close to the surface and overthrusted them on autochthonous Triassic. Then formed the folded structure of the deposit cleavage and most of quartz-carbonate veins and nests. In the orebearing horizon during the retrograde epigenesis sulfides and barren minerals were intensively remobilized, and les pitchblende and coffinite.

By oxydation processes in the upper parts of the deposit started precipitation of cementation copper minerals and secondary uranium minerals.

GEOGRAPHICAL CHARACTERISTICS

The uranium deposit Žirovski vrh is situated about 30 km west of Ljubljana. It lies in the NE part of the Žirovski vrh hill which is a neotectonical block. The block is cut by numerous faults into smaller blocks (1).

GEOLOGY OF THE DEPOSIT

In the area of the deposit outcrop Carboniferous, Permian and Triassic beds. The north and west part of the region which belongs to the geotectonic unit of Sava folds consists of Upper Triassic beds on which lie overthrusted older Carboniferous and Permian beds (2).

Uranium ore occurs in Gröden sedimentary beds of the Middle Permian age. These beds which consist mostly of sandstones and less of siltstones and conglomerates were deposited on the area of black argillaceous slate of Carboniferous-Permian age. Sedimentological studies revealed the existence of an angular erosion unconformity between the Carboniferous-Permian slate and the Gröden beds. A detailed description of the deposit and its geological structure with corresponding geologic sections is given in an earlier paper (3).

The Gröden clastic beds of Žirovski vrh are of fluvial origin, according to opinions of most geologists. They are reported to be deposits of fluvial environments (braided, meandering rivers, deltas) with corresponding subenvironments (playa lakes, swamps). They were deposited in a warm semiarid to arid climate of the Permian alpine-dinaridic region.

In the immediate surroundings of the deposition area of Gröden beds existed the sea, as indicated by outcrops of Permian neoschwagerina limestones, a temporal equivalent of the Gröden clastic beds, in the surroundings of Bled and Bohinjska Bela, some 30 km to the north.

The Gröden beds attain at Žirovski vrh 900 m (4). Of the total thickness, 200 to 300 m belongs to the uraniferous gray series in the lower part of the column. The upper part consists of the red series measuring 300 to 550 m. The ore bearing horizon is about 100 m thick, and it is situated about 230 m above the Carboniferous-Permian bedrock (5).

Sedimentological studies by Pečnik, Budkovič and Skaberne showed that in the deposition area of the Gröden beds the fluvial environment changed periodically, which resulted into rhythmical deposition and periodical formation of reducing and oxidation environments. Deposits of the gray series with uranium ore were deposited mostly in river beds, but also in lakes and even in swamps, where reducing environments prevailed. Deposits of the red series were mostly deposited on flood plains and show indications of highly oxidizing environments which prevailed after the retirement of the river into its beds. The color of the Gröden beds was influenced also by physico-chemical processes during the diagenesis, epigenesis and retrograde epigenesis.

After the deposition of Gröden beds the major part of the Slovenian territory has been invaded by a transgression. During the entire Upper Permian prevailed deposition on a shallow shelf of the renewed Tethys geosyncline. It continued during the entire Scythian stage of the Lower Triassic.

TECTONIC STRUCTURE OF THE DEPOSIT

Tectonic setting for the area surrounding Žirovski vrh has been best explained by Mlakar (6) and Placer (7). According to them, the Žirovski vrh deposit is situated in the Žiri - Trnovo nappe which is the largest tectonic unit of the Idrija - Žiri territory and the Trnovski gozd high plateau. From the fact that the mineralized Gröden sandstones and the underlying Carboniferous - Permian beds belong to the Žiri - Trnovo nappe whose transport during overthrusting has been estimated by Mlakar (6) at 25 to 35 km, it follows that the U deposit originally was not situated in the present area.

The structure of the deposit and distribution of ore bodies in space have been considerably influenced by Tertiary tectonic phases. The deposit which was submerged during geologic history to more than 6000 m was overlain by Triassic, Jurassic and Cretaceous beds. During the paroxysm of the Alpidic orogeny, probably towards the end of Miocene, orogenic forces of the Rhodanian phase, to which the 1st stage of retrograde epigenesis may be attached according to Drovenik and others (8), uplifted to near surface the beds containing several Slovenian deposits, among others also Žirovski vrh. Violent orogenic movements folded and overthrusted Paleozoic beds above autochthonous Triassic strata. During this phase were formed numerous fissures and tectonized zones, and probably also the structure of the central part of the deposit in the form of the letter S (3), as well as cleavage which is the most expressive feature in the deposit. Fissures and tectonized zones were filled mostly by gangue minerals, and to a lesser degree also by sulfides, whereas primary uranium minerals mostly do not occur in them. During the 1st phase of retrograde epigenesis also the majority of quartz carbonate veins and nests was formed (9).

Deformation of the Žirovski vrh deposit continued also during the 2nd phase of retrograde epigenesis which is attributed to neotectonic times. According to Premru (1) this period started in the Middle Pliocene. During this period of the Alpidic orogeny the deposit suffered faulting tectonics. Numerous fissures cut the mineralized and barren beds, and faults of N-S and NW-SE directions cut the deposit into several blocks. Numerous fissures were filled primarily by quartz and carbonates - open quartz carbonate veins and veinlets were formed. Where meeting mineralized beds they contain sulfides, mainly pyrite, and to a lesser degree also sphalerite.

Due to these tectonic movements the deposit was cut into smaller blocks shifted one relatively to the other, which also influenced the orebodies.

PETROLOGICAL CHARACTERISTICS AND MINERALOGICAL COMPOSITION OF THE GRÖDEN CLASTIC BEDS OF THE ŽIROVSKI VRH AREA

Petrological characteristics and mineralogical composition of the Gröden clastic beds in the Žirovski vrh area are relatively well known. Generally prevail fine to coarse grained and conglomeratic sandstones which are attributed according to the amount of matrix and percentage of lithic grains mainly to lithic arenites and lithic graywackes. Sandstones contain thicker or thinner intercalations of mudstones and conglomerates.

Most frequent in sandstones and conglomerates are quartz and lithic grains, less abundant are feldspars, and even less grains of muscovite, chlorite, biotite and accessory minerals. Cement is of the pore, basal and contact types. It consists of the matrix and the cement. The epimatrix of the contact type with the characteristic pseudofluidal texture prevails, whereas cement in barren clastic beds consists mainly of carbonates, quartz, feldspars, and also of illite, sericite, chlorite, barite and hematite. In mineralized clastic beds ore minerals prevail, mostly sulfides and pitchblende which is in places accompanied also by coffinite.

Cementing minerals crystallized during diagenetic, epigenetic and retrograde epigenetic processes, whereas the epimatrix with pseudofluidal texture was formed during retrograde epigenesis, when strong directed stresses resulted into intragranular movements and forming of the secondary porosity.

CARBONATE CONCRETIONS

In medium and fine grained sandstones, especially in siltstones and silty mudstones from which consist the upper fine grained parts of sedimentary sequences, occur autochthonous concretions several mm to 20 cm in diameter. Rocks in which they occur are former depositions of flood plains, shallow lakes or maybe even swamps. Carbonate concretions are distributed along the entire thickness of the fine grained part of sequences, or in particular horizons only.

In conglomerates and sandstones of lower coarse grained parts of sedimentary sequences Skaberne (10) found redeposited concretions which form intraclasts together with fragments, lumps or even blocks of siltstone. Investigations by the mentioned author indicate that carbonate concretions were formed even before the coming of high waters which eroded the base and deposited the following sedimentary sequence in which lower part the redeposited concretions can be found. This means that the majority of carbonate concretions originated during the early diagenesis, and perhaps even during pedogenesis.

During epigenesis and retrograde epigenesis the growth of concretions continued. Also some new, most probably nonseptarian concretions were formed. These cannot practically be distinguished from the older ones. Later growth of concretions is however indicated by calcite forming on numerous concretions the so-called pressure shadows. These could have been formed during strong directed stresses, probably at the end of epigenesis or at the beginning of retrograde epigenesis as a consequence of folding and overthrusting.

QUARTZ CARBONATE VEINS AND NESTS

Mineralized and barren Gröden clastic beds of Žirovski vrh are often cut by variously thick veins and nests which contain mainly quartz and calcite, in places also chlorite, albite and sulfides, whereas primary uranium minerals were not found in them. Veins and nests are in no genetic connection with the uranium ore, and they are not the result of any magmatic hydrothermal activity. They were formed as a result of tectonic movements during epigenesis and retrograde epigenesis. Their formation was accompanied by rearrangement of components of barren and ore minerals which migrated into tectonized parts of the rock where dilatational and metasomatic quartz carbonate veins and nests formed. Minerals which crystallized in veins and nests belong to a number of generations. They occur also in the country rock where they form cement. However, individual generations of mentioned minerals from veins in the cement practically cannot be distinguished under the microscope. In veins more generations of minerals were determined than in the country rock. This may indicate that in the cement of sandstone not all generations of minerals occur that are present in veins.

CHARACTERISTICS OF THE ISOTOPIC COMPOSITION OF OXYGEN AND CARBON IN CALCITE FROM VARIOUS VEINS AND NESTS

Mass spectrometric analyses show the variation of $\delta^{18}O$ of calcite from various veins and nests in the range from +13.47 % to +19.54 % (Figure 1). We must point out that calcite from closed veins that were formed during epigenesis or in the 1st phase of retrograde epigenesis usually has lower $\delta^{18}O$ values than calcite from open veins and calcite crystals from vugs in quartz carbonate nests which formed in the 2nd phase of retrograde epigenesis. This may be explained by a change in isotopic composition of oxygen in solutions, or by a drop of temperature of solutions which resulted into a change in fractionation in the system calcite - water (11). In a similar way can be explained also the increase of concentration of the heavy oxygen isotope in the younger generations of calcite from various veins and nest.

Calcite from various veins and nests does not essentially differ in isotopic composition of carbon from massive parts of concretions of which we established an approximate amount of 50 to 75 % of carbon dioxide, which was formed by oxydation of plant remains whose $\delta^{13}C$ had an average value of +21.90 % (11). Since veins started to form already during epigenesis, although the majority of closed veins and nests was formed only in the 1st phase of retrograde epigenesis (9), calcite in them was deposited at a considerably higher temperature as it was during the forming of concretions. If solutions from which crystallized calcite in vens and nests had a similar isotopic composition of carbon as solutions from which crystallized calcite of the massive part of concretions, calcite from veins and nests would have due to temperature

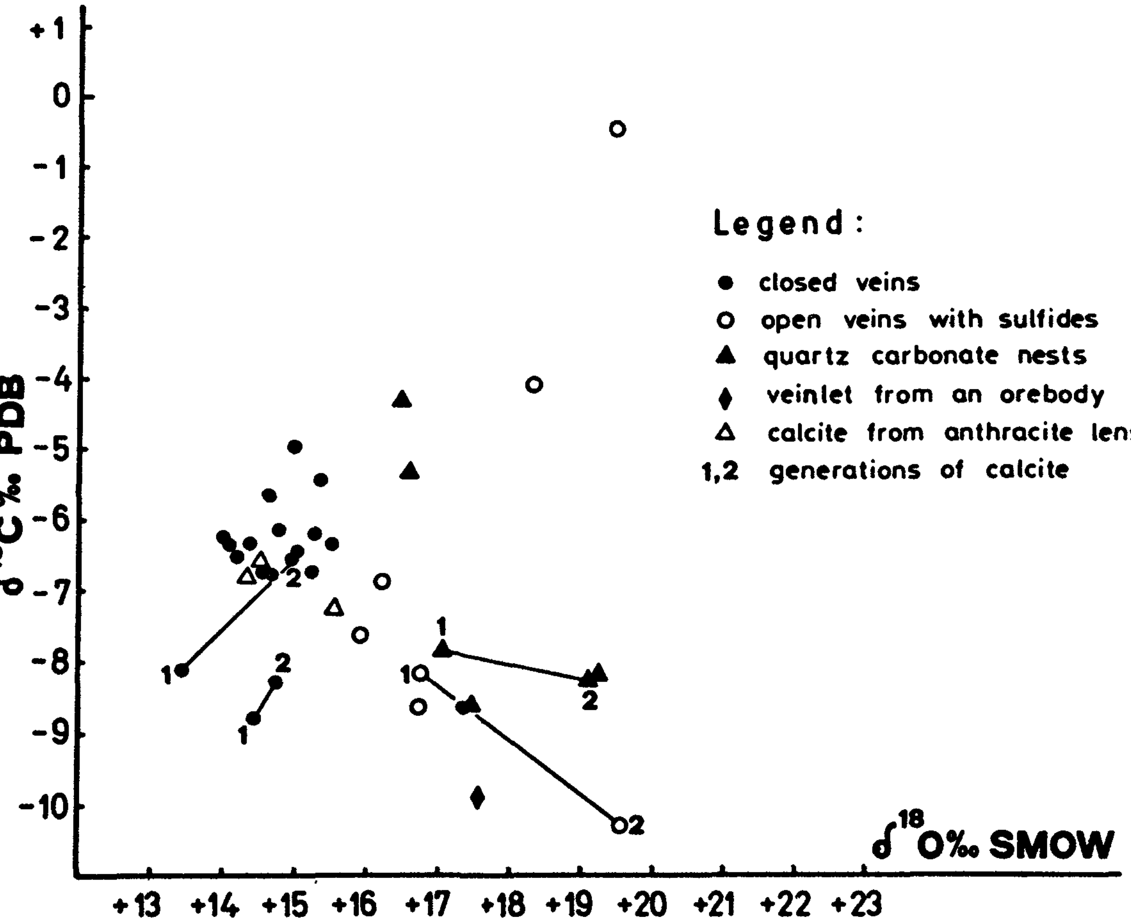

Figure 1. Isotopic composition of oxygen and carbon in calcite from quartz carbonate veins and nests, and anthracite lenses. Lines connect generations of calcite in the same sample of vein.

dependence of the factor of isotopic fractionation smaller values of $\delta^{13}C$ than established by mass spectrometric analyses. This leads to the idea that solutions during epigenesis and during the 1 st phase of the retrograde epigenesis contained more heavy carbon isotope in comparison with solutions during pedogenesis and diagenesis which were enriched with light carbon isotope.

The isotopic composition of carbon in calcite from youngest, i.e. open quartz carbonate veins with sulfides which started forming during the 2nd phase of retrograde epigenesis, attributed to the beginning of the neotectonic period, is extremely variable. The $\delta^{13}C$ value of the mentioned calcite varies from -0.5 % to -10.32 %, in the range in which fall the $\delta^{13}C$ values of all carbonate samples from the deposit analyzed till now. The obtained data indicate, according to our opinion, intrusion of considerable quantities of meteoric water with a varying isotopic composition of carbon. Water percolated along faults and fissures, and it was probably at times more and at others less enriched with carbon dioxide of organic origin, in function of climate and local conditions. The isotopic analyses made until now indicate a usually lower value of $\delta^{13}C$ of calcite in youngest veins and some nests of younger generation than in older ones. This is well illustrated by calcite of the 2nd generation from open veins with sulfides and from the nest, both being enriched with light carbon relative to that of the 1 st generation. In older veins the youngest generation is enriched with geavy carbon isotope with respect to calcite of the older generation.

The diminished values of δ^{13} C in calcite from youngest veins and nests can be explained, as already stated, by introduction of meteoric water enriched with carbon dioxide of organic origin. Increasing of contents of isotope δ^{13} C in younger generation of calcite from older veins, however, could be the result of changes in isotopic composition of this element in solutions during crystallization of the younger generation of calcite, or the result of changes in temperature.

Isotopic composition of oxygen and carbon in calcite of the 2nd generation from open veins, the values δ^{18} O being +19.54 % and of δ^{13} C being -10.32 %, is very close to the isotopic composition of both elements in calcite which would crystallize in the deposit now. By considering the fact that the percolating ground water in the deposit has on the average the δ^{18} O value of -8.96 %, and the value of δ^{13} C (of total carbonate) according to first data from -11.94 % to -14.01 %, the temperature varying between 9 and 11°C, then calcite which would crystallize in isotopic equlibrium with oxygen and carbon from percolating groundwater would have the value δ^{18} O approximately in the range from +21.87 to +22.60 % and the value of δ^{13} C approximately in the range between -9.86 % and -11.93 % (Dolenec 1983). We conclude on the base of present investigations that calcite from the youngest open veins with sulfides crystallized at a temperature between about 22 and 40°C. Solutions from which it deposited were close in their isotopic composition of oxygen, hydrogen and carbon to present groundwater in the deposit (11).

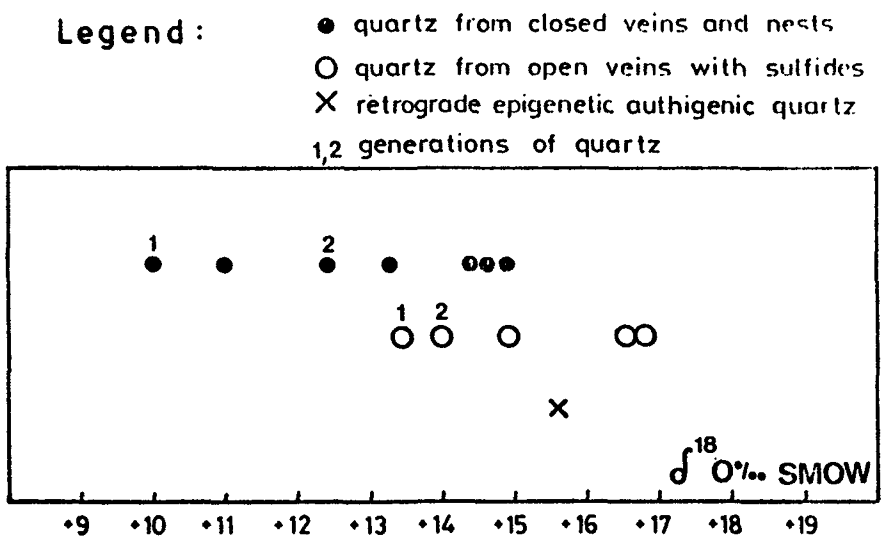

Figure 2. Isotopic composition of oxygen in quartz from veins and nests in Žirovski vrh

CHARACTERISTICS OF THE ISOTOPIC COMPOSITION OF OXYGEN IN QUARTZ FROM VARIOUS VEINS AND NESTS

We found by mass spectrometric analysis a variation of δ^{18} O of quartz from various veins and nests in the range from +10.0 to +16.7 %, the isotopic composition of oxygen in quartz having similar characteristics to that of calcite from veins and nests (Figure 2).

The lowest δ^{18} O is in general typical for quartz from older veins and nests formed during the 1 st phase of retrograde epigenesis. The highest δ^{18} O was measured in quartz from youngest open veins whose formation is attributed to the 2nd phase of retrograde epigenesis.

A further indication of the mass spectrometric analysis concerns an enrichment of lighter isotope of oxygen in quartz of the older generation in veins and nests in which both generations were investigated, with respect to quartz of the younger generation. These differences are relatively small and do not exceed 3 ‰, according to our latest studies (11). We think they are most probably the result of a change in isotopic composition of oxygen in the solution during the crystallization of older and younger generation, and of the change in temperature.

On the basis of isotopic composition of oxygen in quartz and calcite from various veins and nests, and of the sequence of their crystallization, Dolenec (11) thinks that quartz was deposited during the 1 st and the 2nd phases of retrograde epigenesis at higher temperatures than calcite. If assuming that quartz which formed in the youngest veins before calcite of the 1 st and the 2nd generations crystallized in isotopic equilibrium from solutions having their isotopic composition similar to that of present groundwater in the deposit, then their temperature of formation should have been situated between 71 and 93°C. About at these temperatures crystallized in open veins also sphalerite and pyrite. The latter crystallized in these veins again during crystallization of calcite, at the temperature of solutions between 22 and 40°C.

Also quartz which crystallized in fissures during the 1 st phase of retrograde epigenesis is older than calcite. Dolenec (11) assumes that it mainly precipitated in isotopic equilibrium with oxygen from solutions at temperatures between approximately 175 and 255°C. Pore solutions should have been during this phase enriched with heavy oxygen isotope with respect to solutions of the 2nd phase of retrograde epigenesis; their δ^{18} O varied, following these assumptions, in the range between +1 ‰ and 3 ‰. Calcite which precipitated in fissures after crystallization of the mentioned quartz was formed at an even lower temperature which most probably did not exceed 140°C.

MINERAL COMPOSITION OF URANIUM ORE

After detailed microscopic and x-ray studies of the mineralized sandstone from various parts of the deposit it has been established that pitchblende is the principal ore mineral, acompanied by coffinite in some orebodies.

Kurat (12) which studied the mineralized sandstone in detail by the electrone microprobe determined in ore uranium minerals with a considerable amount of silica dioxide. They belong mostly to the group of soddyite and coffinite. We determined by x-ray analysis of numerous samples of mineralized sandstone mainly pitchblende only, to a small degree also coffinite, while other uranium minerals in nonoxidized orebodies were not detected by x-ray analysis.

In mineralized sandstone where pitchblende represents most of cement, it intensively replaces detritic grains floating in it, and cements older generations of sulfides. Pitchblende occurs also in form of thin, on the average 10 m large isometric grains, or in several 100 m large, mostly irregular fields and arcs, and in colloform coatings around detritic grains.

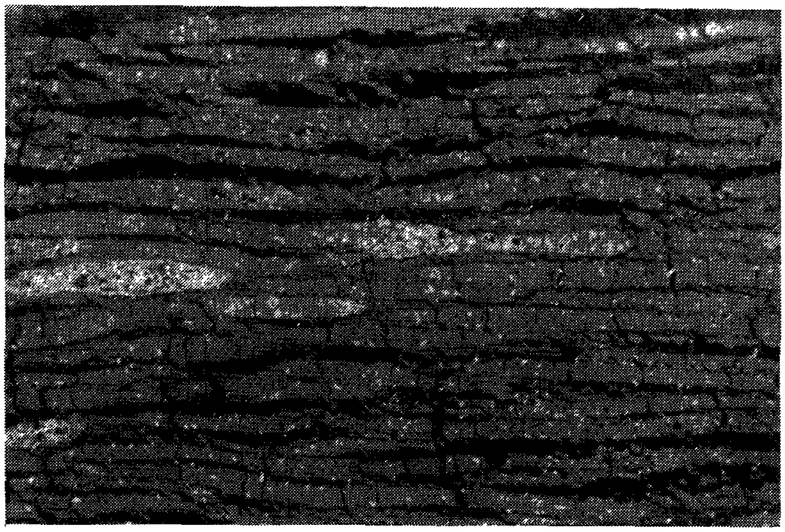

Figure 3. Pseudomorph of pitchblende after plant remains. Reflected polarized light, 375x.

In richest parts of orebodies occur in pores between detritic grains up to ·200 m large grains of pitchblende with beotryoidal forms. They contain in places inclusions of framboidal and euhedral pyritic grains.

In samples containing high amounts of anthracite detritus, pitchblende forms pseudomorphs after plant remains filling up plant cells (Figure 3). In some pseudomorphs next to pitchblende also coffinite appears. The amount of coffinite in pseudomorphs is very variable. Some do not contain it at all, and in others it may be present in appreciable quantities, as indicated also by x-ray analyses (11).

Pseudomorphs of pitchblende and coffinite after plant remains prove that pitchblende mineralization occurred during the early diagenesis, however somewhat later than the first generations of sulfides. This is indicated by the presence of pseudomorphs of galena, sphalerite and chalcopyrite after framboidal pyrite which was found by us in cells, filled up by pitchblende.

On the basis of a detailed microscopic analysis we came to the conclusion that pitchblende and coffinite form at least two generations. Pitchblende of the 1st generation crystallized simultaneously with coffinite of the 1st generation, and it is most abundant in the investigated samples. Its precipitation started before the forming of authigenic quartz rims with regular crystal faces. This is indicated by inclusions of pitchblende observed along contacts of quartz grains and their authigenic rims (Figure 4). However, most of the pitchblende and coffinite of the 1st generation crystallized after the growth of authigenic quartz rims, and probably also authigenic feldspar rims.

The second generation of primary uranium minerals is relatively rare. It precipitated during the 1st phase of retrograde epigenesis, when pitchblende and coffinite were redeposited into cleavage joints and some other very thin fissures.

Drovenik (13) found pitchblende also in some veinlets together with pyrite. Most probably it should be attributed to the 3rd generation of pitchblende which may be found only in traces, and which precipitated obviously after crystallization of pyrite and bravoite, most probably already during the 2nd phase of retrograde epigenesis.

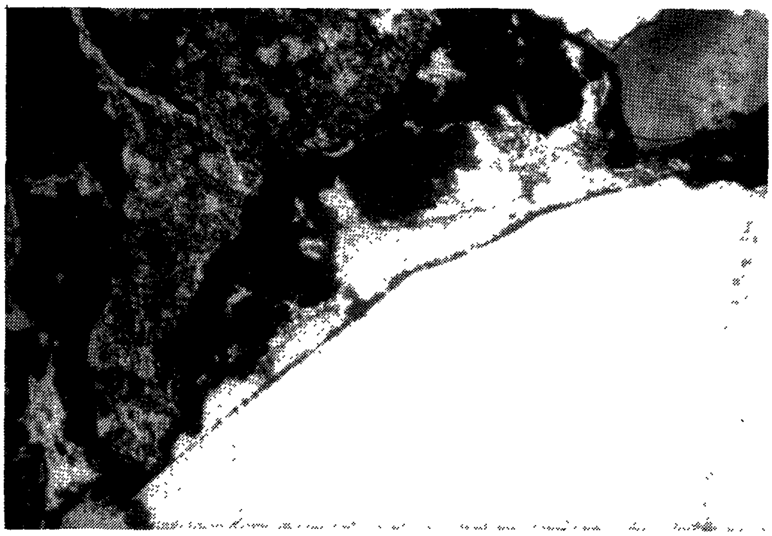

Figure 4. Pitchblende caught between detritic quartz grains, and authigenic quartz rim. Transmitted polarized light, +N, 300 x.

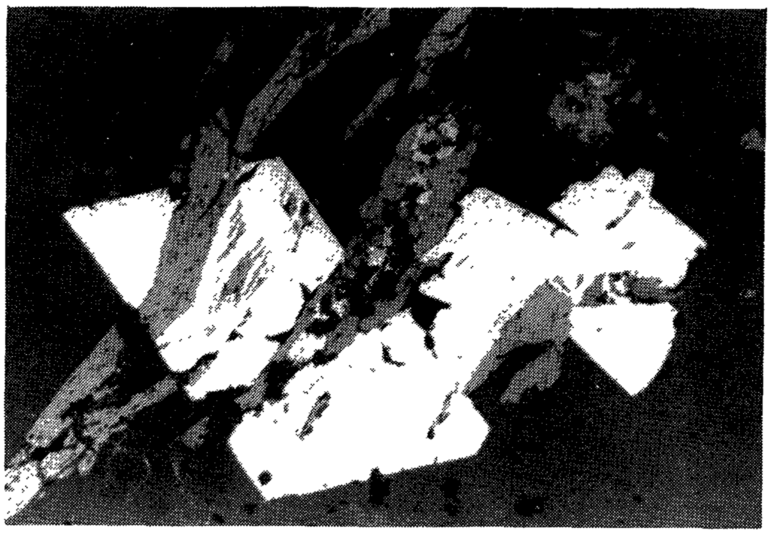

Figure 5. Metacrysts of arsenopyrite contain inclusions of anthracite fragments. Reflected plarized light, 950 x.

Pitchblende and coffinite are accompanied by su'.fides which belong to several generations precipitated during diagenesis, epigenesis and retrograde epigenesis. Their total amount varies in orebodies from traces to five percent (8). Pyrite prevails and is frequent in all orebodies. Pitchblende contains also galena, chalcopyrite, tennantite and sphalerite. The mentioned minerals occur in irregular monomineral and also polymineral grains and fields which may measure up to several 100 m in diameter. They occur in cement of sandstone where they fill pores between detritic grains, and they are abundant also in anthracite lenses. In anthracite lenses and in their immediate surroundings occurs also arsenopyrite. As a rule arsenopyrite appears in metacrysts from several 10 to several 100 m in diameter (Figure 5). We found arsenopyrite also in cement of mineralized sandstone.

The mineral paragenesis of uranium ore is completed by marcasite, bravoite, bornite, digenite, covellite and chalcosite.

These minerals are usually not frequent in ore. In oxydized mineralized sandstone occur along with primary uranium minerals and sulfides also secondary uranium minerals.

More or less simultaneously with ore minerals precipitated also the gangue minerals: quartz, feldspars, calcite, dolomite, sericite, chlorite, barite and gypsum.

ORE AND ORE BODIES

The statistical analysis (14) shows that the ore is found most frequently in dark gray medium to coarse grained sandstone, corresponding to a large thickness of the gray strata.

The orebody in the deposit Žirovski vrh is of rather peculiar nature. One must distinguish between the area covered by the ore end the area meeting the extraction criteria, the reason being the non-homogeneity of the mineralization itself (14).

The most heterogeneous ore bodies are those of the disseminated morphological ore type. Here, inside the orebody, patches with ore concentration varying from high to barren are distributed at random. The banded type consists of thin bands of ore parallel to the bedding of sediments. Ore which is connected with larger carbonized wooden remnants is more rare, but can have extraordinarily high pitchblende concentrations. Ore bodies containing one single morphological type of mineralization are scarce; most ore bodies present associations of several types.

ISOTOPIC COMPOSITION OF SULFUR IN SULFIDES

First data on isotopic composition of sulfur in sulfides from the uranium deposit Žirovski vrh were published by Ristić and Markov (15) and by Drovenik and others (16). Later these data were completed by a considerable number of analyses of various generations of sulfides formed during various phases of postsedimentation processes (Dolenec 1983).

It can be seen, if considering the present data on the isotopic composition of sulfur in sulfides from Žirovski vrh, that in the mentioned deposit δ^{34} S of sulfide sulfur varies between +2.58 and -45.73 %, in a range of 48.25 %, around a mean value of -26.29 % (Figure 6). The obtained data indicate and enrichment of sulfides of Žirovski vrh by the light isotope. Enrichment by the light isotope and a broad range of δ^{34} S are most probably the result of biogenic reduction of sulfates from groundwater solutions.

The isotopic composition of sulfur further indicates precipitation of sulfides with relatively abundant light isotope during diagenesis in the immediately vicinity of decaying vegetation remains. At margins of this environment crystallized varieties having a relatively higher amount of heavy sulfur. This means that at plant remains the isotopic fractionation and biogenic reduction of sulfates were both more intensive. During epigenesis and retrograde epigenesis the isotopic composition of sulfur became homogenized. The process resulted into narrowing of the variation range of δ^{34} S in younger sulfide generations with respect to those from diagenesis, and enrichment of some sulfides in veins with δ^{34} S.

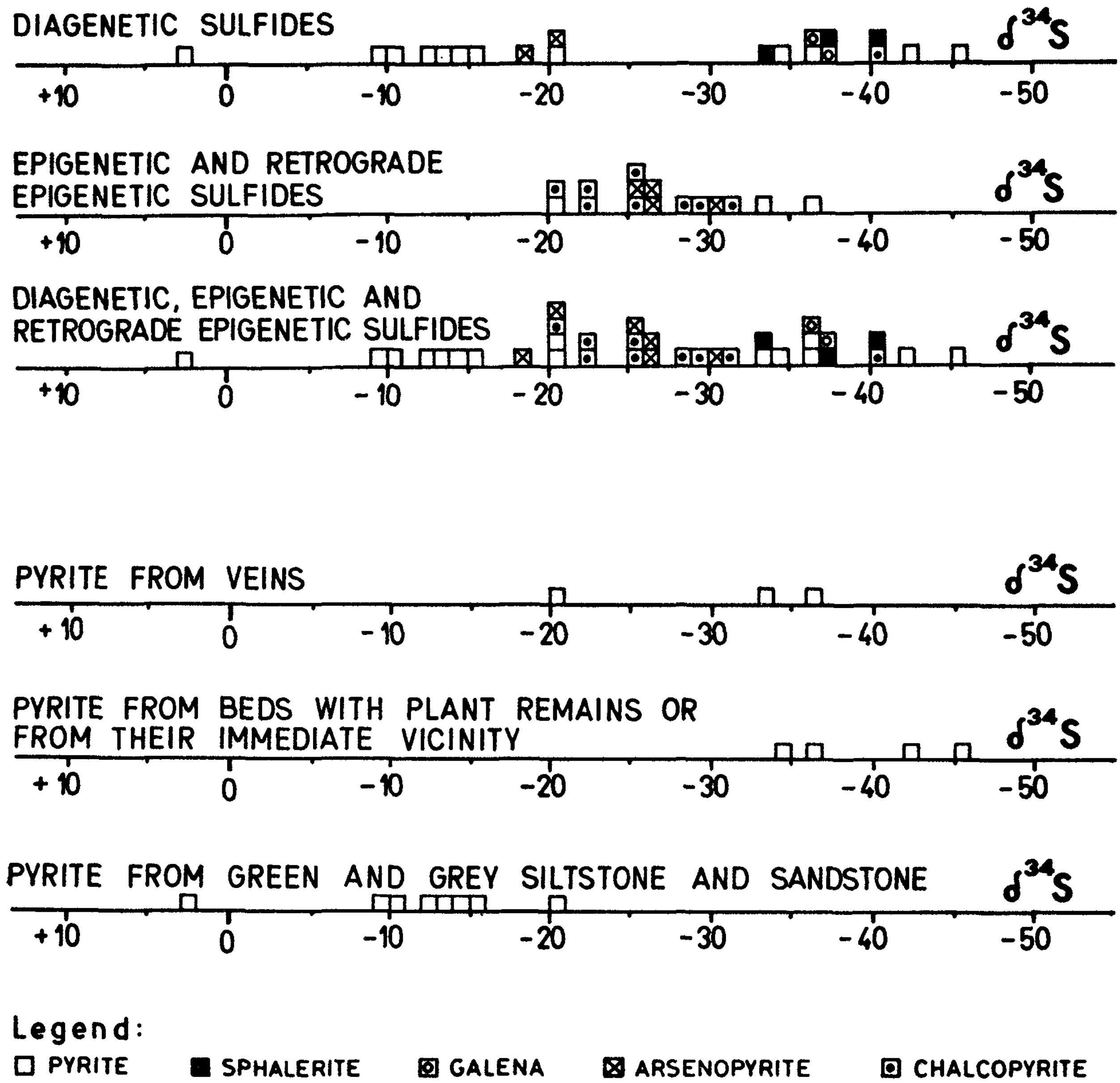

Figure 6. Isotopic composition of sulfur in sulfides from Zirovski vrh. Included are also results of measurement published by Ristic and Markov (1971) and Drovenik et al. (1976).

ISOTOPIC COMPOSITION OF LEAD IN GALENA

Interesting results were obtained with analysis of the isotopic composition of lead. It has been found that in the deposit Žirovski vrh occur two kinds of lead: the normal lead which crystallized in galena during diagenesis and which probably contains very little radiogenic lead, and the anomalous lead. The latter was formed mostly during epigenesis and retrograde epigenesis as a result of radioactive disintegration in uranium minerals. It is contained in youngest generations of galena which precipitated during the retrograde epigenesis (Figure 7).

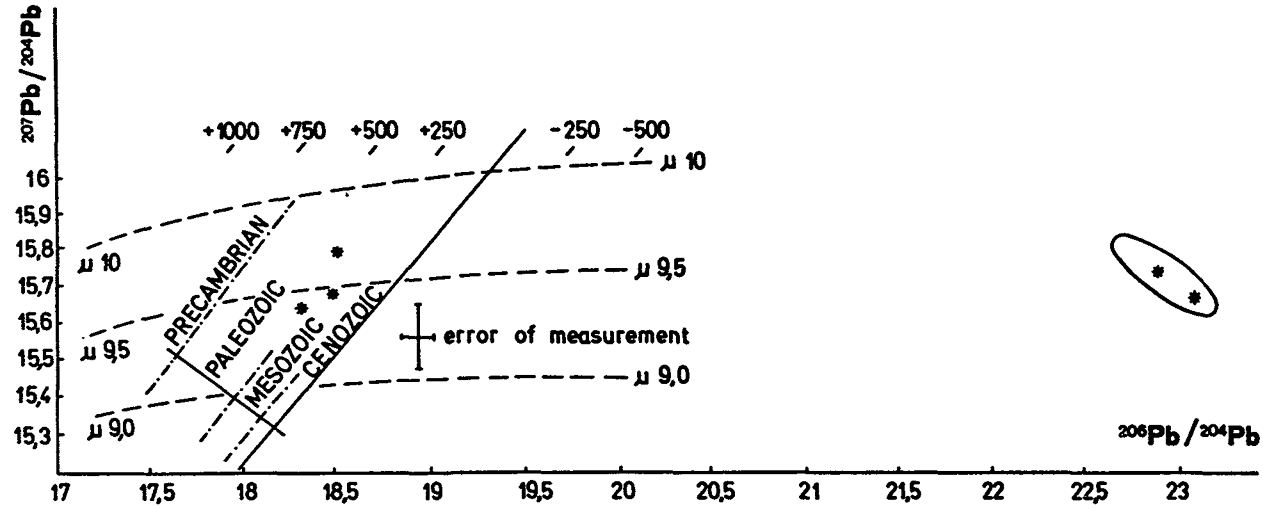

Figure 7. Relationship between isotopic ratios $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ in analyzed samples of galena from Žirovski vrh. Holmes - Houtermans' model.

GENESIS OF THE DEPOSIT

A number of papers has been published on the uranium deposit Žirovski vrh up to now, but none did go deeper into its genesis, and the alterations it was subjected from Middle Permian until today. To this topic we therefore dedicated our field and extensive laboratory investigations.

The genesis of the uranium deposit was undoubtedly a very complex process which cannot be well understood without taking in consideration processes which lead to lithification of the Gröden beds. Let us look then how was formed, according to our beliefs, the uranium deposit Žirovski vrh.

Surface waters carried detritic grains and plant remains into the depositional basin. After deposition of detritic grains started the processes of maturing and forming of sedimentary rocks which strongly altered the primary character of sandstones. These processes are partly purely mechanical, but mainly they are of chemical nature, and they are in close connection with the action of pore solutions. The result of physico-chemical processes was the change of color of sandstones, deposition of uranium ore and of several generations of sulfides and of gangue minerals.

DIAGENESIS

During diagenesis the processes in clastic beds ob Žirovski vrh took place in immediate vicinity of surface at relatively low temperature and pressure. Where sandstones which contained plant remains were protected from oxidation, reducing environment existed. In it important part was played by anaerobic bacteria, especially the dissimilation sulfate reducing bacteria. As a result of activity of the mentioned bacteria in the reducing environment could be formed large amounts of hydrogen sulfide which had an important part in precipitation of sulfides and genesis of uranium ore.

We found by microscopic investigation that in the reducing environment first pyrite of the 1st generation precipitated. It occurs in the form of tiny framboidal grains which were deposited most abundantly in immediate vicinity of plant remains.

Framboidal pyritic grains served as nuclei on which precipitated pyrite of the 2nd generation. It occurs in euhedral grains on the average 15 m in diameter. Probably more or less simultaneously with pyrite of the 2nd generation formed also pseudomorphs of pyrite after plant remains. On individual framboidal pyritic grains in immediate vicinity of plant remains deposited marcasite of the 1st generation. It occurs in rod-like crystals and irregular fields. This mineral most probably crystallized simultaneously with pyrite of the 2nd generation.

After crystallization of pyrite of the 1st and 2nd generations, and marcasite of the 1st generation, other sulfides precipitated. This was the generation of galena, sphalerite, tennantite and chalcopyrite. These mineral crystallized in plant cells, but may be found also in cement of the mineralized sandstone. Depositional succession of the mentioned minerals was not uniform, and it varied considerably.

In immediate closeness to plant remains and in sulfide pseudomorphs in places also the 3rd generation of pyrite and 2nd generation of marcasite were found. Both minerals precipitated after crystallization of the 1st generation of other sulfides, but before the deposition of uranium ore.

During diagenesis also uranium ore was precipitated. Crystallization of the 1st generation of pitchblende and coffinite most probably started only after the deposition of the 1st generation of sulfides. Younger sediments during this stage already covered the ore-bearing horizon which was at this time most probably at a depth of about 100 m.

Groundwaters were in the arid to semi-arid climate of this time most probably somewhat alkaline, and they carried uranium into the reducing environment mostly in the form of di- and tricarbonate ionic complexes. They were not stable in the reducing environment, where they started to disintegrate. Uranyl ion became reduced and uranium precipitated. Reduction of the unranyl ion was induced by hydrogen sulfides which was sufficiently abundant in the reducing environment. Since solutions contained also sufficient quantities of silica, coffinite could precipitate along with pitchblende. Coffinite has a similar area of stability as unraninite (17). Relatively low grade, more or less peneconcordant orebodies of economic importance were formed. Higher enrichments of uranium in reducing environment as characteristic for the rolltype uranium deposits in sandstones did not take place, since the ore-bearing horizon was constantly sinking, up to the paroxysm of the Alpidic orogeny in Tertiary. Orebodies became partly subject to weathering only during the retrograde epigenesis when groundwaters of meteoric origin got access into the ore bearing horizon. However, sandstone at that time was completely cemented, so that also during this phase formation of rich orebodies typical for roll deposits was not possible. The presence of silica in solutions is indicated during crystallization by early diagenetic quartz rims which in places started forming, as already said, even before pitchblende and coffinite ceased to precipitate.

Source of uranium and of other metals were probably various rocks and possibly also ore deposits which weathered in the surroundings of the depositional basin. Further, it is possible that a part of uranium and other metals were leached from various detritic grains which weathered in the depositional basin, and from sediments of playas of that time.

Together with pitchblende and coffinite crystallized also sulfides, galena, sphalerite, chalcopyrite, tennantite and arsenopyrite which occur most ferequently in inclusions in pitchblende. According to our opinion this is the 1st generation of arsenopyrite and 2nd generation of other sulfides. They precipitated also after crystallization of primary uranium minerals, and they filled up in most occasions only partly, and exceptionally completely the remaining pores between detritic grains, overgrown by pitchblende and coffinite. More or less simultaneously with the mentioned sulfides was deposited also the 4th generation of pyrite found only in a few parts of orebodies, and even there in traces.

Succession of crystallization of the mentioned sulfides was variable, and does not show regularity even in the frame of same orebodies. In general sulfide minerals precipitated individually, only at rare occasions, in immediate surroundings of plant remains, they show structural characteristics of crystallization from sulfide gel.

Along with ore minerals crystallized in the reducing environment of Gröden sandstones during diagenesis also gangue minerals quartz, feldspars, calcite and barite.

Before the beginning of marine transgression in Upper Permian the ore bearing horizon was sunk to a depth of 500 to 600 m. Porosity and permeability of sandstones were much reduced due to deposition of ore and gangue minerals. The system of pore solutions became more and more closed, and an important role in transfer of components of various minerals probably started to play diffusion. Ore minerals did not crystallize any more, but a more intensive precipitation of gangue minerals started, especially of quartz, and to a lesser degree also feldspars and calcite. By deposition of the mentioned gangue minerals started the principal phase of cementation in which the remaining pores were partly or completely filled by gangue minerals. How long this phase lasted, is not known. It is believed that crystallization of quartz, feldspars and calcite continued also during epigenesis.

Results of mass spectrometric measurements of isotopic composition of sulfur indicate a higher fractionation of sulfur isotopes during diagenesis than during epigenesis or retrograde epigenesis. This is most probably the consequence of biogenic reduction of sulfates from groundwater solutions. The isotopic composition of carbon in diagenetic carbonates gives an indication of the part played in their genesis of carbon dioxide of organic origin, most probably released during decay of plant remains. However, during these processes most probably no considerable fractionation of carbon isotopes did occur.

EPIGENESIS

It must be known that it is extremely difficult to place an exact boundary between diagenesis and epigenesis. Diagenetic processes result into a certain lithification of the rock which was attained by ore bearing Gröden sandstones most probably only at the beginning of the Upper Permian, when the ore bearing horizon was situated at a depth of 500 to 600 m. About at that depth diagenesis was terminated and epigenesis began in the Gröden sandstones of Žirovski vrh, according to our beliefs.

In the beginning the temperature of epigenetic processes did not exceed much the temperature during diagenesis. By further subsidence during Triassic, Jurassic and Cretaceous deposits became more and more compact, and pores between detritic grains became mostly completely filled up. Epigenetic processes now occurred at considerably higher temperature and pressure. If taking into consideration the reconstruction of the nappe structure of the Idrija - Žiri region (6), (7), it can be seen that the ore bearing horizon attained in Tertiary, before the paroxysm of the Alpidic orogeny, a depth of about 6000 m. In that depth tempera-ture due to normal geothermal gradient attains about 200°C, and the lithostatic pressure approximately 1500 bars.

During epigenesis continued in the ore bearing horizon the geothermic differentiation. Even before reaching their maximum depth during epigenesis, the Gröden beds were fractured for the first time. During this phase were fractured sulfide pseudomorphs and plant remains. Fissures in sulfide pseudomorphs and fractured anthracite fragments are an indication of epigenetic redistribu-tion especially of ore minerals, but also of gangue minerals. In these fissures we found the 2nd generation of arsenopyrite and 3rd generation of chalcopyrite, tennantite, galena and sphalerite.

Typical for epigenesis is complete absence of remobilization of pitchblende and coffinite. Also pyrite and marcasite did not crystallize during that phase. Most probably were mobile only those metals ehich form with hydrogen sulfide and sulfur less soluble solid phases than pyrite and marcasite. This means that in the ore bearing horizon in general migrated only Cu, Pb, Zn, As, and to a smaller degree also Fe.

During epigenesis continued crystallization of gangue minerals which started depositing during epigenesis, calcite, quartz and feldspars. Calcite started crystallizing anew also after crystalli-zation of epigenetic sulfides.

Pore solutions became more and more enriched with the heavy oxygen isotope during epigenesis due to reactions with various minerals. Their $\delta^{18}O$ attained at the end of epigenesis, accor-ding to our opinions, the probable value of about +3 %.

Isotopic composition of sulfur in epigenetic sulfides indica-tes isotopic homogenization of this element during this phase, the range of $\delta^{34}S$ of epigenetic sulfides being much narrower with respect to those from diagenesis.

At the end of epigenesis and at the beginning of retrograde epigenesis also isotopic homogenization of oxygen was carried out at higher temperature. It effaced the primary isotopic composition of oxygen in carbonates which crystallized during diagenesis and epigenesis. The isotopic composition of carbon in this processes was not changed (11).

RETROGRADE EPIGENESIS

The Gröden beds were preserved from possible further epigenetic and metamorphic alterations by the Alpidic orogeny. The latter uplifted probably at the end of Miocene, during the Rhodanian oro-genic phase, the beds which contained the deposit close to the surface. As a result of orogeny also the physico-chemical condi-tions of crystallization changed.

During the 1st phase of retrograde epigenesis radical changes occurred in the ore bearing horizon. As a result of strong direc-tional stresses and tectonic movements occurred the destruction of primary texture intragranular movements and forming of secon-dary porosity. During this phase ore minerals were intensively redistributed, especially sulfides, and to a smaller degree also pitchblende and coffinite. Precipitated the 2nd generation of pitchblende and coffinite, the 3rd generation of arsenopyrite, and the 4th generation of chalcopyrite, tennantite, galena and sphalerite.

Next to ore minerals crystallized also gangue minerals.

Linked with their precipitation is among others also formation of ring-like authigenic quartz and feldspar rims, of sericitic quartz epimatrix with characteristic pseudofluidal texture, and most of quartz carbonate veins and nests.

The isotopic composition of oxygen in pore solutions was during the beginning of the 1st phase of retrograde epigenesis close to isotopic composition of this element in solutions at the end of epigenesis. Later it became somewhat enriched with the light oxygen isotope due to flow of meteoric waters into the system of pore solutions. It should also be said that the temperature of these solutions from which during that phase of retrograde epigenesis ore and gangue minerals crystallized varied approximately in the range between 255 and 93°C.

The isotopic composition of sulfur in sulfides precipitated during the 1st phase of retrograde epigenesis indicates no considerable fractionation of sulfur isotopes, since sulfides which crystallized during this period show a much more homogenous isotopic composition with respect to those from epigenesis.

During this phase of retrograde epigenesis occurred also mobilization of radiogenic lead which crystallized in galena.

Solutions from which crystallized calcite during the 1st phase of retrograde epigenesis contained in comparison to diagenetic solutions more heavy carbon isotope.

Variability of the isotopic composition of oxygen in carbonates and quartz which crystallized during the 1st phase of retrograde epigenesis either in various veins and nests, or in the cement of sandstones, is in general the consequence of isotopic composition of oxygen in solutions, and of temperature.

During the 2nd phase of retrograde epigenesis which started with the neotectonic period, the principal part in reworking of components of various minerals was played by solutions having the isotopic composition of oxygen, hydrogen, carbon and sulfur similar to those of the present groundwater in the deposit.

Along with ore minerals precipitated also gangue minerals. Temperature of solutions from which these minerals crystallized during the 2nd phase of retrograde epigenesis was less than 93°C. Temperature of solutions out of which precipitated calcite at the end of the 2nd phase of retrograde epigenesis, attained only about 22°C. Isotopic composition of carbon in this calcite indicates crystallization from solutions which contained also carbon dioxide of organic origin from soil.

During oxidation processes which affected during the 2nd phase of retrograde epigenesis the upper parts of the deposit, started to form cementational copper and secondary uranium minerals. They form in the deposit also now.

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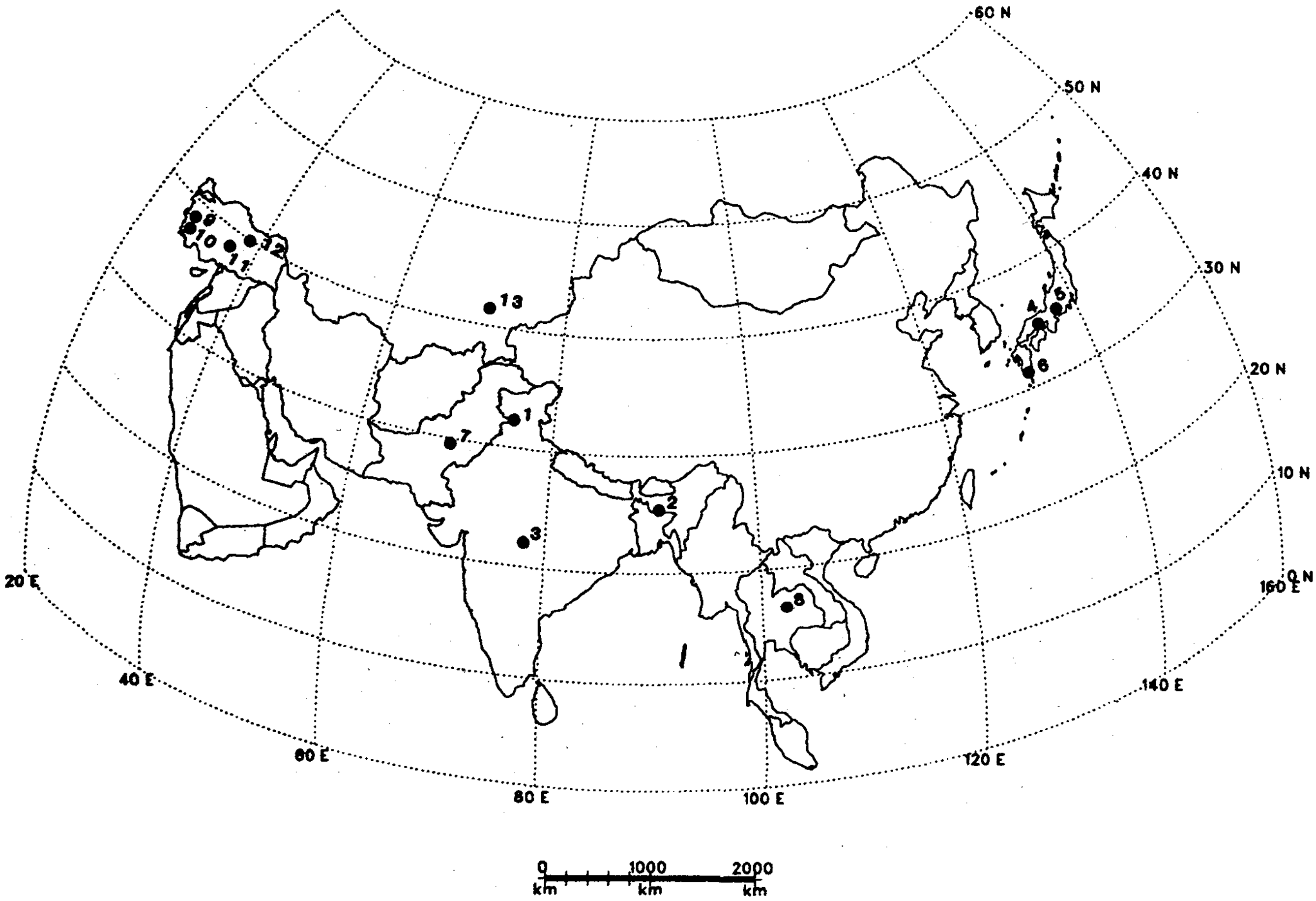
ASIA

MAP AND INDEX LIST FOR SANDSTONE-TYPE URANIUM DEPOSITS IN ASIA



ASIA

India:

1. Jammu and Hamirpur, Beas-Sutlej Valley, Mio-Pleistocene Siwalik formations
2. Meghalaya, Shillong Plateau, Cretaceous Mahadek formations
3. Bhawra-Satpura, Gondwana Basin, Madhya Pradesh, Permian Motur and Bijori formations

Japan:

4. Ningyo-toge deposit, Miocene conglomerate, arkose, siltstone
5. Tsukiyoshi deposit, Tono district, Miocene conglomerate, arkose, siltstone
6. Tarumizu, Pliocene conglomerate, sandstone, claystone

Pakistan:

7. Dera Ghazi Khan area, Miocene-Pleistocene Siwalik System

Thailand:

8. Phu Wiang district, Khorat Plateau, Jurassic Sao Khua Formation

Turkey:

9. Eclinlitas and others, Salihli-Koprubasi District, Menderes Massif, Neogene sediments
10. Kocarli deposit, Menderes Massif, Neogene sediments
11. Fakili deposit, Neogene sediments
12. Eskine and Cukurovasi deposits, Sebinkarahisar, Eocene conglomerate

USSR:

13. Ferghana Basin, Tertiary arkosic sandstone

URANIUM MINERALISATION IN SOME PHANEROZOIC SANDSTONES OF INDIA

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Abstract

Peneconcordant sandstone type uranium mineralisation occurs in (i) the Lower Gondwana Permian beds in the Satpuras of Madhya Pradesh; (ii) the Cretaceous Mahadek beds along the southern slopes of the Shillong Plateau; and (iii) the Siwalik formations along the northwest Sub-Himalayan foothills. Each of these has evolved in a specific tectono-sedimentological regime -- the Gondwanas in graben-like basins, the Mahadeks along the fringes of a horsted-up block of the Peninsular Shield, and the Siwaliks in the southern foredeep of the rising Himalayas. The Gondwanas and the Siwaliks are fluviatile and the Mahadeks fluvial to marginal marine. The evolution of these basins is not marked by any acid or alkalic magmatism but the Gondwanas are associated with post- and the Mahadeks with pre-sedimentation basic volcanism.

The sediments in all the three regimes have a uranium-rich provenance, the speedy tectonic uplift which gave rise to accumulation of uranium-bearing immature sediments. The genetic model of enrichment envisages activation of hydro-dynamic gradients due to tectonic uplift and mobilisation of uranium from oxidised zones through groundwater media and its increment in the reduced zones below the water table aided by organic carbon and Fe^{2+}. In the Mahadeks of Gomaghat area, however, initial pene-syngenetic enrichment seems likely followed by epigenetic additions from the overlying oxidised upper Mahadeks. Uranium mineralisation is mostly due to uraninite, pitchblende, coffinite and many secondaries.

The three sedimentary sequences signify the vast possibilities of locating workable uranium ore bodies in each of them.

Some of the exploration problems are briefly discussed.

INTRODUCTION

Radiometric investigations in the sedimentary formations in India during the last two decades have led to discoveries of significant occurrences of uranium in three major stratigraphic horizons, each of which is characterised by its own style of geological evolution. It is proposed to present in this paper a brief account of the geology, stratigraphy and tectonic setting of these sedimentary sequences and discuss the nature and extent of uranium mineralisation, the sources of uranium and the geological factors which seem to have aided in bringing about the uranium enrichment. In the order of their antiquity, these sequences include

(i) the Motur and Bijori formations of Permian age of the Satpura Gondwana basin in Madhya Pradesh;

(ii) the Mahadek formations of Cretaceous age along the southern fringes of the Shillong Plateau in Meghalaya; and

(iii) the Siwalik formations of Mio-Pleistocene age along the foothills of sub-Himalaya (Plate I).

The Motur-Bijori beds form a part of the Gondwana sediments deposited in graben-like basins in Central India. These basins were shallow erosional depressions formed along zones of structural weakness in the Precambrian basement and thereafter developed into larger and deeper basins as a result of gravity faulting. An interplay of subsidence, sedimentation and episodic faulting facilitated the development of a large thickness of Gondwana sediments, which also happen to be the main hosts for India's coal resources. The tectonism could possibly be the counterpart of the Hercynian orogenic movements in the Himalaya (1 and 2).

The Mahadek sediments form the basal beds in a major sequence of sediments deposited in a transgressing sea coast along the fringes of a horsted up block of the present Shillong Plateau, an extension of the Peninsular Shield to the northeast. This horsting took place in early Jurassic along the Dauki fault system, interpreted earlier as a tear fault (3) and subsequently as a basement fault system controlling the Jurassic volcanism and subsequent sedimentation and tectonism (4).

The Siwalik sediments were laid in a major fore-deep formed as a result of the rise of the Himalaya in the Tertiary times. The phased vertical uplift of the Central Himalayan axis and consequent deepening of the fore-deep resulted in the vast accumulation of sediments from Eocene through Mio- Pleistocene to the recent.

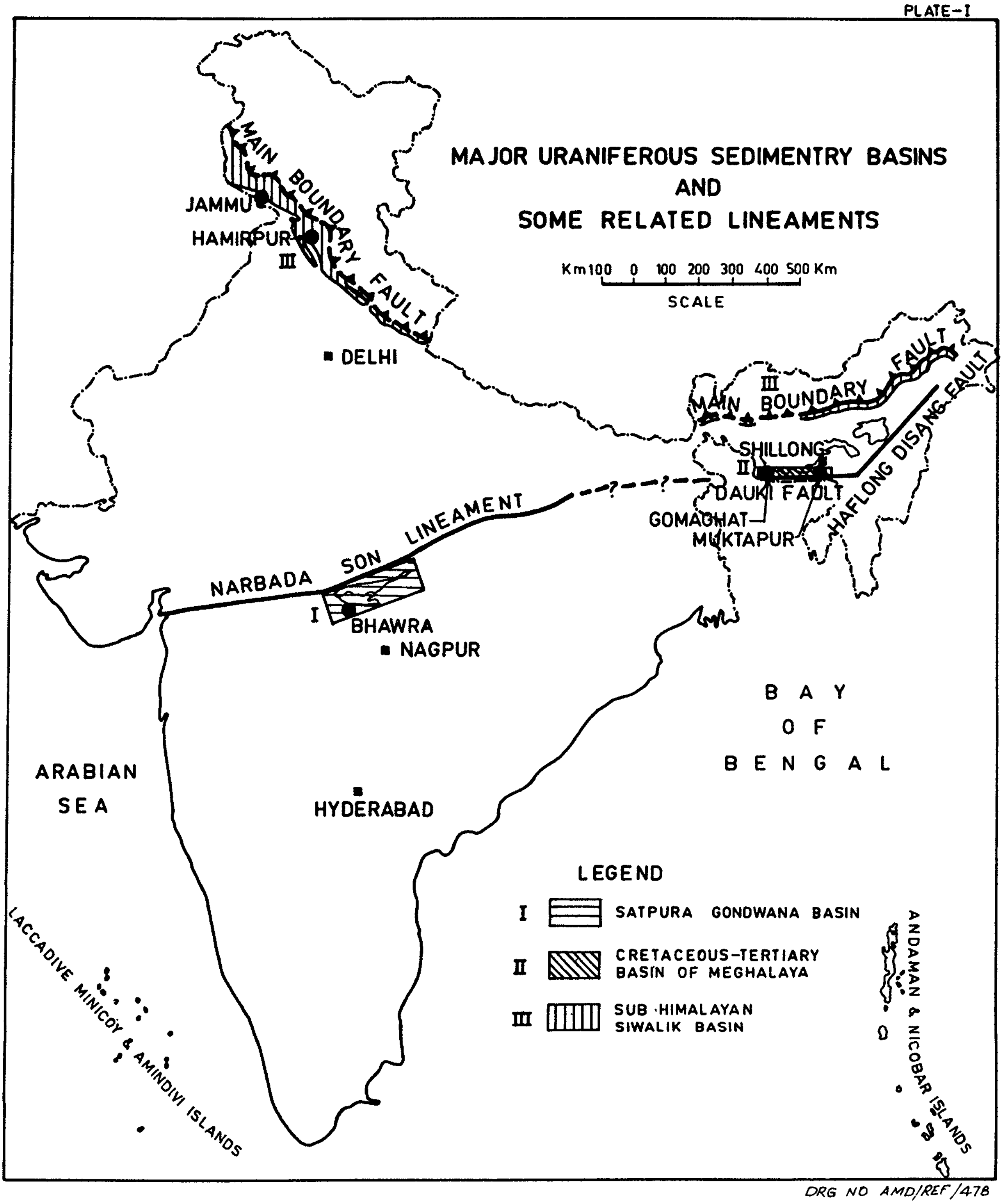
It is thus seen that the three major stratigraphic successions, which host uranium mineralisation, evolved through specific tectono-sedimentary regimes, each of which has thus the potential for future discoveries.

MOTUR AND BIJORI FORMATIONS OF MADHYA PRADESH

The Gondwanas, of which the Motur and Bijori formations form a part, are exposed in the Satpura range, a major geomorphic feature in the Peninsular Shield, bounded by the Narbada-Son lineament in the north and Tapti in the south (5).

Stratigraphy

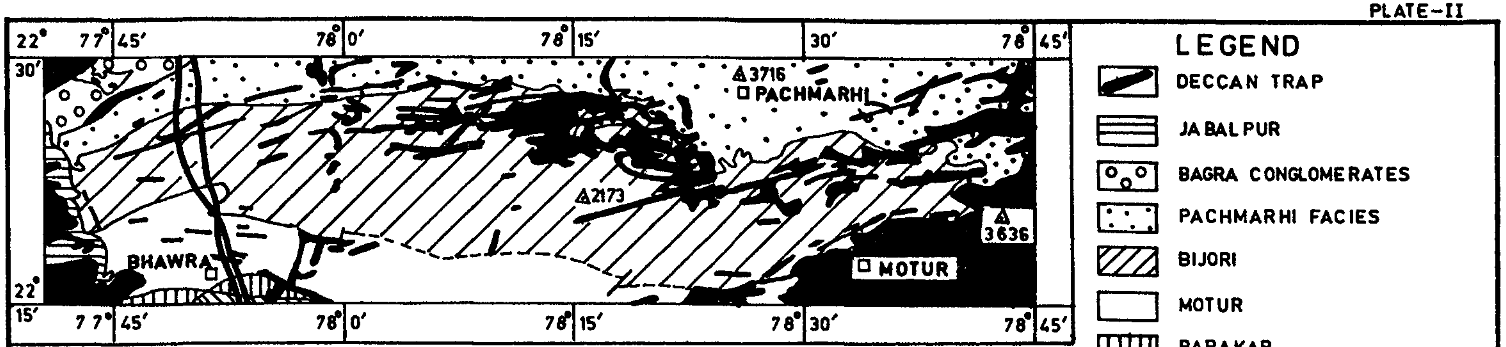
The Motur beds are successively underlain to the south and southwest by the Barakars and Talchir series of the Lower Gondwanas and by the Precambrian crystallines. To the north and northeast, they are overlain by the Bijoris, Pachmarhis and younger beds of the Upper Gondwana sequence. The entire Gondwana sequence is intruded by the numerous basic dykes and overlain by the Deccan flows.



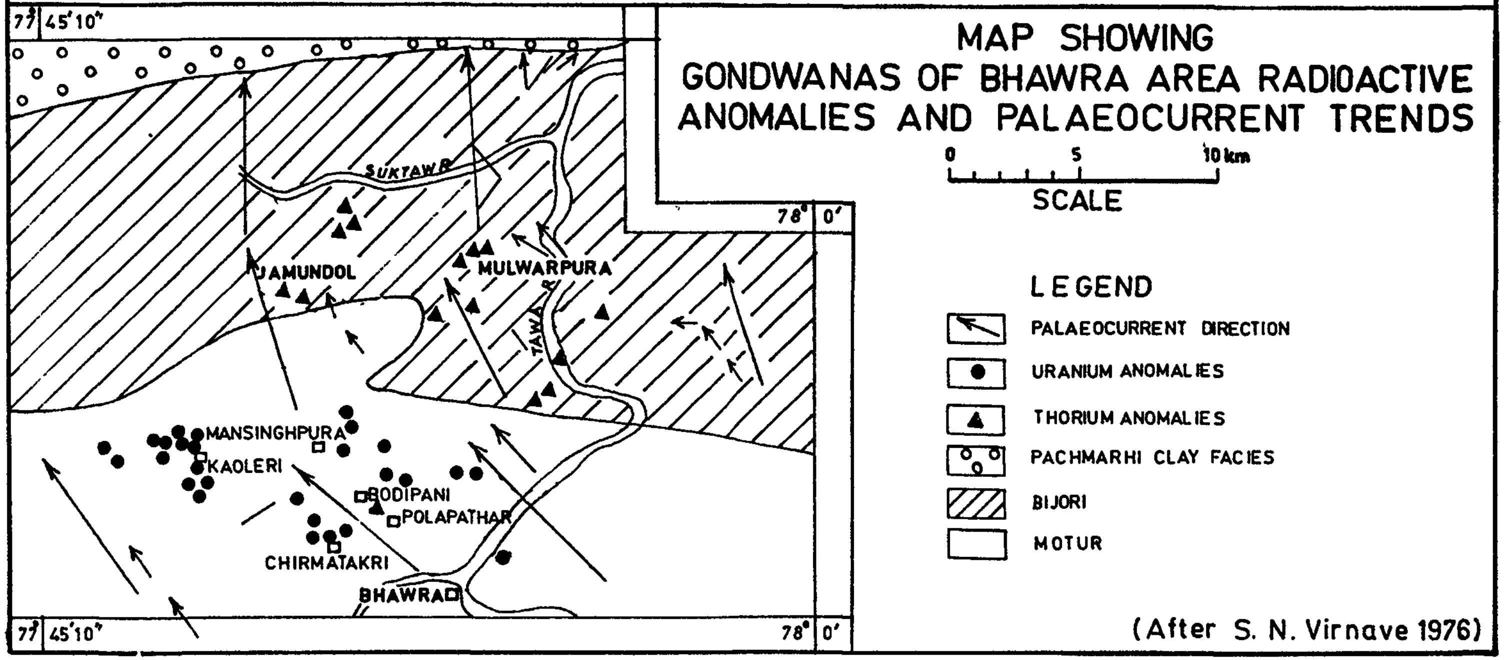
Structure

The Moturs in Bhawra area host significant uranium mineralisation and have a thickness of about 1200 m. They have an E-W trend with dips of 5 to 20° to the north. Locally they are folded into broad anticlines and synclines. Cross bedding and ripple marks are frequent, indicating a palaeo-current direction from the southeast.

PLATE-II



GEOLOGICAL MAP OF SATPURA GONDWANA
(After Crookshank 1936)



MAP SHOWING
GONDWANAS OF BHAWRA AREA RADIOACTIVE ANOMALIES AND PALAEOCURRENT TRENDS

(After S. N. Virnave 1976)

DRG. NO. AMD/MP/283.

Lithology

The Moturs consist of immature arkosic sandstones and felspathic greywackes, pebbly to cobbly in places, siltstones and shales, with stray carbonaceous matter and pyrite specks. The Motur clays comprise varying proportions of kaolinite, illite and montmorillonite. The contact between the Moturs and the Bijoris is gradational and the Bijoris are more argillaceous, carbonaceous and more fossiliferous.

Environment

In the Bhawara and adjoining areas in Betul and Hoshangabad districts the Moturs are deposited in channel fills and have been the main targets for exploration (6 and 7).

Radioactivity

Significant concentrations of uranium occur in the Motur beds at Polapathar, Mansinghpura, Bodipani, Chirmatekri, and Kaolari close to their contact with the overlying Bijori beds (Plate-II). The uranium occurrnces are tabular and peneconcordant. Black oxide of uranium and coffinite are the main minerals. Some uranium is adsorbed in the clays. Enrichment of uranium in ferruginous cappings on the sandstones, as a result of chemical weathering, is not an uncommon feature.

The sandstones at the contact of basic intrusives are indurated but show no enrichment of uranium. Possibilities of these intrusives aiding uranium mineralisation either by way of being source rocks or as providing thermal gradients or as barriers to water movement have now been proved to be remote, as a result of deep drilling, indicating negative results.

The raioactivity in the overlying Bijori and Pachmarhi beds is due essentially to concentrations of refractory minerls like monazite and zircon, thorium values predominating over uranium.

MAHADEK FORMATIONS OF MEGHALAYA

The Mahadek formations are traceable from Lumshlong in the Jaintia Hills westwards into East and then West Khasi Hills upto near Parmador. The Mahadek exposures are bounded to the south by thick successions of younger Cretaceous and Tertiary beds and are limited by the Dauki fault system. They are traceable higher up into the Shillong Plateau upto Latitude 25°25' largely as outliers and are overlapped still further north by younger formations which then overlie the granitic basement (Plate III).

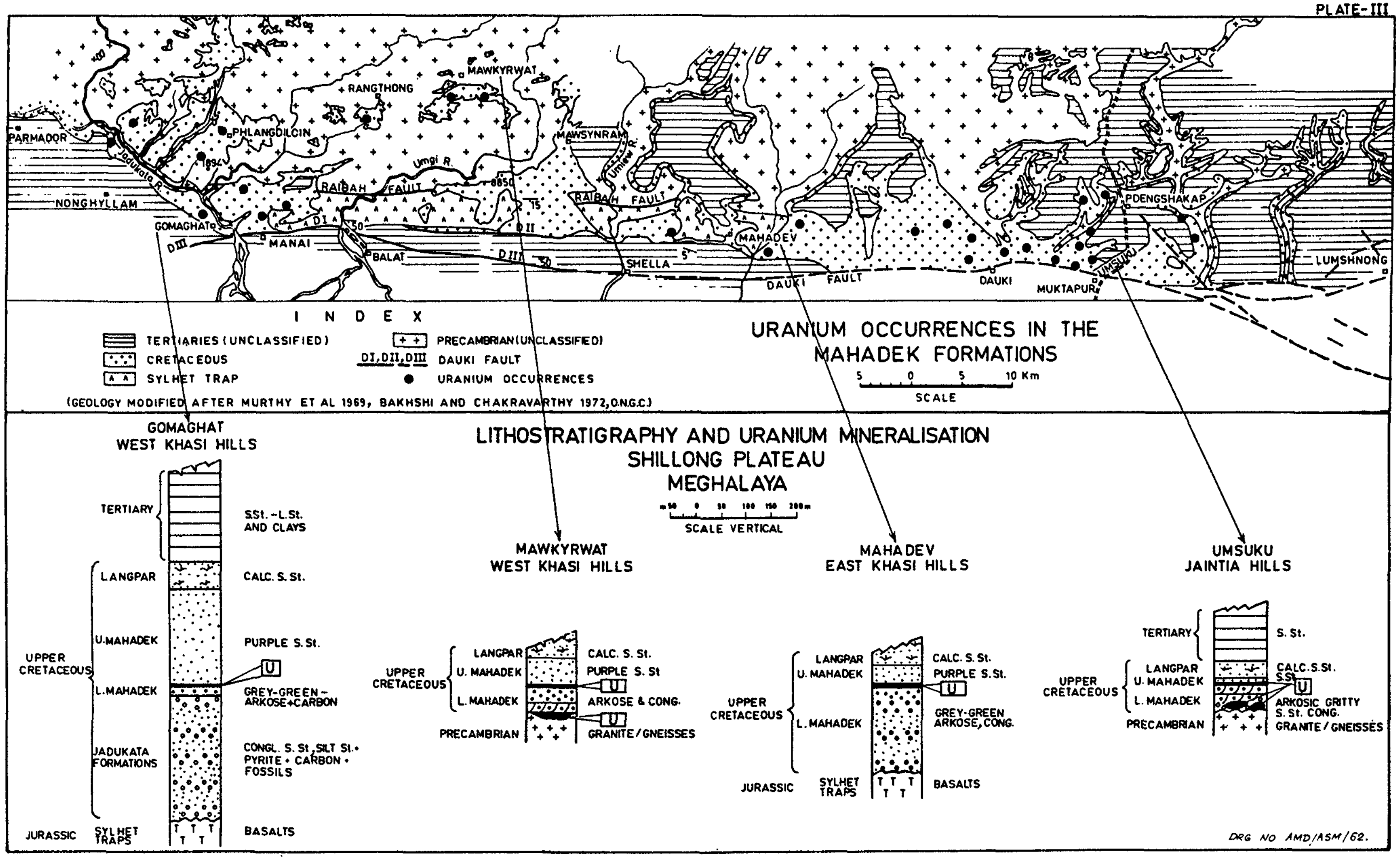
Geomorphology

As a result of vertical uplift, since the post Miocene, the Shillong Plateau presents a very youthful topography with many deep gorges, some of which expose the entire sequence of sedimentaries overlying the Precambrian granitic or Jurassic Sylhet Trap basement, including the low dipping basal Mahadeks.

Stratigraphy

The broad stratigraphic framework in the area as a whole, and the specific lithostratigraphy in the important areas of uranium anomalies viz., (i) Muktapur-Pdengshakap in Jaintia Hills (ii) Mahadeo in East Khasi Hills, (iii) Gomaghat in West Khasi Hills, and (iv) the Mawkyrwat-Phlangdiloin in the Upper Plateau region in West Khasi Hills, are presented in Plate III.

PLATE-III


PARMADOR
NONGHYLLAM
GOMAGHAT
PHLANGDILOIN
RANGTHONG
MAWKYRWAT
Ungi R.
Jadukata R.
RAIBAH FAULT
MANAI
BALAT
SHELLA
MAWSYNRAM
Umiew R.
MAHADEV
DAUKI FAULT
DAUKI
MUKTAPUR
UMSUKU
PDENGSHAKAP
LUMSHNONG
DI
DII
DIII
I N D E X
TERTIARIES (UNCLASSIFIED)
CRETACEOUS
SYLHET TRAP
PRECAMBRIAN (UNCLASSIFIED)
DI, DII, DIII DAUKI FAULT
URANIUM OCCURRENCES
(GEOLOGY MODIFIED AFTER MURTHY ET AL 1969, BAKHSHI AND CHAKRAVARTHY 1972, O.N.G.C.)
URANIUM OCCURRENCES IN THE MAHADEK FORMATIONS
5 0 5 10 Km
SCALE
LITHOSTRATIGRAPHY AND URANIUM MINERALISATION
SHILLONG PLATEAU
MEGHALAYA
SCALE VERTICAL
GOMAGHAT
WEST KHASI HILLS
TERTIARY
SSt.-L.St. AND CLAYS
LANGPAR
CALC. S. St.
U. MAHADEK
PURPLE S. St.
UPPER CRETACEOUS
L. MAHADEK
GREY-GREEN-ARKOSE+CARBON
JADUKATA FORMATIONS
CONGL. S. St, SILT St.+ PYRITE+ CARBON+ FOSSILS
JURASSIC
SYLHET TRAPS
BASALTS
MAWKYRWAT
WEST KHASI HILLS
LANGPAR
CALC. S. St.
U. MAHADEK
PURPLE S. St
UPPER CRETACEOUS
L. MAHADEK
ARKOSE & CONG.
PRECAMBRIAN
GRANITE/GNEISSES
MAHADEV
EAST KHASI HILLS
LANGPAR
CALC. S. St.
U. MAHADEK
PURPLE S. St.
UPPER CRETACEOUS
L. MAHADEK
GREY-GREEN ARKOSE, CONG.
JURASSIC
SYLHET TRAPS
BASALTS
UMSUKU
JAINTIA HILLS
TERTIARY
S. St.
LANGPAR
CALC. S. St.
U. MAHADEK
S. St.
UPPER CRETACEOUS
L. MAHADEK
ARKOSIC GRITTY S. St. CONG.
PRECAMBRIAN
GRANITE/GNEISSES
U
DRG NO AMD/ASM/62.

Structure

The Mahadek and overlying sediments have low dips of 5 to 20° S in general, but dips tend to be steeper (30°-70°) as the Dauki fault system is approached, resulting in a major monoclinal flexure. This structure can be a favourable future target for exploration for uranium, as it provides low pressure areas into which uranium-bearing ground water could migrate.

Further north, the Raibah fault limits the Jurassic Sylhet Traps against the Precambrian basement rocks (granitoids and quartzite-greenstone sequences) and is covered by the Mahadeks in some areas.

Environment of deposition

Distinctive variations falling within the range of fluviatile to marginally marine environments are indicated by the lithostratigraphy and primary structures in the Mahadek sediments.

In the Jaintia Hills, the sheet-like character of lithologic units and the relative paucity of cross-bedding and other fluvial structures in the Mahadeks, the sparse development of shales and mudstones indicate a marginally marine environment (8). In the Gomaghat area, the basal Jadukata formations (260 m thick) represent an euxinic to marginally marine environment as evidenced by the presence of carbonaceous and resin matter, pyrite and marine fossils. The overlying grey sandstones of lower Mahadeks (15-20 m thick) are poorly current-bedded arkosic wacke and were formed in a fluvial to marginal marine regimes. The purple sandstones (about 190 m thick) overlying the Lower Mahadeks are highly friable, coarse-grained subarkoses with greenish glauconitic patches. They appear to have been deposited possibly on a continental shelf. Semi-arid and oxidising conditions seem to have prevailed either during their deposition or shortly thereafter. The younger sequence of Tertiaries are mostly marine deposits.

In the upper region, the Mahadeks are chasracterised by profuse cross-bedding and rapid facies variations indicating their fluvial nature and deposition along flood plains, palaeo-channels and palaeo-depressions chiefly controlled by palaeo-topography (9).

Uranium Mineralisation

Significant uranium mineralisation has been noted in the (i) Muktapur-Umsuku-Tarangblang-Pdengshakap in Jaintia Hills tract, (ii) Shella-Therria-Lynkhat-Pungtung-Mahadeo tract in East Khasi Hills, (iii) in the Mawkhyrwat-Phlangdiloin in the upper reaches of the Shillong Plateau, and (iv) in the Gomaghat-Alukwadi-Rilang-Nonghylong tract south of the Jadukata river, West Khasi Hills.

The lithostratiphic variations in these areas are accompanied by differences in modes of occurrence of uranium. In the Pdengshakap-Tarangblang area, uranium enrichment is predominantly in the lower conglomerate-grit overlying the basement granite and in the middle grey green sandstones. Uranium is confined to coalified material with occasional concentrations as high as 10% U_3O_8. In Gomaghat, uranium enrichment is confined to the grey-green sandstones of Lower Mahadek, close to the contact with the overlying purple and grey sandstones (Upper Mahadeks), which show evidences of oxidation and leaching. The Lower-Upper Mahadek contact could possibly be a redox interface and part of the uranium enrichment may be a result of mobilisation of uranium from these beds and accretion in the underlying Lower Mahadeks. The underlying carbonaceous pyrite-bearing pebbly sandstones of the Jadukata formations do not show any uranium enrichment in spite of their favourable lithology, possible because the sources in the provenance had not been uplifted at the time of their deposition. The ore body in Gomaghat is tabular and concordant to the bedding and is strata-bound. Uranium occurs in both carbon trash as well as the matrix in the sandstones.

In the Mahadeo area, uranium is confined to carbonaceous streaks in greyish green arkosic Lower Mahadek sandstones overlying the Sylhet trap basement. In the Mawkhyrwat-Phlangdiloin area, uranium concentrations occur in two horizons : (i) in the grey Lower Mahadeks along its contact with the purple Upper Mahadek sandstones (as in Gomaghat), and (ii) in the basal massive cross-bedded sandstones overlying the granitic basement possibly deposited in a basement depression (10).

Concept of an open versus closed system

Many of the outliers of the Mahadeks are open systems as ground waters could permeate through them, oxidize and remove uranium. However, since the present topography is a result of post-Pleistocene uplift, plossibilities of uranium being preserved in closed systems within outliers of large extent cannot be ruled out, although the peripheries of such bodies could be exposed to leaching. There could also be palaeo-topographic depressions and down faulted troughs within the outliers, in which uranium could still be preserved. Exploration in these areas is being drawn up on these considerations.

Mineralogy

Pitchblende, uraninite and coffinite, metakahlerite and metazeunerite occur in coaly fragments in Pdengshakap-Tarangblang. Uranopilite and thucolite are suspected. Coffinite and davidite have been identified in Mawkhyrwat and uraninite along with coffinite and uraniferous goethite, pyrite, chalcopyrite and ilmenite in Gomaghat.

Provenance

The geomorphological evolution of the Shillong Plateau, the palaeo-current directions in the sandstones and their heavy minerals indicate that Mahadek sediments were derived from the Precambrian crystalline rocks in the Shillong Plateau where intrusive bodies of Myliem granites and some of the carbonaceous phyllites occur with relatively higher content of uranium.

SIWALIK FORMATIONS

Geomorphology

The general topography of the Siwaliks is characterised by strike ridges and valleys. The Beas-Sutlej valley area where the Siwalik outcrops are broadest, presents a youthful topography characterised by 100-m deep gorges, most of which are sub-parallel to the dominant NW-SE tectonic grain of the area. This topography helps in tracing uranium-bearing beds in some of the gorges. It is suggestive of a recent uplift of the whole basin and the consequent changes in the hydrodynamic conditions that brought about a redistribution of uranium in the formations.

Stratigraphy

The Siwaliks, which are 5000-6000 m thick, are divided into three major sub-groups: Lower, Middle and Upper Siwaliks.

The Lower Siwaliks consist of fine to medium grained grey to green sandstones indurated with carbonate cement and interbedded with chocolate and maroon sandy clays and "clayey conglomerate" beds. The Middle Siwaliks consist dominantly of incoherent coarse-grained, arkosic sandstones, interbedded with thinner beds of clays. They gradually pass upwards into the Upper Siwalik sequence of massive conglomerates, alternating with coarse sands, boulders, cobbles and pebbles.

The radioactive sandstones in the Middle-upper Siwalik transition are mainly lithic and felspathic wacke and in the Lower-Middle-Siwaliks transition lithic and quartz arenites.

Environment of deposition

The Siwalik sediments are characterised by large-scale tabular and trough cross-beds, "cut and fill" structures and lunate and linguoid-type ripple marks, flute and load-casts. The marked facies variations, the immaturity and poor sorting of the sediments and preservation of carbonaceous matter (4% to 9% in places) imply rapid sedimentation and quick burial beneath a high water table, giving rise to non-oxidizing conditions (11).

The Lower Siwaliks are products of fluvial-deltaic intermixing, the Middle Siwaliks channel flood-plain deposits and the Upper Siwaliks Piedmont-type deposits. Some of the Upper Siwalik sediments were laid down possibly along braided channels.

Structure

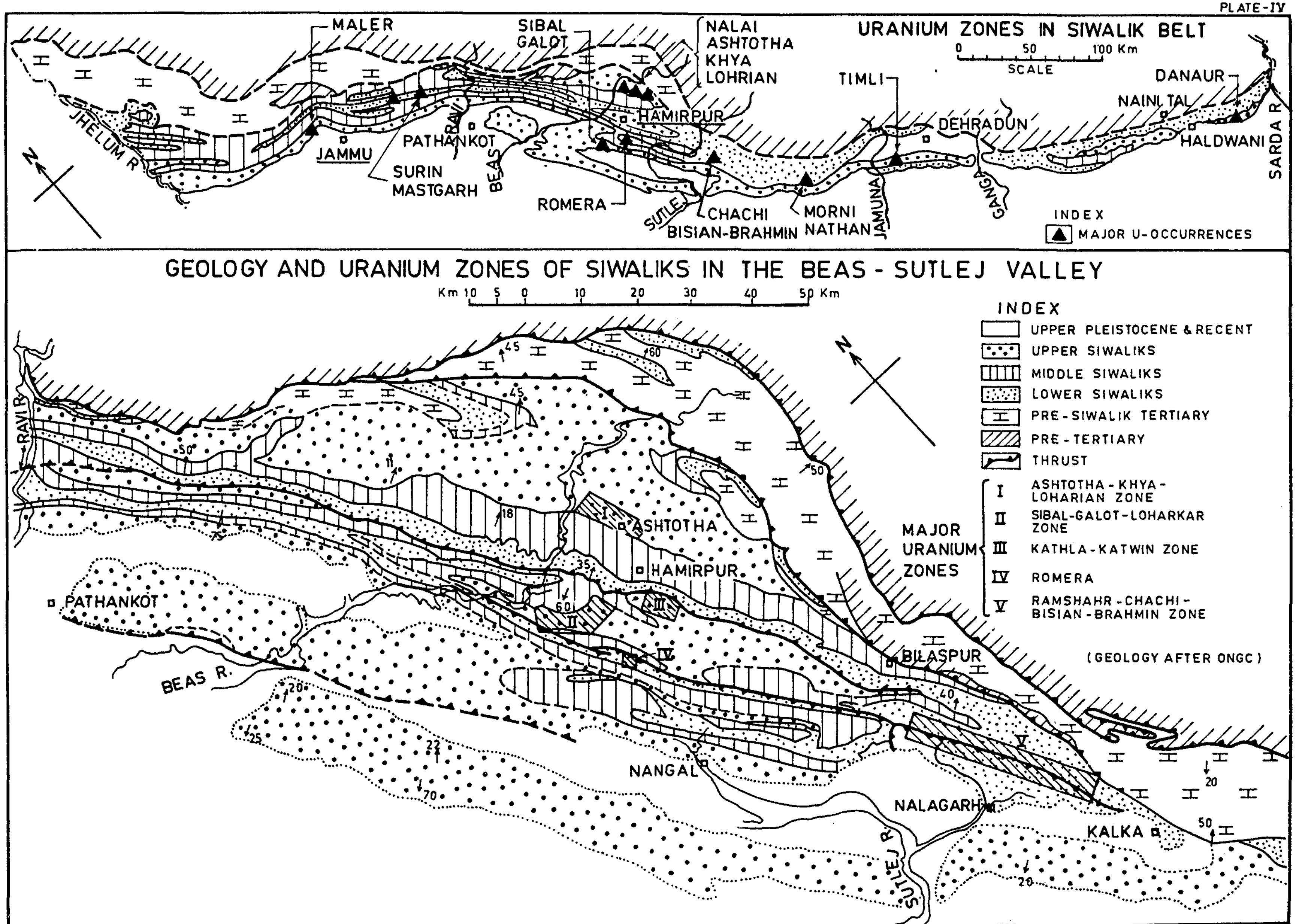
Lower-Middle-Upper Siwalik sequences are repeated due to thrusting and fold structures. The overall tectonic features are best described in relation to the Siwalik exposures in the Beas-Sutlej valley, where the Siwalik belt has the maximum width of some 80 km. The Siwalik belt tends to become very narrow to the NW in Jammu and SE towards Lohit. The general tectonic trends in the Beas-Sutlej basins strike NW-SE. The outermost ridges emerging from the Indo-Gangetic plains are anticlinal, exposing mainly Upper Siwaliks, and are followed further NE by folded tectonic units comprising Lower, Middle and Upper sequences separated by a number of thrusts and high angle reverse faults. These tectonic units have narrow tight anticlines and broad synclinal structurs and the latter, by virtue of low dips and numerous exposed anomalies, have been of much interest in uranium exploration. The Siwalik belt is limited to the north by the main boundary fault system extending arcuately from Bilaspur in the SE to Dharmashala in the NW.

Uranium minerlisation

Uraniferous zones in the Siwalik belt could be divided into five major geographic units and uranium concentrations are confined to two major stratigraphic horizons: (i) the Lower-Middle Siwalik transition, and (ii) the Middle-Upper transition. In each of these horizons the mineralisation is not confined to a specific bed or stratigraphic level but to a number of sand bodies spanning a sedimentary thickness of 100-200 m. The more important occurrences of uranium in each of the five belts are indicated in Plate IV (12, 13, 14, 15 and 16).

The most favourable sediments for uranium mineralisation are: (i) the channel-fill conglomerates and associated sandstones of the Middle-Upper Siwalik transition zone; (ii) Piedmont type conglomerates with thin sand lenses of Upper Siwaliks; (iii) grey cross-bedded sandstones of the upper part of the Middle

PLATE-IV



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Siwaliks; and (iv) grey to greenish-grey sandstone and associated clay-clast conglomerates of the upper part of the Lower Siwaliks.

Tectonic uplift

Phased uplift of the Siwalik with intervening periods of relative quiescence has resulted in a number of perched uranium enriched zones of significant extent and grade well above the present ground water table. This indicates that processes of enrichment of the uranium have been continuously taking place pari-passu with uplift (17).

Source of uranium

Palaeo-current directions, the antecedent character of the Himalayan rivers, the evolutionary history of the Siwalik fore-deep and the petrography of the Siwalik sediments reveal that they were derived from the Lesser and Central Himalaya, where extensive uranium mineralisation of the vein type are known in many parts of the provenance and the granitoids of the Central Himalaya are also known to be enriched in uranium.

Mineralogy

Uraninite and coffinite are the main uranium minerals. Uranium is enriched in the calcium phosphate in vertebrate fossils (7). Carbonaceous matter acts as a locus for fixing uranium, though not always. Finely crystalline pyrite is present. Azurite and malachite occur in the Lower-Middle Siwaliks in Romehra, Baroti, Kundlu and Nalagarh and the copper content varies from 0.01% to 1.88% Cu. The high copper content is due to clastic deposition of chalcopyrite and its subsequent oxidation in carbonate waters. Selenium, ranging from 4 to 280 ppm possibly fixed in pyrite has been noted in Astotha and Sibal-Galot areas in the Hamirpur area (18).

The presence of Bayleyite in Astotha, Khya and Timli, uranophane and beta-uranophane in Ramshahr, Morni and Astotha, tyuyamunite in Morni, autunite and torbernite in Romehra, schroeckingerite, swartzite and andersonite in Timli and schoepite in Timli and Katla deserve mention. These minerals occur along joints and fractures and in carbonised woody matter and as efflorescent deposition on rock surfaces in especially the Timli area.

DISCUSSION

The three sedimentary basins have evolved largely as a consequence of regional vertical tectonics. The disposition of the Gondwanas is intracratonic and that of the Siwaliks and the Mahadeks along the fringes of uplifted, more or less cratonised but reactivated blocks. These locales have no relationship to any of the recognisable plate tectonic margins.

The working genetic model of uranium enrichment envisages initial deposition of uranium-rich sediments in specific lithostratigraphic horizons. Subsequent enrichment took place as a result of tectonic uplift and consequent generation of the necessary hydrodynamic gradients. Uranium was mobilised from oxidised zones through groundwater media and deposited in zones of reduction, organic carbon and Fe^{2+} being the major reductants. The role of other precipitating factors, such as mixing of waters with resultant changes in Eh-pH conditions, influx of gaseous hydrocarbon reductants from deep below as a result of bacterial action, and nascent hydrogen cannot be ruled out.

The three areas witnessed no episodes of acid or alkaline magmatism subsequent to sedimentation. But the intense post-depositional basic magmatism in the Gondwana and immediately before deposition in the Mahadek regions, and the presence of deep crustal fractures and hot thermal springs in all the three areas, may be invoked to suggest a magmatic hydrothermal mineralisation. But the absence of uranium in the vicinity of basic magmatic bodies or the faults and hot springs negate such assumption. Detailed geochemical and isotopic studies may throw more light on this aspect.

The environments of deposition are fluvial in Moturs and Siwaliks and marginal marine to fluvial in the Mahadeks. The Mahadeks especially in the southern reaches of the Shillong horst are more sheet-like and the uraniferous beds in them are more consistently concordant and have a bed-like character. Possibilities of penesyngenetic enrichment (19), in these beds (especially in Gomaghat) cannot be ruled out, but evidences also indicate subsequent epigenetic increments from the overlying Upper Mahadeks. The Siwaliks and Motur mineralisation are peneconcordant and epigenetic enrichment through the media of ground water is more the general rule. In the Siwaliks, there have been more than one cycle of migration-accretion and in some areas this process seems to be active even today in the Upper Siwaliks.

The confinement of the uranium zones to specific lithostratigraphic horizons in all the three areas is related to episodes of tectonic uplift of provenance which helped to expose rocks initially enriched in uranium to mechanical and chemical weathering. Such uplift together with favourable arid-humid climatic interludes helped to transport uranium-rich sediments into the basins of deposition. Thus, there is a correlation between episodes of uplift of the provenance and uranium enrichment in specific sedimentary horizons.

The three areas, apart from their importance as hosts of mineralisation, throw open numerous possibilities of locating uranium ore bodies in the tectono-sedimentary sequences of which they form a part. In fact each represents a distinct geochemical uranium province.

Problems of Exploration

Three major problems in exploration for uranium need emphasis. In geological sequences of fluvial sediments, facies changes both along and across bedding set limitations on predicting the nature of sediments under younger cover. Secondly palaeo hydrodynamic conditions to which uranium mineralisation is related is difficult to be deciphered as post-ore tectonics modify the earlier settings. In areas of mostly uplift, all older water tables may be expected to be above the level of the present water table. But in areas with more complex tectonic history, such a simple rule cannot be applied and tracing of the palaeo water tables pose major problems. A multi disciplinary approach integrating geology with borehole geophysics possibly may help in the solution of this problem. Thirdly, the well known favourability criteria (20) are of a general nature and qualitative and many sedimentary sequences may answer these criteria but still not host any mineralisation of significance. More parameters of favourability, therefore, need to be identified.

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GEOLOGIC ENVIRONMENTS OF NINGYO-TOGE AND TONO URANIUM DEPOSITS, JAPAN

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Abstract

The regional geologic environments on the Ningyo-toge and Tono deposits, the most potential uranium occurrences in Japan, are summarized.

Although the geologic age of the host rocks in those two areas is different (in latest Miocene to earliest Pliocene age for the Ningyo-toge deposits and in middle Miocene age for the Tono deposits), they are similar to each other in their occurrence as the channel-filling sandstone type uranium deposits. The ore bodies occur in the basal conglomerate and arkosic sandstone resting on the granitic rock of late Cretaceous to early Paleogene age, with close-controlled layout by the drainage pattern on the paleosurface. The period of uranium precipitation seems to be soon after the deposition of host rocks.

The hydrogeochemical survey in the Tono area has revealed that high-alkaline, uranium- and fluorine-enriched groundwaters are confined into the disintegrated basement granite and permeable beds in the ore horizon. Uranium contents of the basement granites in both areas are relatively higher than the domestic averages, and assumed to be the potential source of ore uranium. Fracture systems around the basins, formed by the regional tectonic movements, played the important role for leaching of uranium from the source granites.

1. INTRODUCTION

The Ningyo-toge and Tono uranium deposits, the most potential reserves in Japan, were discovered by carborne survey in 1955 and in 1962, respectively. Before the discoverly of the Ningyo-toge deposits, the possibility of development of sedimentary-hosted uranium deposit had been assumed to be doubtful. At that time, the route of the carborne survey was selected in and around the granite mass in which several vein type uranium occurrences had been found. Therefore, new discovery of radioactive anomaly at the Ningyo-toge pass was an unexpected success.

Thereafter, intensive exploration and research works including grid drilling, revealed the characteristics of deposits, especially direct structural control by the paleochannels. The target of exploration was also drastically converted from the vein type metallic deposits to the Neogene lacustrine sediments overlying on the granitic basement. This change of strategy resulted in the next discovery in the Tono area, seven years later. Although the geologic age of the host rocks is different in both areas, the factors of structural control is remarkably resembling in each other as the typical basal-groundwater type of sandstone deposits.

Since the numerous works have been presented concerning those two areas, the description of deposits and minerals is simplified in this paper for avoiding the repetition. Special emphasis is put on the analysis of regional environments and occurrence of the uranium anomaly in groundwater, because they should be the effective indicators for the fundamental exploration works in the future.

2. GENERAL CONCEPTS ON THE NEOGENE SEDIMENTARY BASINS IN JAPAN

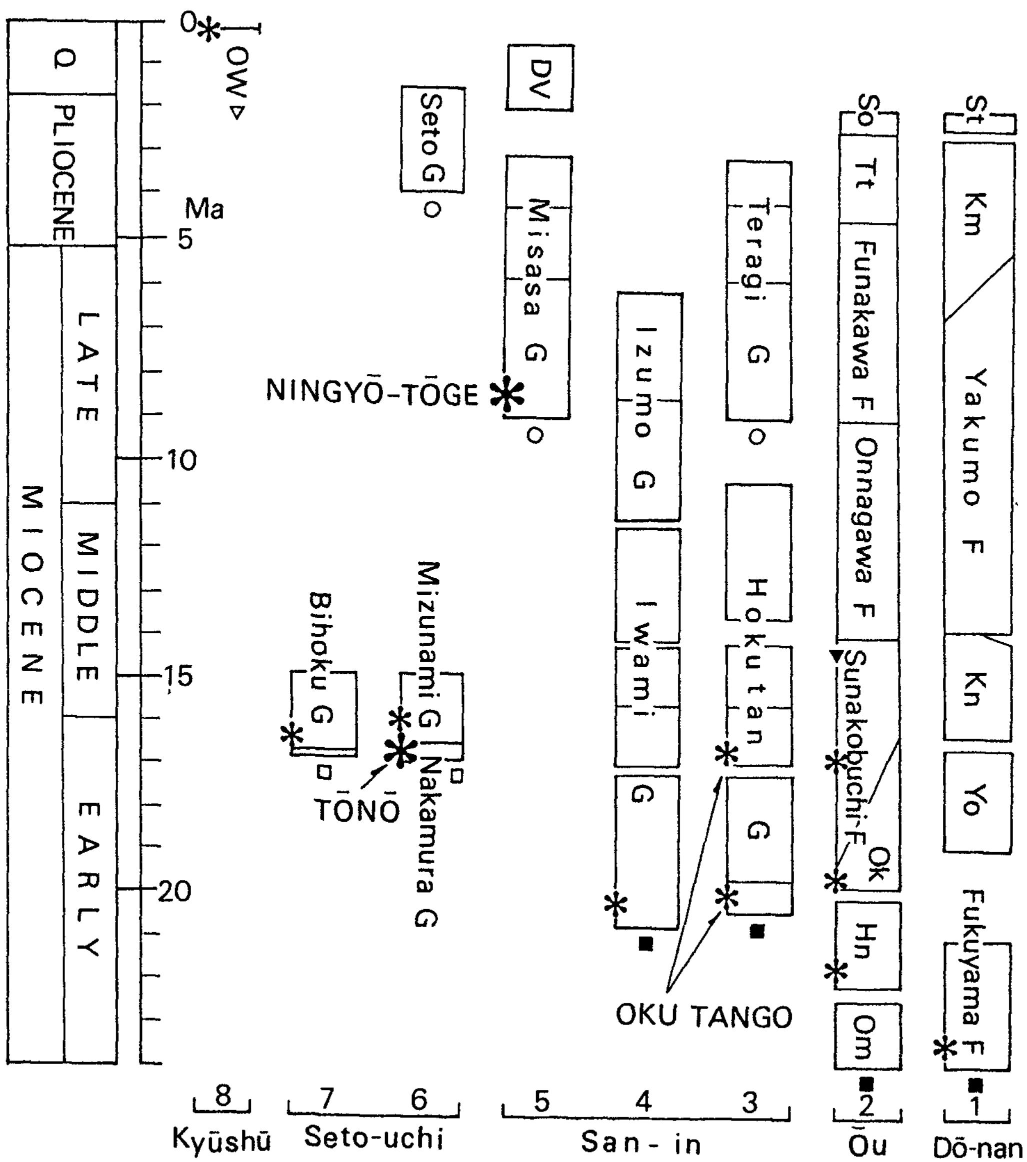
The most uranium occurrences of sandstone type deposits in Japan are distributed at the marginal parts of Neogene sedimentary basins. The geologic province at that time is divided into three regions: namely,

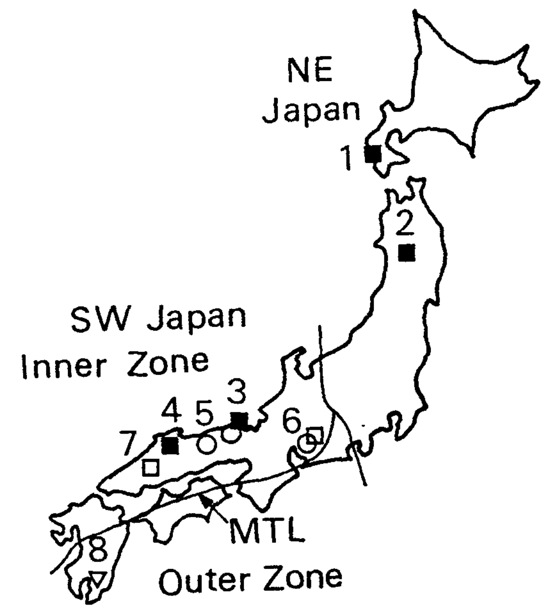
1) the "Green Tuff" region in Northeast Japan,
2) the "Green Tuff" region in the Inner Zone of Southwest Japan, and
3) the "Non Green Tuff" region in the Inner Zone of Southwest Japan (Seto-uchi province).

Simplified correlation diagram of each region are shown in Fig.1.

In the so-called "Green Tuff" region, violent tectonic movement had started in 20 to 23 Ma. Rapid depressions with numerous block faults in connection with volcanic activities took places all over the region, without any relation to the previous geologic structure.

Several uranium occurrences have been known in the tectonic basins in these "Green Tuff" region, throughout Northeast and Southwest Japan. Generally they are in small scale and of no economic interest. While the maximum thickness of sediments in the basin is ranging up to 3,000 m, the ore horizons are restricted in the normal sediments in the lowermost member of the formation, especially its lacustrine marginal facies. In the most cases, they are alkosic and contain organic matter. Owing to the local time lag of the depressions, the age of the host rocks of anomalies is diverse. The layout of the anomalies tend to be controlled by the fracture systems in the host rocks (4).





Abbr.: G:Group F:Formation
Q:Quaternary
DV:Daisen Volcanic Rocks
OW:Onobaru Welded Tuff
(Formation Names) Hn:Haginari
Km:Kuromatsunai Kn:Kunnui
Ok:Okuramata Om:Omata
So:Sasaoka St:Setana
Yo:Yoshioka

Symbols: ✱ Sandstone-type U dep.
Miocene basin ---
■ "Green Tuff" region
□ "Non Green Tuff" region
○ late Mio.-Pliocene basin
▽ Pleistocene basin
▼ U occurrence in Kuroko

Fig. 1 Correlation Diagram of Principal Uranium Occurrences in Neogene Sedimentary Basins
----compiled from (1),(2),(3)----

Another type of sedimentary basins in Miocene age develop in the "Non Green Tuff" region in the Inner zone of southwest Japan, in other words, Seto-uchi province.

The province is located approximately 50 km north in parallel to the Median Tectonic Line (MTL). In the province, the first event of the depression took place in 16 Ma, under the control of the parallel and/or conjugate faults of MTL. The subsidence in the region was much more gentle comparing to the movements in the "Green Tuff" region.

Just after the subsidence of the tectonic basin, detritus began to settle on the bottom of the basin in the lacustrine environment. In the middle to final stage, the basins were gently submerged into the shallow inland sea, so-called "Paleo Seto-uchi Inland Sea". Mudstone and siltstone beds in the upper horizons, somewhere tuffaceous, represent the sediments in this stage (Fig.2).

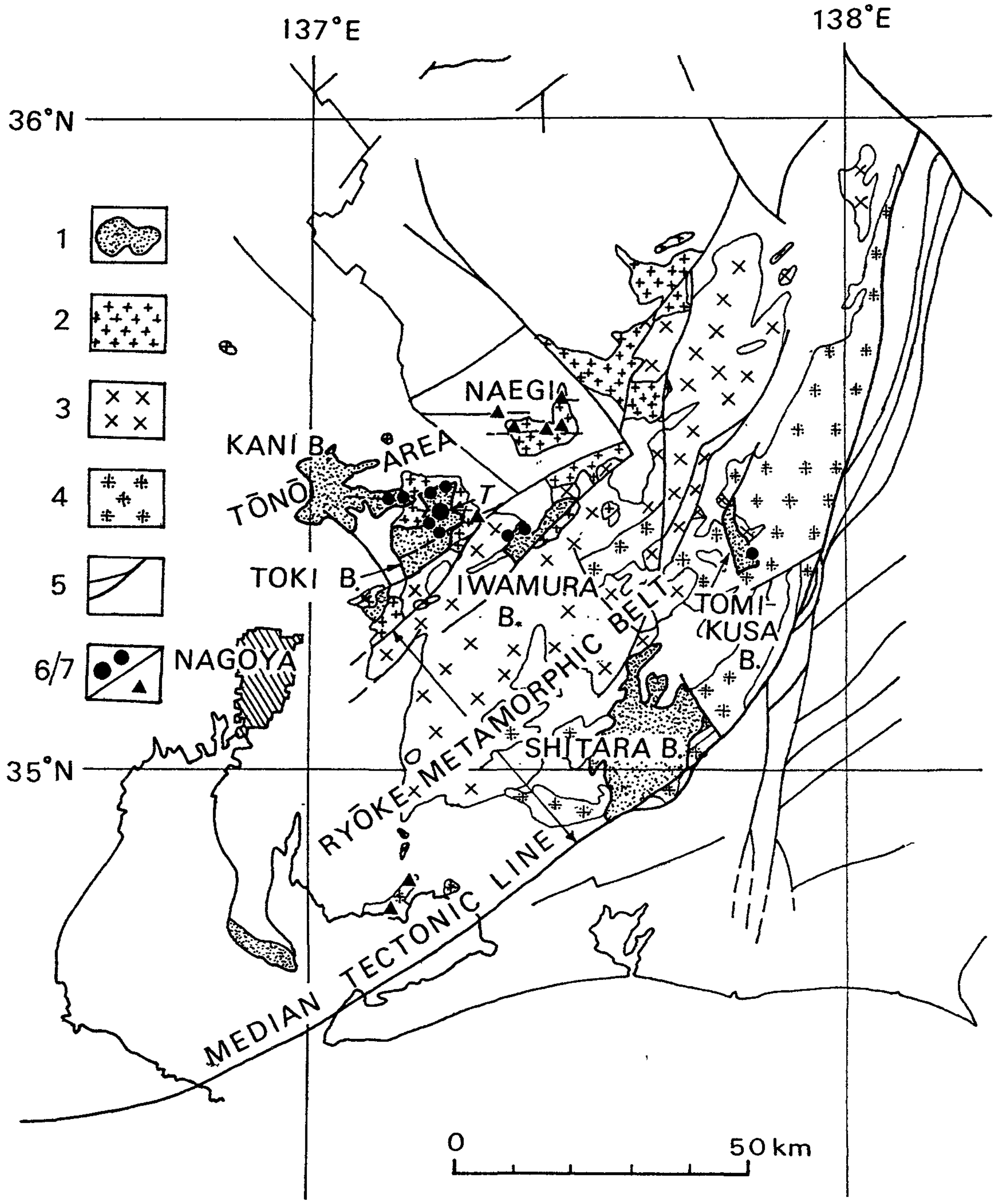
So far as the conditions for uranium concentration concerned, geologic environments of this region was more favorable than the "Green Tuff" region. In fact, uranium deposits in Tono area are embedded in this region.

In 9 Ma, late Miocene age, two inland sedimentary basins appeared in the eastern part of San-in province. The eastern one is the sedimentary basin of Teragi Group which rested on the "Green Tuff" formations of Hokutan Group. The western one is the basin of Misasa Group in which the Ningyo-toge deposits developed. Basement rocks of Misasa Group are well eroded pre-Tertiary granites and metamorphic rocks. During the period of the "Green Tuff" movement, this area still remained as a barrier between the Hokutan basin and San-in basin (Fig.3).

In the bottom part of Teragi and Misasa basins, thin normal sediments such as basal conglomerate, arkosic sandstone and siltstone are found, while the main parts of the group are consisted of the volcanic materials. In contrast to the other provinces, tectonic disturbance around the basins are moderate.

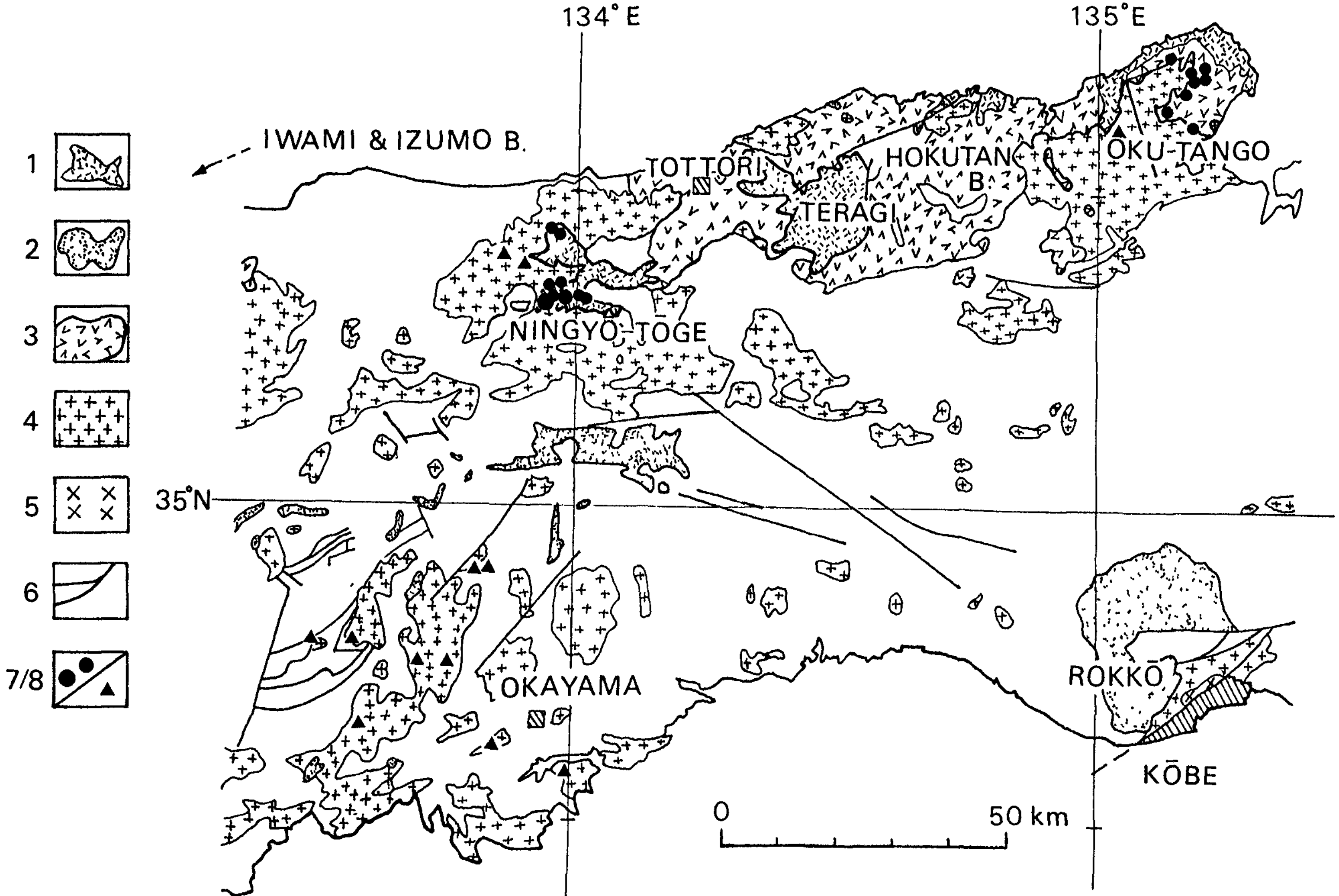
In late Miocene to early Pliocene age, a withdrawal of inland sea took place in the Seto-uchi province. The second subsidence and transgression occurred in the almost same area in late Pliocene age. In the Tono area, widespread loose conglomerate, arkose sand and clay beds of the Seto Group are identified to be the sediments in this stage.

As an exceptional occurrence, several uranium concentration are found in the ore horizon of Kuroko deposit in the "Green Tuff" basins. Such an ore bed overlies thick volcanic



1: Miocene sedimentary basin 2: Granitic rocks, late Cretaceous-early Paleogene 3: Do. (Younger Ryoke plutonic rocks) 4: Do., early Cretaceous (Older Ryoke plutonic rocks) 5: Faults 6: Sandstone type U deposit 7: Vein type or pegmatite U deposit
T : Tsukiyoshi Deposit, Tono Mine (PNC)
-----compiled from (5)-----

Fig. 2 Schematic Geologic Map around the Tono Area



-----compiled from (5)-----

1: Sedimentary basin, late Miocene - Pliocene 2: Do., middle Miocene (Seto-uchi belt) 3: Do., early-middle Miocene ("Green Tuff" region) 4: Granitic rocks, late Cretaceous - early Paleogene 5: Do. (Younger Ryoke plutonic rocks) 6: Faults 7: Sandstone type U deposit 8: Vein type or pegmatite U deposit

Fig. 3 Schematic Geologic Map around the Ningyo-toge Area sediments, and different genetic models should be proposed concordant with the genesis of metallic elements in the deposit.

3. SOURCE MATERIALS

So far as the case studies in Japan concerned, undoubtedly the most favorable source material of uranium is granitic rocks. The period of the intrusion of such granitic rocks were principally in latest Cretaceous to earliest Paleogene age (60 to 70 Ma, approximately).

An example of uranium and thorium content in granitic rocks related to the uranium occurrences or anomalies are summarized on Table 1 and Fig.4.

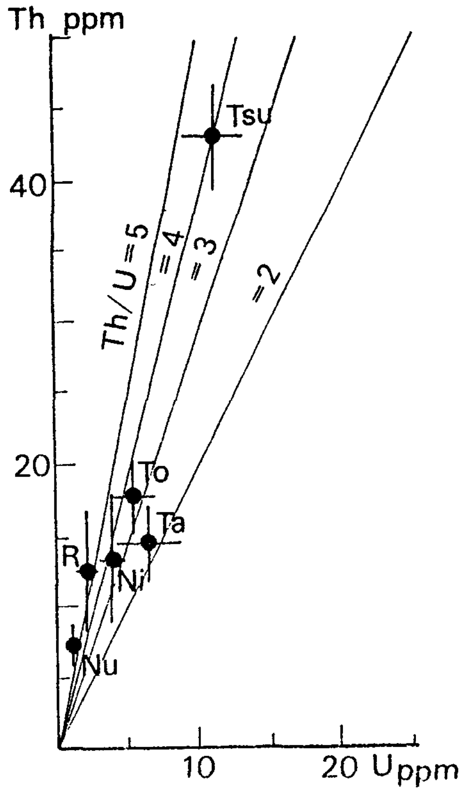
Ishihara et al.(6) confirmed that granites in the Inner Zone of Southwest Japan average 2.8 ppm of U and 12 ppm of Th with Th/U ratio of 4.3. These values are accepted as the reasonable standards.

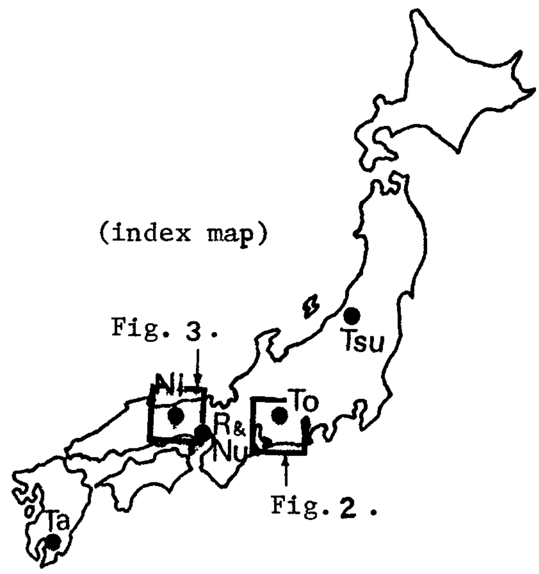
Comparing to them, however, several granite masses have higher concentrations of uranium and thorium. In case of Kogawa granite in Niigata prefecture, Northeast Japan, it contains about 3.5 times of uranium and thorium. In case of Rokko granite and Nunobiki granodiorite in the Rokko Mountains, Hyogo prefecture, Southwest Japan, analysis revealed the significant amounts of deficiency of uranium and high Th/U ratio. The rocks in the Mountains have been subjected to stress resulting in thrusts since 0.5 Ma, consequently, the phenomenon is evidently caused by the leaching of detectable amount of uranium by the circulation of carbonated waters through the well-developed fractures and shear zones. In such groundwaters, remarkable uranium concentration is also detected(7).

Abbr.: Area	Rock Name	No.S.	U ppm	Th ppm	Th/U	
Tsu:Tsugawa	Kogawa gr.	7	10.7±2.7	43.1±4.0	4.0	b)
To :Tono	Toki gr.	24	5.3±2.1	17.8±4.6	3.4	a)
R :Rokko	Rokko gr.	13	2.0±0.6	12.6±4.6	6.4	b)
Nu :Rokko	Nunobiki gd.	6	1.0±0.3	7.5±1.6	7.5	b)
Ni :Ningyo-toge	Ningyo-t.gr.	4	3.8±1.0	16.5±5.1	4.3	a)
Ta :Tarumizu	Takakuma gr.	5	6.4±2.7	14.6±3.2	2.3	a,c)

a) After (6). Recalculated.
b) After (7). Analyst:Mochizuki,T.(GSJ).
c) Reference on Tertiary granite of the Outer Zone, Southwest Japan (No water anomaly).
No.S.: Number of specimens.

Table 1. Uranium and Thorium Contents in Granitic Rocks





← Fig. 4.
Uranium - Thorium ratio in Granitic Rocks
(cf. Table 1)

In case of the Nigyo-toge and Tono areas, uranium and thorium in granites average slightly higher than the Ishihara's values, but still remain in the moderate level as well as Th/U ratio. It means that even the concentration of uranium in the source rock is not prominent, in case that the other geologic conditions are optimum, uranium may moved to the host sediments and able to be formed the deposits.

Volcanic materials in the upper horizons in both area are believed not to be the source materials of uranium. In Misasa Group of Ningyo-toge area, andesitic tuff and tuff breccias are widely extended over the basin. The situations are almost same in the Toki and Kani basin in Tono area, except for the volcanic substances are more acidic and in smaller amount. The layout of the uranium occurrences, however, is limited in the area of granite basement, or strictly limited outskirt zone of it. Such a fact is inadequate to the tuff-origin theory.

4. GEOLOGICAL SETTING AND OCCURRENCE OF URANIUM DEPOSITS

The geological setting and uranium occurrence in the Ningyo-toge and Tono deposits have been described in detail in various reports(8,9,10,11, for examples). Therefore, only some brief repetitions are given in this chapter.

4.1. NINGYO-TOGE AREA

-----Geological Setting-----

The Ningyo-toge area is situated on the Honshu Island Divide in the Chugoku Mountains, bordering Okayama and Tottori prefectures. The altitude of the mining site is around 700 m.

Before the deposition of the Misasa Group, gentle eroded paleosurface had been spreading over the area.

The basement rocks are principally granitoids (medium- to fine-grained hornblende-biotite granodiorite, medium- to fine-grained biotite adamellite, coarse-grained biotite granite, aplitic biotite granite etc.). In the eastern part of the area, phyllitic rocks of Sangun metamorphic belt and in the western part, small andesite and rhyolite masses are cropping out.

The mineralized horizon is in the lowermost part of Misasa Group. The host rocks are loose boulder to pebbly conglomerate and arkosic sandstone with poor sorting at the bottom. Boulders in the conglomerate consist of granitic rocks from the basement as well as pre-granite andesite and rhyolite derived from western part of the area. matrix of the conglomerate is also arkosic.

The layout and features of conglomerate and arkosic sandstone, about 10 m thick in total, are typical channel-filling sediments. On the top of arkosic sandstone, laminated mudstone is resting. In the upper horizons of the Misasa Group, three or four volcanic cycles are distinguishable.

-----Uranium Concentration-----

Uranium concentration is principally limited in the basal part of conglomerate and sandstone. Impermeable bed of mudstone is effective as an cap rock for controlling groundwater system. In general, mudstone is barren, but in several limited sites above the bonanza, it is also mineralized.

Mineralization controlled by the stagnate water table is occasionally in the host rock up to 40 m above the unconformity plane. Secondary migration of uranium along the minor faults which disturbed the primary ore body is also observed in the mudstone horizon.

The principal ore minerals in the area is ningyoite with small amounts of uraninite. Ningyoite impregnates in sandstone and arkosic matrix of conglomerate with fine-grained pyrite, marcasite and gypsum. High grade ore is black, sooty mass in appearance. Uranium concentration in organic matters such as lignite log is also remarkable.

In oxidized zone near the present surface, the principal secondary mineral is autunite. Autunite coats over the pebbles in basal conglomerate, fills on the microfracture of pebble, and impregnates in the sandstone and matrix of conglomerate.

-----Hydrogeochemistry and Groundwater System-----

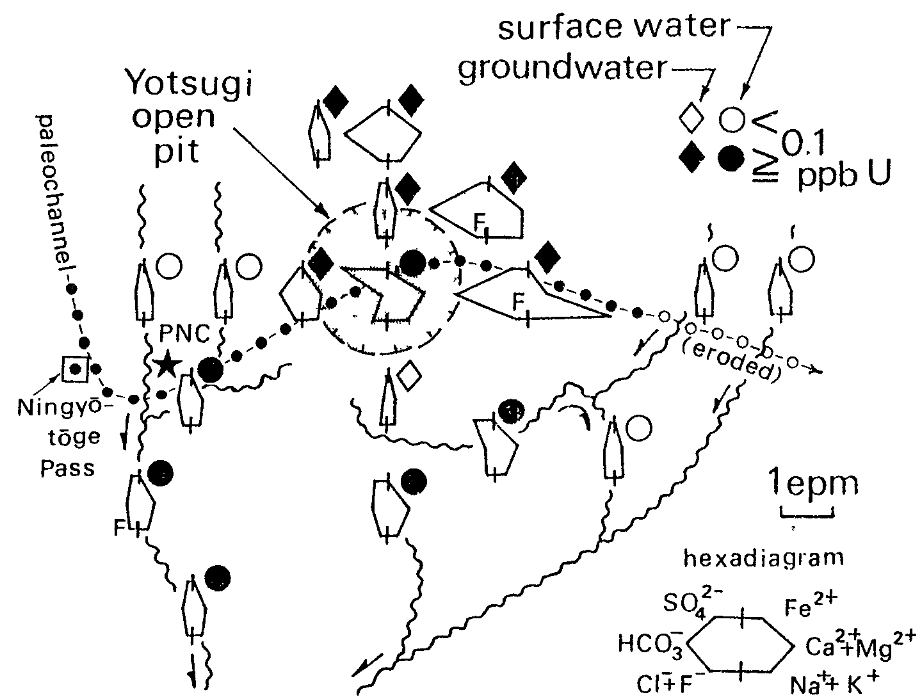
The main paleochannel in the Ningyo-toge area trends approximately west to east. As recent drainage system is perfectly discordant, the paleochannels has been eroded into small pieces. In this time, the aquifers in the area are in small scale(Fig.6A).

For this reason, in addition to the thin overburden, yield of groundwater is inferior to the other uranium areas. Rapid runoff of the stream water, especially on the granitic river floor, prevents effective recharge of groundwater system. Background level of uranium in the stream waters is less than 0.1ppb, and no anomaly is analysed out of the mining areas. It means that the stream water anomaly should be an indicator for the uranium concentration in the upper stream.

At present, no mine water can be collected from the underground galleries because they are temporally closed. Previous works (13,14,15) proved that mine water was neutral to moderately acidic, and contained reasonable amount of uranium and sulfate ion which caused by the oxidation of primary uranium minerals and sulfides.

Water sampling in and around ore body is possible only in the monitoring wells of Yotsugi open pit, where test operations have been carrying on by the Power Reactor and Nuclear Fuel Development Corporation (PNC). Although rainfall migration is suspected through mudstone cap rock by disturbance of stripping and excavating, the analysis proved out that common chemical compositions of the waters were increasing towards the downstream of the paleochannel(Fig.5). It implies that the local hydroauric gradient is still preserved the trend of the paleochannel.

No evidence is confirmed that the recent mineral spring water in the area would be the effective carrier of mobile uranium. The age of ningyoite by means of U-Pb method is



coll. in Nov. 1980
analyst : Mochizuki,T.

Fig. 5. Composition of Waters around Yotsugi Open Pit, Ningyo-toge Deposit

reported approximately 10 Ma(16). Taking into account of the experimental errors, the mineral age and the biostratigraphic age of host rock are in coincidence. It supports the conclusion of previous works that the deposition of uranium took place just after the sedimentation of the host rocks.

4.2. TONO AREA

-----Geological Setting-----

Tono area is located around 40 km northeast of Nagoya City, Central Japan.

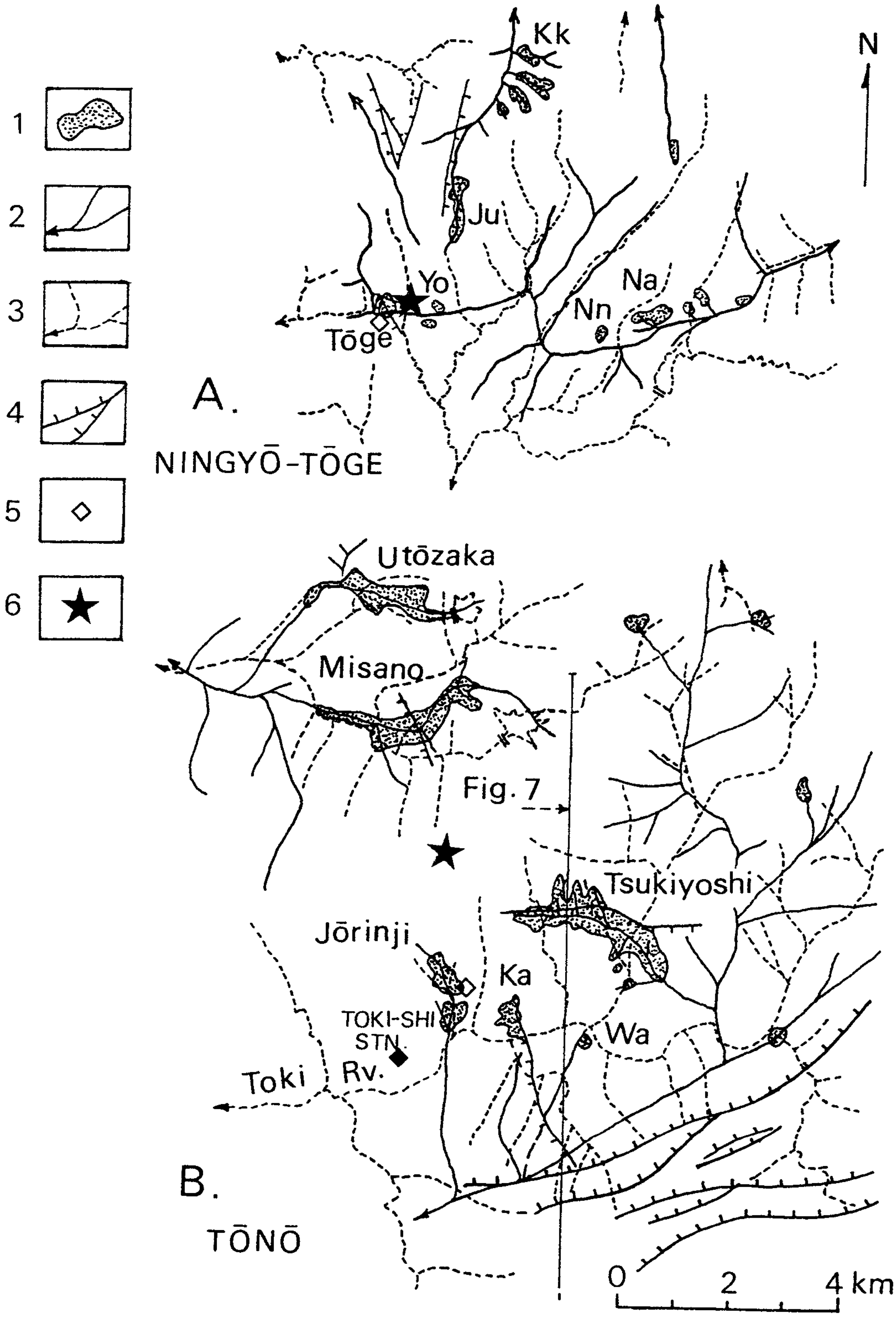
In the area, three tectonic basins of Miocene age, Iwamura, Toki and Kani Basin, have been situated trending east to west. Those basins are in the first Seto-uchi submerging belt, which had been formed along the compression zone parallel to the Median Tectonic Line(17). Reflecting such geologic conditions, the basement rock in the area has been dislocated more violently than in the Ningyo-Toge area.

The first step of the formation of tectonic basins was the block subsidence. At the western margin of Kani basin, an andesitic volcanism took place just after the depression. Such events are essentially resembling to the first step of development of "Green Tuff" basins, where the subsidences and block movements were remarkable. Different from the "Green Tuff" region, however, tectonic movement was comparatively moderate in the Seto-uchi zone, and did not continue to the main stage.

Basement rocks in the area are chiefly composed of granite and granodiorite. Besides granitic rocks, Mesozoic chert and pelitic rocks are distributed in the central to western part of Kani basin, and Ryoke metamorphic rocks, in the eastern part of Iwamura basin.

The paleochannels in the basins are arranged concordant with the fractures or faults of the basement. In case of granitic rocks, paleosurface has been severely weathered and disintegrated. The unconformity plane between decomposed granite and in-situ arkosic sandstone is often indistinguishable (Fig.6B).

The channel-filling materials are conglomerate with arkosic matrix and coarse- to medium-grained arkosic sandstone. The deposition took place under lacustrine environment. Thin coal seams are also intercalated, which tend to be thickened towards the northern part of Toki basin as well as towards the center of Kani basin. They were previously operated for the fuel of local use, but no uranium concentration is detected in the workable lignite bed.



1: Uranium deposit 2: Drainage system, at present 3: Do., paleochannel 4: Faults 5: Site of the first discovery
6: PNC office
Kk: Kannokura Ju: Junikawa Yo: Yotsugi Na: Nakatsugo
Nn: Nakatsugo-nambu Ka: Kawai Wa: Wago
-----arranged from (9)-A and (10)-B-----

Fig. 6. Drainage Systems in the Ningyo-toge and Tono Area

Except for the Kani basin, where no transgression had occur, middle and upper parts of the Miocene sediments are composed of shallow marine facies of siltstone-sandstone alterations. Tuffaceous siltstone and pumice tuff beds are also frequently intercalated. Abundant shell fossils, found at the lowermost horizon of marine facies, are effective to determine the biochronological age of the bed, as well as the microfossils in the upper horizons, or plant fossils in the lacustrine beds in the lower horizons.

Those sediments are classified into two principal groups. The beds including coal seams and arkosic substance are called the Toki Group, "Toki Lignite-bearing Formation", or the Nakamura Group. Marine facies and tuffaceous members in the middle to the upper horizon of lacustrine facies are called the Mizunami Group. No distinct disconformity is provided between those two groups. Therefore, the name of Mizunami Group is often used in its broad sense, representing whole Miocene sediments in this area.

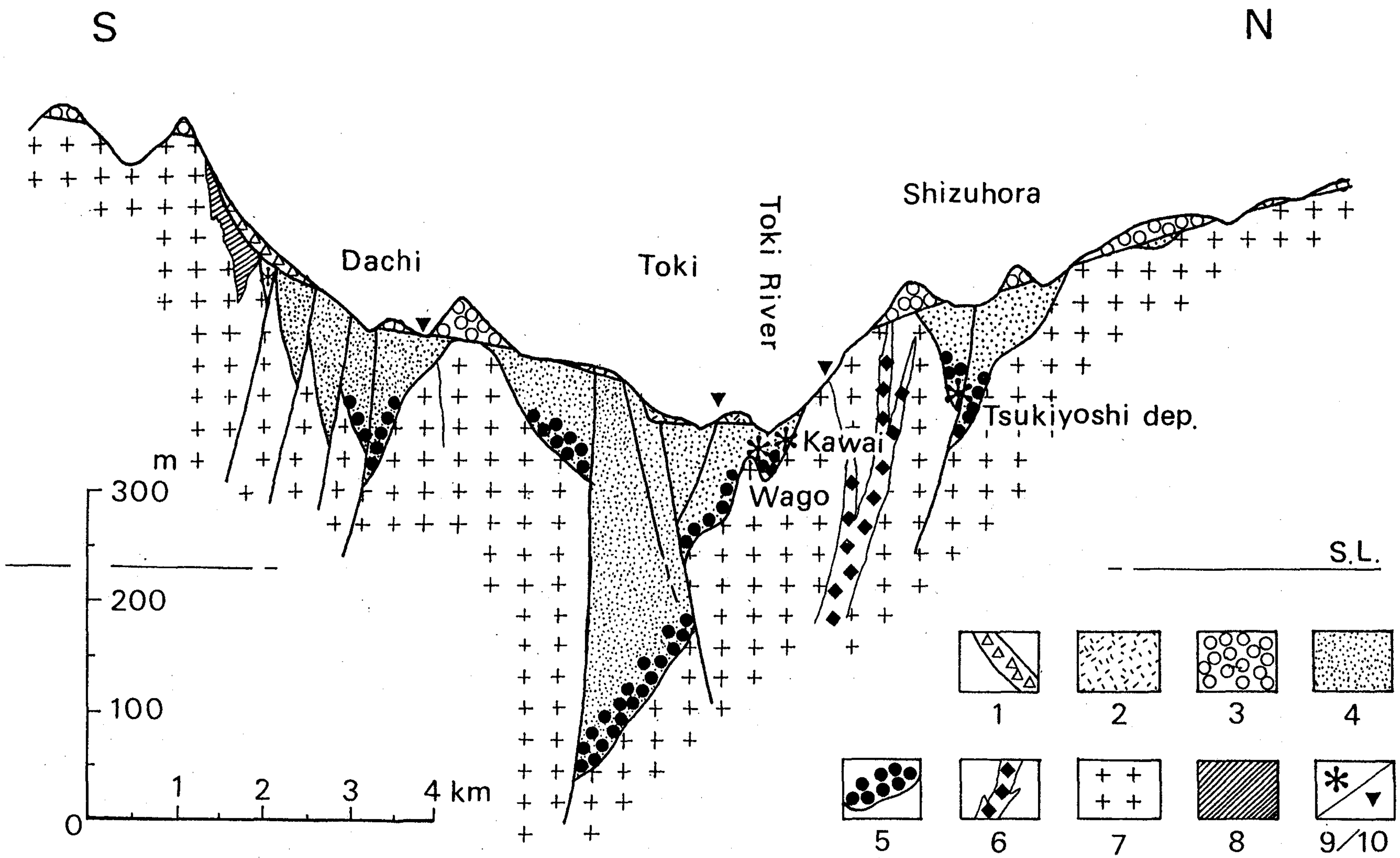
-----Uranium Concentration-----

The main ore bodies of uranium occur in the bottom of Toki Group. Strong anomalies are also in the marginal part of marine facies occasionally.

The Tsukiyoshi deposit of the Tono Mine, one of the most potential ore reserves in Japan, has been operating by PNC for the test of underground solution mining. Occurrence of uranium has been described precisely by Katayama et al.(10). Uranium concentration has taken place along the chemical front in permeable bed being situated just above the unconformity plane. On such a chemical front, considerable amounts of uranium is adsorped on clinoptilolite-heulandite in the matrix of conglomerate. Zeolites and calcite in the matrix are assumed to be a product of diagenesis.

Except for the small amount of uraninite and coffinite, few tetravalent uranium minerals are observed in the unoxidized zone. In the oxidized zone, uranocircite and several common secondary minerals are found. On the wall of the gallery, liebigite and andersonite are locally blooming.

The occurrence of uranium in the area evidently indicates the characteristics of the basal groundwater type of deposit. While no uranium indications is found in the overlying sediments in Tsukiyoshi area, several stacked anomalies have been detected between 40 and 90 m above the unconformity plane in the eastern part of Kani basin(18). It suggests that, at least, a part of uranium was also concentrated on the stagnate water tables in previous times,



1: talus breccia 2: river terrace 3: Seto Group 4: Mizunami Group 5: Toki Group
6: quartz-porphyry 7: granite 8: hornfels 9: U deposit 10: mineral spring

Fig. 7. Schematic Cross Section of the Toki Tectonic Basin

probably not much later than the sedimentation of the host rocks.

-----Hydrogeochemistry and Groundwater System-----

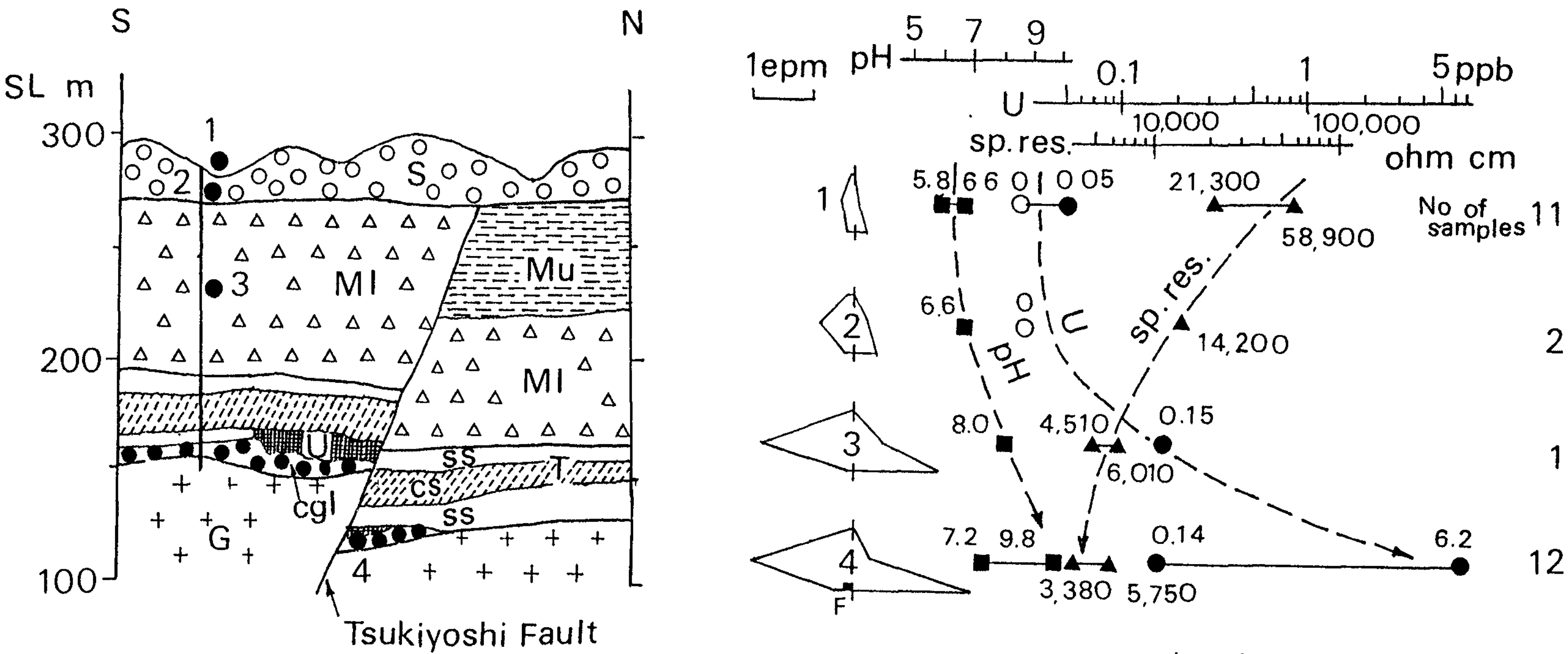
The groundwater system in the Tono area is more complicated than in the Ningyo-toge area. It is because that the overburden is up to 300 m thick, and several aquifers are stacked up in the same locality. Lineaments in the area, including main faults by which the development of the basins have been controlled, seem to be still effective as the conduit of groundwaters.

The hilltop of the area is covered by loose pebbly conglomerate of the Seto Group of late Pliocene to earliest Pleistocene age. Groundwater in this group, being directly recharged by rainfall, is immediately discharged through the unconformity plane between the Mizunami Group. Resident time of water is too short to accept the considerable amounts of soluble matter from the conglomerate. Consequently, water from the Seto Group is comparatively pure, in high specific resistivity, free from uranium and in high tritium content (43.1 ± 5.3 T.U. collected in December, 1977),(Fig.8).

Groundwaters in the aquifers of the Mizunami Group are more stagnate, and contain more solutes than the groundwater in the Seto Group. Sodium, calcium, and bicarbonate are essential but in moderate level. The yield of the groundwater from those aquifers is in limited scale.

Uraniferous groundwater occurs principally in the basal part of the basin where the Toki Group is resting on granitic rock. Being affected by the minerals such as zeolite, calcite and montmorillonite in the host rock, the water contains higher level of bicarbonate and sodium ions. In general, concentration of fluorine ion is notable. Uranium anomalies in waters are also in common, especially in the marginal part of the basin, where the small paleochannels are arranged. Such waters are alkalic, in low levels of specific resistivity and tritium content(0.38 ± 0.12 T.U. Do.). It means that the water is stagnate in the basemental aquifer, and vertical recharge between the aquifers in different horizons is scarcely happening.

Several mineral springs are flowing out through the fractures. Some of them, especially in the granite area, are uraniferous. Composition of the spring waters are not identical, but varies reflecting on their mode of occurrences. For instance, mineral spring water along the major fault zone in the center of Toki Basin, contains the notable amount of sodium and chlorine ions. The most of



samples: 1: surface water
(hexadiagram -- from Kyuroku-bora)
2: groundwater, Seto G. (sublevel A conduit)
3: do., Mizunami G. (sublevel C conduit)
4: do., Toki G. (main level No. 11 bore hole)
coll. in Dec. 1976

abbr.: S:Seto Group M:Mizunami G. (u:upper l:lower) T:Toki G. (cgl:conglomerate ss:sandstone and shale cs:coaly sandstone) G:Granite U:uranium deposit

-----index cross section is simplified from (10)-----

Fig. 8. Characteristics of Waters around the Tsukiyoshi Deposit

uraniferous fissure waters are characterized in abundance of calcium, sodium, fluorine and bicarbonate ions, which are effective carrier of uranyl complex.

5. DISCUSSION AND CONCLUSION

The potential uranium occurrences in the Ningyo-toge and Tono deposits are not extraordinarily in their fundamental characteristics in comparison with the other smaller deposits or indications. The layout of the deposits is restricted in the basal or marginal parts of the formations, and directly controlled by the aquifer of basal-groundwater in channel-filling sediments. The favorable conditions in both areas seem to be the circulation of mineral spring waters.

Throughout all over the deposits since Neogene Tertiary age, no specific period is found concerning the uranium mineralization. The youngest one is in Tarumizu area, southern Kyushu Island, where uranium indication has been observed in the bottom of Pleistocene welded tuff overlying the leucoclatic granites of 16 Ma age. The time factor is only playing the role which restricts the horizon of mineralization in each basins.

The fact that the uranium indications are widespread throughout the Neogene time and region, suggests the mechanism of uranium transportation and concentration should not be the special events. Considering in the scale of individual basin, observations imply that the intense uranium leaching took place at the early stage of subsidence. The favorable conditions at that time seem to be the deep weathering on the surface, or along the fractures in the granitic basement, where the groundwater migration took place. In case that the water is carbonated, large amount of uranium could be released from the disintegrated basal granite by circulation of carbonated waters through the numerous shear zone and fractures, as seen in the Rokko Mountains at present.

In the following stages, the basin was widely spreading over the eroded surface on the granites. At that time, supply of uranium to the sediment might be exhausted. that is the reason why the indications are limited in the basemental sediments. Contemporaneous to the diagenesis, uranium undergoes the redistribution in the mineralized horizon.

The model discussed above suggests the possibility of discovery of unknown blind deposits at the bottom or margin of smaller sedimentary basins in the granite areas. Further investigations will be expected in such localities as well as the exploration works in the acidic tuff area.

Acknowledgements

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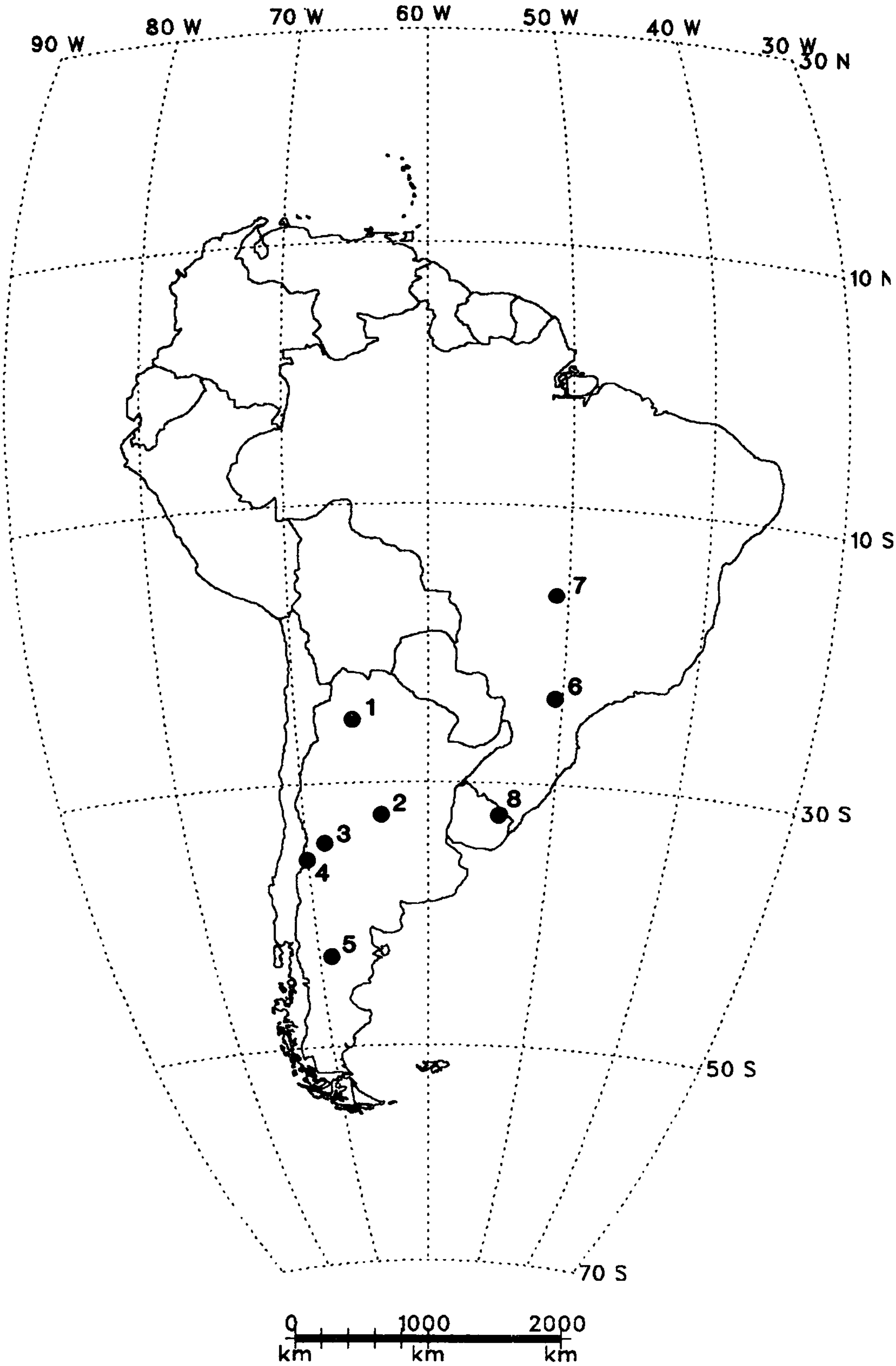
SOUTH AMERICA

MAP AND INDEX LIST FOR SANDSTONE-TYPE URANIUM DEPOSITS IN SOUTH AMERICA



SOUTH AMERICA

Argentina:

1. Tonco-Alemania District, Salta Province, Cretaceous Yacoraite Formation
2. Rodolfo, Cosquin District, Cordoba Province, Eocene Cosquin Formation
3. Los Reyunos, Sierra Pintada, Mendoza Province, Permian Cochi-co Group
4. Huemul, Malarque District, Mendoza Province, Cretaceous conglomerate and sandstone
5. Pichinan-Sierra Cuadrada, Chubut Province, Cretaceous Chubut Group

Brazil:

6. Figueira, Parana Basin, Permo-Carboniferous Rio Bonito sandstone and siltstone
7. Amorinopolis deposit, Parana Basin, Devonian Ponta Grossa sandstone

Uraquay:

8. Cerro Largo, Permian-Carboniferous San Gregorio-Tres Islas Formation

THE SEDIMENTARY CONTROLLED URANIUM DEPOSITS IN ARGENTINA AND THEIR RELATION TO THE GEOSTRUCTURAL DEVELOPMENT

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Abstract

The main features of the geostructural evolution of Argentina and their relation to the location of uranium deposits in sandstone are described.

The importance of the Precambrian-Eopaleozoic igneous-metamorphic complex is highlighted; it acted as "nesocraton" occupying the central and extra-Andean southern part of Argentina, yielding sediments and the uranium to the Paleozoic, Mesozoic, and Cenozoic intracratonic basins and mobile belts.

The lithology, stratigraphy, structure, and environment of the basin are described together with their uranium favourability.

I-. INTRODUCTION

Ninety percent of Argentina's uranium resources (RAR + EAR = 53.400 t U) are in stratiform uranium deposits in continental clastic sediments of Carboniferous-Permian, Cretaceous or Tertiary age. (1) . Although these geologic periods correspond to worldwide uranium host-rock ages (2) , it is not only a matter of age, but the combination of the environmental and geological conditions of the uranium geochemical cycle. The exogenic phase of this cycle is formed by:

- source areas with leachable uranium.
- host areas with suitable conditions of transmissivity and precipitation of the uranium.
- adequate media favouring the liberation and circulation of the uranium (climate, morphology, etc.)

In Argentina the deposits of the sandstone-type are also controlled by the geostructural development of the "Central Craton" (3) , a positive structure since the Eopaleozoic, which yielded the material and the uranium that filled the epi-and intracratonic basins that formed from the Paleozoic to the Cenozoic.

The uranium deposits of the type are located mainly in continental and paralic clastic sediments that are very little disturbed. These types of sediments are formed in desertic climates having occasional wet periods. These climatic conditions prevailed in some basins during the Carboniferous, Permian, Cretaceous and Tertiary, providing conditions favourable for the formation of uranium deposits in the sediments of the basins. (4)

II-. GENERAL OUTLINE OF THE "CENTRAL CRATON" AND ITS URANIFEROUS BACKGROUND

II.I-. General evolution and composition

The central craton was a stable basement, that formed the backbone of the central and southern areas of Argentina, and controlled its geological development. Structurally acted as a 'nesocraton' according to the definition of Harrington (5) , that is, as a stable positive region, through later geologic episodes.

This sialic continental block, southwest of the Brazilian Shield, is formed by the nesocratons of the "Sierras Pampeanas" and the "Plataforma Patagónica" (Figure 2) and formed by Precambrian-Lower Paleozoic igneous and metamorphic complexes.

The metamorphic rocks were derived from pelites, psamites and limestones deposited in mobile belts in the upper Proterozoic. The Uruaguano orogenic cycle (900-1300 my) and especially the upper Brasiliano cycle (500 - 650 my) generated phyllites, quartzites, amphibolites, crystalline limestones and gneisses.

In the Eopaleozoic, this Precambrian core acted as a positive body bordered on the east and west by mobile belts where marine and in a lesser extent continental sediments were deposited.

The Caledonian diastrophic cycle produced an intense folding of the Eopaleozoic sequences and magmatism with pre, syn and post-tectonic intrusion that affected the craton, intruding granitic and granodioritic stocks and batholiths, and pegmatite dikes. In the Sierras Pampeanas these intrusives show three radiometric ages 520, 450 and 330 - 300 my (6) .

From the Neopaleozoic to the Quaternary, the craton has been intensely eroded, and the diastrophic cycles from Variscan to Andean generated epirogenetic tilting and faulting of blocks along meridional trends, activated until the Quaternary.

Research on uranium fertility of the craton shows that several of its igneous sequences have an uranium content higher than clarke.

The most conspicuous granitic intrusives are those 450-350 my old. They are present in several orographic regions of the Sierras Pampeanas (Sierras of Belén, Fiambalá, Velazco, Achala, Comechingones, etc.) with 20 ppm U (7) . These plutonic bodies show uranium deposits in veins and stockworks (Los Gigantes, Comechingones, etc.). To this magmatism of the Craton we can add the plutons and effusives of the Variscan magmatism, that are also anomalously high in uranium.

II.2-. Present morphologhy of the craton and marginal morphostructural sequences

The Craton is exposed in the Sierras Pampeanas formed by low ridges from 500 to 1500 m high, and in some cases by mountains of up to 2500 m altitude, divided by N-S valleys, and on the Patagonian Platform with a "mesa" topography of 500 - 1000 m of altitude and occasional ridges up to 1500 m high. (Figure 2).

Bordering the Craton to the east is the Chaco Paraná Plain with a thick Quaternary cover, and to the west there are mountains ranges with peaks of more than 6000 m altitude in the morphoestructural regions known as Puna, Precordillera and Cordillera Principal, in the Andean orogenic belt (Figure 1).

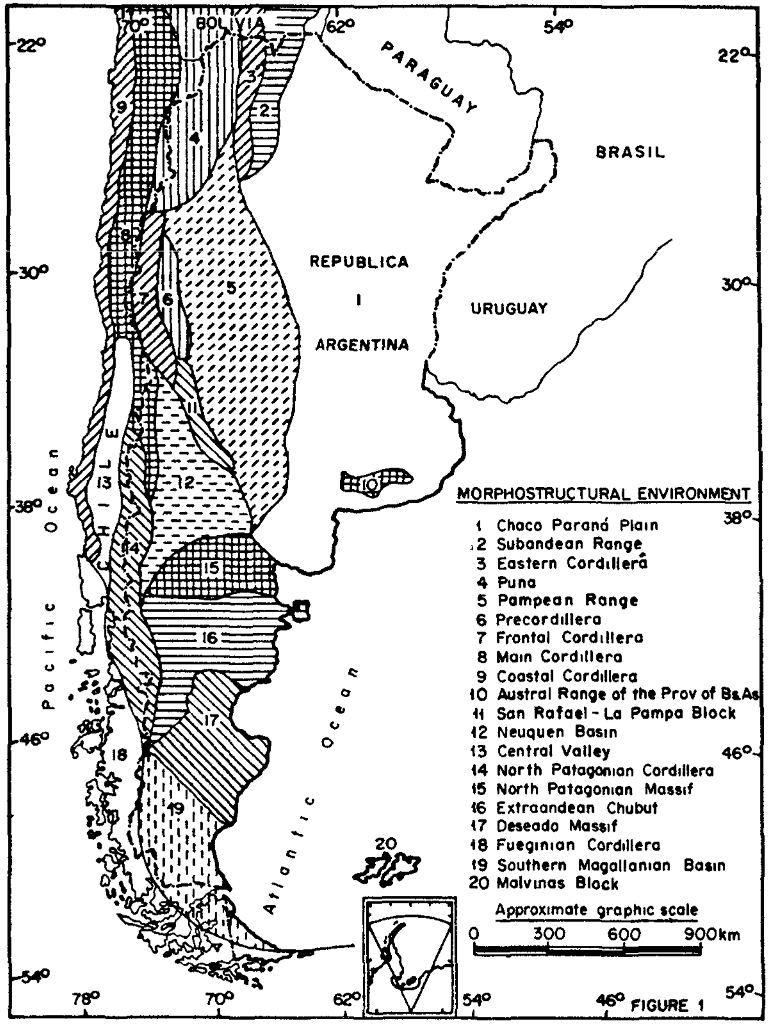

FIGURE 1

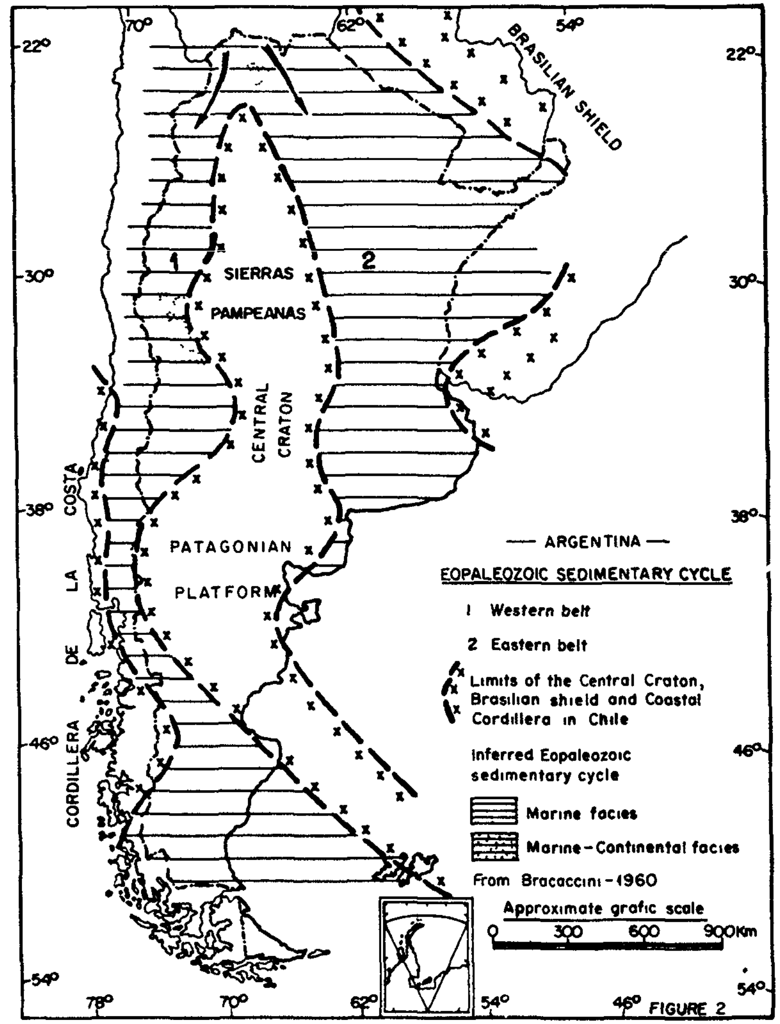

FIGURE 2

III-. URANIUM POTENTIAL OF THE PALEOZOIC MESOZOIC AND TERTIARY SEDIMENTARY BASINS

The Paleozoic, Mesozoic, and Cenozoic sedimentary cycles were affected by orogenic events that produced the dislocation and degradation of their lithostructural sequences, making it very difficult to identify the original areas of deposition and almost impossible to reconstruct the original basins.

In our case it is important to understand the distribution of the basins and the character of their sediments in order to differenciate the deep marine sediments of very little potential for uranium deposits,from the paralic and continental sediments,favourable for groundwater circulation and precipitation of uranium.

In order to understand the distribution of the favourable sedimentary basins, it is necessary to consider the tecto-magmatic periods that generated source areas and specific paleo-climatic conditions,that made possible the liberation and circulation of uraniferous solutions (8).

To simplify the interpretation, we will consider only the main sedimentary geologic cycles:

- Eopaleozoic cycle: Cambrian-Ordovician and Silurian-Devonian.
- Neopaleozoic-Triassic cycles: Carboniferous-Permian-Triassic.
- Mesozoic cycle: Jurassic-Cretaceous.
- Tertiary cycle: Eocene to Pliocene.

III.I-. General outline of the Eopaleozoic geologic evolution

The Eopaleozoic started in the Cambrian with a transgression that entered the northwestern part of Argentina and occupied two mobile belts, one the eastern side of Craton (Bolivianides) and the other on the western side (Cuyanides).

After this ingression there were two sedimentary cycles: the Cambrian-Ordovician and the Silurian-Devonian, separated by the movements and magmatism of the Ocloyica phase (Taconian) and culminated by the Chanic orogeny (Bretonian).

III.1.1-. Geological-uraniferous analysis of the Eopaleozoic Sedimentary basins

Considering the Eopaleozoic lithostratigraphic sequences in the most important morphostructural areas of Argentina (Figure 1), there seems to be very little chance for the occurrence of sandstone-type uranium deposits.

Dominantly marine sedimentation filled several geosynclines in the western and eastem mobile belts with diamictite, shale, sandstone, conglomerate, which in places was to greenschist phase.

These rocks were formed under sublittoral conditions with only few continental episodes (Devonian molasse, with plant remains in the Precordillera geosyncline)(9).

In the filling of these basins almost all the material came from the Central Craton with a possible contribution of material derived from the uraniferous granites of the Cambrian Tilcara orogenic phase (Sierra Molinos, Tasti, etc.) and the Silurian Iruyica orogenic phase (Chani and Ancasti ranges, etc.). Because provision of uraniferous material in the Eopaleozoic was neither accompanied nor followed by appropriate climatic conditions, the uranium ended up in the sea and was perhaps included in euxinic pelitic beds such as the Calingasta Ordovician shale. This would explain the lack of uranium deposits in the Eopaleozoic and the presence of uranium in Devonian continental clastic sediments that contain plant remains and were deposited under favourable climatic conditions in basins on the Brasilian Craton (Amorinopolis).

III.1.2-. Uranium and the Eopaleozoic diastrophism and magmatism

The Tilcara, Iruyica, Ocloyica and Chanica diastrophic cycles of the Caledonian and Variscan orogenies produced folding and metamorphism; magmatism is evidenced by stocks, batholiths and a variety of hypabysal bodies. This magmatism was mainly located on the Central Craton and in the western mobile belt, with pre-syn and apo-tectonic acid intrusives and basic postplutonic bodies (Figure 6).The acid igneous bodies show the highest leachable uranium clarke and thus constituted likely source areas of the granites of the Sierras Pampeanas: the Aconquija show 14 ppm. U; Fiambalá up to 20 ppm U, Cafayate up to 31 ppm U and Sierra Grande (Córdoba) 8-10 ppm. U.

Beginning with the Eocarboniferous uplift and erosion exposed these igneous bodies as uraniferous source rocks of the sedimentary cycles that followed.

III.2-. General outline of the Neopaleozoic-Triassic geologic evolution

A new sedimentary cycle started at the end of the Chanica phase, with the Central Craton acting again as a source area for the filling of the cratonic basins. The development of the basins started with the deposition of the sediments in the early Carboniferous, and continued with few interruptions until the Triassic. The Variscan orogeny folded the Neopaleozoic sequences in the mobile belts and formed granite-granodiorite intrusives and volcanic facies from rhyolites to basalts.

III.2.1-. Uranium geologic analysis of the Neopaleozoic-Triassic sedimentary basins

These basins were located on the western and eastern belts of the Central Craton, as a new basin in the northern part of Argentina, and as several intracratonic basins. The basins of the orogenic belts were filled with marine and continental sediments of glacial origin, providing environments unfavourable for the formation of stratabound uranium deposits. At the same time the intracratonic basins were formed and filled with red neomolasse under desert climatic conditions and wet periods, creating favourable environments for the formation of stratabound uranium deposits.

a-. Western mobile belt

According to the present interpretation of the western mobile belt, it consists of two orthogeosynclines of about 2000 km in lenght, each separated by a sill. The outer one was formed at the present position of the Pacific ocean coastline, and the inner one at the western rim of the Central Craton (10) . The internal orthogeosyncline is exposed mainly in Argentina, and it is represented by several sedimentary basins separated by ridges. Of these basins, the most outstanding are the Tepuel in the south; the San Rafael in the south part of the Mendoza province; and the basins of Uspallata, Barreal, Calingasta, and Río Blanco that together comprise the Cuyo basin. (Figure 3).

The Tepuel basin is a zone of subsidence containing essentially undisturbed neritic Carboniferous sediments which were not favourable for the deposition of uranium. The overlying Permian was deposited as littoral and continental sediments that appear to have been favourable for the deposition of uranium concentrations, but so far no deposits has been found.

The Cuyo basin was a recurrent orogenic belt in the Paleozoic geosyncline, where the Precordillera tectonism created a ridge (Protoprecordillera) (11) that divided the two environments, the external neritic and the internal paralic facies; the latter became continental to the east and finally interfingered with the red neomolasses of the intracratonic basins.

The uranium-rich igneous bodies of the Central Craton, provided the uranium-bearing material that filled the eastern portions of these environments. This uranium was deposited in the Carboniferous continental sandstones with plant remains, forming conformable deposits along a large N-S belt located between the intracratonic basins of the Sierras Pampeanas and the inner side of the Cuyo basin.

The San Rafael basin,as exposed at Sierra Pintada, Nevado; elsewhere repeats this structural cycle with marine-littoral sequences in the Lower Carboniferous, which changed to a continental desertic environment in the upper Carboniferous, Permian and Triassic. It was deposited on a stable basement that during the orogeny became as an area of tectonic relief, creating horst and grabens, and accompanied by vulcanism. The Permo-Triassic basins were filled with fluvial psammites and pelites, pyroclastics, hypabysal igneous bodies, and acid lavas.

The Sierra Pintada uranium distric, with strataform uranium deposits (20.000 t U), is located in the Permian Sandstone of the Sierra Pintada (Cochicó Formation).

The deposition of uranium was controlled by the structure and the paleorelief, its origin is interpreted as a product of leaching of the interbedded rhyolithic tuff; the action of volcanic gases or the remobilization of uranium from the source areas of the Central Craton,located in eastern part of the uraniferous district. (Figure 3).

b-. Salta-Bolivian basin

The Salta-Bolivian basin is in the southern most part of the marine depositional center that enters Argentina from Bolivia. It is separated from the eastern mobile belts by ridges. The basin was filled during the Carboniferous with sandstones and neritic-littoral pelites followed by tillites and mudstones of continental glacial origin. Permian rocks are absent but the Triassic is represented by sandstones, limestones, and marine shales.

No uranium deposit is known in the basin which is consistent with the low favourability of its sediments and the cold climate presumed not suitable for mobilization of uranium.

c-. Eastern belt

The Eastern belt, situated beneath the Pampa Plain, is known by drilling and geophysics. It is still a subsiding structure composed of several minor basins filled during the Neopaleozoic with great thicknesses of diamictites, and during Triassic time were covered by red molassic sediments.

Uranium favourability is low, not only because of thick cover but also because the lithology and the paleo-climatic conditions were not suitable for uranium mobilization.

d-. Internal basins of the Craton

The internal basins of the Craton are located mainly in the central-western areas of the Sierras Pampeanas. They represent several depositional centers generated by the isostatic compensation of the Craton due to the intense Acadic orogeny in the western mobile belt.

The filling of the basins by the red molasses was the result of the destruction of the igneous-metamorphic complex that formed the Central Craton. The red molasse reflects a climate alternating from warm and dry with seasonal rains to wet periods with moderate temperatures.

The sediments are mainly gray psamites and pelites, with plant remains and less abundant red pelites from oxigen-rich environments and gray coaly pelites of lacustrine euxinic origin.

The most important of these basins is the Paganzo basin exposed over more than 100.000 km2 and limited on the west by the Cuyo basin of the western mobile belt and to the north, south and east, by ridges and arcs of the Central Craton.

The central part of the basin formed by the Paganzo group (12) , with the Carboniferous, Permian and Triassic, forming a column of sediments of up to 2000 m thick of gray epiclastic sediments with plant remains, red pelites and tuffs from a distant vulcanism. Within the gray sandstones containing organic matter, there are several conformable uranium deposits (Los Colorados, Chepes, etc.).

At the same time, in the western part of the basin and close to its transition into the littoral environment of the Cuyo basin there are again red molasses from the Carboniferous to the Triassic in a north-south band of a length of more than 500 km, with stratiform uranium bodies, which are irregulary distributed in fluvial Carboniferous sandstones with plant remains (Medano Rico-Jachal-Guandacol) and in continental yellowish Permian pelites (Tinogasta). (Figure 3).

The location of the uranium deposits, is related to the distribution of different lithologies of the Craton, being more favourable in the areas where the source rocks were the igneous bodies of the Craton and less favourable in the areas where the source rocks were metamorphic terrane. An additional factor was the paleogeographic conditions in the basin that controlled the movement of the groundwater toward the Cuyo basin, where we find the mineralized belts of Guandacol-Jachal and others. (13)

Other smaller basins without known uranium deposits are located in the central areas of the Sierras Pampeanas (Ambargasta, Chuñahuasi, etc.) and on the Patagonian platform (La Golondrina).

III.2.2-. The uranium and the Variscan diastrophism

The Variscan diastrophism which affected only slightly the Salta-Bolivian basin and the Eastern mobile belt by some subsidence and minor orogenesis, acted mainly on the Western mobile belt with folding and metamorphism decreasing toward the Central Craton.

Magmatism was active during two intervals, the Carboniferous and the Permian Triassic. The Carboniferous saw intrusions of granodioritic stocks and plutons with rhyolitic and basaltic vulcanism, while the Permian-Triassic yielded granite batholiths and extensive layers of tuff and rhyolitic porphyry.

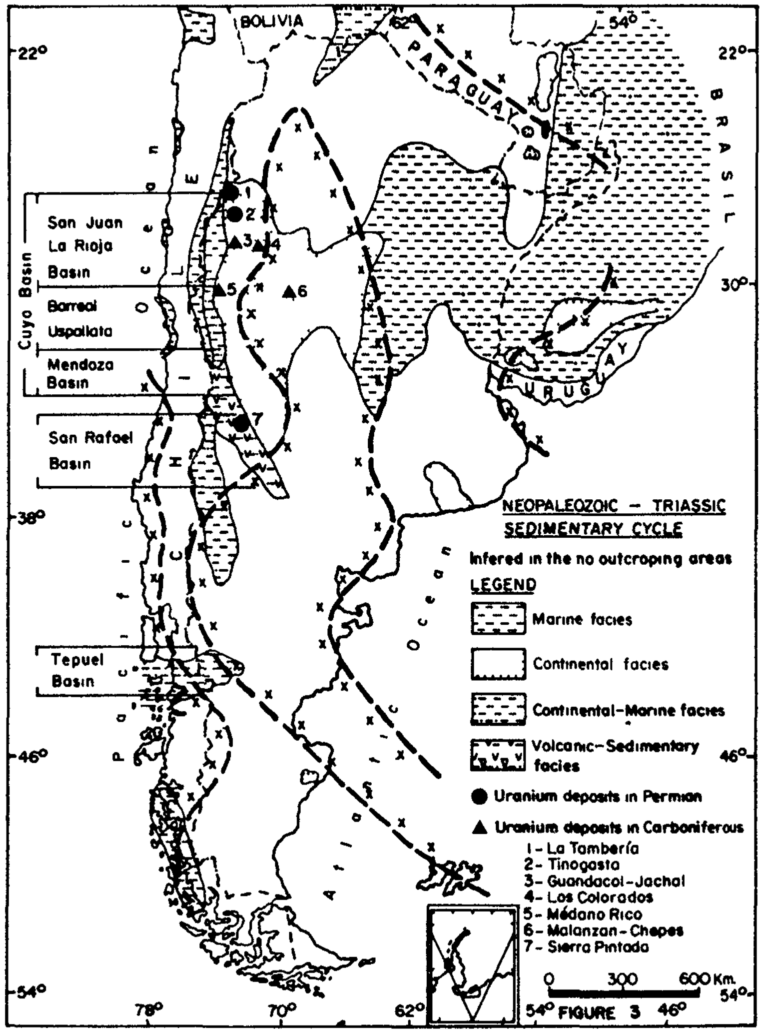

FIGURE 3

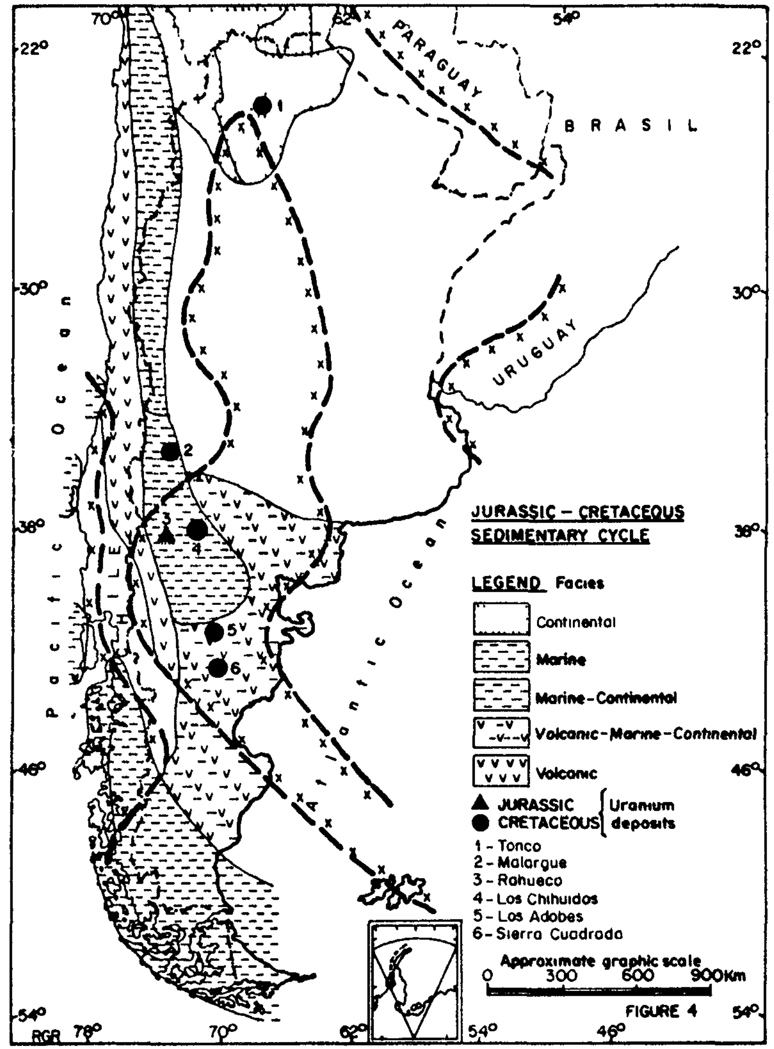

FIGURE 4

These igneous associations are located in the western belt that is connected with the Pacific Ocean environment and also as smaller outcrops in the Sierras Pampeanas and the Patagonian Platform (Figure 6).

The acid igneous rocks of this magmatism have vein-type uranium deposits (Cacheuta, etc.) and also have an uranium content higher than the clarke, so they were especially good source areas. Examples are Cordillera Frontal with granites of 8-20 ppm. U and the Sierra Pintada rhyolites with 17 ppm U.

III.3-. General outline of the geologic evolution of the Jurassic-Cretaceous

The Australic phase starts the Jurassic-Paleocene geological cycle with the Craton still taking part in the structural evolution and with the filling of the mobile belts and internal basins.

The Cimeric orogeny generated different geotectonic events. In the western mobile belt, then were liminar and aggradational geosynclines, vulcanism and deformation. There were diamictic subsidence accumulations and basic vulcanism in the eastern belt, continental sedimentation in the Jujuy basin, and continental sedimentation and acid vulcanism in the internal basins of the Craton.

III.3.1-. Geological analysis of the Jurassic-Cretaceous sedimentary basins with respect for uranium potential

The depositional centers are distributed in broad internal basin in the nesocraton of Patagonia and in the different basins of the marginal belts around the craton. (Figure 4).

These basins have good uranium potential because of the fertility of the source areas, the acidic synsedimentary vulcanism, the climatic and environmental conditions of the sedimentation, and the red molassic rocks with organic remains and bitumen.

a-. Western mobile belt

The Western mobile belt was occupied by the Andean and Magallanean basins. The Andean basin enters Argentina from Perú and Chile at latitude 28° S, showing evidence of an early orogenic evolution (Geoliminar) extending from the Jurassic to middle Cretaceous, and a later stage (Tardiliminar) from the Neocretaceous to Upper Tertiary. The Geoliminar stage was developed in two N-S belts, with different lithologies. (14) . The internal "euliminar" was developed in Chile, with dominant intermediate vulcanism, sea ingressions, granodioritic intrusions, and metamorphism. The external "mioliminar" is exposed in northern Chile and mainly in Argentina, with red molasse from Malm and the middle Cretaceous, and two marine events in the middle Jurassic and in the Eocretaceous. In the central area those sequences, stretch to the east over more than 100.000 km2, fill basin of the syneclisa type (Neuquén basin).

The Tardiliminar stage started with the inter-Senonian phase and in the upper Cretaceous produced a paleogeographyc pattern extending from the Pacific to the east with marine sedimentary facies in the Cordillera de la Costa; volcano-sedimentary sequences in the Cordillera de Abanico in central Chile (15) and red molasse to the east, in the Neuquén basin.

The lithofacial and structural conditions of the Neuquén basin and the uranium content of the source rocks, generated uranium deposits in littoral sandstones with organic material in the Jurassic (Rahueco) and specially in fluvial clastic beds with bitumen (Los Chihuidos, Malargue, etc.) (Figure 4).

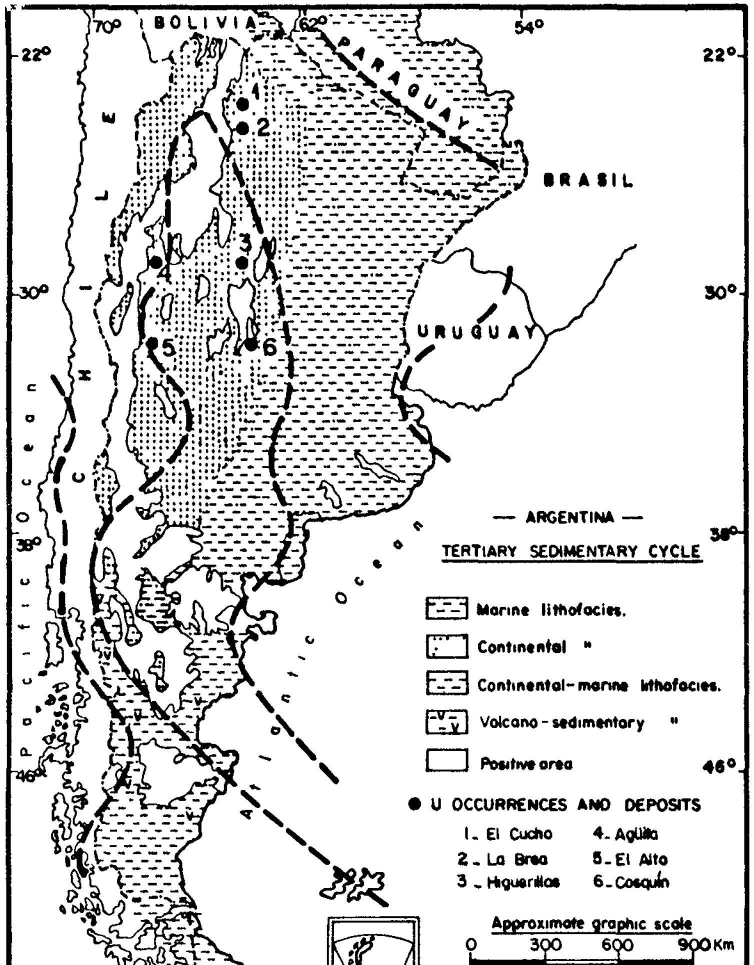

FIGURE 5

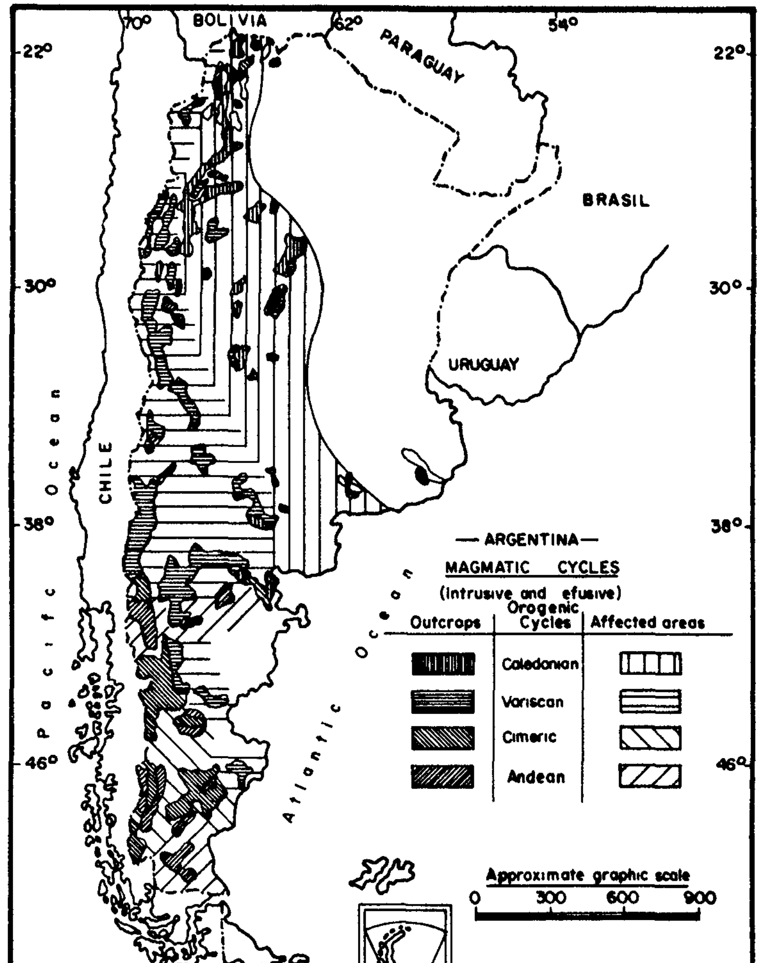

FIGURE 6

The Magallanes basin in the southern part of Argentina is a geosyncline that has poor potential for uranium deposits, because it is mainly filled with pelites and flysh marls and continental and littoral sediments (pyroclastic and epiclastics) are only along the margins. No uranium deposit is known in the basin.

b-. Jujuy-Bolivian basin

The Jujuy-Bolivian basin in the southern part of the Subandean basin of Perú and Bolivia, has no Jurassic rocks in Argentina. Subsidence started in the Nevada phase and the basin filled with continental facies in middle Cretaceous, littoral facies in upper Cretaceous, and continental sediments in the Paleocene.

The Yacoraite Formation (Upper Cretaceous) is characterized by oolitic limestones, bioclastics and pelites in the central part of the basin, becomes more sandy towards its western margin, and pelitic sediments are interlayered with coal and bitumen. These sediments are a product of the erosion of the fertile igneous complexes of the Sierras Pampeanas . Along a band of more than 200 km there are sandstones with uranium deposits produced by the remobilization of the syngenetic uranium in the bituminous pelites. The uranium was redistributed in the sandstones by the underground waters and fixed as vanadates in stratiform bodies (Tonco-Amblayo, etc.). (Figure 4).

c-. Eastern belt

Its Mesozoic sequences lie under the Pampean Plain with isolated outcrops near the Brasilian Craton. The sedimentation cycle started with the lower Cretaceous basaltic sequences that now crop out in the southern part of Brasil; overlying this sequence are marine limestones and black shales and red molasse of the upper Cretaceous.

Because of low favourability of the facies and the deep burial of the sequences they are of no interest for uranium.

d-. Internal basins of the Craton

The most important internal basin is located in the Patagonia nesocraton cratonized by the Cimerian diastrophism and created by taphrogenesis forming a depresion of more than 150.000 km2, which since the Jurassic occuppied the extra-Andean Patagonia.

The filling of the basin started with marine platform sequences (Liassic), followed by continental sediments of oxygen-rich and euxinic environments, which are interlayered with intermediate vulcanites (Dogger) ended with gray psephites and psammites with plant remains and intercalations of acidic tuffs in the Cretaceous (Chubut Group).

These sequences show only little folding brought about by tectonism and epirogenic tilting during the Andean orogeny, because of the rigid basement.

The Chubut Group contains many conformable uranium deposits in the central and northern part of the basin (Los Adobes, Sierra Cuadrada, Sierra Chata, etc). It is believed that the uranium originated through the leaching of the acidic tuff by superficial water or volcanic gases. Another idea suggests that the uranium came from the cratonic fertile rocks that surround the basin.(Figure 4).

III.3.2-. Uranium and the Cimerian diastrophism and magmatism

The Cimerian diastrophism acted mainly in the western mobile belt or Andean basin, where it generated a north-south regional overthrusting of the "euliminar" vulcanites over the "mioliminar" molasses, with an intense folding of them decreasing toward the Craton. In the remaining mobile areas there was a general subsidence and relief faulting in the Craton.

The magmatism of this orogenic cycle is mainly expressed as a volcanic belt in Chile and is present in Argentina in the Patagonian Cordillera and extra-Andean Patagonia as Jurassic intermediate porphyric vulcanism; Cretaceous granitic plutons, and related acidic vulcanism with an anomalous uranium clarke. In the rest of the country, this expression of magmatism is present in the northwest as granitic stocks in the Abralaite range, and Rangel (with anomalous content in U and Th), and as basic vulcanism in Sierras Pampeanas. (Figure 6).

III.4-. General outline of the geologic evolution of the Cenozoic

The Cenozoic geologic evolution of Argentina is closely related to the Andean orogeny. Its different phases modelled the geology of the country by uplifting the Andes, fracturing the Craton, and epirogenically tilting the eastern and littoral areas.

The Tertiary sedimentary cycles included two different environments, a marine environment in the eastern part of the country and a continental environments in the central and northwestern parts. Tertiary igneous activity included granodiorite and granite intrusions in the Andes cordillera and an extensive acid to basic vulcanism over large areas. (Figure 5).

III.4.1-. Uranium geological favourability of the Tertiary basin

The probability of finding conformable uranium deposits in the Tertiary basins is closely related to the two sedimentary styles. (16) .

The favourability seems to be very small in the Patagonian environment and in the subsurface of the Chaco-Paraná basin where the marine environment prevails.

In the extra-Andean Patagonia, the Magallanes basin was an area of shallow marine sedimentation from the Cretaceous until the Oligocene. The rest of the Patagonian areas shows periodic Atlantic shallow-water ingressions starting in the Eocene with paralic, littoral and even continental facies,mixed with intermediate pyroclastic sequences.

No Tertiary uranium deposit has been located in these areas that have favourable source rocks but unfavourable lithologies.

In the Chaco-Paraná basin, the Tertiary of the subsurface is composed of Atlantic marine sequences of Eocene and Miocene age, so there were no really good conditions for the formation of conformable uranium deposits.

Continental sedimentation is present in basins between the ridges and elsewhere on the Craton in the central and northwestern parts of the country.

The basins in the mountain areas are located on the eastern sides of the Andean orogen,in a meridional band 1.500 km long that in the Eocene-Pliocene was filled with red neomolasse and intermediate pyroclastic intercalations.

The sources of sediments for the basin were from the erosion of the Central Craton and the Paleozoic and Mesozoic sequences having uranium-fertile rocks. Its regional structural features are north-south folding with inverse faulting. The paleoclimatic conditions were an alternation of warm dry seasons with wet periods as indicated by plant remains. The favourability of this environments is indicated by some uranium occurrences in the Miocene-Pliocene sediments of these basins (La Brea, El Cucho, etc.). (Figure 5).

On the other hand the internal basins are located in the Sierras Pampeanas as narrow north-south structural depressions between blocks of the basement, tilted by the Andean tectonics. The basins were filled from Eocene to Pliocene by fluvio-lacustrine sediments orginating from the erosion of the Central Craton whose metamorphic or igneous composition defined the uranium potential.

In one of the depressions we find the Cosquin district with carnotite deposits stratiform with the sandy pelitic sediments of Eocene age. The genesis of the deposits is difficult to define, it does not appear to have been associated with the classic geochemical reduction, but rather it resembles a paleocalcrete.

III.4.2-.Uranium and the Andean diastrophism and magmatism

The Andean diastrophism consisted of various tectonic events in the Andes belt along with epirogenic oscillations of the Craton and the rest of the mobile belts in Argentina.

The Andes belt following the sub-Hercinian phase (Upper Cretaceous) that terminated the geoliminar period was affected by three tectonic events in the tardiliminar period namely the Laramic (Paleocene), Incaic (Finieocene), and Quechua (Finimiocene) and one postliminar event the Diaguitic (Plio-Quaternary). The Diaguitic raised the Andes chain overthrusting and normal faulting of the Paleo-Meso-Cenozoic sequences, which decreased its effect toward the Craton.

In the rest of the country there were Atlantic transgressions and regressions and only gentle north-south folding and fracturing.

The magmatism of this orogenic cycle was formed by intrusions of granitoid plutons in the high Andes Cordillera, an andesitic-rhyolitic regional vulcanism, and concluding basaltic extrusion.

In Argentina the magmatic bodies have not yet been studied for their uranium content, but it is worth mentioning that the vulcanites of the Puna show abnormal uranium contents for hypabysal dacitic bodies of Cerro Galan and Aguiliri and dacitic ignimbrites of Coranzuli. This situation had a parrallel in the vulcanism that extended from Perú (with uranium deposits in the Pliocene Rhyolites of Macusani) to the Highland of Bolivia (Cotaje) and to northest of Chile and the Argentina Puna, which creating more than 300.000 km2 of potentially uraniferous environments.

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SEDIMENTARY AND TECTONIC ENVIRONMENTS FOR URANIUM MINERALIZATION ON THE PARANA BASIN, BRAZIL

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Abstract

The Paranã Basin is an isolated intracratonic basin in Southeastern South American and is characterized by Paleozoic and Mesozoic clastic sediments and by the location of one of the world's largest lava flows. Uranium mineralization occurs mainly in lower Devonian epineritic feldsphatic sandstones and in fluvio-deltaic channels developed in middle Permian mudstones and sandstones. Stratigraphic and sedimentologic conditions plus tectonic barriers in association with underground water controled the mineralization. Two uranium deposits with 4250 and 6800 tonnes U of RAR plus EAR were found containing primary (pitchblende and coffinite) and secondary (autunite, sabugalite, uranocircite) minerals. A paleochannel model for the Permo-carboniferous mineralization is quite well established whereas many questions are still open for the confirmation of a model for the Devonian occurrences. Host rock sedimentary environment, ore-forming conditions and source rocks are discussed.

I - INTRODUCTION

Uranium anomalies and occurrences have been known in the Paranã Basin since the 1950's when the first exploration was carried out jointly by Brazilian and USGS geologists. Uranium was detected in Carboniferous (Cambuī, Figueira, Criciūma), Permian (Irati Fm), Triassic (fossils) and Cretaceous (Faz. Roncador) rocks. Trenching and pitting of the Permo-Carboniferous revealed secondary mineralization. However, they were not rich and geologically different than those found in the Colorado Plateau which, at that time, exemplified the sedimentary type of uranium occurrences. The limited knowledge on the uranium geology at that time did not allow the evaluation of these anomalies. With a large country to explore and more promising prospects to develop (Poços de Caldas, Tucano , Jacobina) the Paranã Basin was left as second priority.

Later, in 1963/64, a systematic carborne radiometric reconnaissance covered most of the road system and many new anomalies were found in the sediments as well as in the basement rocks. Evaluation of the data indicated favourability of the Permo-Carboniferous sequences in Paranã and Santa Catarina . Airborne surveys over the Cretaceous of the northeast side (São Paulo State) and over the Sul-Riograndense Precambrian shield did not revealed significant occurrences. Efforts was then concentrated on the grey sediments above the glacial deposits of the Itararē Formation and in 1970 subsurface mineralization was found in Figueira, which later became the first uranium deposit in the basin.

In 1971, another airborne survey in the north of the basin (Silurian, Devonian, Carboniferous) yielded several radiometric anomalies. Ground check indicated most of them as laterite crusts.

The experience until then was to discard lateritic anomalies, very common in Brazil , as *geochemical concentrations of uranium without* potential. Few pits over these laterites showed abundant secondary minerals below the surface. Shallow drilling discovered ore-grade material which later was developed into the Amorinopolis deposit.

II - GEOLOGIC AND TECTONIC SETTINGS

The Paranã Sedimentary Basin is located in the central-eastern part of South America covering 1.600.000 km^2 (figure 1). Its sediments extends over four countries, Brazil (1.000.000 km^2), Argentina (400.000 km^2), Uruguay (100.000 km^2) and Paraguay

FIG 1 - LOCATION OF PARANÁ BASIN, GEOGRAPHIC LIMITS AND MAJOR TECTONIC FEATURES

(100.000 km^2). Its geographic limits are bounded by tectonic features as: the Canastra and São Vicente Archs on the North, the Asuncion and Pampeano Archs to the West and the Martin Garcia Arch towards the South (figure 1). The eastern border corresponds to the former Brazilian-African Arch, which was broken during the early Jurassic, at the time of the rifting and drift of the continents, and eroded leaving the Atlantic massif a reminder of its presence.

Along the Atlantic border three basement flexures are known, which depict the sediments; 1) the Sul-Rio Grandense Arch; 2) the Torres Synclinal and related gravity faults, which brought the sediments below sea level and which now constitute the continental platform; and 3) the Ponta Grossa Arch, very prominent on the geologic maps as it extends to the west into the Paranã Basin.

The Paleozoic sediments crop out only in a narrow band in both eastern and northwestern rims of the Basin; the rest of the surface is covered by Mesozoic rocks. To the northeast , these Mesozoic rocks extend beyond the Paleozoic and are in direct contact with the Precambrian basement. The major axis of subsidence was oriented

N-S during the Devonian and after the carboniferous changed to variable positions due to the influence of large structural lineaments oriented N-NW and E-W developed in the basement (Tietê and Paranapanema lineaments). The present structure was acquired in the Mesozoic when the marginal archs were established.

The Ponta Grossa Arch, with its associated structures, had an important role on the sedimentary evolution of the Basin, namely, originating two sub-basins, one to the north (Alto Paranã)and another to the south (Catarinense), with different sedimentation rates and environments. Towards the south , between the Western Pampeano Arch and the extension of the Asuncion Arch, a NW appendice of the Paranã Basin was developed. It is the Chaco-Paranã sub-basin (1).

On the northwest, the basin has regional characteristics related to the source of sediments.

During most of the Paleozoic the Asuncion Arch should have been a highly elevated terrain including the present low-lands of the Pantanal Matogrossense. This highland was the source of large volumes of sediments which were transported to the west (Chaco and Chiquitos basins in Paraguay and Bolívia) and to the East (Paranã Basin).
These northwestern events developed regional sedimentation characteristics related to the source of material which suggests another sedimentary series, a Western sub-basin (2). The asymmetric disposition of the lithologic elements, coarse in the west, suggest that side as the main source of clastics. The principal faults and tectonic lineaments are either NW (parallel to the Ponta Grossa Arch) or N-NE with large vertical displacements and seem to represent reactivation of Precambrian directions.

The Paranã Basin, therefore is now divided in five sub-basins: the Chaco-Paranã , the western, the Uruguay-Sul Rio-grandense, the Catarinense and the Alto Paranã (fig.1).

III - SEDIMENTARY HISTORY AND ENVIRONMENTS

SILURIAN

The first sediments deposited were of middle Silurian age (lower Landoverian) and consisted of mainly marine sequences of red diamictites with coarse pebbles of granite and gneisses interbeded with fossiliferous shales, siltstone and fine micaceous sandstones (fig.2). They are known as Vila Maria Formation (3) whose maximum thickness is 245m. These sediments were deposited locally and seem to have been restricted only to the northeastern border of the basin (Goiãs and Mato Grosso States). The direction of sedimentation was eastward. Although the lithology and stratigraphy are favourable for hosting uranium mineralization , no radiometric anomalies or other uranium indications were observed in these sediments (3).

Above this sequence and transgressing over the basement an extensive cover of coarse sediments was deposited consisting of polymitic basal conglomerate followed by a kaolinic, unsorted , angular grained , cross-bedded unfossiliferous sandstones. They constitute the Furnas Formation recognised as mainly of marine origin but with certain continental contributions.

The age of Furnas Fm is late Landoverian and its thickness is over 400m. Field investigations yielded negative results for possible uranium mineralization. Point source radiometric anomalies observed in the upper layers seems to be related to uranium occurrences in the Ponta Grossa Formation above.

DEVONIAN

The deposition of Furnas sandstone was interrupted and a period of erosion followed before the first sediments of the Ponta Grossa Fm were deposited over all of the Paranã Basin, therefore transgressing over the Furnas and depositing part of its clastics on to the Precambrian basement (fig.2)

The lower Ponta Grossa sediments consist of grey and red micaceous laminated shales, locally bituminous or carbonaceous silty epineritic red sandstones, siltstones , and shales of irregular and subordinated sandstones. It has abundant fossils is cross bedded , and is overlain by dark-grey to black infraneritic shales and finally grey shales.

Along the northeastern border (Goiãs State), where the Amorinõpolis uranium deposit , is located ,the Formation is divided in three members (3):

a) Lower member over 270m thick with siltstones,sandstones and subordinated shales. Within the siltstone occur horizons of a feldspathic sandstone, 3-8m thick of yellow-reddish colour where oxidized and in some places mineralized with uranium. Pollen studies in this member and abundant fossils in the transition zone above yielded and Ensian age for these sediments.

b) Middle member, 250m thick, consists mainly of red iron-cemented,locally micaceous coarse sandstones with shale and polymitic clasts and channel structures.

c) Upper member is 60-200m thick and consists of fine-grained sandstones that grade into dark shales.The sandstone is characterized by ripple marks and flaser structures , calcareous cement and animal borings. Also common are ferruginous beds with oolitic hematite and chamosite. This abundance of iron oxide was important in the formation of extensive laterites, which exist at the present surface and which yielded the radiometric anomalies that led to the Amorinõpolis deposit. Pollen studies gave an Givetian age.

The lithologic and stratigraphic characteristics of the above sequence plus their fossil associations suggest that the eastern border of the Paranã Basin was raised during the final deposition of Furnas Fm, thus ending the sedimentation and begining of an erosion period (3). Over this eroded sequence started, in the Ensian, a marine trangression with the deposition of the shallow-water sediments of the Ponta Grossa Fm (conglomerates, fine clastics and arkosic horizons of the lower member). Still under shallow water was deposited the progradational sequence (middle member) suggesting a deltaic nature when the influx of sediment exceeed the rate of the basin subsidence. At the end, finer clastics were deposited indicating a decrease in the rate of subsidence.

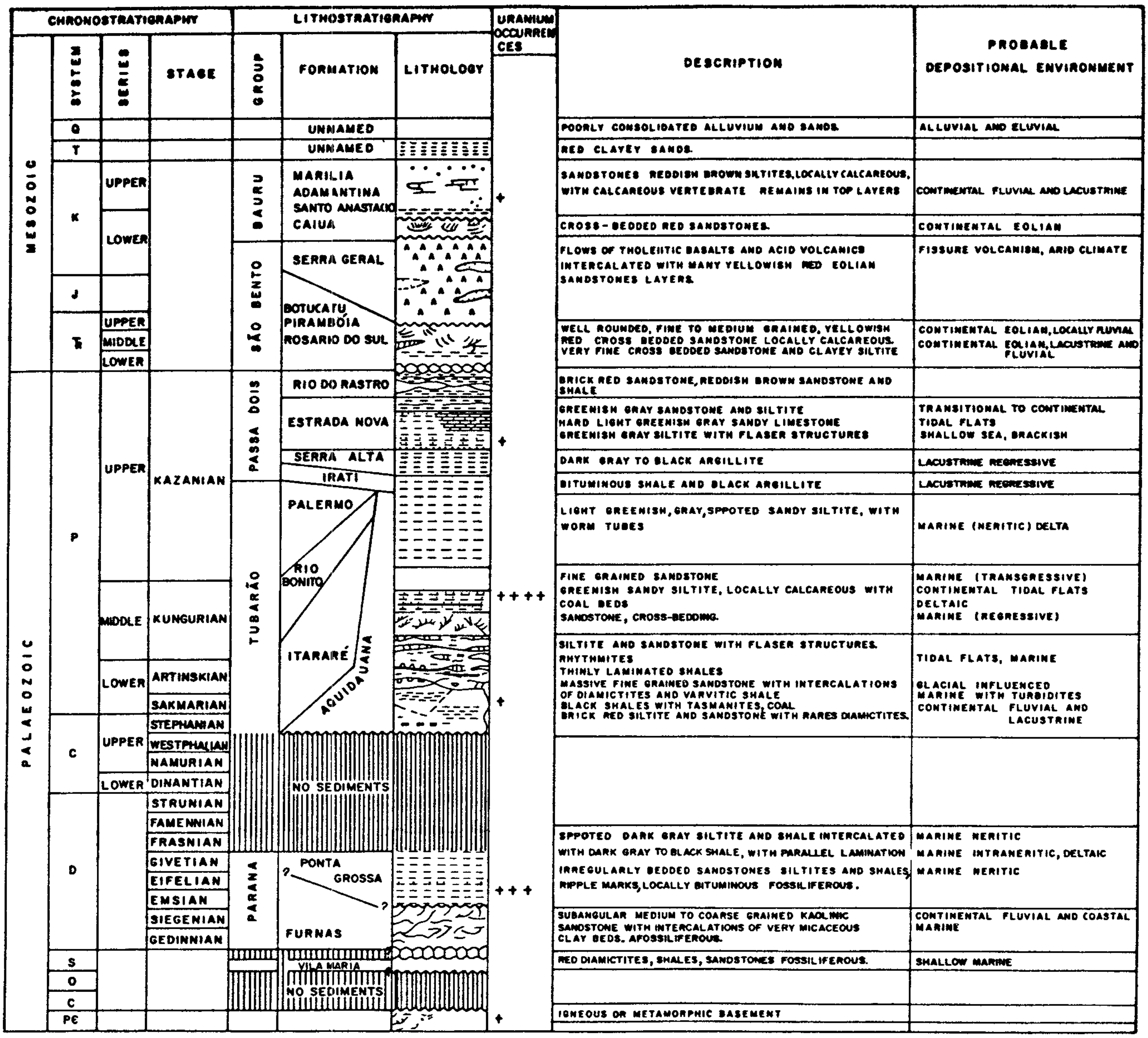


Figure 2 STRATIGRAPHIC COLUMN OF PARANA BASIN

PERMO-CARBONIFEROUS

The entire Paranã Basin went through a long period of erosion from the late Devonian (Givetian) to the late Carboniferous (Stephanian) with an epirogenic uplifting of its southern part in late Carboniferous time (4). This resulted in the formation of regional depressions in the north which later received over 1.000m of sediments. These sediments, which consist mainly of red sandstones and conglomerates, are the Aquidauana Formation (fig.2).

Almost contemporaneous with the Aquidauana Formation a complex sequence of sediments were deposited in the center portion of the Basin by the interaction of several environments , such as glacial (with tills and roches moutonnées), fluvial, lacustrine-glacial, and on the the eastern rim deltaic and marine . Associated with glacial deposits occurred eolian sediments . This complex sequence denominates the Itararé Subgroup, which is a very important stratigraphic marker for uranium exploration as it represents the lowest stratigraphic limit for uranium occurrences in the Permo-Carboniferous rocks. In Uruguay, the Itararé sediments are diamictites, rhytmites and bituminous shales but coal is absent. Here it is known as the San Gregório Formation.

Discordantly overlying the Itararé Fm is the Rio Bonito Formation, which consist of a sequence of a) sandstones , b) siltstones, shales, coal seams and limestones, c) sandstones.The lower sandstones are residual channel deposits, and the middle member may host up to 10 coal beds with thicknesses varying from few centimeters to 2 meters.The upper 30% consists of dark-grey fine-grained sandstones interbedded with mudstones, carbonaceous shales and some coal. Laminated bedding, ripple marks and small-sized cross beds are common.

The coal basins were not large. Of the five coal beds in Santa Catarina State (Catarinense Sub-Basin), only three cover more than 1000 km^2 of area. In the southern part, the coal is present in post-glacial sediments (Rio Bonito Fm) whereas in the northeastern it is intercalated with the glacial sediments and associated calcareous sandstones(Itararé Fm). Due to the close relationship between the uranium mineralized sandstones with the coal of the Rio Bonito the presence of coal constitutes an important stratigraphic marker for uranium exploration in the Basin. Relatively substantial amounts of the uranium (30-40%) in the Figueira deposit are contained in the carbonaceous siltstone and coal , which poses a metallurgical problem for its recovery.

The Rio Bonito Fm was deposited as a consequence of a regressive event of the Permian waters resulting in many deltas developed from east to west covering all the central region of Santa Catarina with coastal plains along the eastern border (2). Non-marine sediments prevailed in the north. The Rio Bonito Fm is the most important depositional environment for uranium in the Paraná Basin. Many uranium anomalies and prospects as well as the Figueira deposit are known along the eastern rim.

New subsidence led to the deposition of lacustrine sediments of the Palermo, Irati and Serra Alta Fms in a central depression with direction SW-NE (fig.2). The Torres synclinal was also developed in the late Permian.

Starting with the Irati Fm, the sedimentary environment of the Paraná Basin becomes one of continuous and slow regression with coastal plains in the south and more continental deposits of the thick Estrada Nova Fm to the north and the almost purely continental red sandstones and brown siltstone and shales of the Rio do Rastro Fm to the south, while erosional conditions developed toward the northern part of the Basin. Geochronological datings (6) indicated 256 ± 19 Ma for the Irati Fm, 243 ± 14 Ma for Estrada Nova and 228 ± Ma for the Rio do Rastro Fm. All these ages correspond to the Kasanian and agree with ages given by the fossils. Stratigraphic evidence also indicates that Rio do Rastro sediments persisted through early Triassic. Uranium anomalies in the Irati, Estrada Nova and Rio do Rastro Fms are explained by geochemical concentrations due to the presence of organic material.

In summary, the geologic-tectonic conditions which characterizes the Paraná Basin during the Paleozoic are (fig.2):

Lithology: Clastics and subordinated chemical sediments.

Begining of sedimentation: Middle Devonian (localy) and late Carboniferous on regional scale.

Deposition sequence: Rapid transgression followed by slow regression with some fluctuations.

Tectonics: Complete structural characterization of the Basin at the begining, minor uplifting and folding created sub-basins and finally emergence.

Uranium: uranium occurrences found in the regressive sequences.

MESOZOIC

The general geotectonic pattern of the late Paleozoic continued into early Mesozoic times with no marked unconformity. With the Basin emergent only sediments of continental origin were formed. This was a period of stability of the Brazilian Platform.

The first sediments deposited over the Rio do Rastro Formation were red beds of the Rosário do Sul Formation, which is considered to be Triassic. It consists mainly or ripple-marked, cross-bedded, poorly sorted fine to medium-grained sandstone and minor paleosols. Red pelites, rich in vertebrate fossils, occur in the middle. The Rosário do Sul is better developed in the southern part of the Basin (Rio Grande do Sul and Uruguay) where it is 286 m thick. Overlying the Rosário do Sul is the Pirambóia Formation that consists mainly of poorly-sorted (polished and subangular quartz grains) white sandstone. Locally siltstone and conglomerate are intercalated with the sandstone. The depositional environment was fluvial under semi-arid conditions. The maximum thickness is about 350 m. The Permian Rio do Rastro and the Triassic Rosário do Sul and Priambóia Formations possible correlate chronologically with the Missiones Formation of Argentina.

The next sedimentary record in the Basin is a complete over of red, eolian sandstones of the Botucatu Formation that transgressed over older sediments and to the northeast over basement rocks. The Botucatu Fm which is Triassic or possibly Jurassic in age, is characterizes by large (15m) high-angle (30^{o}) cross stratification and the almost absence of matrix cementing the rounded, well-sorted dull grains. Local siltstone and claystones indicate small temporary subaqueous conditions. Its thickness rarely reaches 100m. The entire Triassic sequence in the Paraná Basin is barren of uranium mineralization.

Then , in the early Cretaceous, the Paraná Basin was the stage of the most singular volcanic event of the entire continent. It is known as the "great volcanism" which consisted mainly of lava flows moving up through large crustal fractures and covered all the basin and extendd into Uruguay, Paraguay, and Argentina with a total of more than 1 million km^2 (Fig.3). Based on subsurface data, Soares and Landin (7) estimated a volume of 10.000.000 km^3 of lava for this flood volcanism. Drill holes in São Paulo State intersected lava sheets with thickness more than 1.500m in 32 successive flows.

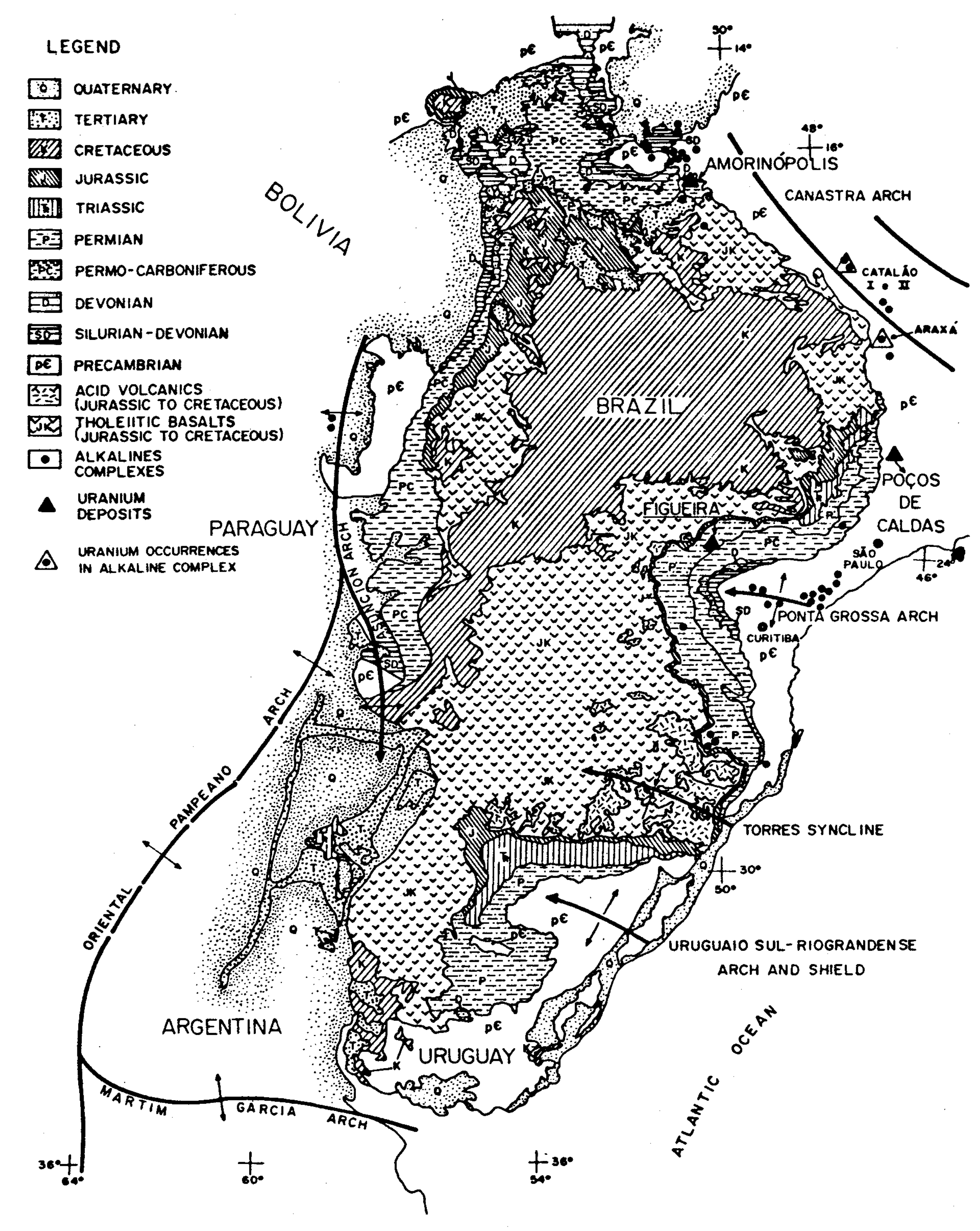


FIG. 3 GENERALIZED GEOLOGIC MAP OF PARANÁ BASIN WITH URANIUM RESOURCES AND ALKALINE PROVINCES

This volcanic sequence is the Serra Geral Fm (Fig.3) . Along with these flows there was intrusion of volcanics in all types of rocks. Dykes are abundant along the eastern border, Ponta Grossa Arch and coast of São Paulo State as are sills, which may be as much as 200m thick. Radiometric ages indicated a range between 115-135 Ma for this great volcanic activity.

The Mesozoic geologic-tectonic characteristics are summarized as:
Sedimentation: dominance of clastic, red bed and eolian sandstone. Triassic best developed.

Environment: almost exclusively continental. Some fluvial deposition with anastomosed drainage. Increasing arid conditions.

Tectonics: Minor and gentle subsidence. Strong uplifting and folding initiated new source areas for sediment. Rifting in early Cretaceous. Intensive volcanism with flood basalts and alkaline complexes.

Uranium: uranium mineralization absent in the sediments but present in the alkaline rocks. Low potential.

IV - URANIUM MINERALIZATIONS

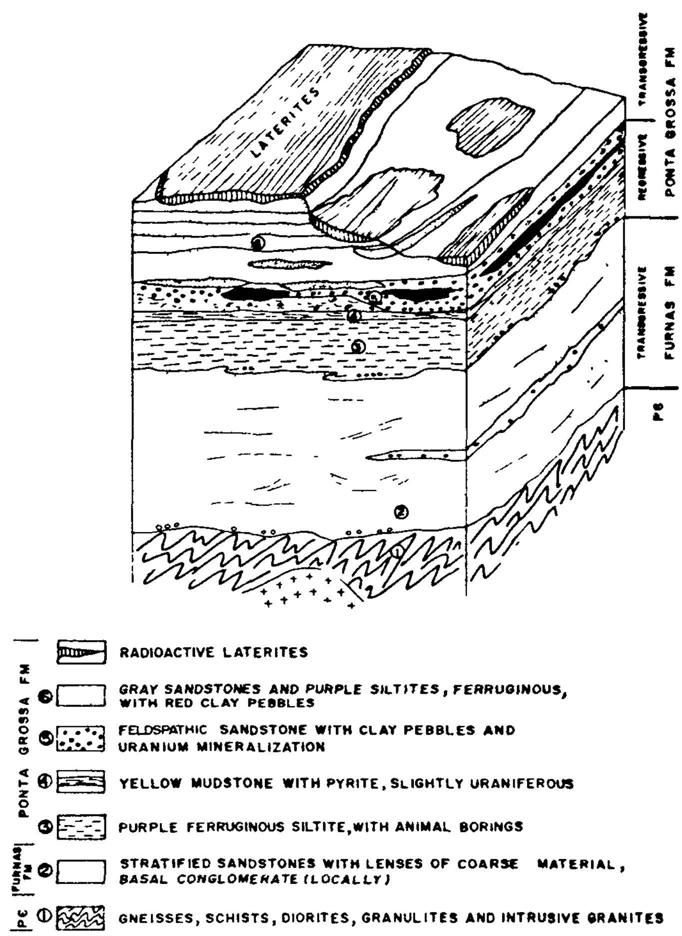
DEVONIAN

1 - AMORINÓPOLIS DISTRICT

Numerous uranium anomalies were found in the lower and middle members of the Ponta Grossa Fm along the northeastern border of the Basin. In the Goiás State, around the area of Iporã-Amorinópolis (Fig.3), 31 anomalies were selected for evaluation. These anomalies occur: a) associated with fractures some of which are filled with ultrabasic and alkaline dykes of Cretaceous age, b) associated with ferriferous laterites developed over large areas in the northeastern border of the basin , and c) associated with geochemical cells of oxi-reduction. The later is the most important type and one deposit (Amorinópolis) has been found.

The local stratigraphy shown in Fig.4 consists of at the base a Precambrian basement with gneisses, micaschists and granites (Araxá Group) and ultrabasic intrusions. Over this basement lies the grey-yellowish micaceous sandstone (Furnas Fm) with oblique stratification and representing an epicontinental, transgressive, marine environment. It is overlain by the Ponta Grossa Fm. The lower part is a grey-purple pyritic siltstone with mudstone lenses. This siltstone has irregular bedding with interdigititation and animal borings. Overly the siltstone is a yellow-ochre micaceous and sometimes pyrituous mudstone which in turn is overlain by a medium to coarse-grained , brown, poorly sorted, feldsphatic sandstone. This dandstone is defined as a sedimentary blanket (19) and is the host of the uranium mineralization (3). The uppermost sediments are red mudstone , and at the very top a sequence of a purple ferruginous siltstone and grey fine-grained sandstone with red mudstone nodules.

Figure 4 STRATIGRAPHIC SEQUENCE OF AMORINÓPOLIS



The regional structure is characterized by asymmetrical blocks of grabens and horsts developed by the raising of the basement in the Cretaceous during the emplacement of the Morro dos Macacos ultrabasic mass. These tectonic blocks were tilted providing fractures for the later emplacement of dikes of ultrabasic and alkaline rocks (70 ± 5 Ma) which cut the sedimentary sequence.

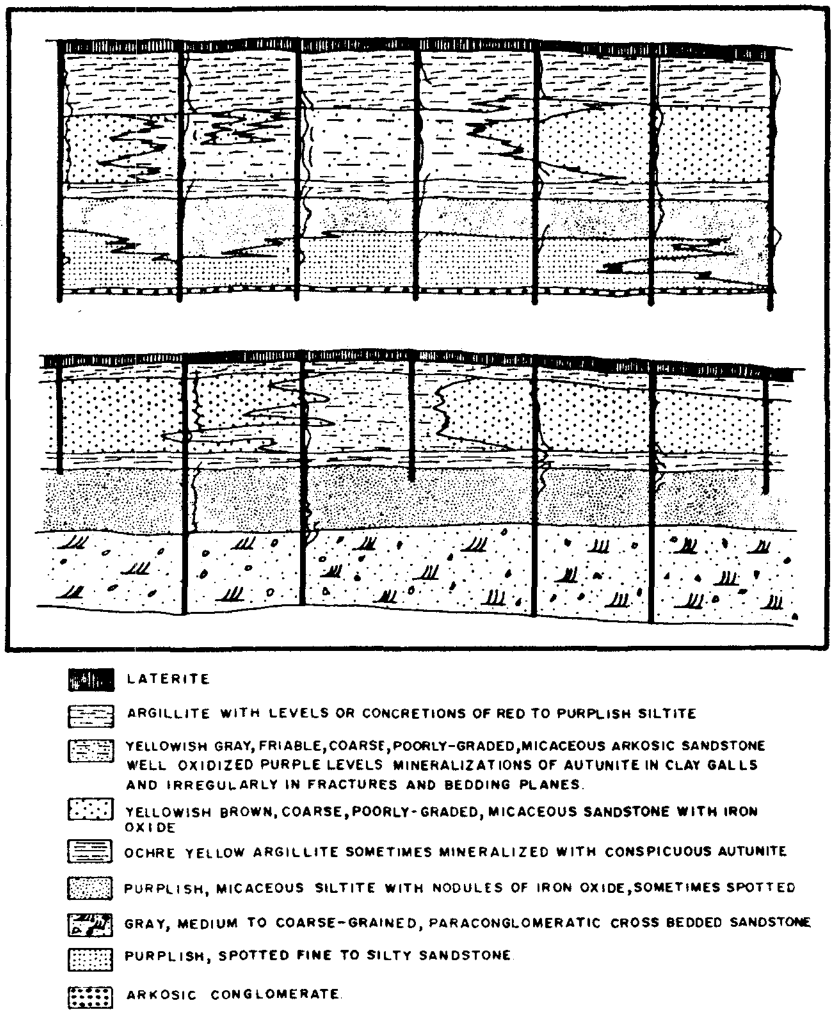


FIG. 5 - CROSS SECTION INTERPRETATION FOR THE MINERALIZED CHANNELS IN MIDDLE DEVONIAN SEDIMENTS.
(AMORINÓPOLIS)

Uranium mineralization occurs mainly in the feldsphatic sandstone blanket. It has an irregular and fairly continuous form but has been eroded away between the local mesas. Fig. 5 shows cross sections with interpretations of the mineralization. The dominant mineralization is secondary and consists of disseminated autunite and sabugalite. Mudstones nodules are highly enriched in uranium which increases the average grade of certain reserve blocks. Primary mineralization in the form of pitchblende and coffinite is found at depth below the weathered surface and far from exposures in the sides of the mesas (Fig. 6).

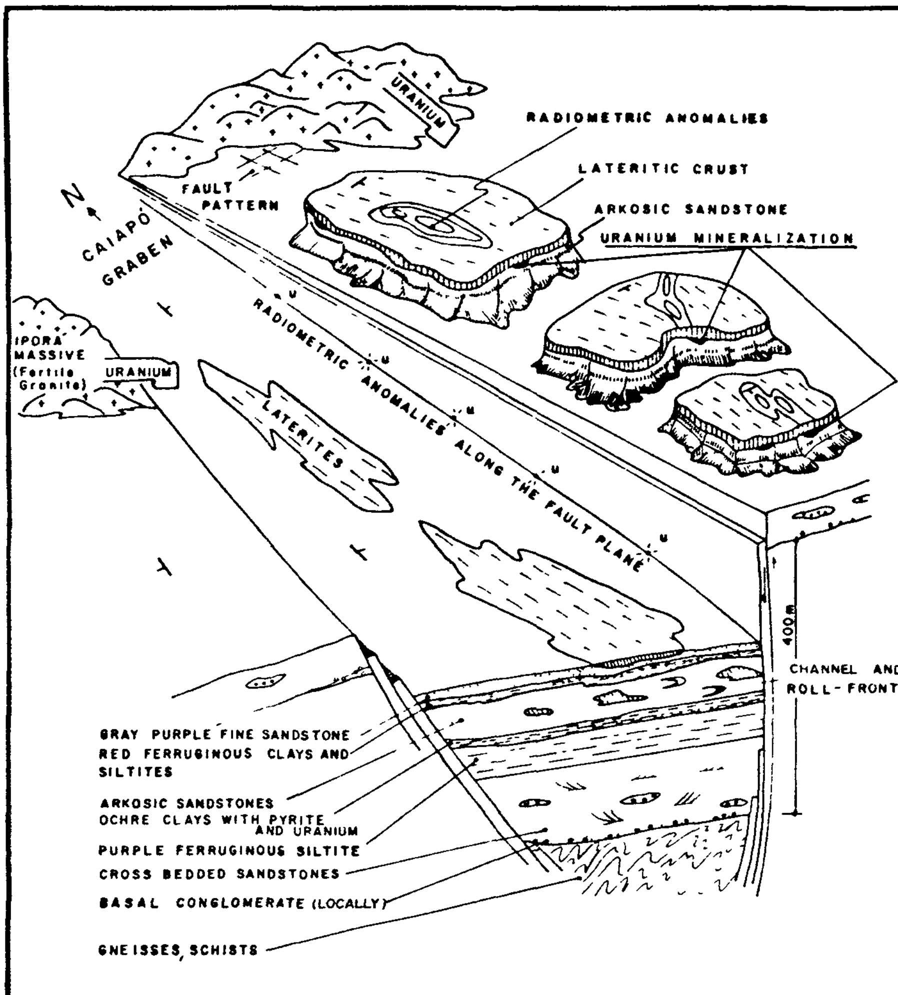


FIG 6 - INTERPRETATIVE SKETCH OF THE REGIONAL GEOLOGIC AND TECTONIC SETTINGS OF AMORINÓPOLIS

The mineralization seems to have been controlled essentially by the physico-chemical conditions of the host feldsphatic sandstone and the hydrodynamic flow of the mineralizing solutions. The lithostratigraphic control is defined in terms of favourability of sandstone where the lower and upper layers are mudstone or very fine sandstone that provided a stratigraphic confinement. Another important control is tectonic; faults, dikes and sills were structures that controlled the direction of the hydrodynamic flow of mineralizing solutions.

According to NUCLEBRÁS the RAR resources are 1.700 tonnes U plus 2.550 tonnes of EAR distributed in several prospects. The potential for large deposits in the feldsphatic sandstone is not yet determined. However , it could be limited because of the small thickness of this favourable sandstone blanket (3-8 meters) as well as the small area in the horsts where the present deposits are known (Fig.6). However better potential may exist, for example in the grabens where this sandstone is preserved from oxidation. Furthermore, in the graben better stratigraphic and tectonic traps could yield richer mineralizations both in the feldsphatic blanket as well as in the upper fine-graines sandstones.

2 - LAS CAÑAS ANOMALY

Radiometry anomalies were detected in the lower Devonian sandstones of the Durazno group parallel to the national road 6 near las Cañas (9). The anomalies are located in a reddish, angular coarse-grained cross-bedded sandstone with abundant mudstone fragments and in a matrix rich in limonite. Above is a thin (2m) kaolinitic siltstone/mudstone where kaolin has been mined. The uranium concentrations range from 125 to 1340 ppm. The lower Devonian has small outcropings of mineralization between Durazno and Sarandi del Yi. This ocurrence is of minor importance.

PERMO-CARBONIFEROUS

1 - THE FIGUEIRA DISTRICT

The Permian sediments in Brazil and Uruguay shown many uranium anomalies and one deposit, Figueira, is 350 km NW of Curitiba in the State of Paranã, Brazil. The Figueira deposit occurs in the lower Permian sediments of Rio Bonito Formation near the eastern margin of the basin (Fig.3). In that area, the Rio Bonito is divided by Saad (10) into three units:

The basal unit (15 to 30m) is composed of very fine-grained to conglomeratic sandstones which are light to dark grey in colour and of intercalations of arkose, siltstones, coal, dark shales and occasional horizons of grey limestones. These sediments are commonly cemented with carbonate and also contain pyrite. Designated as unit a in Figure 7 this unit has been interpreted to have been deposited in deltaic channels on deltaic plains and in swamps.

The middle unit (± 85m) consists of greyish-green or yellow siltstones intercalated with variegated and light to medium-grey limestones. White to red sandstones characterized by parallel lamination are also found in this unit designated as b in Figure 7. These sediments were probably deposited on a marine shelf below wave base. It is the host of the main uranium mineralization.

The upper unit (± 20m) consists of very fine-grained laminated sandstones with intercalations of siltstones. These sediments designated as unit c were probably deposited on the shallow part of a shelf or close to the shoreline. In certain areas they also host uranium mineralization.

The development of these many types of depositional environments, which was the response to the regional tectonic arching, was an important factor in the genesis of Figueira mineralization.

In unit b, uranium is associated with sandstones, siltstones, clays, and carbonaceous sediments, including coal. When in the sandstones the uranium occurs in form of interstitial uraninite in a carbonate cement. When in the siltstones and carbonaceous clays the uranium occurs in form of organo-mineral complexes with phosphate and barium. When in the coal it is in the form of organic complexes.

The main ore body is lenticular in shape and follows the north-south trend of the channel. It is about 300m long and 600m wide.The uranium minerals are mainly uraninite, some coffinite, uranium in organic complexes and uranocircite. The associated elements are Mo, Pb,Zn,Cu, As and Th. Se,V, Ni, Ge occur as trace elements. Molybdenum is most important and is found as jordisite, and zinc occurs as sphalerite. Magnetic and uraniferous pyrite is common in the mineralized zones. In the channel sandstone, uranium concentration averages 0.17 to 0.42% U,molybdenum averages 0.12 to 0.42% , molybdenum oxide , and thickness ore ranges from of 1.5 to 3.5m. Outside the channels, uranium concentrations decrease to 0.02 - 0.07% U. The U/Mo ratio decreases as the uranium concentration increases. Another characteristics of the Permo-Carboniferous mineralization is a radiometric disequilibrium of about 20% in favor of chemical values.

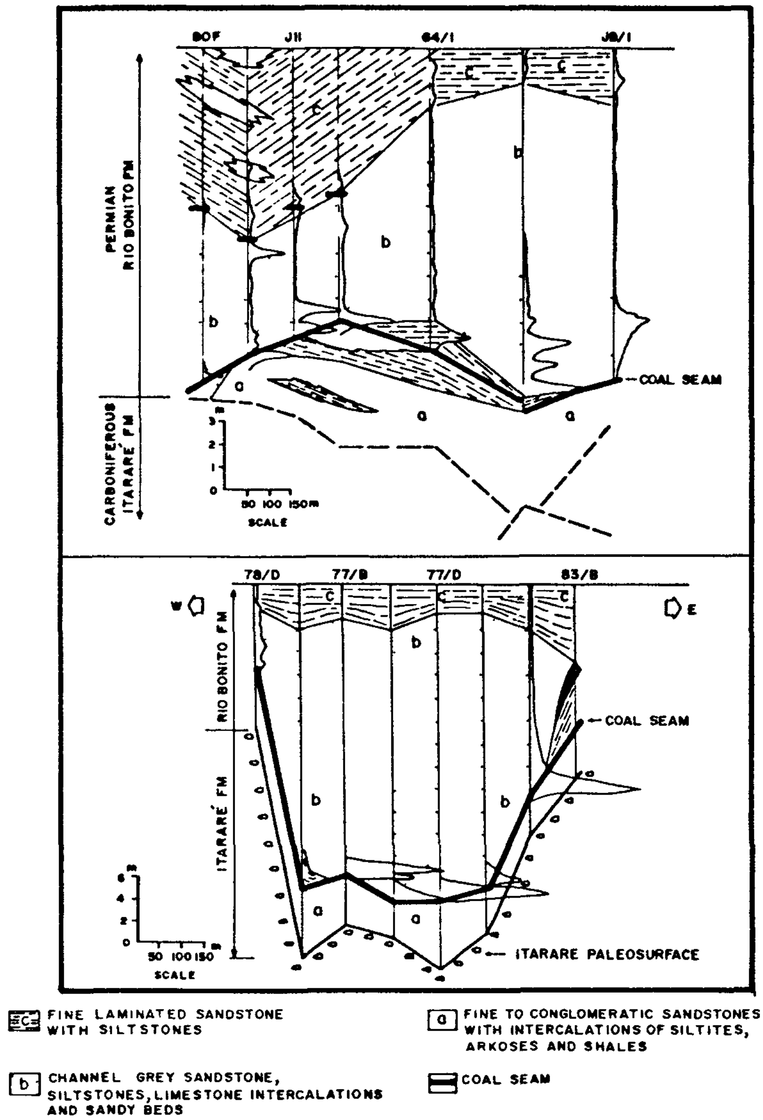


FIG 7 - CROSS SECTION INTERPRETATION OF THE MINERALIZATION IN THE PERMO-CARBONIFEROUS SEDIMENTS OF FIGUEIRA (SAAD,1973)

According to NUCLEBRÁS the resources are 6.800 tonnes of U from which 5.900 tonnes are RAR and 900 tonnes EAR. Exploration carried out in surrounding areas where similar occurrences exist, such as at the Harmonia and the Ibaiti prospects did not yield encouraging results.

2 - SAPOPEMA/TELÊMACO BORBA

In the region of Figueira a cluster of uranium occurrences are known both in surface (Telêmaco Borba) as well as subsurface (Sapopema) which are stratigraphically correlated with the Rio Bonito Formation (11).

Sapopema is situated 25km west of Figueira. The mineralized horizons are fluvial channels consisting of mudstone with carbonaceous material within the unit a and minor concentrations in unit c defined above. The uranium content varies from as to 1440 ppm eU over thickness of 0,20 to 1,5 meters.

Telêmaco Borba anomalies were detected by an airborne radiometric survey. They occur in the basal beds of Rio Bonito Fm and some correspond to sandstones dikes cutting coal seams which because of their small dimensions have no potential. Other anomalies are in sandstone channels developed over the coal beds.

3 - ALFREDO WAGNER, VIDAL RAMOS, DOMO DE LAJES

These areas are located in the State of Santa Catarina, just north of the Torres syncline . These uranium occurrences are in the Rio Bonito Fm and found in stratigraphic positions similar to those of Figueira. Secondary mineralization was found in sandstones and siltstones with carbonaceous material. The mineralization is stratiform and the grades range from 425 to 1700 ppm U.

4 - CERRO BULÃO, CERRO PARTIDO AND BOLENA

Uranium occurs in fine to medium-grained sandstones with organic matter and in carbonaceous shales of Itararé and Rio Bonito Formations bordering the Rio-Grandense Shield (Fig.3). These sediments were deposited on the border of the Paraná Basin in paleotopograghic troughs which are coincident with the present day drainage system. The sediments are directly over the basement. About twenty such "residual basins" are known but the main ones are those of Cerro Bulão, Cerro Partido and Bolena. The Bolena area is located west of the city of Bagé, and is part of the Candiota coal basin. The Cerro Bulão and Cerro Partido basins cover areas of 5 km^2 and 30 km^2 respectively, and are located south and northwest of the town Encruzilhada do Sul. Autunite and uranocircite are disseminated in the sandy matrix of the sediments and the grades vary from 170 to 4250 ppm of U. The mineralized volumes are small and reduces the potential for these prospects.

5 - MELO-FRAILE MUERTO

In the northeastern Uruguay, near the border with Brazil (Fig.3) eighteen anomalies were detected, most of then by carborne radiometric surveys. Sixteen (Divisa Norte, Sur, Paso de la Arena, Paso de Las Piedras, etc) are in the Carboniferous San Gregório-Tres Islas Fm (12), which is equivalent to the Itararé Fm. The San Gregório Fm contains clastics of glacial origin whereas the Três Islas is characterized by fluvial and deltaic sediments. The contact between then is gradational and they are difficult to separated.

The Carboniferous sediments consit of tillites, fluvioglacial sandstones and lacustrine mudstones overlain by sandstones and siltstones. The sandstones are of two types: 1) a yellow-cream, massive, cross-bedded well-cemented feldsphatic sandstone of shallow water (ripple marks origin) . It is about 10m thick ; 2) A less resistant brownish sandstone with thickness varying from 1 to 7m. The latter is also feldsphatic, cross-bedded and showns limonitic stains. Thin sections show this limonite replacing pyrite. Most of the uranium anomalies are associated with the upper sandstone. Above , are shales and fine-grained sandstones in which no uranium enrichment was found. Chemical analysis show low uranium values for these anomalies , from 70 to 170 ppm . Radiometric disequilibrium is present and preferential leaching of uranium is dominant. Some of the anomalies are radium rich (adsorbed in the ferruginous zones). The most promising results were found at La Divisa Sur where some drill hole samples showed 0.14% U in dark shales, associated with pyrite and organics.

Numerous other radiometric anomalies are known (UTE, Valentines, La Portera, El Salero, La Rinconada, etc) but, in general, they have similar characteristics (9) (12). The important aspects to be noted in these anomalies are: 1) they are confined to the San Gregório-Três Ilas Fms and only secondary uranium has been found and 2) they are all geographically located along the contact line of the basement with the Carboniferous.

TERESA CRISTINA, CÂNDIDO DE ABREU, BARRA DO GARÇAS

Uranium anomalies in the Upper Permian are known along the eastern and northeastern flanks of the Paranã basin. They include the anomalies at Teresa Cristina, Cândido de Abreu, Rio Claro in the State of Paranã, Lages in the State of Santa Catarina, Barra do Garças and the Domo de Araguainha in the State of Mato Grosso. Radiometric anomalies are also known to occur at this stratigraphic interval in drill holes in many parts of the basin.
These anomalies are found in either the Teresinha or Corumbataī Fms, which consist of siltstones, sandstones and minor carbonates. High radiometric values may be associated with phosphates and, less frequently, with organic matter. The mineralization is, in general, syngenetic with some secondary autunite. Uranium content may reach 1270 ppm U over a thickness of 1 meter.

TRIASSIC

No uranium mineralizations are known in the Triassic sediments of the Paranã Basin.

CRETACEOUS

Uranium anomalies have also been found in the Bauru Group of upper Cretaceous, but they seem to be of minor importance such as geochemical concentrations in iron-rich horizons . In some places, the uranium was reported associated with sauropod fossils.

V - URANIUM SOURCES

There are three possible sources from which uranium could have been mobilized into the sediments during Paleozoic and Mesozoic time, namely, the basement rocks, the sediments themselves, and the Cretaceous volcanics and associated rocks.

The Basement:

Basement rocks outcrops in relatively small areas located a) around the Ponta Grossa Arch b) in the Uruguay-Riograndense shield and c) along the Serra da Bodoquena in the west of Mato Grosso do Sul State, and NE Paraguay (Fig.3). In order of outcroping surface the dominant lithologies are as follows:

a) 1 - Granulitic gneisses and micaschists, kinzigite, leptites, all reworked during the Brazilian Tectonic Cycle(480-600 Ma). 2 - Sintectonic granitoids. 3 - Phyllites, schists, limestones, calc-silicate rocks. 4 - Post-tectonic granitoids (few).

b) 1 - Gneisses , migmatites, granulites, amphibolites reworked in the Brazilian Tectonic Cycle. - 2 - Syn-and post-tectonic granitoids. 3 - Volcanics (Є-O).

c) 1 - Garnet-muscovite schists, garnet quartzites, biotite schists. 2 - Granites.

Basement rocks are, therefore, mainly medium to high-grade metamorphics with tendency to basic affilitation and, accordingly, would have small potential as uranium source rock. Exception is made for the post-tectonic granitoids, the volcanics and some granites.

The volcanics (andesites) of the Uruguay-Sul Riograndense shield (b) with an age of 450 Ma show some fertility and contain some uranium occurrences associated with copper mineralization. Same for the rhyolites (550 Ma) of Castro (a) in which uranium may reach 100 ppm. Among the granitoids there are few which contain some uranium such as Lavras do Sul, Encruzilhada, Caçapava granites in the south (b), the Varginha granite in the east (a), the Iporã and São Vicente granites in the north.

These possible sources are however small in volume and surface expression when compared with the total basement lithologies and their contribution would be proportionaly small and local. Indeed, no uranium enrichments are observed in the first sediments deposited (and originated from basement erosion) in spite of favourable conditions.

The Sediments:

The majority of the Paleozoic sediments are shallow water clastics that consist mainly of quartzose and arkosic sandstones, siltstones and mudstones. In terms of volume the sediments are largely oxidized (Furnas, Ponta Grossa, Aquidauana Fms). The possibility that these sediments hosted substantial syngenetic uranium for later remobilization seems limited.

The Mesozoic was characterized by long arid intervals that resulted in thick red beds (Pirambõia, Rosãrio do Sul Fm) and extensive eolian sandstones (Botucatu Fm), all with very low uranium clarke.

Therefore, the potential of the basin sediments as source of uranium is likewise limited.

Cretaceous Volcanics:

As indicated under sedimentary history,the Paranã Basin was the stage of the most singular volcanic event of the entire continent. Although the main flows of this great volcanism are basic (tholeiitic basalts), many acidic rocks are present which can reach up to 61-63% silic oxide. It is interesting to note that basalts of the western regions are older (up to 10 Ma) suggesting a possible eastward "migration" of the volcanism (13), exactly the side where widespread acidic rocks (150.000 km^2) are developed (Fig.3) and where rhyodacites and rhyolites are common. Cordani et al.(14) consider the acidic flows the latest manifestations of the Paranã Basin volcanic cycle.

At the same time alkaline provices with ages between 147-60 Ma (Jacupiranga, Juquiã, Ipanema, Anitãpolis, Tunas, Poços de Caldas, Araxã, Salitre, Tapira, etc) were emplaced along the border of the basin (Fig.3). These alkaline provinces are rich in uranium.

The importance of the volcanic rocks, mainly the acidic and alkalic ones, cannot be underestimated as a source for uranium. Their importance became more apparent because large volumes were eroded. Fúlfaro and Landin (15) suggest that the largest flows occurred in the region of the Ponta Grossa Arch and that they were eroded by later uplift of the region. Therefore, vast amounts of uranium were available and mobilized within the Basin in Cretaceous Time. Fig.3 shows the concentration of uranium occurrences in front of and near the Ponta Grossa Arch , which supports its probable source for the uranium.

VI-MINERALIZATION MODELS

FIGUEIRA

Saad (10), who studyed both surface and subsurface of the Permo-Carboniferous sequences in northeastern Paranã Basin (Alto Paranã sub-basin), has developed an uranium mineralization model for the Figueira region. The model suggests that the uranium mineralization was of syngenetic (minor) and epigenetic origins and consists of a sequence of five phases covering the source,sedimentation, precipitation, remobilization and enrichment of uranium along the more permeable coarser fluvio-deltaic channel sediments. The evaluation by NUCLEBRÁS in 1975 of the uranium occurrences in Sapopema with 20.000m of drilling and logging (11) confirmed the favourability and enrichment criteria proposed by Saad.

During sedimentation of the host paleochannels, the region was slowly deformed by folding which caused successive flooding and accumulation of sediments in three environmental zones as follows(10):

Zone I - Caracterized by sediments of pelitic and biochemical nature indicative of an epineritic environment. This zone is found north of Figueira.

Zone II- Sediments of pelitic nature with large amounts of carbonaceous material in the form of coal and minor sandstone intercalations. This facies is typical of paludal environments, and is found in the central and eastern parts of Figueira.

Zone III- Channels filled with cross bedded sandstone and intercalations of claystone and carbonaceous layers. The channels characterize a fluvial or fluvio-deltaic environment in which coarse highly permeable sediments form the axis and low permeable overbank sediments flank the margins.

The mineralization was syngenetic in the paludal environments (zone II) and epigenetic along the channels (zone III) where the coarser clastics provided a natural way for the migration of mineralizing fluids. The epigenetic uranium underwent several steps of transport and deposition during and after diagenesis of the host rocks. Figure 7 is a cross section interpretation of a Figueira channel. The proposed sequence for the mineralization (10) is:

a) Low uneven uranium concentrations deposited along unit a (Rio Bonito Fm) just above the Itararé Fm.

b) Deposition of unit b as interbedded sandstones, siltstones , mudstones and carbonaceous horizons and the first mobilization of uranium, during diagenesis, and its concentration along channels.

c) As the deposition of clastic material decreased, it was replaced by deposition of chemical and coloidal sediments of unit c. During this phase the uranium deposited along the channels in unit b was subject to frequent remobilization by oxidating fresh water.

d) With unit b sealed by the fine and impermeable material of Unit c and, therefore, protected from the surface oxidation, the action of hydrodynamic flow of slightly alkaline waters along the channels would have transported uranium to the zones of reducing environments and redeposited there.

e) This enrichment process continued through the Paleozoic deposition when the fluid flow confined within the two impermeable lithostratigraphic units (a and c) was responsible for successive remobilizations/depositions.

AMORINŌPOLIS

Contrary to the model of Figueira, the uranium mineralization at Amorinōpolis is not as well understood and many questions remain to be answered. Several hypothesis have been proposed but none is completely satisfactory.

First, an orientation of the uranium anomalies was observed along the main Precambrian regional tectonic grain and, therefore, the mineralization phenomena was proposed to have been asssociated with fluids moving up along fractures. This hypothesis was quickly discarded.

A second hypothesis called for a close-to-surface enrichment due to present day climatic conditions. The suggestion was that semi-arid conditions of the Iporã-Amorinōpolis region, with an evapotranspiration larger than precipitation, could have provided the necessary conditions for a paleocalcrete-like enrichment. With the identification of primary minerals, pitchblend and coffinite, this idea was also discarded.

With additional surbsurface work it was noted that uranium with an irregular form occurs preferentially within the feldsphatic sandstone in paleochannels (16) where the erosion cut through the surface forming mesas (Figure 6). Uranium minerals were found in zones of organic matter including remanents of fossil wood and mud balls rich in organic matter and iron oxides. Furthermore, the elongated and sinuous radioactive anomalies found in laterites reflect the channel meanders. Based on this observation pits and drill holes along these radiometric anomalies confirmed uranium mineralization below. Mineralized "channels" were found with 400m long, 20-40m wide and 1-10 thick.

This led to the development of a "paleochannel model" (16) where the uranium was believed to be syngenetic with the channel sediments. The argument for the syngenetic origin was that the mineralization was restricted to channel sediments. The source rock rock was the fertile Iporã Massif located to the north. The "channels" are oriented N-S to N20W which corresponds to the direction of the faults in the basement as well as the direction of the present drainage. Figure 5 is a cross section interpretation of the mineralized channels.

It should be noted, however, that the channels and consequently the uranium mineralization is not conspicuous. There are neither clear geometric forms nor abrupt changes in the physical aspects of the sediments as normaly found between the uranium deposit and host rock. The mineralized coarse-grained feldsphatic sandstone is fairly homogeneous. Unfortunately the number of "channel like" mineralizations is small.

Due to the regional dip, the mineralized feldsphatic blanket which occurs in the mesas in covered a short distance by the Aquidauana Fm toward the center of the basin making exploration difficult. Therefore, the proposal for a paleochannel model, although with great potential, remains to be tested.

The "geochemical cell" is another model proposed (17). The mineralizing solution would have moved eastward causing the elongated mineralized forms which would be described as fronts of geochemical cells rather than channels. Support for this model was sought using the "two peak geometry" of the natural gamma-ray logs of Amorinópolis. The Amorinópolis gamma-ray logs were compared to some typical roll-front logs from the Powder River Basin in Wyoming to show the similarity of the curves and to suggest roll-fron mineralization. Unfortunately the similarity of the gamma-ray logs in one profile was as far as the authors went in proposing a roll-front model for Amorinópolis. No geochemical evidences such as changes in Ph and Eh (redox recycling process); presence of an oxidized, ferruginous, bleached zone opposite to an unoxidized one; the geochemical and mineralogic characteristics of these zones, and ore cutting across the bedding were given to support the model.

Furthemore, the use of the roll-front or "geochemical" model as an exploration strategy failed to find new uranium resources.

In summary, the Amorinópolis mineralization is:

- Lithostratigraphically controlled by the feldsphatic blanket-like sandstone of the Ponta Grossa Fm.
- Highly concentrated in mud balls and pebbles within the feldsphatic sandstone. Redox zones are present and primary minerals were identified in unweathered rock.
- Controlled in part by tectonics. Faults, dikes and sills provided local conditions for enrichment or displacement of the mineralization as they provided barriers of hydrodynamic flow and control for uranium precipitation.

An interpretative sketch of the regional geologic and tectonic conditions of Amorinópolis is shown in Figure 6. On the eastern side of the graben, the sequence of gravity faults with a total vertical displacement of 400m provided favorable structural traps for uranium. The shale horizons, above and below the feldsphatic sandstone confine the mineralized rock. This hypothesis seems to be supported by the occurrence of radiometric anomalies all along the graben's eastern fault plane.

If this interpretation is correct then a considerable potential would exist in the down-faulted block (Iporá Graben) which has preserved the "channels" or "roll-fronts" from erosion and oxidation. Furthermore, the shales above and below the feldsphatic sandstone and the eastward dip may have provided excellent conditions for redistribution or primary ore into roll-front type mineralization with richer uranium concentration than those found at the surface. However, the large size of the graben and the thick cover of sediments will make any drilling project in the graben risky.

With the small sucess in finding additional ore, the exploration effort ended in 1980 thus leaving unsolved the problem for the origin of the mineralization and as well as a verified deposit model.

ACKNOWLEDGMENTS

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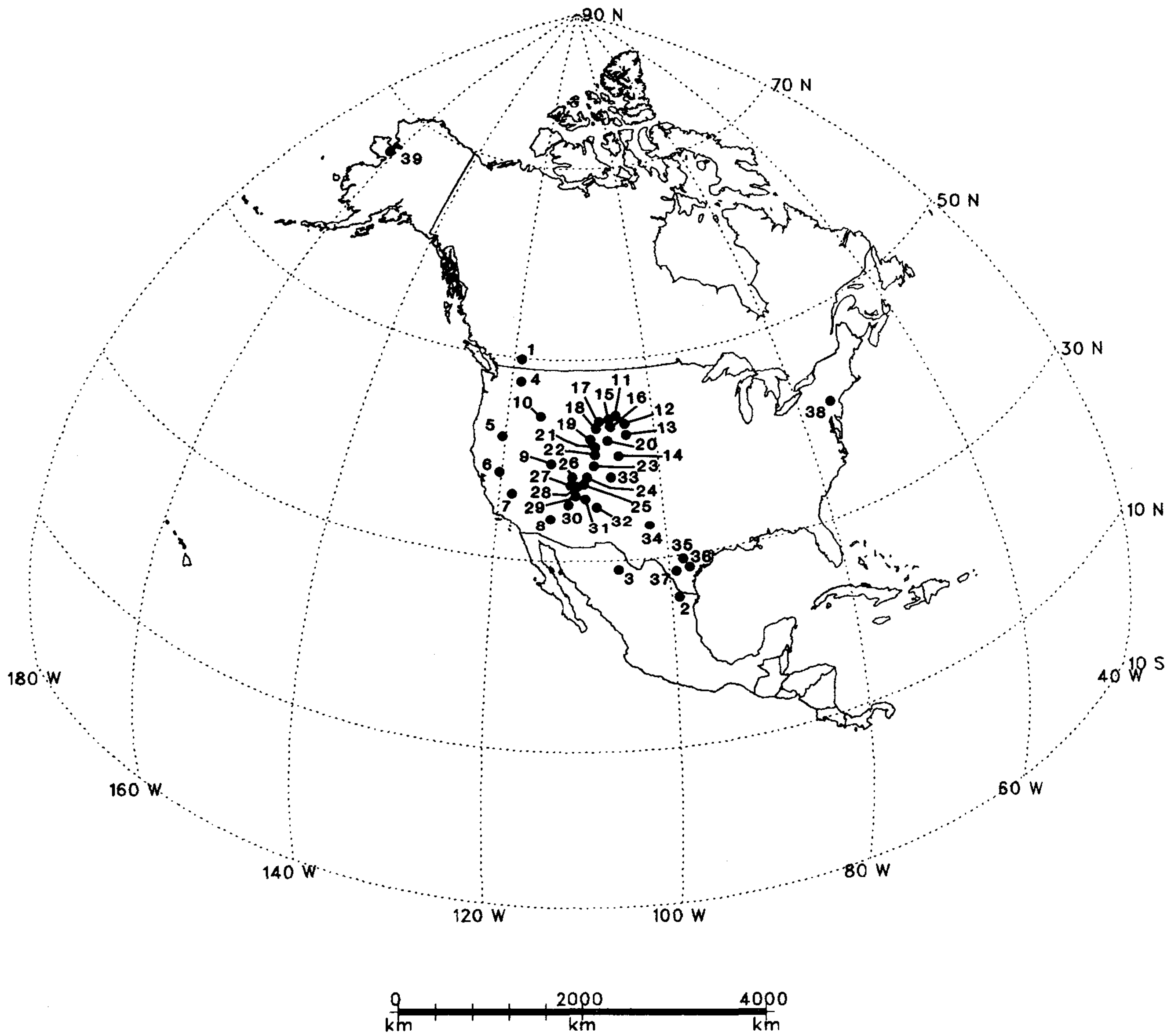
NORTH AMERICA

MAP AND INDEX LIST FOR SANDSTONE-TYPE URANIUM DEPOSITS IN NORTH AMERICA



NORTH AMERICA

Canada:

1. Tyee and Blizzard deposits, Okanagan Highlands, British Colombia, Miocene sediments

Mexico:

2. La Coma, Buenavista, and El Chapote, La Sierrita area, Nuevo Leon, Oligocene sandstone
3. Margaritas deposit, Pena Blanca, Chihuahua, Oligocene sedimentary tuff breccia.

United States:

4. Sherwood mine, Washington, Eocene Sanpoil Conglomerate
5. Aurora deposit, McDermitt, Oregon, Miocene siltstone
6. Juniper deposit,Sierra Nevada, California, Miocene sediments
7. Coso deposit, Calfornia, Pliocene Coso Formation
8. Anderson mine, Date Creek basin, Arizona, Oligocene siltstone
9. Yellow Chief deposit, Utah, Miocene-Pliocene sandstone
10. Coal Creek deposits, Stanley area, Idaho, Oligocene-Miocene Challis
11. Northern Black Hills, Wyoming, Cretaceous Inyan Kara
12. Southern Black Hills, South Dakota, Cretaceous Inyan Kara
13. Crow Butte deposit, Nebraska, Chadron Formation
14. Weld County, Colorado, Cretaceous Fox Hills and Laramie
15. Monument Hill area, Powder River Basin, Wyoming, Eocene Wasatch
16. Highland Flats area, Powder River Basin, Paleocene Fort Union
17. Copper Mountain, Wind River, Wyoming, Eocene conglomerate
18. Gas Hills district, Wind River Basin, Eocene Wind River
19. Crooks Gap district, Great Divide Basin, Eocene Battlesprings
20. Shirley Basin, Wyoming, Eocene Wind River
21. Poison Basin, Wyoming, Miocene Browns Park
22. Maybell-Lay district, Colorado, Miocene Browns Park
23. Rifle mine, Colorado, Jurassic Entrada Sandstone
24. Uravan Mineral Belt, Colorado, Jurassic Morrison
25. Lisbon Valley, Utah, Permian Cutler, Triassic Chinle
26. Temple Mountain district, Utah, Triassic Chinle
27. Henry Mountains, Utah, Jurassic Morrison
28. White Canyon district, Utah, Triassic Shinarump Conglomerate
29. Monument Valley district, Arizona, Triassic Shinarump Conglomerate
30. Cameron district, Arizona, Triassic Chinle
31. Carrizo-Lukachukia, Arizona-New Mexico, Jurassic Morrison
32. Grants Uranium Region, New Mexico, Jurassic Morrison
33. Hansen and Picnic Tree, Tallahassee Creek, Colorado, Eocene and Oligocene sediments
34. Post, Texas, Triassic Dockum Group
35. Karnes County district, Texas, Eocene Jackson and Oligocene Catahoula
36. Live Oak County district, Texas, Eocene Jackson and Oligocene Catahoula
37. Duval-Webb Counties district, Texas, Miocene Oakville and Goliad
38. Mauch Chunk, Pennsylvania, Pennsylvanian Pottsville Formation
39. Death Valley, Alaska, Paleocene sandstone

GEOLOGY AND APPLICATION OF GEOLOGIC CONCEPTS, MORRISON FORMATION, GRANTS URANIUM REGION, NEW MEXICO, USA

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Abstract

The Grants uranium region is the most productive uranium mining area in the U.S.A., having produced 125,034 tonnes U. Most production is from sandstones in the upper Morrison Formation of Late Jurassic age. The productive sandstones are part of a broad alluvial-fan depositional system located largely in the San Juan Basin. A regional oxidation front, formed in the host sandstones, has advanced downdip into the basin from southern outcrop areas. Primary ore deposits are tabular deposits that trend in the direction of sedimentary transport, are in reduced sandstone at and downdip from the oxidation front, and are nearly as old as the host rocks. Redistributed ore deposits are thick deposits commonly localized by faults that offset primary ore and are remobilized primary deposits that have been reprecipitated at the oxidation front. Humate is coextensive with primary ore; yet, more than one ore model may be necessary to explain the origin of the uraniferous humate. Presence of grayish-green, montmorillonitic mudstone and claystone beds may indicate uraniferous humate in adjacent sandstone beds. Because ore occurs in trends, "trendology" is the most commonly used exploration concept. The oxidation front is the most productive environment because the front tends to "hang up" where highly-reducing primary orebodies are encountered, and it is where redistributed ore is found. Deeper in the basin in unoxidized sandstones, favorable depositional environments are good targets for primary ore.

INTRODUCTION

The Grants uranium region is the most productive uranium mining area in the United States, having produced about 40% of the nation's uranium ore to date. Because of the importance of the region, it has been the subject of numerous geological and mineralogical investigations. For additional background information, the reader is referred to papers published in two memoirs on the Grants uranium region (1, 2) and a U.S. Department of Energy-funded geologic-model study (3).

The intent of this paper is not only to offer an overview of the geology and the ore-deposit characteristics of the Grants uranium region, but to emphasize those ideas that the authors believe are particularly important in comprehending the nature of the uranium deposits. The paper also relates how some geologic concepts may be and have been successfully applied to exploration. This paper draws heavily from the experience and thinking of Harlen Holen, who spent many years of his career working in the Grants uranium region.

The authors are indebted to those members of the U. S. Department of Energy's Grand Junction Area Office, both with the department and with Bendix Field Engineering Corporation, who facilitated the preparation of this paper.

GRANTS URANIUM REGION

The Grants uranium region is on the south side of the San Juan Basin of the Colorado Plateau physiographic province, and is located in the northwestern part of the state of New Mexico (Figure 1). It is named for Grants, New Mexico, the center of mining and exploration activity in the area. A belt of deposits, which is about 160 km long, includes, west to east, the Church Rock, Smith Lake, Ambrosia Lake, and Laguna mining districts. Recent discoveries north of the belt have made the early name - Grants mineral belt - inappropriate (Figure 2).

Rocks exposed in the area range in age from Late Triassic to Late Cretaceous. Between the Ambrosia Lake and the Laguna areas, the belt is covered by the Mount Taylor volcanic field of Tertiary age. Uranium has been mined from the Todilto Limestone and the Morrison Formation of Late Jurassic age and the Dakota Sandstone of Late Cretaceous age. The principal deposits are in the Westwater Canyon and Brushy Basin Members of the Morrison Formation, and are the deposits discussed in this paper.

The published discovery of uranium in the Todilto Limestone in the fall of 1950 brought national attention to the Grants area. Soon afterward, outcropping deposits in sandstones of the Morrison Formation were discovered. In April of 1955 a deposit in the Ambrosia Lake area was found by blind drilling. By the late-1950's many large mines and five mills were in operation. Additional mines and mills were put into operation in the 1960's and 1970's, but the depressed market in the 1980's has resulted in the closure of all but a few of the mines and two mills.

Except for 1973, the state of New Mexico, where almost all production has been from the Grants uranium region, has led the U.S.A. in production of uranium each year since 1956. Records of the U.S. Department of Energy indicate that as of January 1, 1983, the Grants region had produced 125,034 tonnes U. Of this total, 121,810 tonnes U, including production from mine water, had come from sandstones of the Morrison Formation. Reasonably assured resources for the region are estimated as about 56,000 tonnes U in the $80 kg U production cost category, and the estimated additional resources in the $80 category are about 61,000 tonnes U.

SEDIMENTARY FRAMEWORK

The San Juan Basin, comprising an area of about 25,000 km^2 is one of the larger structural elements of the Colorado Plateau (Figure 1). The present day structural basin lies at the southeast end of the Late Jurassic San Juan depositional trough (6). The trough was bordered by two northwest-trending positive tectonic elements -- the Uncompahgre highland to the northeast, which was subdued, and the Mogollon highland to the southwest, which was rising and undergoing erosion. Across the trough three broad alluvial fans that correspond, from oldest to youngest, to the Salt Wash, Recapture, and Westwater Canyon Members of the Upper Jurassic Morrison Formation were deposited (7). The depositional paleoslope was generally to the northeast, or down the Mogollon slope, but in the vicinity of the southern San Juan Basin, a large component of the paleocurrent directions was to the southeast, parallel to the trend of the trough axis (6, 7).

Uplift of the Mogollon highland, and probably the Cordilleran geanticline to the west (8), provided source areas for the Morrison alluvial fans. Whereas the Salt Wash provenance consisted chiefly of older sedimentary rocks, the Recapture and Westwater Canyon source areas included significant igneous

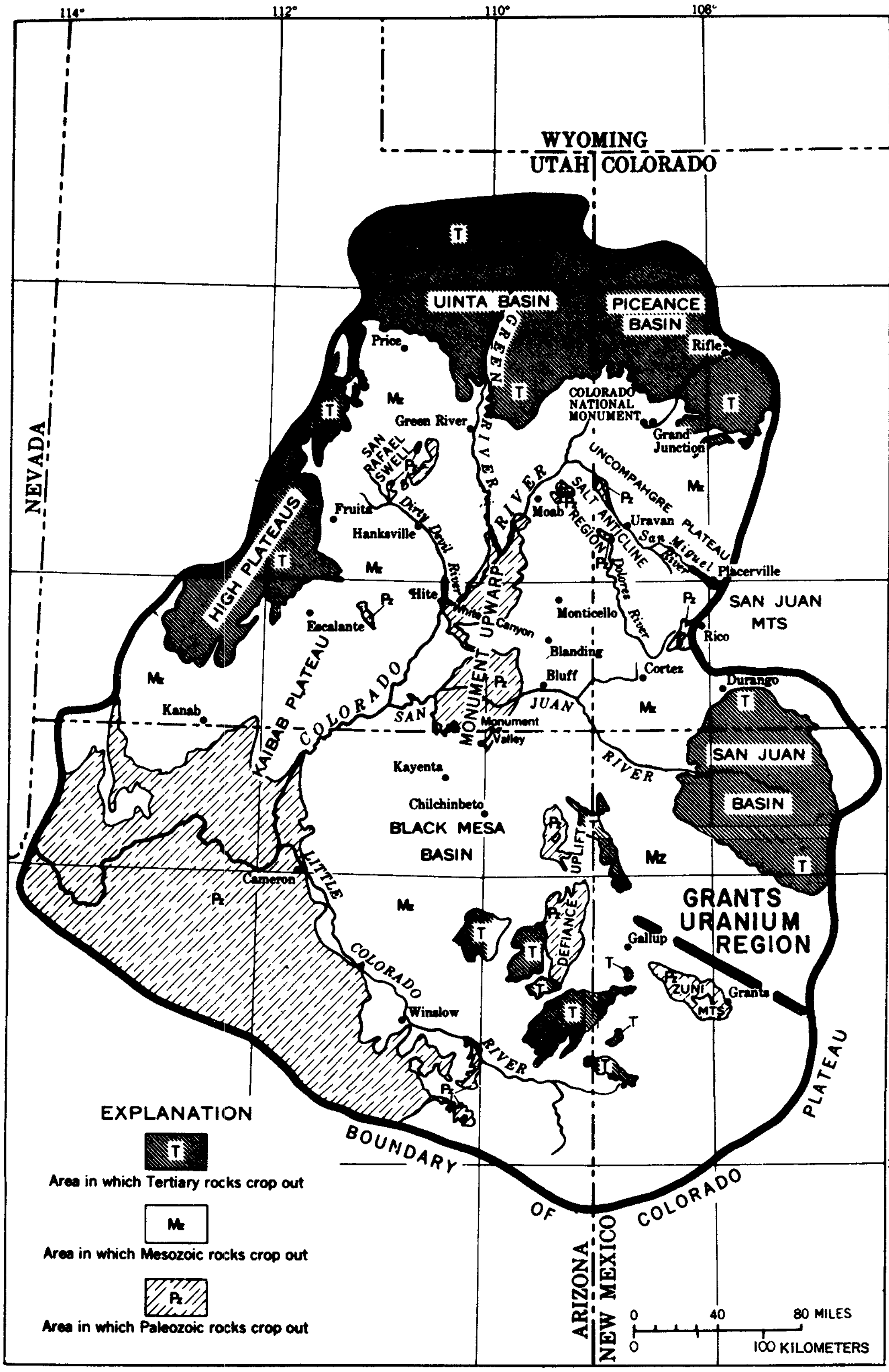

FIGURE 1. Index map of the Colorado Plateau showing the location of the Grants uranium region. Modified from Adams and Saucier (3) and Jobin (4).

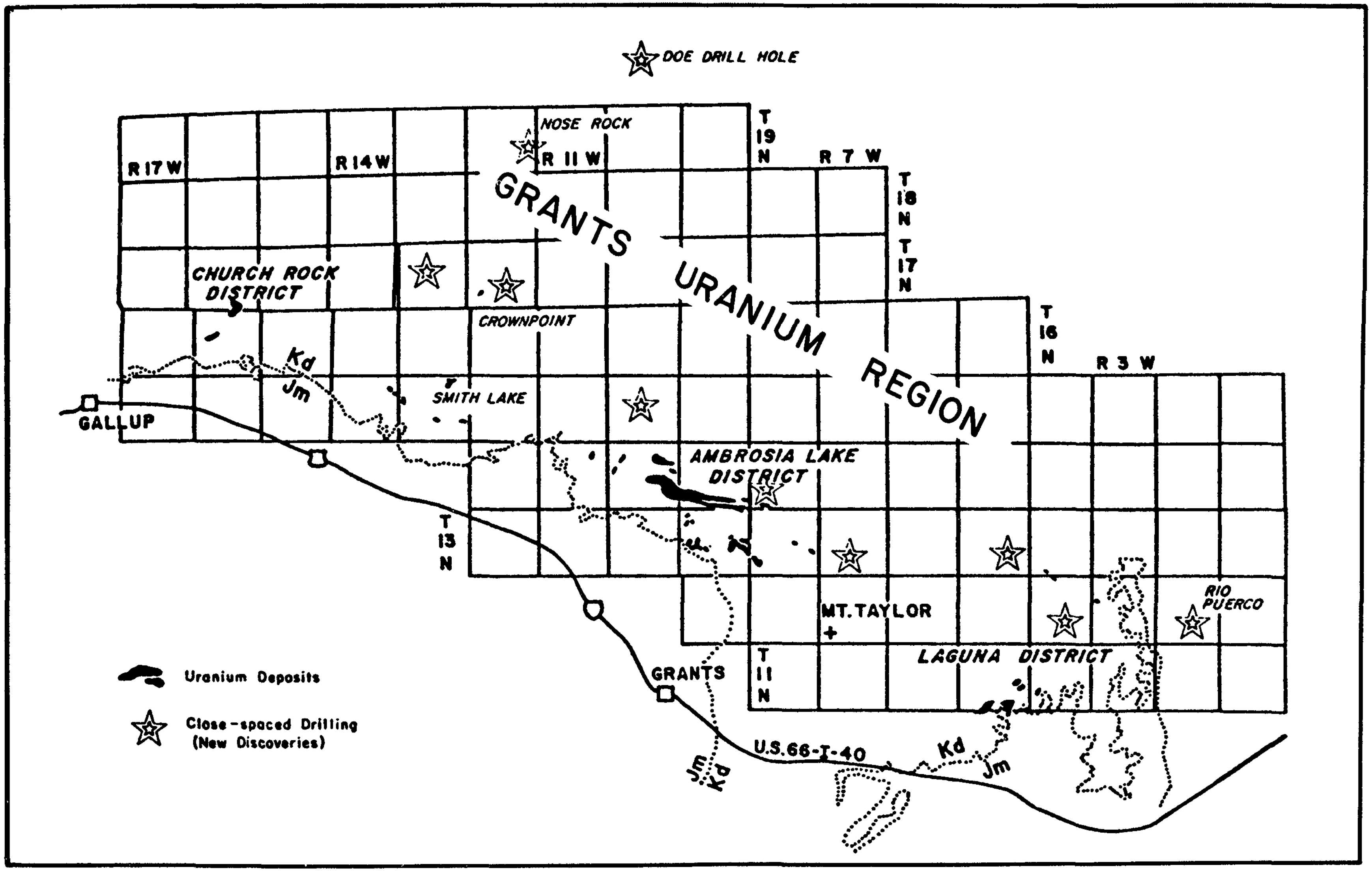

FIGURE 2. Map of Grants uranium region showing major mining districts and areas of recent discoveries. Modified from Fitch (5).

and metamorphic terranes (7). Deposition was accompanied by an increasing amount of explosive volcanic activity, apparently to the southwest of the basin, which culminated with widespread ash-fall material being incorporated into lacustrine and fluvial sediments of the upper Morrison Formation.

The Salt Wash and Recapture Members are in the lower part of the Morrison Formation, and the Westwater Canyon and Brushy Basin Members are in the upper part (7). The Salt Wash alluvial fan is the largest and was deposited chiefly to the west and north of the Recapture and Westwater Canyon fans, which were deposited largely in the vicinity of the San Juan Basin. Thus, the Grants uranium region is south of the depositional limit of the Salt Wash fan. The proximal facies of the alluvial fans consist predominately of sandstone and conglomeratic sandstone, whereas the mid-fan facies consist predominately of sandstone interspersed with mudstone. The Recapture Member contains more interstratified mudstone than the overlying Westwater Canyon. The Brushy Basin, which is the uppermost member of the formation, is composed of mudstone and claystone with some interbedded siltstone, sandstone, and limestone. To the north and northeast, beyond the recognizable limits of the alluvial fans, the Morrison is undifferentiated.

Most of the uranium deposits in the San Juan Basin are within the main sandstone bodies of the Westwater Canyon Member where they are localized near the thickest parts of the host sandstone. However, significant deposits were mined from a tongue of sandstone beds, known as the Poison Canyon sandstone of economic usage, which extends into the Brushy Basin from the upper part of the Westwater Canyon Member in the Ambrosia Lake district, and from other sandstone lenses in the Brushy Basin Member in the Ambrosia Lake and Smith Lake districts. In the Laguna district a northeast-trending belt of sandstone in the upper part of the Brushy Basin Member, known as the Jackpile sandstone of economic usage, contains the major uranium deposits. The maximum preserved thickness of the Westwater Canyon is nearly 100 m. The Poison Canyon ranges to nearly 25 m, and the Jackpile is as much as 70 m thick. In general, the Morrison sandstone units in the San Juan Basin are thick, cross-bedded, coalesced, tabular bodies with scoured basal surfaces. Sedimentary structures and associated facies relationships indicate deposition in fluvial and associated overbank and lacustrine environments.

Several workers (see Hilpert, 9, and Saucier, 6, for example) have suggested that the southern margin of the San Juan Basin was undergoing subtle warping during Westwater Canyon sedimentation that resulted in the stacking of channel-fill sandstone lenses along shallow, southeast-trending synclinal axes. However, a sandstone isolith map of the Westwater Canyon alluvial fan system by Galloway (10) shows a diverging pattern of channel-fill sandstone belts that swing from the southeasterly trend in the southern part of the basin to a northeasterly trend in the northern part (Figure 3). Galloway interprets the Westwater Canyon depositional environment as a wet alluvial fan. The thickest part of the fan and the coarsest sandstone are near the southwest margin of the basin, indicating the area of sediment input. The more proximal part of the fan has been truncated by pre-Dakota (Late Jurassic to Late (?) Cretaceous age) erosion. Braided bed-load channel facies is replaced down fan by straight bed-load, sinuous mixed-load, and finally distributary mixed-load channel facies at the distal margin of the fan system. The major uranium ore bodies are restricted to the mid-fan facies (10).

The host rocks in both the Westwater Canyon and Brushy Basin Members are poorly sorted, fine- to very coarse-grained, feldspathic sandstones. Mineral compositions of Westwater Canyon sandstones, as reported by various workers (see Adams and Saucier, 3), range as follows: 30 to 99% quartz, 2 to 24%

feldspar, 9 to 16% clay, 1 to 35% rock fragments, and a trace to 0.5% heavy minerals. Widespread but irregularly distributed plant material occurs in the sandstones as silicified and carbonized logs, up to 1.2 m in diameter; as accumulations of carbonized branches and grass; and as laminae of macerated and carbonized leafy material. Humate, which formerly was a water-soluble organic substance, locally impregnates the sandstone in large, blanket-like uraniferous masses. Mudstones and sandstones of both Brushy Basin and Westwater Canyon contain abundant montmorillonitic clay apparently derived from alteration of volcanic ash. The release of soluble constituents from volcanic glass detritus during early diagenesis of the Morrison is believed by many workers to be the probable source for uranium in the ore deposits.

In the subsurface the Westwater Canyon sandstone beds are predominantly gray, whereas in the outcrop areas they are predominantly red. Other colors reported for the Morrison sandstones are reddish brown, orange, yellow, buff, and white. The red, hematitic sandstone at the outcrop extends a few to many kilometers into the subsurface where a zone of brown, limonitic sandstone, less than a kilometer to several kilometers wide, borders the gray sandstone. Figure 4 illustrates the patterns of hematitic and limonitic sandstones in the Westwater Canyon Member that resulted from epigenetic oxidation which began as early as middle Tertiary and may be active at present (11).

In contrast to the sandstone, the claystone and mudstone units of the Westwater Canyon and those of the Brushy Basin are predominantly grayish green both in the subsurface as well as at the outcrop. Although the fine-grained rocks of the Brushy Basin are chiefly of red hues elsewhere in the Colorado Plateau, red, purple, and mottled green and red colors are minor in the Grants uranium region. As in other red and gray bed formations (12), the color of the Morrison Formation is a function of the proportions of red hematite, brown and yellow hydrous ferric oxides (limonite), green chlorite and clay minerals, and black organic matter.

Because detrital organic matter was preserved and diagenesis occurred under reducing conditions, the bulk of the Westwater Canyon sandstone and the larger Brushy Basin sandstone bodies are gray and contain pyrite. The permeability of the sandstones have allowed oxidizing ground water to invade these units from recharge areas at the surface causing the alteration of contained iron minerals, the destruction of organic matter, and the remobilization of uranium deposits. The limonitic border zone indicates that the alteration of this zone is younger than the hematitic zone updip because the limonite minerals have not aged to hematite. The relative impermeability of the claystone and mudstones units have protected them from oxidation during the present erosion cycle.

The claystones and mudstones are grayish green because they lack hematite, organic matter, and abundant iron sulfides. Elsewhere in the Colorado Plateau much of the grayish-green claystone and mudstone is thought to have been red originally but was bleached and altered by invasion of reducing fluids. The red beds are thought to form early by the alteration of detrital iron minerals to hydrous ferric oxides, which later dehydrated to hematite, and by the destruction by oxidation of organic matter. The formation of red beds apparently occurred in well-drained fluvial-overbank and lacustrine environments. The thick sections of grayish-green claystones and mudstones in the San Juan Basin suggest deposition in reducing environments that were protected from later oxidation, such as in large lakes (13). Organic matter may have been solubilized in the pore waters of the lake sediments and later expelled under compaction (3, 13).

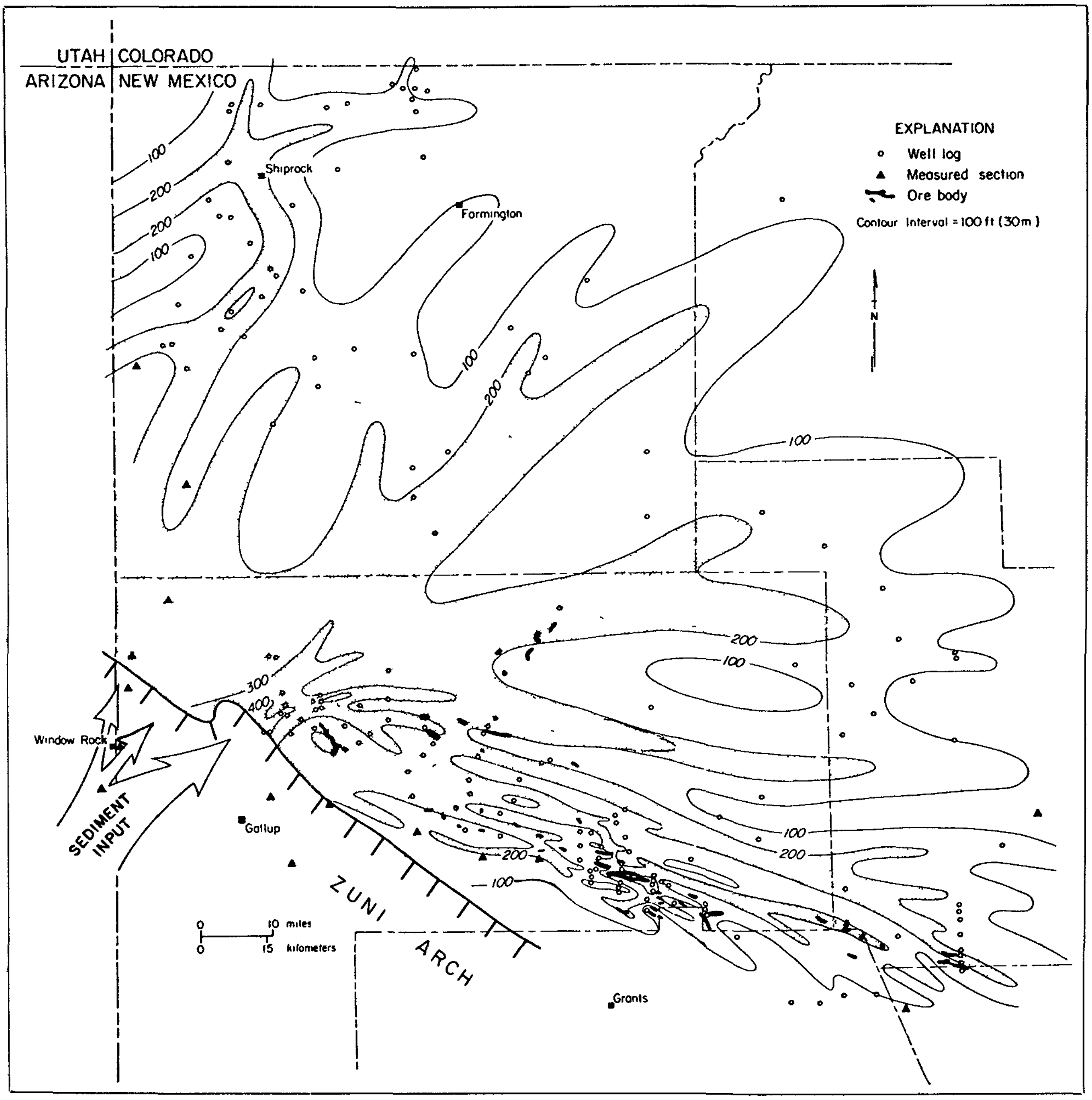

FIGURE 3. Sandstone isolith map of the Westwater Canyon Member of the Morrison Formation. Modified from Galloway (10).

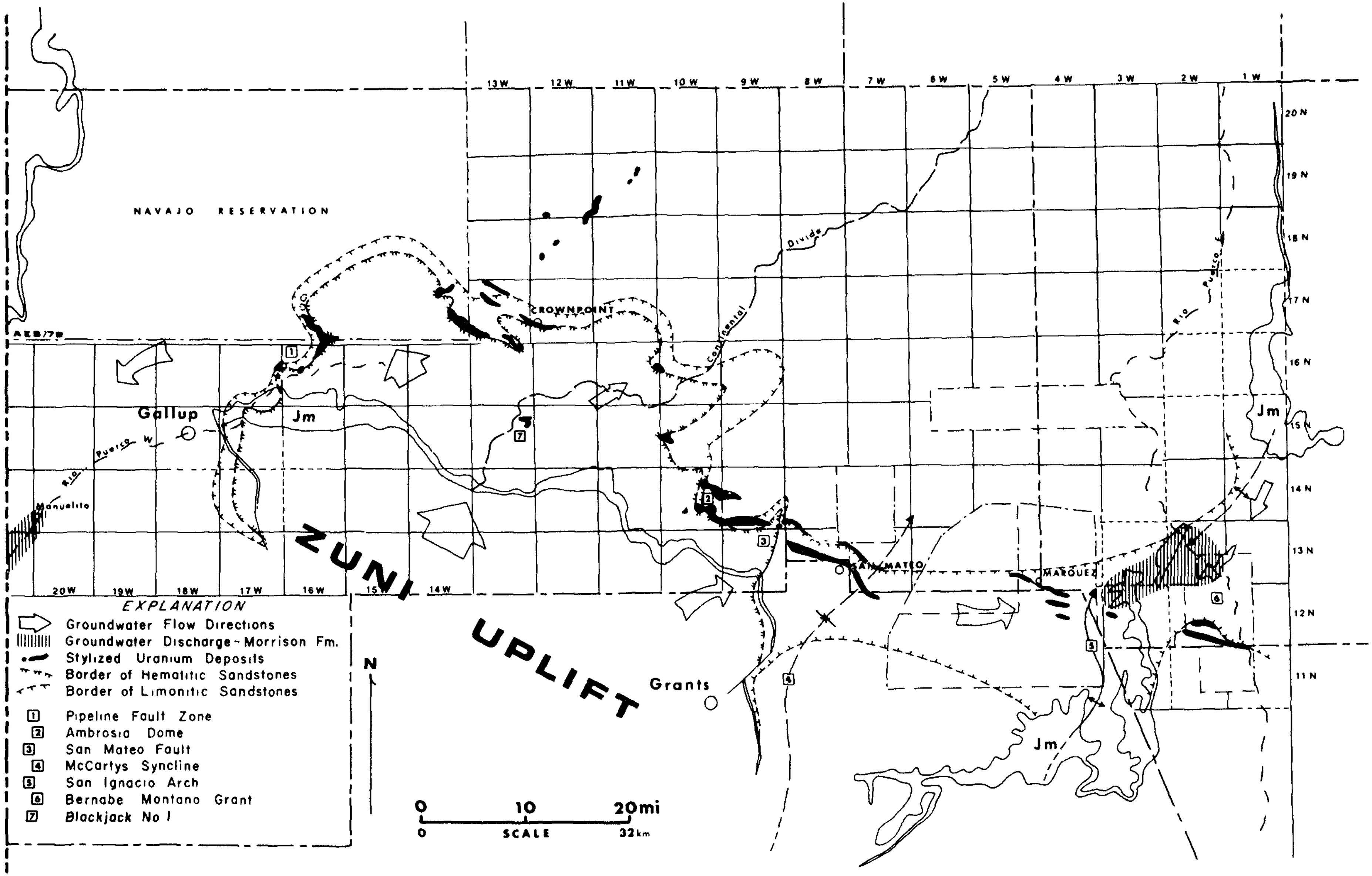

FIGURE 4. Map showing distribution of Tertiary-Quaternary oxidation in sandstone of Westwater Canyon Member, Morrison Formation. See Saucier (11), from which this figure is taken, for full discussion of details shown on map.

ORE DEPOSITS

The ore deposits are, in general, lenticular, tabular masses of interstitial humate and uranium minerals that are roughly parallel to the bedding and generally elongated in the direction of sediment transport of the host rock (Figure 4). Two general types of deposits are recognized: primary and redistributed. Figure 5 summarizes the characteristics of the ore deposits and the geology of the Grants uranium region.

The primary deposits (also called prefault ore, trend ore, black-band ore) are nearly as old as their host rocks; field relationships and isotopic age dating indicate that at least some of these were emplaced immediately following deposition of the host sands. They are characterized by: (1) being generally less than 2.5 m thick; (2) having ore grades generally averaging greater than 0.20% U_3O_8; 3) being offset by Laramide - Tertiary faults; (4) having sharp ore to waste boundaries; and (5) having dark gray to black colors. In large part, the dark colors are due to the humate.

In contrast, the redistributed deposits (also called postfault ore, stack ore, secondary ore) are characterized by: (1) being generally more than 3 m, and up to 46 m, thick; (2) having ore grades generally averaging less than 0.20% U_3O_8; (3) commonly localized by the faults that offset primary ore; (4) having diffuse ore to waste boundary; and (5) having dark, brownish-gray to light-gray color depending on the amount of humic material present.

The origin of redistributed deposits is generally accepted as simply remobilized and reprecipitated primary deposits on the fringes of advancing oxidation fronts that started after regional uplift and erosion in late Miocene or early Pliocene time. In many respects they are similar to the Wyoming roll-front deposits.

The origin of the primary deposits is still controversial. A variety of ore-body characteristics has resulted in confusion regarding ore habit and geometry. At least three types of primary ore are described in the literature: (1) blanket ore -- an undulating blanket with pronounced subparallel thickenings or "rolls" that are subparallel to the direction of sediment transport; (2) channel ore -- ore that commonly follows individual channels for tens of meters to as much as 2 km; (3) roll-front ore -- ore that is similar in geometry to that of the Wyoming roll-front deposits, except that the upper and lower limbs are wider; and thus, they could be confused with blanket-type deposits. Roll-front ore is thought to be related to pre-Dakota oxidation fronts; however, the relationship is not readily ascertained because the oxidized rock has been re-reduced. Some geologists (15, 16) suggest that all of the primary ore is of this type, but they fail to explain the pronounced parallelism of the rolls or trends in blanket ore and the close association with humate, which are not characteristic of the classical roll-front deposits.

Probably the genesis and habit of the primary ore is controversial because there has been a tendency to ascribe primary ore to one mineralizing period and process. Actually the primary ore may be of somewhat different habits and ages. There were three episodes when oxygenated, near surface meteoric waters could have deposited primary ore or remobilized and reprecipitated pre-existing ore: (1) during and soon after deposition of the host sands, (2) during the pre-Dakota erosional interval which spanned the time from Late Jurassic to early Late Cretaceous; or (3) during the present erosion cycle which started in late Miocene or early Pliocene time. Remobilization and reprecipitation of all or parts of some pre-existing deposits probably occurred during the second

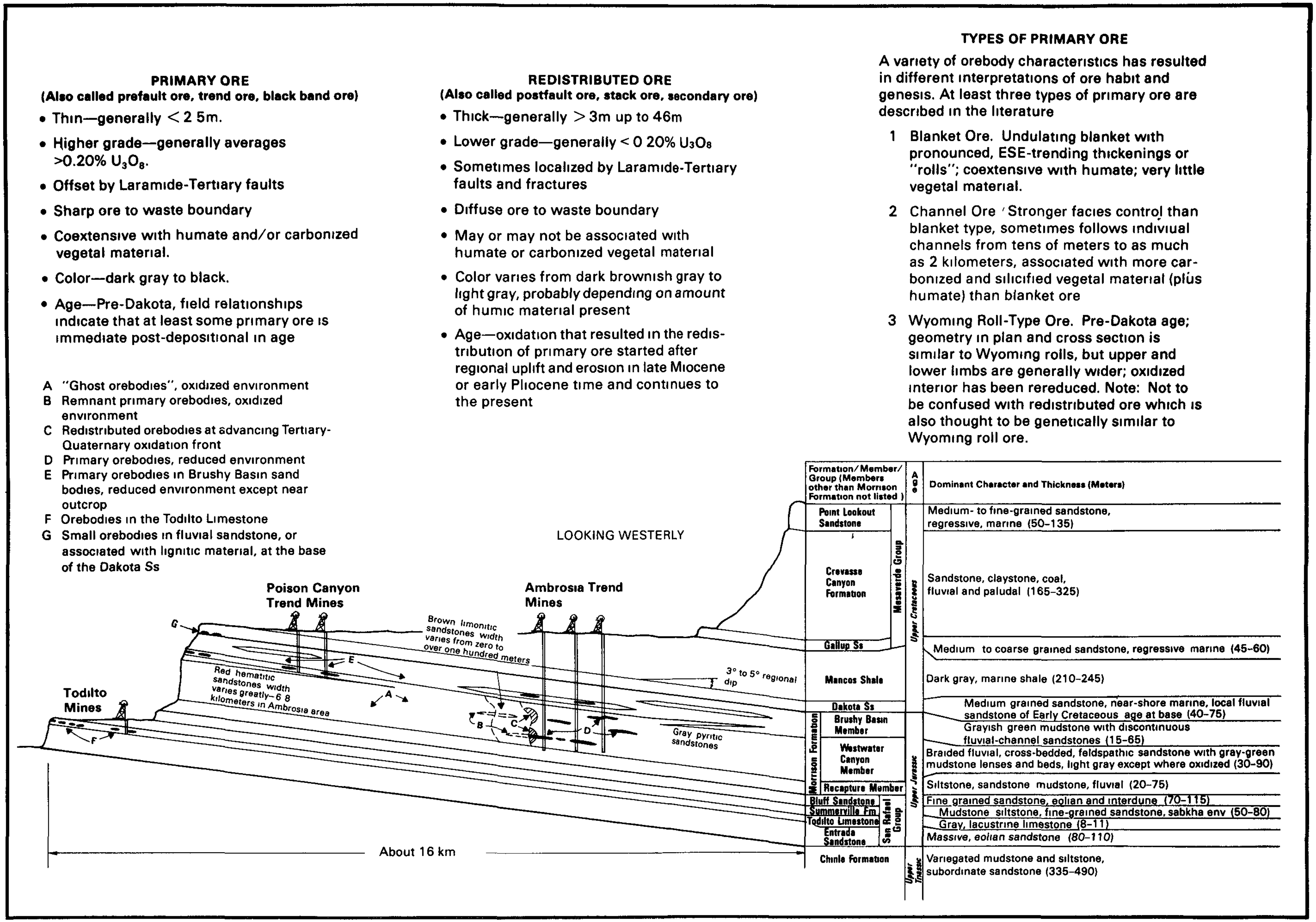

FIGURE 5. Idealized cross section, Ambrosia Lake area, summarizing the uranium geology of the Grants uranium region. Modified from Holen (14).

episode as well as the third. This, coupled with the fact that the oxidation associated with redistribution during the second episode is not readily apparent because of re-reduction, has resulted in confusion in identifying the first and second episodes of mineralization. The picture is further confused because redistributed ore is commonly superimposed on, and is sometimes not readily separable from, primary ore.

The primary ore deposits have been referred to as uraniferous-humate bodies; the uranium is coextensive, at an approximate 1:1 ratio by weight (17), with amorphous organic matter, usually called humate, that coats and is interstitial to sand grains. Carbonized vegetal remains are also present. Although the evidence is not unequivocal, it almost overwhelmingly supports a vegetal source for the humate rather than a petroleum source. In many mines small isolated humate bodies can be traced back to the fossil vegetal material from which they were apparently derived. However, the specific source of the bulk of the humate is still debated.

Humate is also commonly associated with redistributed ore, but in contrast to primary ore the ratio is highly variable. The oxidizing waters that redistributed the primary ore separated uranium from organic material in varying amounts. Some redistributed ore is virtually free of organic carbon (18).

Although X-ray diffraction patterns from samples of unoxidized primary ore indicate the presence of coffinite, it is probable that much of the uranium is in the form of a urano-organic complex. Coffinite is the dominant uranium mineral in unoxidized redistributed ore, but in contrast to primary ore, minor amounts of uraninite have been identified (18).

Other introduced minerals that occur with primary ore include jordisite, ferroselite, pyrite, marcasite, calcite, and kaolinite (18). Molybdenum in the form of jordisite and commonly selenium are distributed zonally around primary orebodies. Vanadium and other metals that may be present in primary ores are probably fixed by the humate. Vanadium minerals, pyrite, ferroselite, and elemental selenium are associated with redistributed ores, but molybdenum is virtually absent (18).

ORIGIN OF URANIFEROUS HUMATE

The primary tabular deposits of the Grants uranium region differ significantly from other known deposits in the U.S.A. in their cumulative size and in their coextensive relationship with humate. Because of this coextensive relationship, the size and geometry of the ore bodies are dependent on humate deposits. Thus an explanation of the origin of the humate deposits is critical to the construction of a detailed geologic model for the Grants uranium region. Many explanations have been proposed, but no one explanation has been thoroughly examined and tested, and consequently, none have gained general accceptance.

Proposed origins for the humate include the vegetated surface of the active alluvial fan (10, 19); plant debris incorporated into the host sandstone (19, 20); plant material deposited with clays and muds of associated lacustrine deposits (3, 13); and Dakota and pre-Dakota swamps developed on Morrison sandstone subcrops (21). Most models propose solution and mobilization of the organic matter in ground water and deposition of the humate where the organic-rich waters mixed with other ground water of different chemical characteristics. Adams and Saucier (3) review many of these and other ideas that have evolved on the origin of the humate.

Some uranium, transported by organic acid complexes, may have co-deposited with the humate. The initial humate deposit was probably in the form of floculated gel that continued to concentrate uranium through the process of chelation and complexing (22). Eventually the humate gel matured and hardened through bacterial action, oxidation and radiation. Some formerly complexed uranium was probably released to form the mineral coffinite (3).

Two recent reports, one by Turner-Peterson and others (13) and the other by Adams and Saucier (3), proposed models in which the humate originated in the grayish-green claystone and mudstone that is common in the upper Morrison Formation of the Grants uranium region. Essentials of these models are as follows: Detrital plant debris and abundant volcanic ash were incorporated into the lake sediments of the Morrison Formation. Early diagensis produced alkaline, reducing pore waters that solubilized humic substances. This pore water, which constituted as much as 70% of the volume of the lake sediments, was expelled under compaction into adjacent fluvial sand beds of the Westwater Canyon. Because the ground water moving through the sandstone was less alkaline and probably less reducing, a geochemical interface was set up causing deposition of solubilized humic substances as insoluble humate. The "lacustrine-humate" model of Turner-Peterson, which is also used to explain tabular uranium deposits elsewhere, involves reactions with iron and aluminum hydroxides and the formation of organo-clay complexes in the precipitation of humate.

It should be recognized, however, that at least locally the humate may have not undergone extensive solution and mobilization. Jacobsen (20), for instance, specifically rejects the concept of an extrinsic source for the structureless humic material in the L-Bar deposits in the Jackpile sandstone of the Laguna area. His observations indicate that vegetal material that was syngenetically deposited as finely divided detritus is an adequate source. Uranium would be subsequently extracted and fixed by the partially degraded carbonaceous material from both surface and ground water during the remaining deposition of the Morrison.

In view of the local differences in orebody characteristics and the resulting differences in genetic interpretations, more than one model may be necessary to account for the concentration of both the humate and the uranium in the primary ore deposits of the Grants uranium region. According to Jacobsen's model for the L-Bar deposits, the present shape of the deposits is essentially the shape of vegetal detritus that was massed by normal sedimentary processes. Such a model might also be applicable to primary deposits that follow channels, which are rich in carbonized vegetal detritus. It would be less applicable to primary deposits of blanket or roll-front forms, which apparently encompassed little vegetal detritus, and which have shapes difficult to explain by sedimentary processes. As stated earlier, blanket ore and roll-front ore are difficult to explain by the same model. It is worth noting, however, that both channel ore and blanket ore are occasionally found in the same mine in the Ambrosia Lake district.

APPLICATION OF GEOLOGIC CONCEPTS

Although the concept was not applied by early uranium explorationists because of its recency, the existence of extensive units of grayish-green, montmorillonitic claystone and mudstone beds adjacent to the sandstone units of the upper Morrison may be a significant recognition criterion of favorability for the occurrence of uraniferous-humate deposits in the Grants uranium region. Similar grayish-green, fine-grained beds occur in the Morrison Formation elsewhere in the Colorado Plateau, but few places are they as widespread as in the southern San Juan Basin. However, the genetic relationships, if any, that may exist between these beds and the uraniferous-humate deposits are still open to question.

After the initial uranium discoveries along the southern San Juan Basin outcrops were made by walking and by carborne and airborne methods, early day exploration consisted of random drilling at ever increasing depths. Little regard was paid to the geology, but it was soon recognized that ore occurred in definite trends and drilling on the trend projection became an important exploration concept. This concept evolved into the important geologic concept of trend deposits, which in turn further reinforced the exploration practice. "Trendology," as it is facetiously called, is still the most widely used exploration tool in the Grants uranium region.

It was also early recognized that most of the important sandstone uranium deposits in the United States were in stream-deposited sediments with certain ratios of sandstone to mudstone. These ratios were said to range from 4:1 to 1:1 in the San Juan Basin as well as in other areas (23). This concept has since been refined, notably by the work of Galloway (10), to assign relative favorability to specific depositional environments within the Morrison alluvial fan system. Major orebodies are restricted to sand bodies deposited in the braided, straight, and sinuous channel environments. The difficulty in recognizing these environments in the subsurface is obvious, but certain characteristic patterns on the electric logs of exploratory drill tests make this task possible (10).

Much of the ore in the Grants uranium region is found at and near the boundary between oxidized hematitic and limonitic sandstone updip and gray, pyritic sandstone, downdip. This pattern resulted in an exploration concept, influenced by geologists with experience with roll-front deposits in the Wyoming Basins, that was widely used if incompletely understood. That the concept is a good one is evidenced by the fact that perhaps 80% of the known orebodies, both primary and redistributed, are within a kilometer or two of the oxidation front (Figure 4). However, significant, primary orebodies were subsequently found many kilometers downdip from the oxidation front (16) and it is now generally accepted that only the redistributed ore is genetically related to the oxidation front. The primary ore often tends to be at or near the oxidation front because the organic carbon and other minerals associated with the ore results in a strongly reducing environment that tends to "hang up" the oxidation front as it progresses downdip. Oxidation is further inhibited because the ore minerals and humate reduce the permeability of the sandstone.

The concept of a regional oxidation front places emphasis on the importance of determining oxidation patterns as soon as possible in an exploration program. Sandstone bodies that are strongly oxidized to red and brown colors, although they are otherwise prospective, are poor targets because pre-existing orebodies have probably been destroyed. Oxidation patterns will vary greatly with the gross transmissivity of sandstone bodies. Lenticular sandstone beds surrounded by impermeable mudstone, such as those in the Brushy Basin Member, may be unoxidized at the outcrop, whereas the more continuous underlying Westwater Canyon sandstone beds may be oxidized many kilometers from the outcrop. For this reason, there is almost no mineralization of the Westwater Canyon in the outcrop area. The outcrop discoveries in the Grants uranium region were made in the Poison Canyon and other sandstone bodies in the Brushy Basin. It was these discoveries that eventually led to the much larger deposits downdip in unoxidized Westwater Canyon sandstone.

The rejection of an area because of apparent pervasive oxidation must be done with caution. Within the Westwater Canyon, the oxidation pattern varies with local changes in transmissivity. Remnant primary orebodies have been found in oxidized sandstone as much as 1 km behind the oxidation front. A large orebody in the Smith Lake area, the Blackjack No. 1, occurs in an island of unoxidized sandstone more than 10 km updip from the regional oxidation front (Figure 4).

The regional oxidation front and nearby ground has been the most productive target in the Grants uranium region. Redistributed ore, a significant portion of the ore at several mines, is located at the oxidation front, and, for the reasons given above, primary ore is often found with the redistributed ore at or near the oxidation front. However, reduced pyritic sandstones of the proper depositional environments deeper in the basin are also good targets for primary ore. Significant mineralization has been penetrated far downdip from the oxidation front at depths exceeding 1200 m (24). It is apparent that there will be an economic rather than a geologic limit to uranium exploitation in the San Juan Basin.

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THE DEPOSITIONAL AND HYDROGEOLOGIC ENVIRONMENT OF TERTIARY URANIUM DEPOSITS, SOUTH TEXAS URANIUM PROVINCE*

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Abstract

Uranium ore bodies of the South Texas Uranium Province occur within the most transmissive sand facies of coastal-plain fluvial and shore-zone depositional systems. Host strata range in age from Eocene through Miocene. Ore bodies formed at the fringes of epigenetic oxidation tongues near intrinsic organic debris or iron-disulfide mineral reductants. Mineralized Eocene units, which include the Carrizo and Whitsett Sandstones, subcropped beneath tuffaceous Oligocene through early Miocene coastal plain sediments. Roll-front mineralization occurred because of this direct hydrologic continuity between an aquifer and a uranium source.

Most ore occurs within coarse, sand-rich, arid-region, bed-load fluvial systems of the Oligocene through Miocene Catahoula, Oakville, and Goliad Formations. Host sediments were syndepositionally oxidized and leached. Reductant consists predominantly of epigenetic pyrite precipitated from deep, sulfide-rich thermobaric waters introduced into the shallow aquifers along fault zones. Mineralization fronts are commonly entombed within reduced ground. Modern ground waters are locally oxidizing and redistributing some ore but appear incapable of forming new mineralization fronts.

1. INTRODUCTION

The South Texas Uranium Province lies along the low-relief inner coastal plain of southern Texas and extends into the state of Tamaulipas, Mexico. Total area of the active province exceeds 40,000 sq. km. Modern climate of the region ranges from arid to subarid, and post-Eocene paleoclimates have generally remained comparably dry [1], [2]. Primary red beds, extensive syndepositional calichification, and minor evaporite deposits occur throughout the younger Tertiary and Quaternary section.

Coastal plain strata dip gently into the Northwestern Gulf of Mexico sedimentary basin. Present outcrop parallels depositional and structural strike. The uranium province straddles the Rio Grande Embayment, a subtle structural trough that trends perpendicular to the basin margin. To the northeast, it extends to the relatively stable San Marcos Platform. These broad, low-relief structural axes are reflected primarily in their effect on total sediment thickness and depositional patterns. Their history, however, extends far back into the Mesozoic.

Uranium was discovered in the Texas Coastal Plain in 1954 by an airborne survey flown for petroleum exploration. A flurry of exploration followed, and several shallow oxidized deposits were discovered and mined. Deeper, unoxidized roll-type deposits were discovered by drilling in 1963. During a decade of intense exploration and development in the 1970's numerous deposits were discovered. Depths of

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potentially commercial deposits exceed 300 m. Open-pit mining dominated early development and is still utilized for many of the shallow deposits. In 1975, the first pilot in-situ leach facility began production. The process has proved particularly appropriate for much of the South Texas ore, which occurs in unconsolidated, highly permeable sand. More than 25 separate leach mine sites have been active.

Exploration and mining have focused on the upper Eocene Whitsett Sandstone and Oligocene through early Miocene Catahoula and Oakville Formations (fig. 1). However, recent exploration has delineated deposits within the Eocene Carrizo Sandstone and Miocene Goliad Sand, significantly expanding the known stratigraphic distribution of mineralization.

With the exception of the Whitsett Formation, host sandstone units were deposited in coastal plain fluvial systems [1], [2], [3], [4]. The Carrizo Sandstone constitutes a bed-load fluvial system that fed a major offlapping Upper Wilcox delta system of the deep subsurface. Deposition of the Whitsett Formation as shore-zone facies upon a submerged platform of older Eocene sediments presaged middle and late Tertiary episodes of clastic influx and basin margin offlap. Outcrop and shallow subsurface deposits of these later episodes consist of the remnant inner coastal plain fluvial systems that fed basinward into deltaic and interdeltaic coastal systems. A shift from the uniform, humid paleoclimate that dominated the early Tertiary to a more arid and geographically zoned paleoclimate in late Tertiary time accompanied the onset of Catahoula deposition.

Structure of the shallow uranium-bearing sandstones is simple. Large-scale growth faults segment the deeply buried stratigraphic foundation of the basin fill. These syndepositional faults are genetically related to the progradational offlap of the continental shelf edge and associated depositional systems (see discussion by Winker [5]). Consequently, offset decreases upward through the section, and most faults die out before penetrating the overlying coastal plain deposits. The few faults that do penetrate the shallow section have displacements of a few tens of meters or less. At depth such faults may displace deltaic and continental slope units by more than 1,000 m. Along the inland margin of the uranium province several fault trends, commonly dated as Miocene or older, displace both the shallow Tertiary and underlying Mesozoic carbonate sections. Seismic data show that the Mesozoic carbonates that are deeply buried beneath thick Tertiary offlap sequences are also broken by numerous faults [6]. Spatial association of many uranium deposits with fault trends led to early proposals for a genetic relationship [7].

2. HYDROLOGIC SETTING AND DEPOSIT GENESIS

The uranium-bearing fluvial systems of the South Texas Uranium Province also include several major aquifers of the coastal plain. The Carrizo, Oakville, and Goliad Formations are principal water-bearing hydrostratigraphic units. The Catahoula Formation is less transmissive and locally serves as a confining unit. However, this apparent anomaly is explained by the pervasive early diagenetic argillation, by flowing ground water, of the abundant volcanic glass contained within Catahoula deposits [8]. The Whitsett Sandstone is a comparatively local water-bearing unit, in part because of its fine grain size, mud-rich facies assemblage, and strike-parallel trend of the permeable sand bodies. Because of this, Whitsett ore bodies occur only in shallow, updip areas very close to the outcrop belt.

Formation of epigenetic uranium deposits records the evolution of the hydrodynamics and hydrochemistry of an aquifer system that either contained or established hydraulic continuity with a uranium-rich source. Evolution of the Tertiary aquifers of the Gulf Coastal Plain may be subdivided into four sequential stages [1, fig. 23]. Boundaries in the evolutionary sequence are transitional.

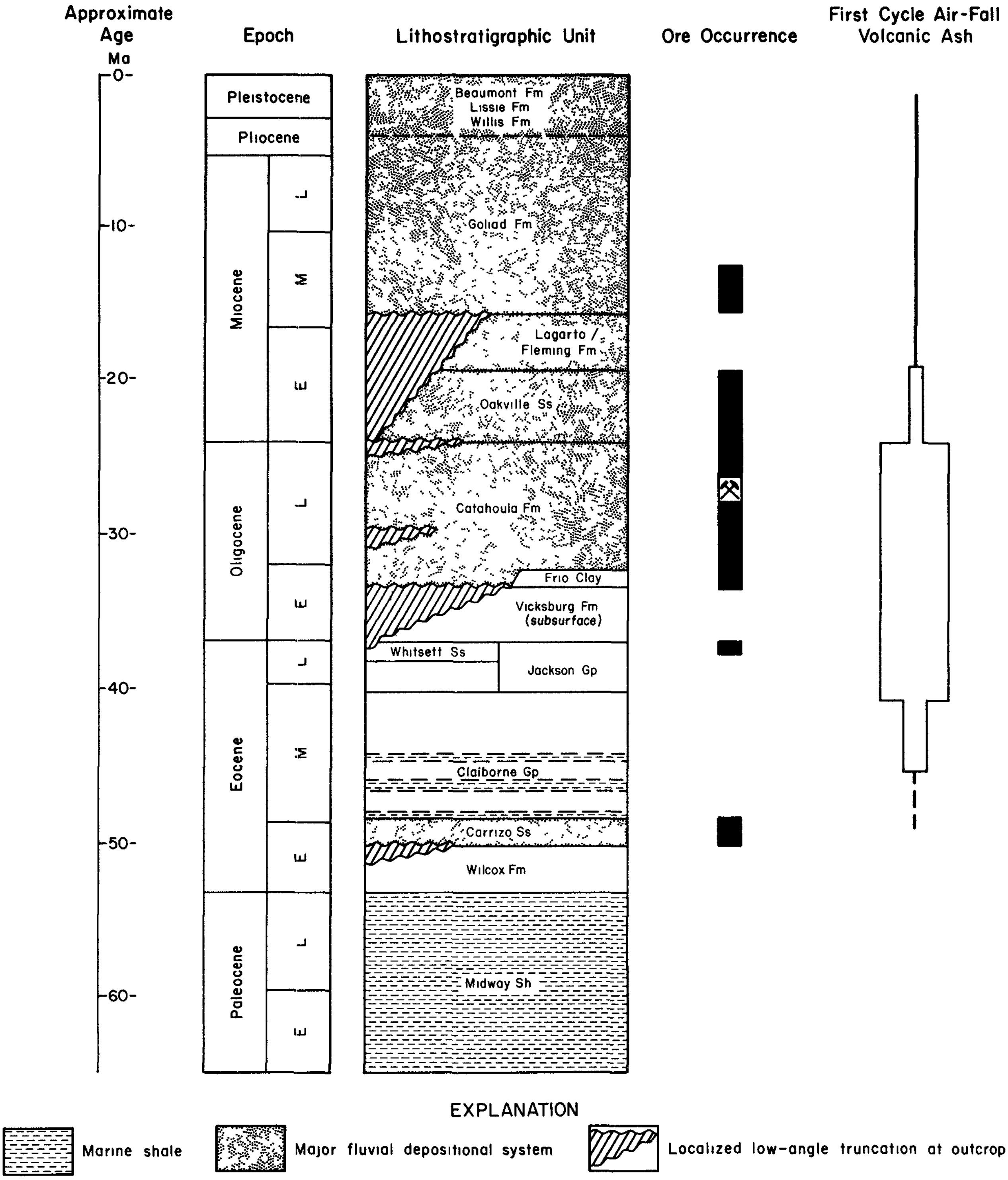

Figure 1. Stratigraphic section and distribution of uranium deposits, South Texas Uranium Province.

(i) During deposition, ground-water flow responded to irregularities in the depositional topography and availability of surface water. Consequently, flow volumes and directions were disorganized and constantly changing.

(ii) With early burial beneath laterally extensive confining layers (such as a widespread floodplain or lagoonal mud), shallow ground-water flow was semi-confined and began to respond to the regional basinward topographic gradient.

(iii) Continued coastward tilting resulted in burial and confinement of all but the updip margin of the aquifer. Discharge became increasingly difficult, and active meteoric circulation may have been restricted to updip portions of the aquifer system. Compactional water or fluids moving up from deeply buried portions of the basin fill may have invaded the aquifer.

(iv) Local uplift and Pleistocene valley incision of the outcrop belt during lowered base level increased outcrop topography and established new and more complex flow cells. Rejuvenation of recharge may also have occurred.

Uranium could have been actively introduced to the aquifer at any time during aquifer history. The most prominent and well-documented source of uranium in the Tertiary section is the abundant vitric volcanic debris that was reworked and deposited with upper Eocene through lower Miocene strata. Detailed study of tuffaceous Catahoula mudstones [8], [9] showed that pedogenic alteration of glass is the most, and perhaps the only, effective mechanism for large-scale mobilization of uranium. Pedogenesis was most active in inner coastal plain environments during post-Eocene deposition. Paleosoils of the Catahoula are highly leached, oxidized, and uranium-depleted. Pedogenic alteration and leaching of volcanic-ash-rich Oligocene and Miocene floodplain muds could have provided a charge of uranium to older, confined aquifers, such as the Carrizo and Whitsett, that subcropped beneath a thin, and perhaps ephemeral, cover of such younger ash [10]. Sourcing within the Catahoula and Oakville fluvial systems likely began with early burial, decreasing as deeper burial restricted ground-water circulation. The development of widespread alteration tongues within these aquifers suggests that final concentration of uranium occurred within semi-confined to confined aquifers. The source of uranium in the younger Miocene Goliad Formation remains uncertain. Uranium was possibly recycled from underlying metal-rich aquifers [11], continued to be released from stratigraphically older volcanics, or was released from sparsely interbedded contemporaneous volcanic debris.

Hydrochemical data show that modern ground waters contain very low concentrations of uranium and associated metals (typically <5 ppb) and appear incapable of forming new deposits [2], [12]. Such values are an order of magnitude below those commonly ascribed to an active, ore-forming ground water [14].

2.1. Concentration and entrapment

Once uranium had been leached, it moved with surficial waters either into the surface drainage system, in which case it was largely lost to the Gulf of Mexico, or into semi-confined or confined aquifers along with oxygen-bearing, recharging ground water. Recharge was efficiently collected into the most transmissive hydrostratigraphic units and then moved basinward in response to the regional hydraulic gradient (fig. 2). Flow was focused through the most permeable elements within water-bearing units, providing an inherent mechanism for concentration of uranium migration through small volumes of the subsurface and producing the commonly observed coincidence of alteration patterns and facies or structural features.

As the oxidizing, uranium-charged ground water moved down gradient, oxidant was consumed by reactions with reductants within the aquifer matrix. Analogous changes in dissolved oxygen and Eh are seen in modern waters of the South Texas Coastal Plain aquifers [12].

Uranium and commonly associated trace metals, including selenium and molybdenum, were concentrated at the sharply defined Eh boundary. The typical occurrence of marcasite as an ore-stage sulfide mineral phase indicates a concurrent drop in pH at the oxidation-alteration boundary [8], [13]. However, such a pH drop at the Eh boundary is not observed in modern ground waters [12].

Uranium deposits are irregular roll-like or tabular bodies that commonly lie along linear to highly sinuous trends, which may extend for several kilometers (fig. 2). The uranium occurs as discrete coffinite and less common uraninite grains, concentrations on titanium-oxide grains, and amorphous phases intimately mixed with dispersed alumino-silicate blebs and grain coats and less commonly with carbonaceous organic debris. Consistently associated metals include molybdenum and selenium. Deposits are zoned, with successive Se-U-Mo concentration peaks defining the polarity of the Eh gradient during ore genesis [15]. Arsenic is erratically concentrated in the ore zone; vanadium is conspicuously absent. Zonation of mineralogic and isotopic composition of iron disulfide minerals has been well documented [13], [16].

The mineralization model described thus far differs little from that of the well-known Wyoming roll-type ore body. However, observations accumulated during the past ten years of active exploration and production show that the history of ground-water flow, aquifer alteration, and mineralization can be much more complex.

(i) Much of the Oligocene and younger fluvial host sequence consists of primary red beds containing little preserved organic debris or other intrinsic reductant.

(ii) Many deposits are described as "rereduced." Roll-type ore bodies lie within iron-disulfide-bearing sandstones far from observed oxidation interfaces.

(iii) Two iron-disulfide phases are present. Isotopically heavy pyrite pervades the aquifers and may occur both upflow and downflow of mineralization fronts. Isotopically light, commonly marcasitic iron-disulfide occurs within the ore zone.

The alteration zonation pattern typical of fluvially-hosted South Texas uranium deposits is shown in fig. 3. Geometric, mineralogic, and isotopic patterns combine to reveal a complex history of alteration of shallow aquifers that includes partial to total syngenetic oxidation, epigenetic reduction and sulfidization, epigenetic oxidation and metallogenesis, post-ore resulfidizing alteration, and young, epigenetic oxidation [2], [8], [13]. This complex history of successive oxidizing and reducing events records alternating flushing of portions of the aquifer by shallow meteoric ground water (oxidizing) and thermobaric waters derived from the deep basin.

The only known ground-water reservoir containing abundant isotopically heavy sulfide lies within the buried Mesozoic carbonate section, which is more than 5 km below the shallow aquifers [2], [13]. Spatial association of epigenetic sulfide enrichment with deep-seated growth faults is strong circumstantial evidence that such structures provide the vertical conduits for expulsion of thermobaric waters. The commonly held hypothesis that epigenetic reduction was a product of gas leakage along the faults is inconsistent with the pervasive distribution of pyrite throughout the aquifer. Free gas should form a cap within sand bodies, producing a pronounced vertical zonation in sulfide distribution, which is not seen. Calcite containing

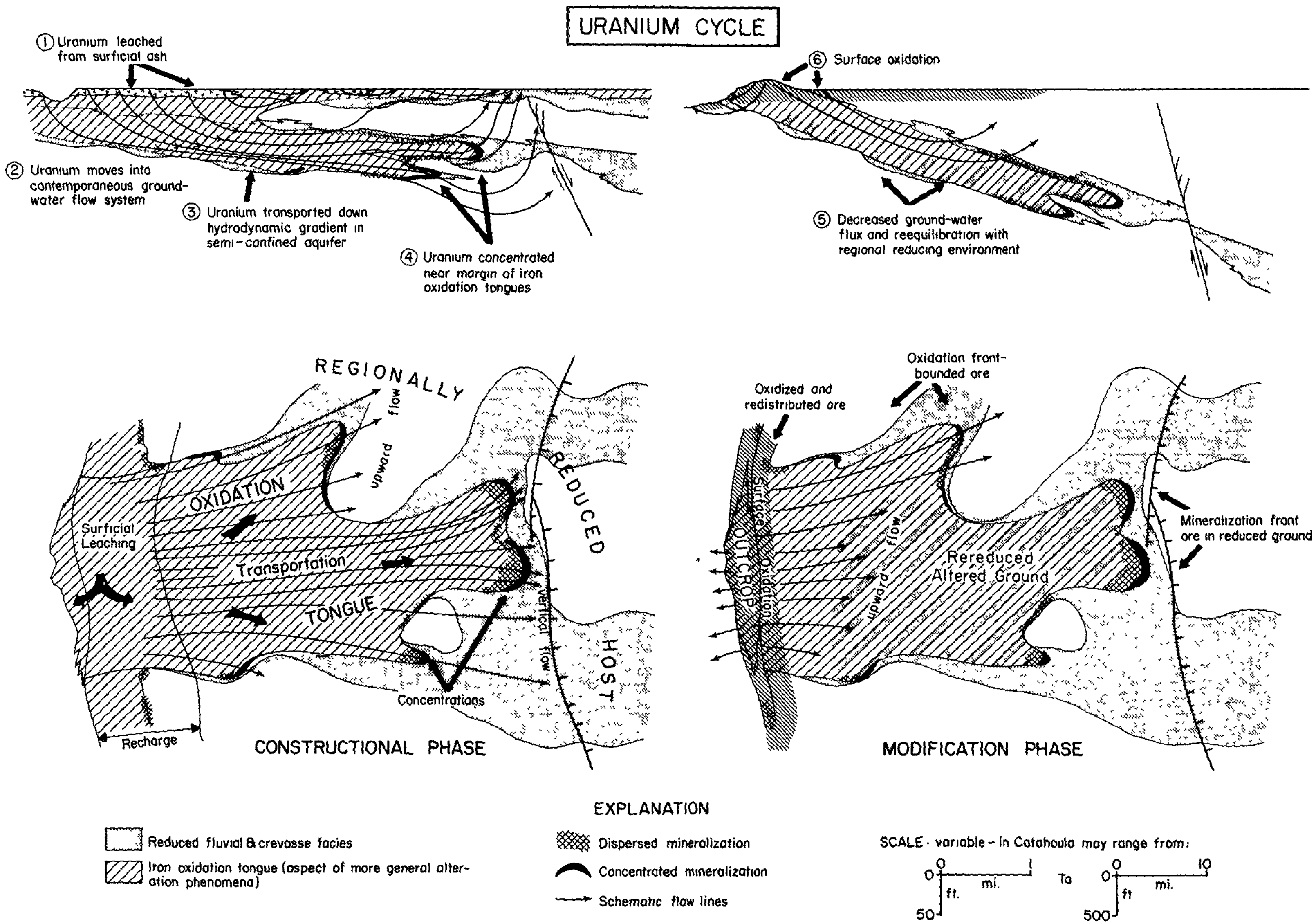

Figure 2. Diagrammatic representation of the constructional and modification phases of roll-type uranium deposit genesis.

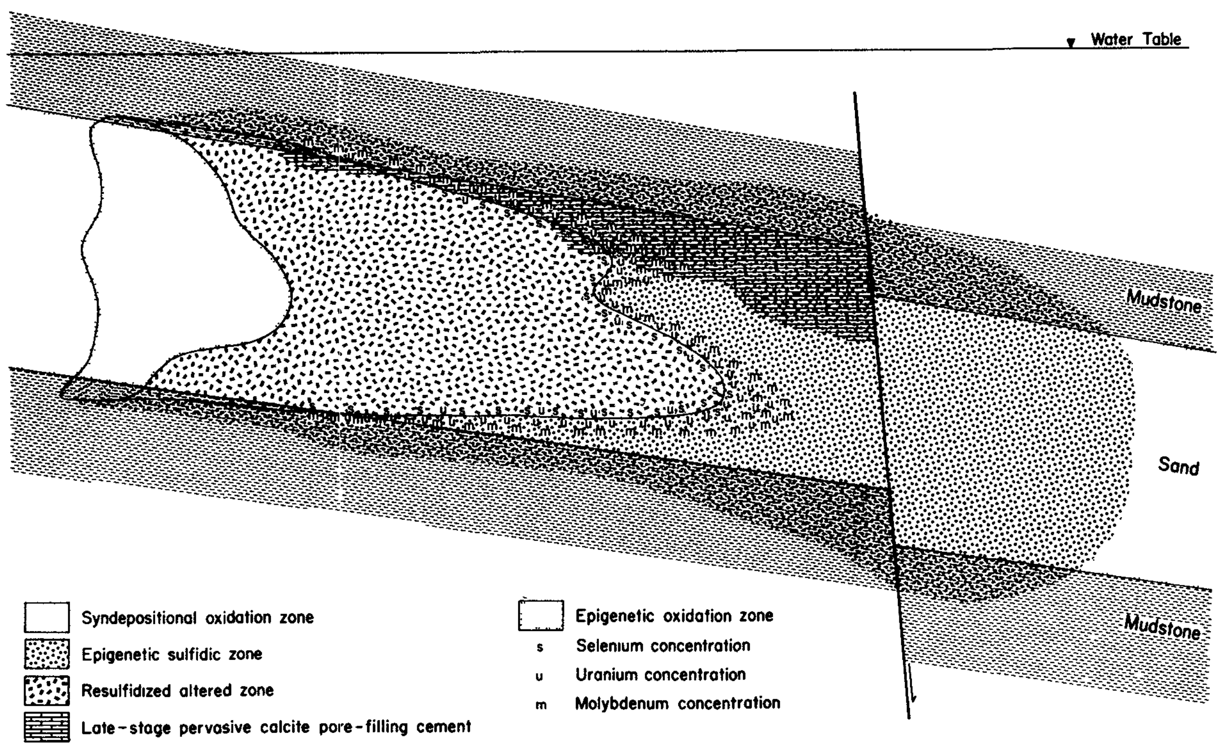

Figure 3. Generalized alteration zonation typical of Catahoula and younger uranium host aquifers. Multiple epigenetic alteration events include pre- and post-mineralization sulfidization as well as ore-stage epigenetic oxidation and modern oxidation. Metals are zoned across the mineralization front. Alteration and mineralization are typically associated with fault zones.

isotopically light carbon derived from leaked natural gas does occur primarily at the top of sand bodies (fig. 3). Further, H_2S and HS^- are both highly soluble in water.

The constructional phase of the generalized South Texas uranium cycle (fig. 2) must therefore include options for variable mechanisms of host reduction. Units such as the Whitsett Sandstone contain abundant detrital organic material and syngenetic sulfide minerals [17]. Other units, such as many of the Catahoula and Oakville sandstone bodies, are dependent on an early introduction of epigenetic sulfide to establish reduced "islands" within an otherwise oxidized aquifer. In such units, the areas of mineralization are likely to be spatially associated with structural features. In the absence of such pre-ore alteration, a geochemical trap for uranium is lacking.

2.2. Post-mineralization modification

The dynamic interaction of the deep and shallow ground-water regimes is also responsible for widescale modification of simple alteration tongue geometry (fig. 2). Upon stagnation of meteoric flow, large portions of rereduced aquifer may remain, obscuring the critical mineralization boundary. Similarity of pre- and post-ore sulfides makes their recognition extremely difficult. Primary reduced ground preserves sulfide replacement textures, visible with reflection microscopy, that are not present in rereduced zones [18]. Resulfidization stabilized the uranium deposit and may be an isotopically datable event [19]. Multiple, nested mineralization fronts show that successive episodes of epigenetic oxidation/mineralization and sulfidization may recur [2].

Other parts of the mineralization front remain actively flushed by meteoric waters with resultant remobilization and redistribution of uranium and daughter products. Radiometric disequilibrium is a common problem in ore-grade determination in the South Texas Uranium Province. Near the outcrop, weathering and active oxidation and remobilization by shallow meteoric circulation has completely redistributed some ore bodies. Small oxidized ore pods of autunite and various unusual minerals, such as umohoite, have been mined.

3. REPRESENTATIVE DEPOSITIONAL/MINERALIZATION SYSTEMS

Sandstones of the Whitsett and Oakville Formations illustrate the diversity of depositional and mineralization styles of South Texas uranium hosts and their contained deposits.

3.1. Whitsett Formation

The Whitsett Sandstone is the uppermost formation of the Eocene Jackson Group (fig. 1), which consists of interbedded sandstone, mudstone, and local lignite, deposited in the upper part of a major shelf-platform aggradational cycle. Secondary progradational and transgressive pulses punctuated the sequence. The total Jackson section averages about 330 m thick in the shallow subsurface; however, uranium is contained in only the uppermost Whitsett sand members.

Principal Jackson depositional features include a South Texas barrier-bar and strandplain system bounded by muddy shelf and lagoonal systems (fig. 4) and an East Texas delta system [20]. Uranium occurs within coastal barrier-bar and associated sand facies where the northern, updip margin of the regional, strike-oriented barrier sand belt intersects the outcrop (fig. 4). Framework depositional elements of the system include strike-oriented coastal-barrier sand bodies and several small, wave-dominated cuspate deltas that prograded into the Gulf of Mexico. More than 30 open-pit uranium mines have exposed a variety of component facies of this system [10]. Uranium deposits occur in coastal-barrier core and back-barrier, tidal inlet, cuspate delta, and suspended-load distributary channel sand bodies. Ore occurs at preferential positions within the different genetic sand facies. Channel-fill deposits, including both tidal inlet and distributary sands, are mineralized near the center and base; coastal-barrier and delta margin sand bodies contain ore near the top. Thus, ore distribution follows the coarsest and initially most permeable portion of the framework sand. Uranium also is trapped in the lower part of lignite beds that cap many uranium-bearing sand bodies. Here, lignitic ore commonly forms an exaggerated upper wing to the roll. In plan view, the geometry of mineralization fronts ranges from linear and strike-parallel to highly sinuous and dip-oriented, reflecting the dominant geometry of the host sand body.

Volcanic ash is abundant within the Whitsett Formation. However, much of the ash is vitric and retains several ppm uranium. Ash deposited in areas of shallow water table or in subaqueous barrier/strandplain environments shows little evidence of effective leaching of metals. Stratigraphic relationships further confirm the dependence of Whitsett mineralization upon external sources. Commercial uranium deposits occur only in a very limited segment of the Jackson barrier/strandplain system. Schematic stratigraphic cross sections (fig. 4) show that Jackson sandstones are largely hydraulically isolated from overlying Catahoula tuffs by the updip lagoonal mudstone (section B) or by the overlying Frio Clay (section A). Only where the upper Whitsett sands lie directly beneath the Catahoula Formation in slight angular discordance, as in the Karnes County uranium district, do roll-type deposits occur within the Jackson sand.

As is typical of shore-zone deposits, Whitsett sands are intrinsically reduced, containing dispersed, syngenetic pyrite and carbonaceous organic matter [17]. It is ironic that the Whitsett ore bodies, which in part lie along shallow faults and overlie sour gas fields, inspired the theory of extrinsic reduction [7] that applies so well to

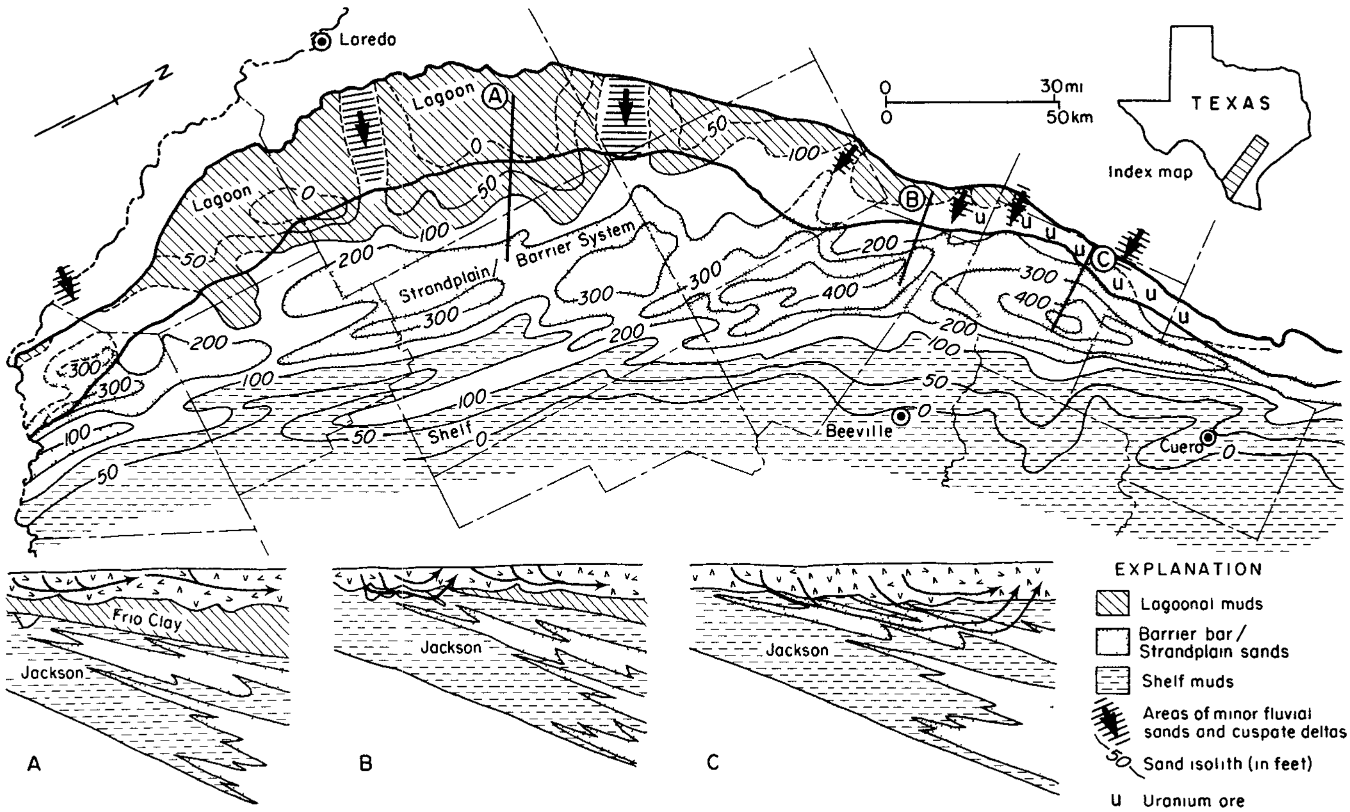

Figure 4. Net-sand isolith and facies map of the Jackson Group (Eocene), South Texas Coastal Plain and stratigraphic relationships of the Jackson and Catahoula aquifers. Modified from [10].

many of the younger South Texas districts but not to this older district. Ore deposits are shallow, reflecting the relatively poor coastward transmissivity of the strike-oriented barrier sand bodies.

3.2. Oakville Sandstone

The Oakville Sandstone was deposited by several large-to-small coastal-plain rivers, which together form the Oakville bed-load fluvial system [21]. Loci of major fluvial axes are interpreted from the regional Oakville sand isolith map (fig. 5A). Major depositional elements include three principal fluvial axes produced by large, extrabasinal rivers and numerous smaller fluvial complexes and relatively mud-rich bounding facies (fig. 5B).

Permeable, highly transmissive framework elements of the Oakville Sandstone consist of bed-load and mixed-load channel fills and associated sheet-flood splays. Floodplain muds and silts are the principal confining facies. Along fluvial axes, amalgamated channel deposits form sand belts more than 75 m thick and 10 km wide. Sand percentages locally exceed 60 percent. Analysis of water-well pump test calculations shows a correlation between fluvial channel facies type and aquifer transmissivity [21, fig. 25]. Updip (proximal) bed-load channel facies exhibit the highest average permeability. More deeply buried distal channel fill facies of the bed-load channel axes, as well as all of the mixed-load channel facies exhibit lower average permeability. Significant reduction in average permeability is also observed near faults. Thus, both depositional facies and shallow structural features demon-

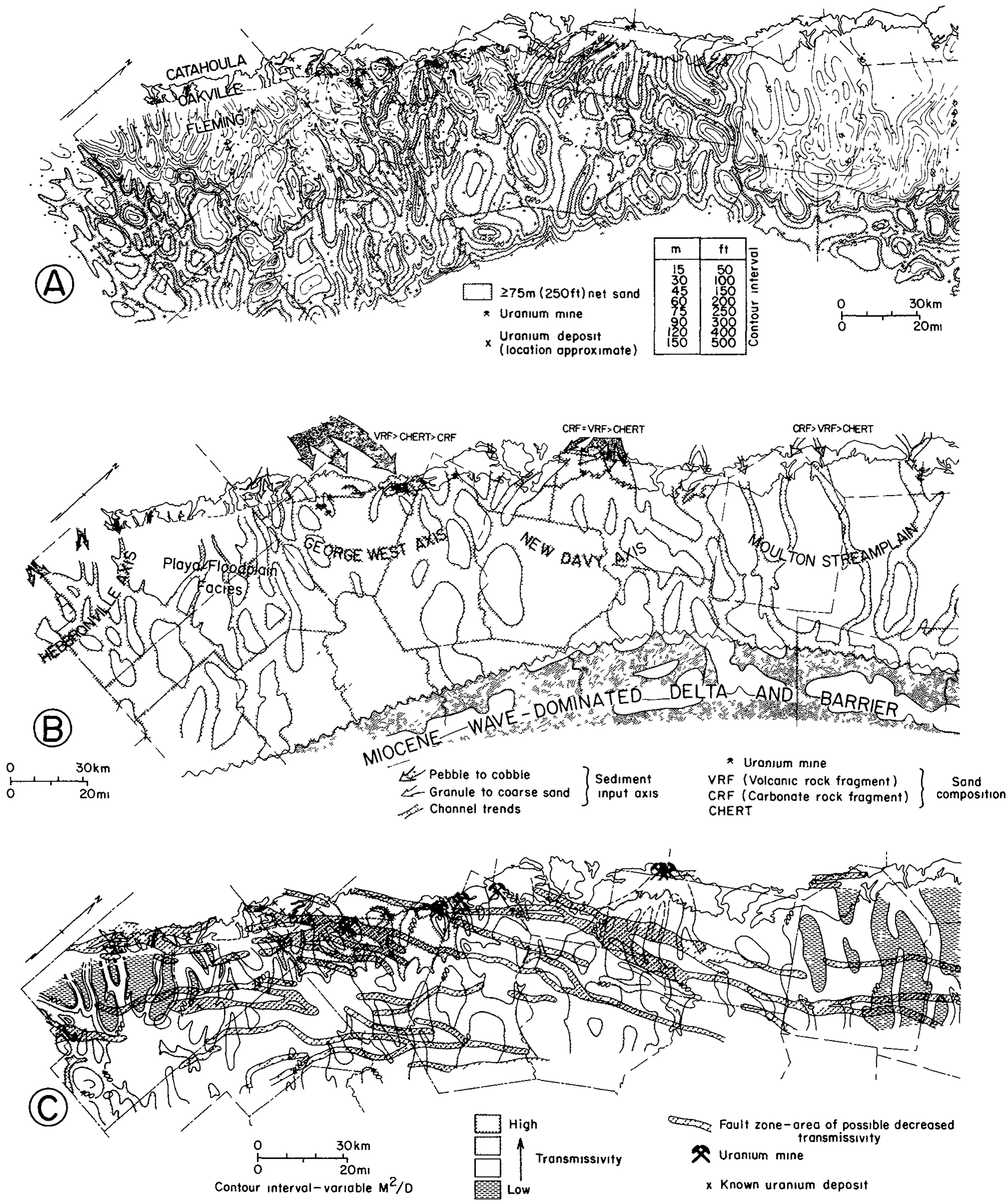

Figure 5. Depositional and hydrogeologic setting of uranium deposits within the Oakville Formation, which is representative of post-Eocene uranium hosts and mineralization style. A. Net-sand map. B. Depositional elements of the Oakville fluvial system. C. Regional semiquantitative transmissivity map showing the distribution of uranium districts and satellite deposits around and within highly transmisssive fluvial axes. Modified from [21].

strably affect overall aquifer characteristics. By using a generalized calibration between facies and permeability, the net-sand map provides the basis for constructing a semi-quantitative transmissivity map of the Oakville aquifer (fig. 5C). The transmissivity map shows that the known Oakville deposits lie within and along the margins of the transmissive elements in the aquifer. More importantly, the size of the deposits is proportional to the relative transmissivity of the associated host. Transmissivity mapping could well be among the most useful regional exploration tools in this and many sandstone uranium provinces.

Oakville uranium districts are closely associated with fault zones (fig. 5C). Iron sulfide is typically abundant, and studies in the two largest districts [21], [22] show this sulfide to be mainly the isotopically heavy, epigenetic pre- and post-mineralization type. Resulfidized roll-type deposits are common.

3.3. Discussion

Comparison of Whitsett and Oakville mineralization styles illustrates a general trend that appears to characterize the South Texas uranium province. Ore bodies in older, Eocene host aquifers are typically simple roll-type sandstone deposits. Successively younger hosts were increasingly oxidized and leached as climatic aridity became more extreme later in the Tertiary period. Consequently, host-preparation in the form of epigenetic sulfidic reduction defines areas of potential uranium entrapment, and uranium deposits are increasingly tied to local structural leak points. Further, repeated influx of reducing formation waters produces complex alteration patterns that cannot be distinguished by simple criteria.

4. PROBLEMS FOR RESEARCH

Although the recent cycle of intensive exploration and mining greatly expanded our knowledge of the geology and genesis of the South Texas uranium deposits, many problems remain.

(i) Vitric volcanic influx, though continuing into later Tertiary time, was much reduced by the middle Miocene. No substantive work has tested speculative source mechanisms for these younger ores.

(ii) Although tens of thousands of test bores have been drilled, the proprietary nature of the data has precluded district-wide or subregional syntheses of alteration patterns and geochemical trends. Most of our present concepts are based on local sampling of only tiny portions of larger alteration features. Consequently, relationships of alteration to structural and depositional elements are poorly documented. Further, attributes of none-ore sediments are poorly described.

(iii) Recognition of resulfidized altered zones remains a major exploration problem. Entombment of mineralization fronts within reduced, sulfidic strata invalidates simple visual identification of alteration zones as a guide to exploration.

(iv) Circumstantial evidence has provided a strong case for intrusion of sulfidic formation waters from great depth. However, the mechanics of this process and its significance in the larger history of basin filling remain problematical.

(v) In-situ leach mining has proved to be a viable recovery method for many of the South Texas districts. Both extraction and aquifer restoration require detailed understanding of fluid flow and mineral reactions within the ore host. Failure of some extraction efforts and unexpected complications in restoration indicate the need for combined geologic-engineering studies.

5. ACKNOWLEDGMENTS

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GEOLOGIC ENVIRONMENT OF URANIUM IN LACUSTRINE HOST ROCKS IN THE WESTERN UNITED STATES

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Abstract

Uranium deposits in lacustrine rocks constitute a major uranium resource in the United States. They have formed principally in the sediments of alkaline, slightly to moderately saline lakes of mid-Tertiary age. Favored lacustrine basins were those that formed under semiarid to arid climatic conditions, that had interior or intermittently interior drainage, and that had dominantly granitic or acidic volcanic source terranes. The largest uranium deposits occur in lacustrine carbonaceous siltstones and mudstones of Miocene age in Tertiary basins of western Arizona, where as much as 1.8 million metric tons of uranium may be present. Limestone, dolomite, chert, gypsiferous mudstone and siltstone, and altered water-laid tuff contain numerous although generally minor occurrences.

Uranium is trapped in lacustrine sediments by a variety of mechanisms; the most important of these are probably reduction in anoxic environments, coprecipitation with silica or humic materials, and incorporation of uranium into the structure of mineral species.

1. Introduction

Lacustrine rocks and sediments of Tertiary to Quaternary age host uranium occurrences and deposits in many areas of the western United States. The uranium occurs in fine-grained clastic, chemical, and biogenic sediments which were commonly extensively altered by diagenesis. Host lithologies include shale; phosphatic shale; carbonaceous, mudstone, siltstone, and very fine grained sandstone; altered water-laid tuff; limestone; gypsum; diatomite; marl; chert; opal; and dolomite. Table 1 includes brief descriptions of several lacustrine uranium deposits in the western United States. Locations of these deposits are shown in Figure 1.

The most economically important type of uranium deposit in lacustrine rocks occurs in clastic, carbonaceous, commonly tuffaceous, very fine grained sandstones, siltstones, and mudstones (termed lacustrine carbonaceous uranium deposits); thus, these deposit types are discussed in this volume. The deposits range in grade from slight enrichment of uranium (5-15 ppm) in the Tertiary lacustrine oil shales of Colorado, Utah, and Wyoming [1,2] to high-grade, large-tonnage uranium deposits (locally more than 1.00 percent uranium, total resources more than 1.8 million metric tons uranium) in Miocene lacustrine carbonaceous siltstones and mudstones in western Arizona [3]. Because of the generally low porosity and permeability of the host rocks, most uranium deposits in lacustrine rocks are either syngenetic or early diagenetic. Some deposits are either demonstrably epigenetic or are believed to be epigenetic; they appear to have formed by epithermal mineralizing fluids that invaded porous and permeable lake

Table 1-- Brief descriptions of lacustrine uranium deposits and occurrences in the western United States

No.	Deposit/location	Age	Principal host	References
1	Virgin Valley, northwestern Nevada	Pliocene	Opalized diatomite	5
2	Aurora mine, McDermitt caldera, northcentral Nevada	Miocene	Carbonaceous, tuffaceous siltstone	6,7
3	Rita Blanca Lake Beds, northern Texas	Pleistocene	Limestone; carbonaceous, gypsiferous siltstone	8,9
4	Anderson mine, Date Creek basin, Arizona	Miocene	Carbonaceous, tuffaceous siltstone and mudstone	3,10, 11,12
5	Harvard Hill, Barstow Basin, California	Miocene	Silicified, tuffaceous, carbonaceous mudstone and siltstone	13
6	Anderson Ranch, west Texas	Oligocene	Limestone, carbonaceous siltstone	14
7	Reese River Valley, central Nevada	Miocene to Holocene	Zeolitized tuff, chert	15
8	Artillery Peak, western Arizona	Oligocene to Miocene	Cherty dolomite, siltstone and fine-grained sandstone	16,17
9	New River area, central Arizona	Miocene	Dolomite	16
10	Lake Pleasant, central Arizona	Miocene	Limestone, gypsiferous mudstone	16
11	Tonto basin, east-central Arizona	Miocene	Carbonaceous siltstone, tuffaceous mudstone	17
12	Gamma group of mines, Churchill County, Nevada	Miocene	Carbonaceous siltstone	18
13	Panaca area, Lincoln County, Nevada	Pliocene	Carbonaceous siltstone	18

14	Mustang, Esmeralda County, Nevada	Tertiary	Carbonaceous mudstone	18
15	Chadron area, central Nebraska	Oligocene	Gypsiferous clay, gypsum, carbonaceous gypsiferous clay	19
16	Antero Basin, central Colorado	Oligocene	Carbonaceous, water-laid tuff and volcaniclastic sandstone, silicified limestone	20
17	Rincon Mountains, southeastern Arizona	Oligocene	Mudstone, limestone, and shale	16
18	Townsend Valley, southwestern Montana	Oligocene	Carbonaceous siltstone	21
19	Green River Formation and its equivalents, western Wyoming and northeastern Utah	Eocene	Phosphatic shales	22

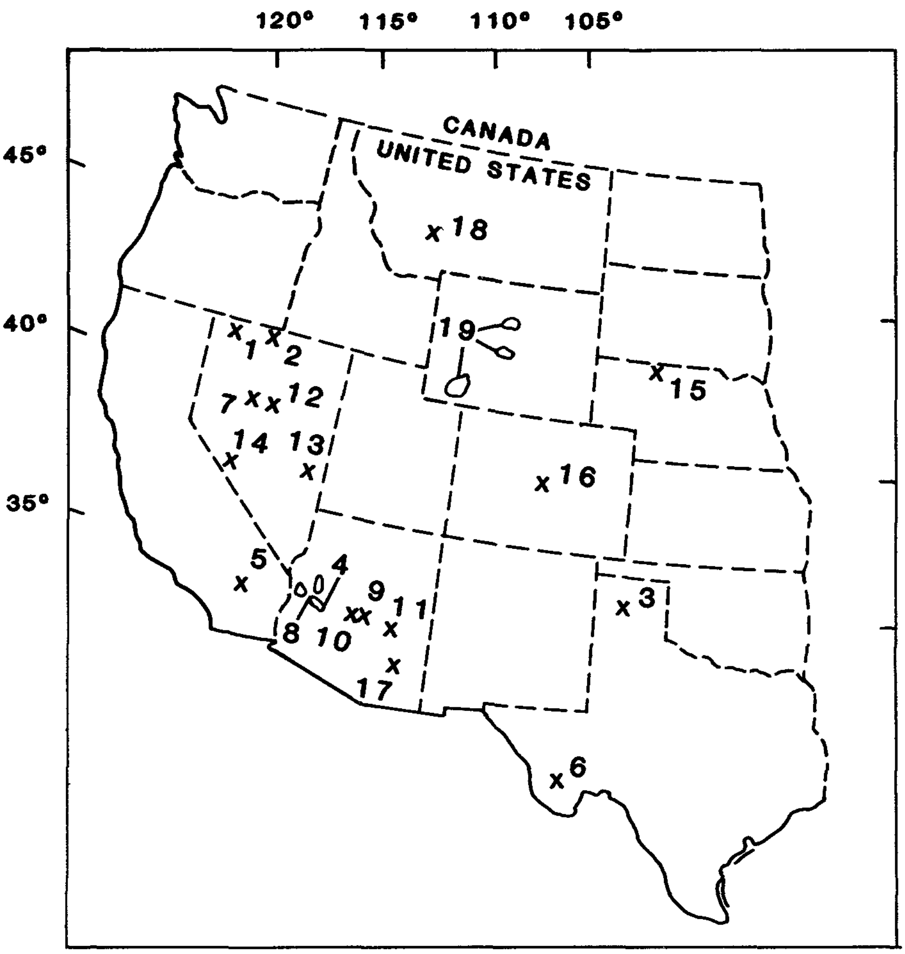

Figure 1--Location of lacustrine uranium deposits in the western United States. Numbers refer to brief locality descriptions in table 1.

beds sometime after deposition of the host [No. 1, Table 1] or by hot springs that deposited uranium in nearby lake beds [No. 2, Table 1]. Deposits similar in size and grade to the well-known uraniferous bituminous sediments in the Permian Lodeve basin of France [4] have not yet been found in the United States.

This report briefly describes the general setting of uranium deposits in lacustrine rocks and then, because of their importance in the United States, describes in greater detail the geology of uranium deposits in lacustrine carbonaceous rocks.

2. General geologic and climatic setting of lacustrine uranium deposits

Lacustrine uranium deposits occur in alkaline, moderately saline lakes that commonly formed from the early Tertiary to the Pleistocene under semi-arid to arid climatic conditions in closed or intermittently closed basins in the western continental interior of the United States. These basins had dominantly acidic volcanic or granitic sediment source terranes [Nos. 3-19, Table 1]. Formation of these basins during much of the Tertiary was controlled by active continental margin tectonics. Mountain building and regional uplift related tocontinental margin tectonics allowed arid conditions to develop in the rain shadows of mountain ranges that trend north-south. Closed or intermittently closed basins formed in the areas that were being regionally extended. Small closed basins formed on the broad pediment surfaces at the western edge of the central United States as large volumes of debris were shed from the broad uplift of the entire western United States during the Tertiary [see No. 15, Table 1]. Finally, closed basins also formed during periods of volcanism that were commonly associated with tectonism. These basins formed as intracaldera moats [No. 2, Table 1] or intercaldera basins dammed by extrusive rocks [No. 6, Table 1].

During the Tertiary, several areas of uranium-rich source rocks were exposed to erosion in the western United States. These rocks include Precambrian granites, orogenic plutons related to continental margin tectonics, and extensive ash flow sheets related to extension.

Mechanisms for the entrapment of uranium in lacustrine environments vary considerably but three processes seem to dominate: reduction in anoxic environments; adsorption of uranium onto amorphous precipitates; and incorporation of uranium into the structure of phosphate and other mineral species. In most deposits, these processes appear to have been aided by the preconcentration of uranium by evaporation of the lake water.

Conditions for the formation of uranium deposits in lacustrine carbonaceous rocks differ in some detail from the formation of non-carbonaceous lacustrine uranium deposits. Specifically, the paleoenvironmental conditions must have allowed the accumulation and preservation of organic matter. The climate in the basin area must have been sufficiently wet to have allowed the development of plant growth and lakes deep enough for anoxic bottom conditions to have formed, yet arid enough for alkaline moderately saline waters to have formed. In some basins, these conditions were apparently brought about by the substantial relief in the basin area. Adjacent mountains are inferred to have trapped moisture which then moved downslope into the basin where at lower elevations warmer, semi-arid to arid conditions prevailed.

3. Lacustrine carbonaceous uranium deposits

Lacustrine carbonaceous uranium deposits differ from typical sandstone uranium deposits in that they are largely restricted to carbonaceous mudstones and siltstones rather than to porous and permeable sandstone beds. Moreover, uranium was deposited during sedimentation and the earliest stages of diagenesis of the host rather than after sedimentation of the host unit. Nevertheless, many processes thought to be responsible for the formation of other sandstone uranium deposits operated in the formation of lacustrine uranium deposits. The best studied uranium deposits in lacustrine carbonaceous rocks are in the Date Creek basin in western Arizona.

Although the average grade of lacustrine carbonaceous uranium deposits in the western United States is generally relatively low (0.01-0.10 percent U), the deposits in some areas are quite large. In the Date Creek basin, the Anderson mine orebody contains about 12,500 t of U at an average grade of 0.07% using a cutoff of 0.03%, and about 50,000 t at a cutoff of 0.01%. Mineralized lacustrine sediments throughout the drilled parts of the basin contain Reasonably Assured Resources of 570,000 t of U with an average grade of 0.023%. Additional resources probably occur in undrilled parts of the Date Creek basin. Mineralized lacustrine rocks have also been identified by drilling in the Big Sandy

Basin and Sacramento Valley to the north and northwest of the Date Creek basin. In aggregate, these three basins may contain as much as 1.8 million t of Reasonably Assured and Estimated Additional Resources. These deposits thus constitute a major uranium resource for the United States. They fill the "resource gap" between presently economic deposits and low-grade uranium resources such as those in the Chattanooga Shale or the Conway Granite.

3.1 Geology of the Date Creek basin deposits

Uranium deposits in the Date Creek basin in western Arizona occur principally in carbonaceous, tuffaceous silts and muds deposited in early Miocene interfan lakes. These uranium deposits are exposed at the surface at the Anderson mine in the upper part of the early Miocene section on the northeastern flank of the basin. Uranium deposits also occur in the subsurface in laterally equivalent and stratigraphically lower lacustrine rocks deposited along the axis of the basin. The basin developed during a prolonged period of crustal extension as an early phase of severe extension characterized by regional detachment faulting and close-spaced normal faulting gave way to less severe, probably deeper seated extension characterized by high-angle normal faulting and basin formation. This tectonic transition was also marked by a change in the composition of accompanying volcanism from dominantly intermediate (52 to 70% SiO_2) to dominantly bimodal (basaltic and rhyolitic) volcanism [23]. High-angle normal faulting and crustal sagging persisted for some time after the deposition of the lacustrine units and the host section was downdropped into a structural trough that served, in part, to preserve the units from erosion. In addition, a basalt caprock, extruded during a later phase of basaltic volcanism dated at 12-14 m.y. B.P., protected the host section from erosion. Lowering of the regional erosional level during the last 5-10 million years has exposed the basinal sediments to gradual dissection.

Extension during basin formation produced high relief as reflected by the sedimentary megabreccias and the coarse alluvial fans. The alluvial fans marginal to the basin lakes had sources composed of Precambrian to lower Tertiary igneous and metamorphic rocks and mid-Tertiary volcanic rocks. Precambrian granitic rocks north of the basin are anomalously radioactive and contain vein and pegmatite uranium deposits. The most intense mineralization in the basin took place in the interfan lake closest to the fan with the uraniferous Precambrian granitic provenance.

Silicic ash-fall tuffs periodically inundated the basin. Ash beds are seldom preserved in the alluvial fan facies and ashy debris was commonly washed into the lakes and incorporated into the lacustrine facies. The ashy material has been extensively altered and silicified; the principal alteration products are clinoptilolite and di-octahedral and tri-octahedral smectites. The ash-rich lake beds at the Anderson mine and elsewhere are enriched in uranium (generally 10 ppm or more), but whether they initially contained that much uranium or if uranium was added from a source other than the ash during diagenetic alteration is uncertain.

Pollen and plant megafossils recovered from rocks in the section indicate that palms, ferns, bullrush, and marsh grass grew near the lake margin; grasses and semi-arid shrubs existed on the alluvial fans; while a temperate deciduous hardwood forest grew in adjacent mountains. These vegetation variations suggest a relief of about 1,500 meters for the basin area, roughly comparable to that in western Arizona today [24].

Alluvial and lacustrine sedimentation in the basin was dominated by debris flows initiated by sheet flooding during heavy storms. Sandstone bodies are generally sheet-like and internally very poorly sorted with matrix-supported clasts. Subaqueously deposited sediments at the mine resemble turbidite sequences in that thick internally chaotic proximal beds change laterally to thin distal graded beds with laminated tops.

3.1.1 The Anderson mine

The sedimentary section at the Anderson mine consists of an upward succession composed of basal andesite flows; a lower clastic unit composed of arkosic sandy conglomerate, arkose, and siltstone; a lower lacustrine unit composed of carbonaceous mudstone, fine-grained sandstone, tuffaceous siltstone, and marl; an intermediate clastic unit of arkosic sandy conglomerate to fine-grained sandstone and local green mudstone; an upper lacustrine carbonaceous unit similar to the lower one with the addition of partly silicified dolomitic limestone and calcareous tuff; an upper tuff and carbonate unit composed of highly altered tuffaceous mudstone, chert, marl, and minor dolomitic limestone; and, finally, a coarsening-upward upper clastic unit of highly calcareous, locally tuffaceous siltstone, sandstone, and conglomerate. In surface exposures, the upper tuff-carbonate unit contains a highly silicified, carbonaceous, tuffaceous mudstone and siltstone facies that forms the host for the orebody mined at the surface in the 1950s. The amount of tuffaceous debris incorporated in the section increases upward reaching a maximum in the tuff-carbonate unit. The sequence averages 300 m thick in the mine area. The lacustrine facies at the Anderson mine intertongues to the west and south with coarse clastic sediments deposited in adjacent alluvial fans. To the north and east the section laps onto the older volcanic rocks.

Clastic crystalline and reworked tuffaceous detritus, along with entrained plant debris, washed across alluvial fans and into the lakes during episodic floods. Virtually all the plant remains are fragmental and have been transported. No coals or lignites are present in the section. Root casts occur locally at the top of some beds. Large branches are occasionally preserved in the alluvial fan facies, whereas smaller plant debris is commonly preserved in the lacustrine facies. Within the lacustrine facies plant debris are commonly sorted; larger plant fragments, including small branches and twigs and occasionally short segments of logs, remain in the thicker, subaqueous debris flow beds, whereas finely macerated plant debris was deposited in thin laminated distal turbidites. Plant debris and tuffaceous material in the thick, proximal debris flow facies tended to be silicified, probably because of the greater porosity and permeability of the beds and because the beds were deposited onshore or in shallow near shore waters where oxidizing silica-rich ground waters moved through them. The fine plant debris in the more distal facies was also preserved, but was coalified rather than silicified, probably because the beds were deposited in anoxic lake-bottom water below wave base and because the beds had low porosity and permeability. Black, bright vitreous material occurs as thin laminae intercalated with clastic laminae in the siltstones or as disseminations within the clastic laminae. This material is interpreted to be solidified colloidal humic material (gelinite maceral). Bacteriogenic sulfide in the form of framboidal pyrite is coextensive with coaly plant debris in these anoxic sediments.

Bioturbation is locally common in the more proximal beds, but is absent in the more distal turbidite facies. Fragmental gastropod debris is common in the basal part of the graded beds in the distal facies.

Gastropods were likely the principal agents for the bioturbation in the shallow, more oxygenated parts of the lake and their shelly remains were periodically swept into the deeper parts of the lake during storms.

The lake sediments at the Anderson mine were deposited during a period of increasing climatic aridity, rapid constriction of lakes in the basin, and corresponding increased alkalinity and salinity in the basin. The floral and faunal remains in the lake sediments and the diagenetic alteration of the sediments themselves reflect these climatic and geochemical changes. Cementation by calcite and dolomite increases upwards in the section. Silicification in the lake sediments becomes progressively more intense; however, this phenomenon may be due to the increased volume of ashy debris upward through the section. The gastropod fauna change from multi-genera diverse assemblages low in the section to restricted one-species populations high in the section. Ostracodes high in the section include a genera found in saline lake waters, and a diatom assemblage observed high in the section is typical of moderately saline waters [24].

Ground water from the adjacent mountains and from within the basin itself leached uranium, vanadium, silica, and other metals from the granitic rocks, arkosic alluvium, ash-falls, metavolcanic rocks and Tertiary mafic volcanic rocks. This ground water moved into the lake environment where the alkaline pH of the water (generated by hydrolysis of ash and feldspars) allowed dissolution of humic acids from degraded plant material in soil horizons or entrained in debris flows. Ground water recharged the lake, probably in the littoral zone around the margin. In quiet, anoxic parts of the lake bottom, uranium, silica, humate, vanadium, and other species precipitated from solution. Increases in salinity by evaporation between major influxes of fresh water may have initiated humate and silica complexation or polymerization, flocculation, and precipitation. Metals adsorbed by the precipitating species were added to the sediment. Lower Eh conditions in the lower layers of a stratified lake may also have aided fixation of metals through reduction at the sediment-water interface, and polymerization of silica species. In addition, in the highly tuffaceous parts of the upper carbonaceous unit and lower part of the tuff-carbonate unit, shallow ground waters flowed through local "trash piles" or "log jams" composed of large fragments of plant debris in the thick proximal debris flows during the early stages of diagenesis and the plant debris was partially replaced by uraniferous silica.

As just noted, uranium deposition occurred in various parts of the lacustrine environment, but tended to favor sediments deposited on the anoxic lake bottom. Because of the nature of the uranium deposition, individual ore bodies have a thin tabular shape and are stacked so that aggregate thicknesses reach 11 m. The carbonaceous siltstone and mudstone hosts are interrupted by unmineralized sandstone beds as much as 30 m thick.

Individual mineralized zones tend to follow specific stratigraphic horizons regardless of facies; however, mineralized zones occur almost exclusively in reduced rocks with carbonaceous plant debris or pyrite or both. Scanning electron microscope studies [11] show that uranium is often disseminated thoughout bands or patches of both colloform organic matter (humate?) and amorphous silica but is not associated with fragmental, coalified plant fragments. Locally, uraninite or coffinite formed, often adjacent to pyrite. Uranium content does not correlate significantly with total organic carbon content, probably because uranium is associated with the colloform organic matter rather than with the coalified plant material whose content in the sediment is highly variable. In the carbonaceous and pyritic rocks, uranium ranges from about 100 to more than 10,000 ppm. In addition to uranium, molybdenum, arsenic, and vanadium are locally enriched in the carbonaceous host rocks. Two stratigraphic horizons within the section are enriched in lithium (as much as 2700 ppm) and fluorine (as much as 3.5 percent), but are lower in uranium. These enrichments occur in highly altered ash-rich mudstones dominated by di- and tri-octahedral smectite clays in the lower part of the upper carbonaceous unit and the tuff-carbonate unit.

During sedimenation, northwest-trending high-angle normal faulting occurred. The paleotopography and faulting influenced facies distribution principally by controlling fan advancement. It also affected uranium distribution indirectly by controlling water depth and the distribution of the anoxic facies. The mineralized lacustrine rocks and the intertonguing alluvial fan deposits lap onto an older irregular volcanic topography. Mineralized facies tend to thin and pinch out over the volcanic paleohighs. Facies change abruptly across intrabasin faults. Locally within the distal turbidite facies, contorted beds composed of a mixture of lithologies seen lower in the section are interpreted as slump deposits possibly generated by shaking during faulting. Differential compaction over and slumping adjacent to paleohighs locally produced dips as high as 22° in the mine area.

During the deposition of the tuff-carbonate unit, alluvial fans began to advance, the lake was reduced in size, and its depocenter moved to the northeast within the mine area. The carbonaceous facies became rather restricted in area, and, during the early stages of diagenesis, was flushed by oxidizing, silica-rich waters. This flushing produced an uppermost ore zone characterized by partially to completely silicified, plant trash-rich tuffaceous siltstones and mudstones with varying amounts of carnotite, weeksite (a hydrous potassium uranium silicate, uraniferous silica, and iron and manganese oxides. These rocks vary from black to varicolored in red, yellow, green and purple depending on the amount of remnant organic carbon left in the rock and the oxidation state of the iron and manganese. Ore grades are higher in this zone than in the lower ore zones, which remained largely reduced.

In the terminal stage of the lake, alluvial sedimentation was minimal. Volcanic ash falls and chemical precipitation contributed most of the sediment to the lake. Finally, an alluvial fan prograded across the lake. These ash-rich sediments were intensely silicified and altered to smectite clays and zeolites. These last lacustrine sediments that form the upper part of the tuff-carbonate unit contain less than 100 ppm uranium.

Minor normal faulting occurred after consolidation of the mineralized units. Locally, uranium was redistributed as carnotite and uraniferous silica along fault and fracture planes, but such redistribution is restricted to the original host rocks. Some uranium may have moved during modern weathering and erosion of the orebody, but because of the low porosity and permeability of the sedimentary host, this movement too is negligible.

3.2 Geology of deposits in the Barstow basin, southeastern California

The Barstow Basin is an elongated, east-west oriented, structural sag or half-graben that formed during mid-Miocene regional extension in southeastern California [25]. The host for uranium deposits is the Barstow Formation, which is comprised of alluvial fan, fluvial, and shoreline and offshore lacustrine sedimentary rocks. At times, one large lake appeared to have filled the basin; at other times, several separate, geochemically distinct lakes were present. Fossil evidence and diagenetic alteration of the sediment suggests that the chemistry of the lake water fluctuated between relatively fresh and alkaline, slightly saline conditions and that the climate was generally semi-arid. The alluvial fans had a variety of source terranes including Mesozoic granitic rocks. Tuffaceous sediments are largely restricted to the lacustrine facies probably because the tuff tended to be washed into the lake. Hot springs locally contributed warm waters that extensively altered the lake sediments and created the borate and lithium-rich tuffaceous sediments that the basin is known for. So little plant debris is preserved in the lacustrine facies that the lake is inferred to have been well-mixed and oxygenated. Locally, however, carbonaceous to highly silicified plant debris occurs in the lacustrine facies and it is in these localities that minor accumulations of uranium have been observed.

3.2.1 Harvard Hill

At Harvard Hill (no.5, Table 1) in the eastern part of the Barstow basin, the Barstow Formation is composed of intertonguing arkosic sandstone; calcareous, tuffaceous siltstone and mudstone; and silicified mudstone, limestone, and chert. Locally, the fine-grained rocks contain abundant partially to completely silicified carbonaceous plant fragments. Gastropods and ostracodes occur in the limestone and tuffaceous mudstone. Uranium occurs as uraniferous silica, carnotite, and probably urano-organic complexes. Detailed geochemical or mineralogic data are not available for this uranium occurrence. No estimates of the uranium resources can be made with available data.

The host section is gently tilted, folded and faulted. Basalt flows are present in the section but their precise stratigraphic position is not clear because of faulting.

3.3 Geology and uranium deposits of the Anderson Ranch area, West Texas

A rock unit near the Anderson Ranch in Brewster County, southwestern Texas (No. 6, Table 1), is host to uranium deposits that occur in partially silicified, carbonaceous limestones and tuffaceous siltstone, mudstone, and shale [14]. This unit, which is the probable lateral equivalent of the Sheep Canyon basalt, is part of a thick sequence of Eocene and Oligocene volcanic and volcaniclastic sedimentary rocks that unconformably overlie Cretaceous marine sedimentary rocks in this part of Texas. The rock unit is composed of interbedded basalt, rhyolite, mudstone, limestone, and shale that was deposited over an irregular surface that formed on underlying early Oligocene volcanic rocks.

During early Oligocene time, southwestern Texas was the site of extensive silicic and local basaltic volcanism. Several caldera systems and volcanic complexes formed in the area. The volcanic and hypabyssal intrusive rocks associated with these centers are host to several epithermal uranium deposits. Between some of these volcanoes small lacustrine basins formed locally, probably by damming of surface runoff by volcanic flows. Uranium deposits occur in the lacustrine rocks.

The fine-grained clastic and limestone units contain vertebrate remains and abundant fragmental ostracod, gastropod, and algal remains. Mineralogically, the mudstone units are composed of quartz, potassium and plagioclase feldspar, analcime, calcite, pyrite, and biotite. The limestone is composed of calcite and minor amounts of quartz, feldspar, biotite, and pyrite. Detrital material in the mudstone and limestone was derived from reworking of the underlying tuffaceous units. The limestone contains abundant silica as patchy chalcedony and quartz in veins. The mudstone and limestone units are enriched in uranium (means of 14 and 46 ppm equivalent U (eU), respectively).

The mineralized zones are thin (30 cm), carbonaceous, calcareous, tuffaceous shale beds within the limestone. The mean eU for one bed was 350 ppm, another, 800 ppm. Uranium correlates significantly with organic carbon, arsenic, sulfur, and molybdenum. Carnotite, autunite, and uraninite have been reported by company geologists.

These uranium deposits apparently formed in the anoxic parts of alkaline, moderately saline lakes analogous in many ways to the lake at the Anderson mine in Arizona. The probable source for the uranium was the large volume of contemporaneous tuffaceous rocks. Studies by Henry and Deux [26] suggest that leaching of uranium from these tuffs has been minor (<1 ppm); however, down-gradient ground-water flow through large volumes of ash provided large quantities of uranium to the water which subsequently discharged into the lake environment.

4. Conclusions

Several empirical geologic criteria can be used to determine if an area is favorable for uranium deposits in lacustrine host rocks. These criteria must suggest that: (1) a favorable source terrane was present; (2) closed or partially closed basins formed; (3) a semi-arid to arid climate developed; and (4) uranium-enrichment processes occurred. The presence of several or all of the following observations would warrant careful examination of the area for uranium deposits in lacustrine host rocks:

1) adjacent granitic terranes are anomalously radioactive, yield high uranium values, contain uranium occurrences or deposits, or contain tin or tungsten deposits.

2) silicic volcanic rocks are present, are anomalously radioactive, yield high uranium values, or contain uranium, lithium, mercury, or fluorspar deposits.

3) arkosic alluvial sediments or silicic volcanic debris or both form part of the basinal section.

4) calcite or gypsum cements occur in sandstone units.

5) zeolites, smectite clays, and silica occur in altered water-laid ash or volcaniclastic sediment.

6) bedded saline minerals occur. Note that this observation suggests that lacustrine carbonaceous uranium deposits are less likely in that part of the section because the climate was too arid.

7) carbonate rocks contain at least minor amounts of dolomite.

8) invertebrate fossils suggest alkaline conditions.

9) vertebrate fossils are present.

10) silicified, partly silicified, or carbonaceous plant debris occur in the section.

11) silica, dolomite, or fossiliferous beds in the section are anomalously radioactive.

12) uranium minerals occur.

Some counter-indications include:

1) the presence of thick coaly units in the section. This suggests that the basin was probably an open hydrologic system because water was abundant enough to support plant life continuously during a substantial period of time. Uranium would likely be flushed through, either immediately or during maturation of the plant matter.

2) the presence of unaltered or little altered ash in the sedimentary section. This suggests that the ground-water geochemistry was not conducive to the leaching and transport of uranium.

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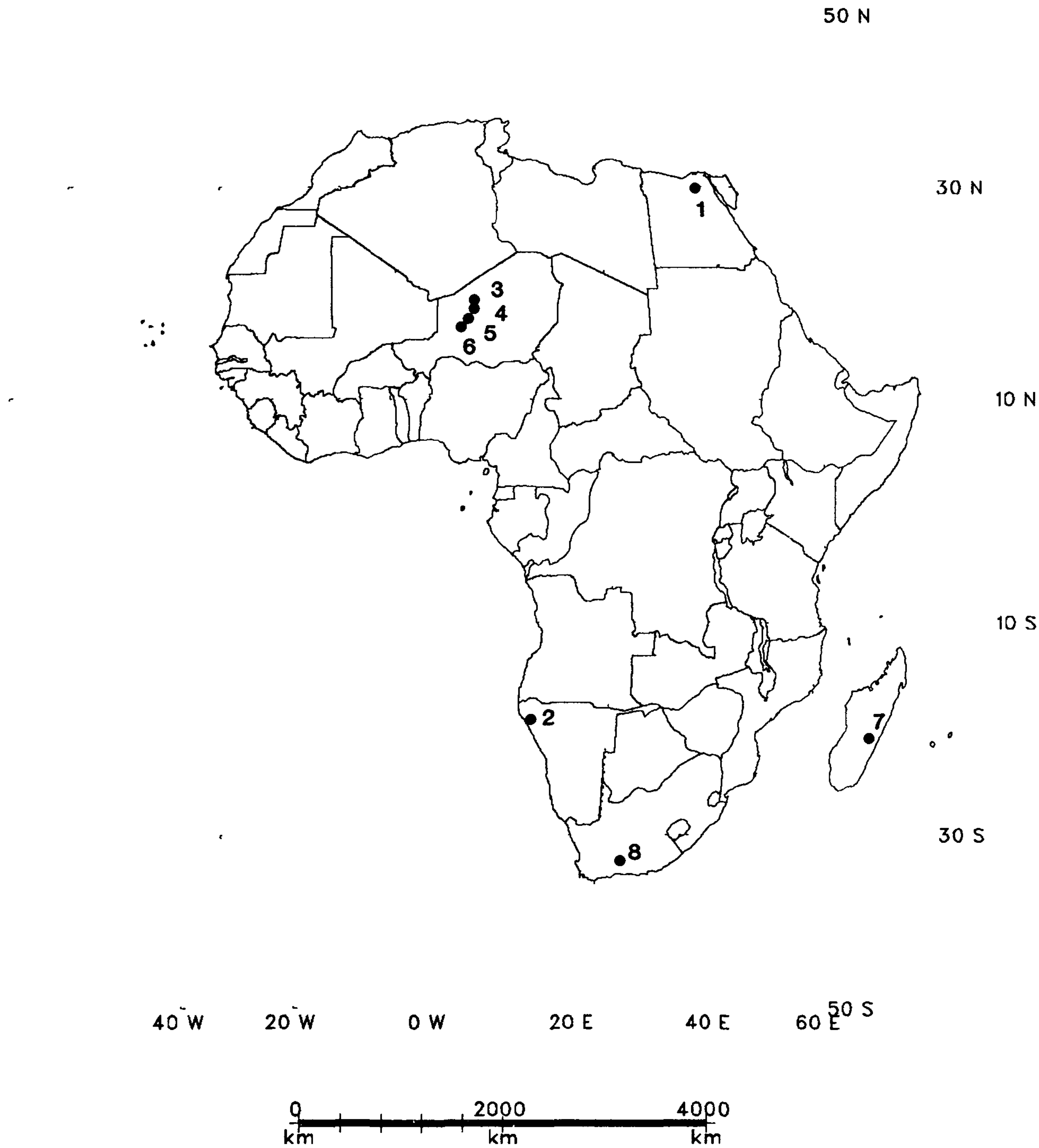
AFRICA

MAP AND INDEX LIST FOR SANDSTONE-TYPE URANIUM DEPOSITS IN AFRICA



AFRICA

Egypt:

1. Gebel Quatrani, Oligocene Quatrani

Namibia:

2. Engo Valley, Skèleton Coast, Permian Dwyka Formation, Karroo Sequence

Niger:

3. Arlit deposits, Air Mountains, Carboniferous Tarat sandstone
4. Madaouela, Akouta, and Ebala deposits, Air Mountains, Carboniferous Guezouman sandstone
5. Imouraren deposit, Air Mountains, Jurassic Tchirezrine 2 sandstone
6. Azelik and Takardait deposits, Air Mountains, Cretaceous Assaouas sandstone

Madagascar:

7. Antsirabe, Plio-Pleistocene lacustrine clay and sand

South Africa:

8. Beaufort West, Karoo Basin, Permian Beaufort Group

GEOLOGIC ENVIRONMENT OF THE URANIUM DEPOSITS IN THE CARBONIFEROUS AND JURASSIC SANDSTONES OF THE WESTERN MARGIN OF THE AIR MOUNTAINS IN THE REPUBLIC OF NIGER

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Abstract

The main uranium deposits of Niger resulted from the complex interaction between paleogeographic, tectonic and petrographic factors and the movement of underground waters. The tectonic framework of crystalline basement controlled the main sedimentation axis and created the favorable areas of reducing environment where large quantities of vegetal organic matter accumulated. The main source of uranium was probably constituted by the intense volcanism of the Aïr Mountains. The first uranium deposits were formed in a fluviatile or fluviodeltaïc environment during the deposition or the early diagenesis of sediments. These deposits originally stratabound have been more or less remobilized by the flow of underground waters sometimes forming roll front-type structures particularly obvious in the Akouta deposit. The late tectonic movements induced gentle undulations in the sedimentary cover, concentrating and protecting the uranium deposits in the synclinal axis. The uranium deposits discovered on the western margin of the Aïr Mountains total 160 000 tonnes of uranium with a grade ranging from 0.12 to 0.45 % U, depending on the mineralized host formations, Jurassic or Carboniferous.

1. INTRODUCTION

The first uranium showings in the Agadez region in Niger were discovered by the "Bureau Minier de la France d'Outre-mer" (BUMIFOM) and the "Bureau de Recherche Géologique et Minière". At that time, the BUMIFOM was exploring for copper according to a convention established with the "Organisation Commune des Régions Sahariennes" during the period 1957 to 1961.

In 1957, a team of the BUMIFOM lead by Mr Kief began to study the copper anomalies around the Azelik structure where sandstones crop out in the middle of the argillaceous Irhazer plain. The geologist in charge, Mr Imreh, who previously had done studies on uranium secondary minerals, recognized among the varicolored samples, the yellow and green oxidized minerals of uranium and copper.

The "Commissariat à l'Energie Atomique" (CEA) after two reconnaissance missions in the Aïr region in 1954 and 1956 had also scheduled the study of the sedimentary cover of the western margin of the Aïr mountains which seemed promissing.

In 1958, the CEA was informed by the BUMIFOM of these findings and sent a preliminary mission. Good results were quickly obtained and during the winter 1958-59 a large prospecting team was formed to carry out airborne prospecting and drilling. Small mineralized lenses were discovered around the Azelik structure. The combination of airborne prospection and good photogeology lead to the discovery of numerous radiometric anomalies and mineralized outcrops along the entire western edge of the Aïr Mountains. Large-scale geological surveys were then conducted at the 1/50 000 and 1/200 000 scales. Among the main targets identified were the Carboniferous sandstones (Guezouman and Tarat) and the Jurassic sandstone (Tchirezrine 2). Detailed geological and structural mapping was done at the 1/20 000 scale on the most favorable zones. Wide spaced geological drillholes showed that structural geology was important for the determination of the axis of thickening of these sandstones and the localization of the most favorable zones for uranium concentrations in relation to the paleogeography.

The results of these works stressed the similarities between the Agadez uraniferous province and the Colorado Plateau, particularly for :

- the main structural framework : continental basins separated by ridges,
- the sedimentological characteristics : porous feldspathic sandstones deposited in fluviatile or deltaïc environnements, highly permeable ; frequent argillaceous intervals,

– the biochemical characteristics : organic matter of vegetal origin in sandstone channels.

Drilling on the most favorable zones according to the sedimentological, structural and chemical data lead to the discovery of the following uranium deposits :

– Madaouela, Akouta and Ebala deposits in the Guezouman sandstones (Carboniferous),
– Arlit deposits (Arlette, Ariège and Artois) and Tassa N'Taghalgue North and South deposits in the Tarat sandstones (Carboniferous),
– Imouraren deposit in the Tchirezrine 2 sandstones (Jurassic),
– Takardait and Azelik deposits in the Assaouas sandstones (Cretaceous).

2. GENERAL STRATIGRAPHY

The general stratigraphic column as established by F. Joulia in the Arlit area, from base to top (fig.1), is :

2.1. – the Teragh or Farazekat sandstones (Lower Visean) : they include very coarse to conglomeratic sandstones and directly overlap the Aïr crystalline basement,

2.2. – the Talak Formation (Lower Visean) comprised mainly of marine clays with fossiliferous zones (brachiopoda). It contains very fine-grained sandstones near the top,

2.3. – the Tagora Group (Upper Visean) : according to the Joulia's stratigraphy the Tagora Group includes two main sequences of sandstones-shales : Guezouman-Tchinezogue and Tarat-Madaouela.

2.3.1. The Guezouman Formation consists of :

. at the base, the Teleflak conglomerate with basement-derived pebbles (quartzite, micaschists, granite, rhyolite) and phosphatic nodules,
. overlain by mainly isogranular, cross-bedded sandstones,
. towards the top these sandstones become finer and finer, passing progressively to the Tchinezogue shales,

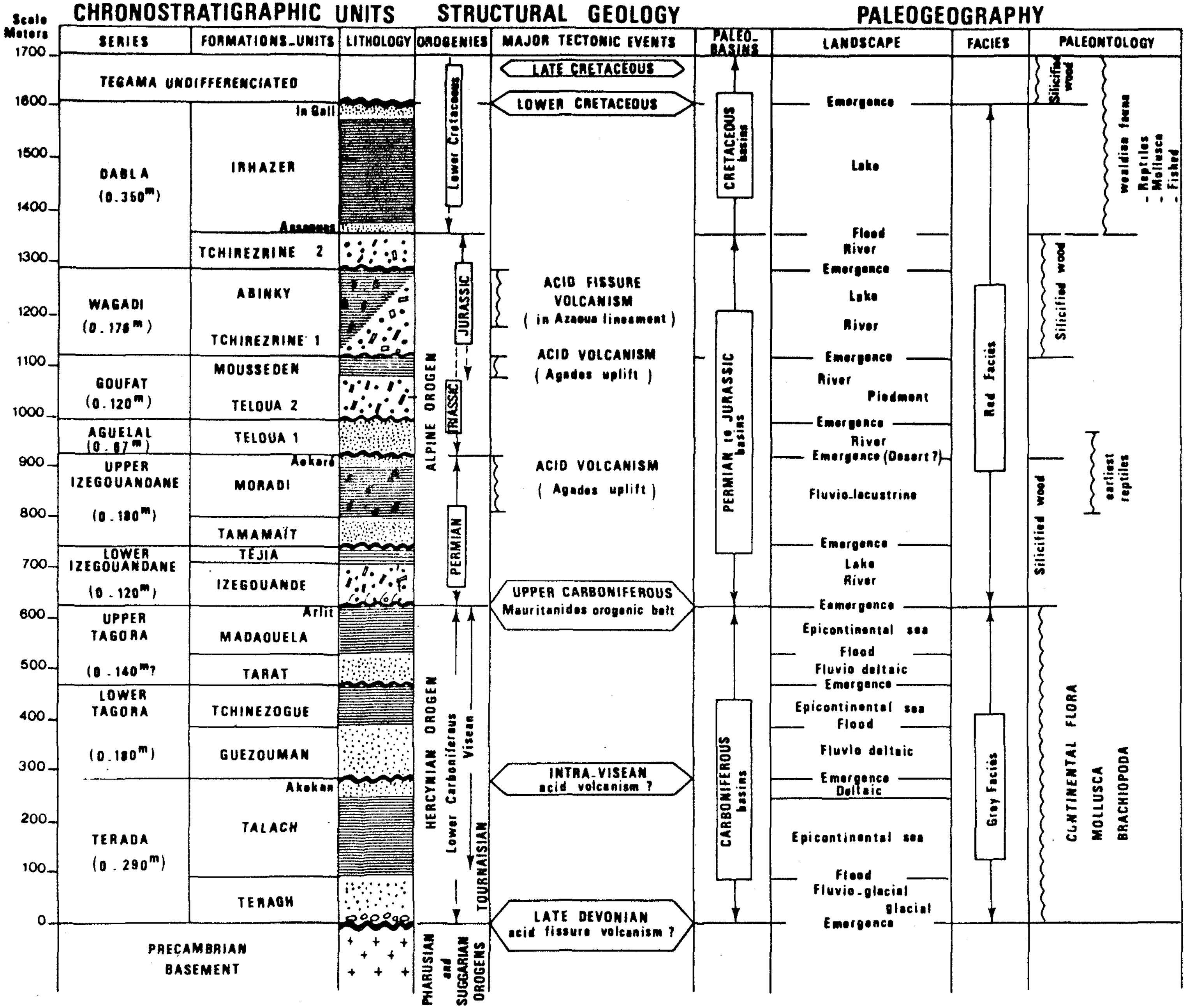
2.3.2. The Tchinezogue Formation consists mainly of silts and shales with some sandstone layers (whitish sandstones in the middle part) : the presence of reference beds allows one to determine the structural deformation in the lower shales and deep scouring in the upper silts and shales. In fact, a slight angular unconformity exists between the whitish sandstones and the lower shales of the Tchinezogue Formation. A better stratigraphy of the Guezouman-Tchinezogue would be :

2nd sequence	↑	Upper Tchinezogue silts and shales Whitish Sandstones
		∿∿∿ Slight angular unconformity ∿∿∿
1st sequence		Lower Tchninezogue siltstones and shales Guezouman Sandstones

2.3.3. – The Tarat Formation consists of medium to very coarse heterogranular sandstones containing more than 80 % quartz grains. Black siltstone and shales with abundant organic matter usually separate the sandstones lenses. Lateral and vertical facies variations are abundant.

2.3.4. – The Madaouela Formation consists mainly of silts and black to grey shales in its lower part, changing to brown to red in its upper part. In the Arlit uranium deposits area, black to grey siltstone and shales usually attributed to the Madaouela Formation correspond, in fact, to the fine-grained facies of the complete sedimentary sequence (sandstones to shales) of the Tarat Formation. The Madaouela Formation truly exists west of the Arlit fault where it reaches a thickness of more than 240 meters. Its base is characterised by massive medium to very coarse arkosic sandstones.

2.3.5. – The Arlit Formation consists of a few meters of eolian green to red argillaceous sandstones and lacustrine shales. This formation makes the transition between the Tarat-Madaouela and Izegouandane Formations.



Scale Meters
CHRONOSTRATIGRAPHIC UNITS
STRUCTURAL GEOLOGY
PALEOGEOGRAPHY
SERIES
FORMATIONS_UNITS
LITHOLOGY
OROGENIES
MAJOR TECTONIC EVENTS
PALEO_BASINS
LANDSCAPE
FACIES
PALEONTOLOGY
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
TEGAMA UNDIFFERENCIATED
DABLA
(0.350m)
In Gall
IRHAZER
TCHIREZRINE 2
WAGADI
(0.178m)
ABINKY
TCHIREZRINE 1
GOUFAT
(0.120m)
MOUSSEDEN
TELOUA 2
AGUELAL
(0.67m)
TELOUA 1
UPPER IZEGOUANDANE
(0.180m)
Aokaré
MORADI
TAMAMAÏT
LOWER IZEGOUANDANE
(0.120m)
TÉJIA
IZEGOUANDE
UPPER TAGORA
(0.140m?
Arlit
MADAOUELA
TARAT
LOWER TAGORA
(0.180m)
TCHINEZOGUE
GUEZOUMAN
Akokan
TERADA
(0.290m)
TALACH
TERAGH
PREÇAMBRIAN BASEMENT
Lower Cretaceous
JURASSIC
TRIASSIC
PERMIAN
ALPINE OROGEN
HERCYNIAN OROGEN
Lower Carboniferous
Visean
TOURNAISIAN
PHARUSIAN and SUGGARIAN OROGENS
LATE CRETACEOUS
LOWER CRETACEOUS
ACID FISSURE VOLCANISM
(in Azaoua lineament)
ACID VOLCANISM
(Agades uplift)
ACID VOLCANISM
(Agades uplift)
UPPER CARBONIFEROUS
Mauritanides orogenic belt
INTRA_VISEAN
acid volcanism ?
LATE DEVONIAN
acid fissure volcanism ?
CRETACEOUS basins
PERMIAN to JURASSIC basins
CARBONIFEROUS basins
Emergence
Lake
Flood
River
Emergence
Lake
River
Emergence
River
Piedmont
Emergence
River
Emergence (Desert ?)
Fluvio_lacustrine
Emergence
Lake
River
Emergence
Epicontinental sea
Flood
Fluvio deltaic
Emergence
Epicontinental sea
Flood
Fluvio deltaic
Emergence
Deltaic
Epicontinental sea
Flood
Fluvio_glacial
glacial
Emergence
Red Facies
Grey Facies
Silicified wood
wealdian fauna
- Reptiles
- Mollusca
- Fished
Silicified wood
earliest reptiles
Silicified wood
CONTINENTAL FLORA
MOLLUSCA
BRACHIOPODA

FIGURE 1

2.4. – The Izegouandane Formation (Permian) is divided into four members, from base to top :

- the Izegouande Member : mainly heterogeneous very coarse to microconglomeratic arkosic sandstones,
- the Tejia Member : red to brown shales,
- the Tamamait Member : red to pink medium to fine-grained micaceous sandstones with abundant calcareous cement,
- the Moradi Member : mainly red to brown shales with scarce sandstones lenses.

All these facies indicate the establishment of increasingly arid climatic conditions.

2.5. – The Agadez Sandstone sequence (Triassic to Jurassic) : it includes several sandstone formations, particularly the Teloua 1, 2 and 3 and the Tchirezrine 1 and 2 Formations.
The base of the Agadez Sandstones is characterized by wind-shaped pebbles and fine-grained sandstone typical of desert conditions.
The next sandstone units with fluviatile characteristics indicate the resumption of humid climatic conditions. The presence of analcime and volcanic shards in the sediments, sometimes in such a quantity as to form thick analcimolite beds (Mousseden and Abinky Formations) indicates a high volcanic activity contemporaneous of the sedimentation.
The Tchirezrine 2 of Jurassic age, which constitutes the last spreading out of coarse sediments of the Agadez Sandstone sequence, is the host for uranium deposits.

2.6. – The Irhazer Formation (Lower Cretaceous) : Tchirezrine 2 sandstones are overlapped by the very thick red shales of the Irhazer Formation immediately above a few meters of fine to very-fined grained sandstone of the Assaouas Member.

3. MINERALIZATIONS IN THE CARBONIFEROUS FORMATIONS

3.1. Mineralizations in the Guezouman Formation

Three deposits have been discovered in the Guezouman Formation : Madaouela, Akouta and Ebala. They all have the same characteristics.

3.1.1. General stratigraphy

The general stratigraphy of the Guezouman Formation is given by cored hole Arli 2378 in the Akouta deposit area (Fig.2). The formation generally consists of medium to fine grained isogranular quartz sandstone beds. Argillaceous breaks are very rare.

3.1.2. Depositional setting of the Guezouman sediments

The Guezouman sedimentation was mainly controlled by basement structures consisting of N 80° E and N 130 ° E faults and N 40° E folds. In the northern part of the Akouta deposit, the mineralization is related to a highly individualized channel, tributary of a well developed delta. This channel formed a favorable trap for uranium.

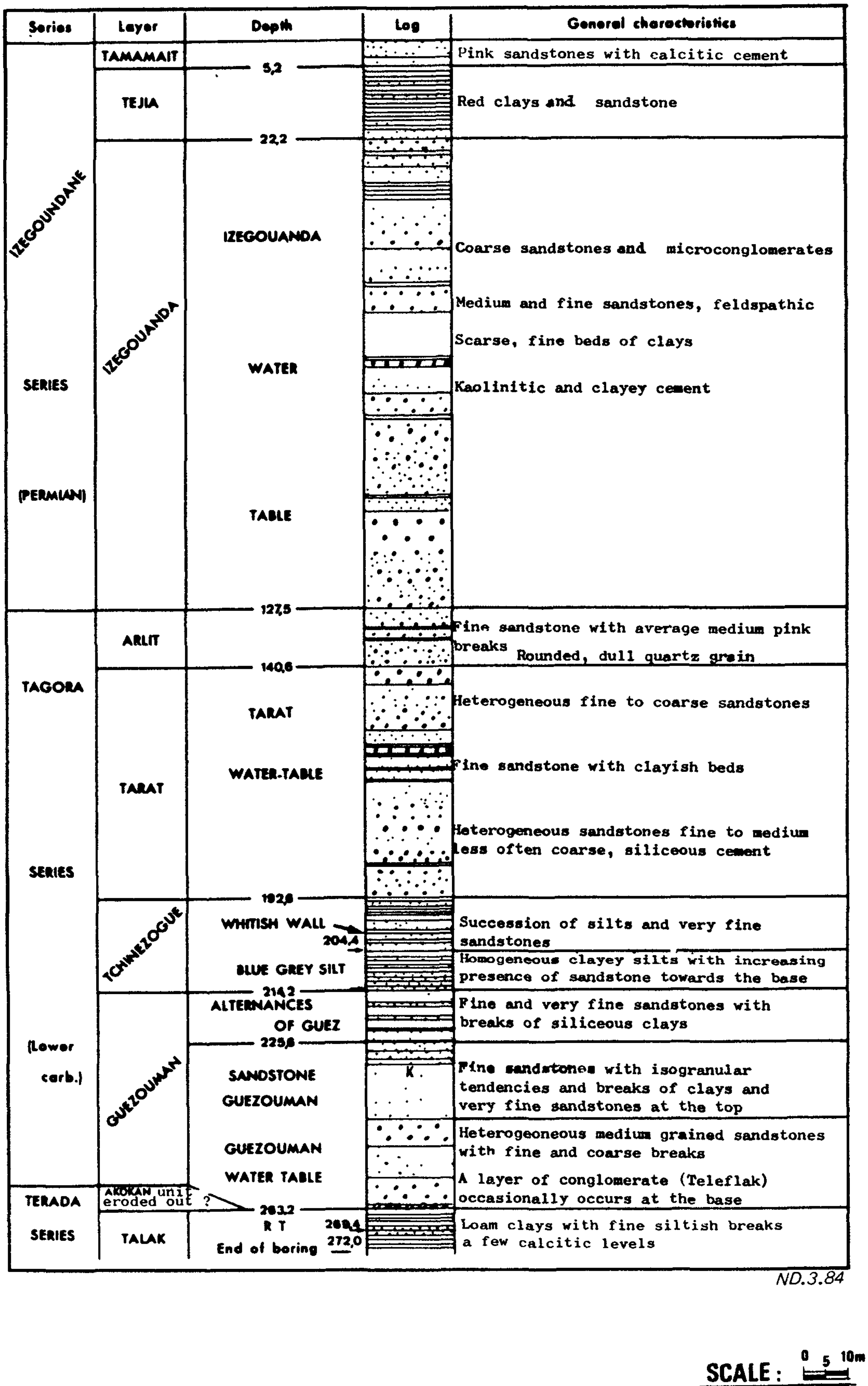
Changes in grain size (essentially grading) were noted both vertically and laterally, although they account for small-scale patterns, they are not sufficient to explain the larger-scale geometry of the mineralization.

3.1.3. Geometry of mineralization

The detailed distribution of the uranium minerals is partly due to the numerous differentiations, such as shale breaks and petrographic variations within the Guezouman Formation, even though this formation appears very homogeneous at first sight.

If one now considers the deposit as a whole, a redox interface crosses at a large scale the original Guezouman paleogeography and the Guezouman sedimentary structures seem to have controlled the uranium concentration. While the channel determines the general shape of the uranium deposit, the sedimentary structures and the lithology affect its detailed distribution. Controls of the mineralization

STRATIGRAPHIC LOG ARLI 2378 figure 2



were therefore the results of the complex interaction of paleogeography, tectonic structure, sedimentary structure, lithology and paleohydrology.

3.1.4. Mineralogy of uranium

Uranium occurs essentially as pitchblende and coffinite with either one or the other dominating. The uranium minerals may occur as well in the intergranular cement as replacement of plant remains ; part of the mineralization may also be included in the quartz overgrowths. Massive pitchblende a few centimeters thick can be found associated with pyrite and phyllite.

3.1.5. Iron sulfides

These are the most constant and abundant associated minerals : mostly marcasite and pyrite are found, sometimes associated with melnikovite.

3.1.6. Other minerals

Many other minerals are associated with the uranium minerals. Jordisite occurs in a significant amount. Vanadates, sphalerite, galena, chalcopyrite are present but less abundant. Native sulfur has been detected. Slight occurences of calcite and selenite have been observed locally in the cement.

3.1.7. Uranium sources and ore deposit model

Possible sources of uranium can be found in the surrounding regions :

A small amount may have been derived from the erosion and leaching of the Aïr crystalline basement, but the major part probably resulted from the volcanic activity, evidence of which is found as early as the Ordovician in Adrar Bouss in the northern part of the Aïr Mountains. Major preconcentrations were certainly penecontemporaneous with the sedimentation with uranium precipitation within the fluvio-deltaic environment in the favorable areas with a high organic matter content.

Uranium remobilization by oxidizing waters penetrating the sandstones both from the east (down-dip from the outcrops) and from the west (from the Arlit fault) contributed to give the deposit its present shape, partly of stratiform type and partly of roll-front type, the latter being particularly well developed in the northern part of Akouta where the limit between very high-grade ore and barren sandstones is very sharp.

No particular concentration of uranium minerals along faults has been identified. The structure contour map of the Talak RT reference level shows that the deposit is now preserved in a synform structure with a down-dip closure by the Arlit and Aokare faults (fig.4).

Lead isotopic dating on a massive pitchblende sample of Akouta deposit has given an age of 338 ± 5 million years.

3.1.8. Characteristics of the Akouta deposit

- mineable reserves : 44 000 tons of U
- average grade : 0.45 % U,
- thickness : 2 to 14 meters,
- depth : 235 et 265 meters from surface.

3.2. Mineralizations in the Tarat Formation

The uranium deposits investigated around Arlit in the Tarat Formation are quite similar to those in the Guezouman Formation, particularly with regards the sedimentology and the structural controls.

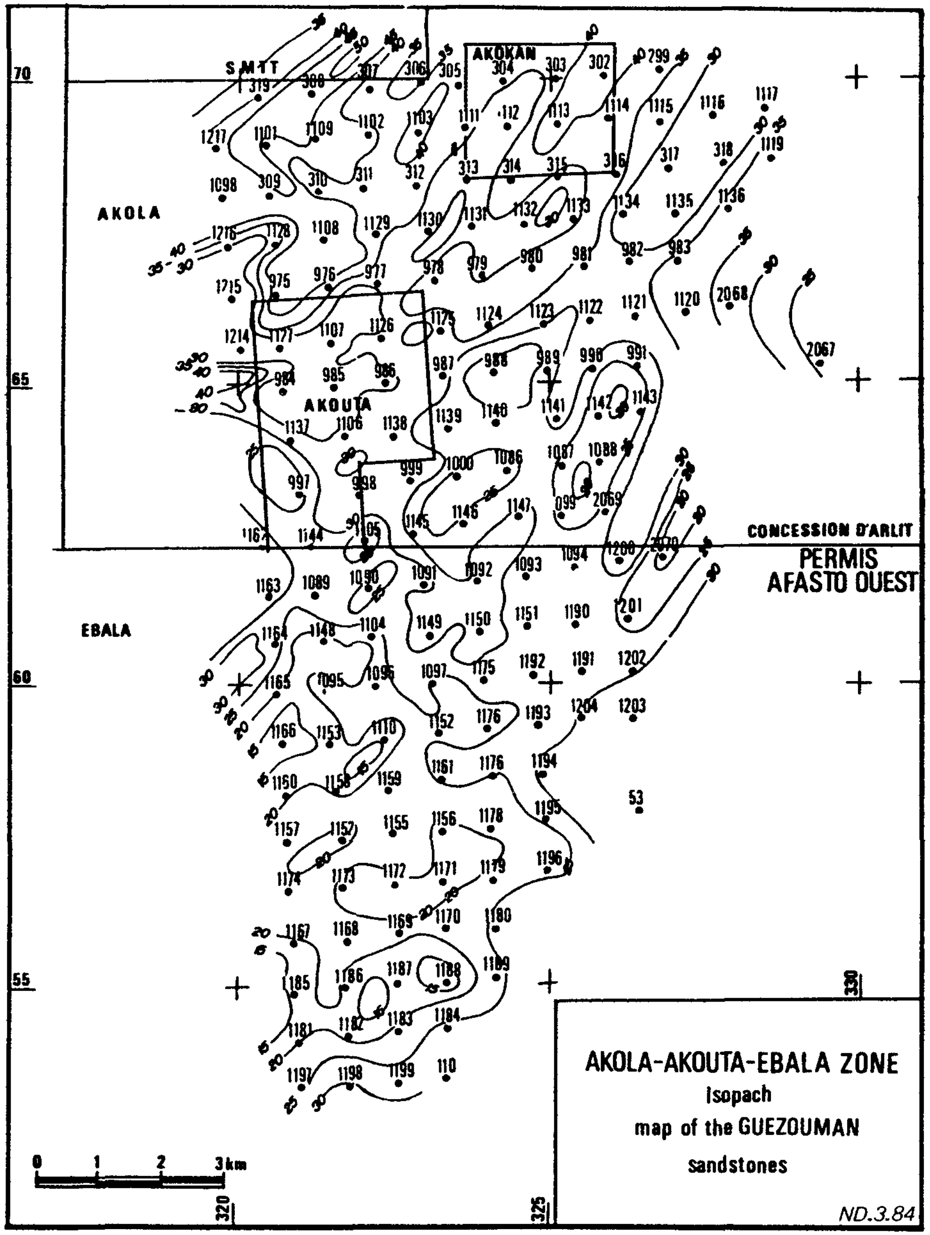


FIGURE 3

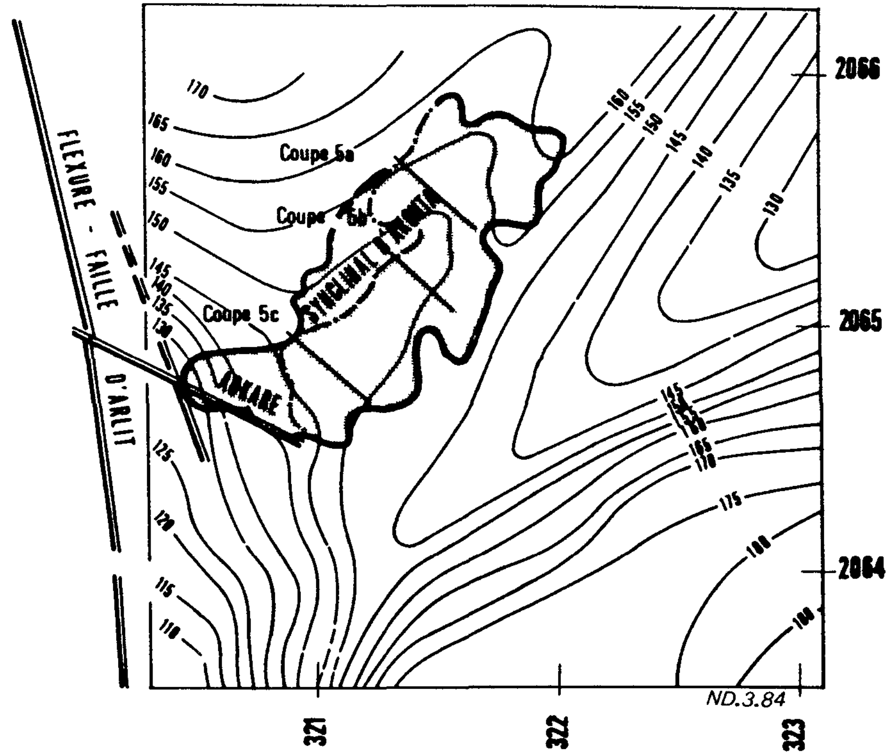
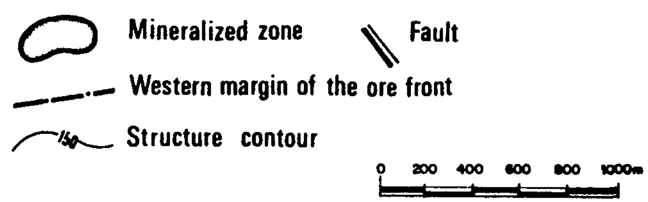
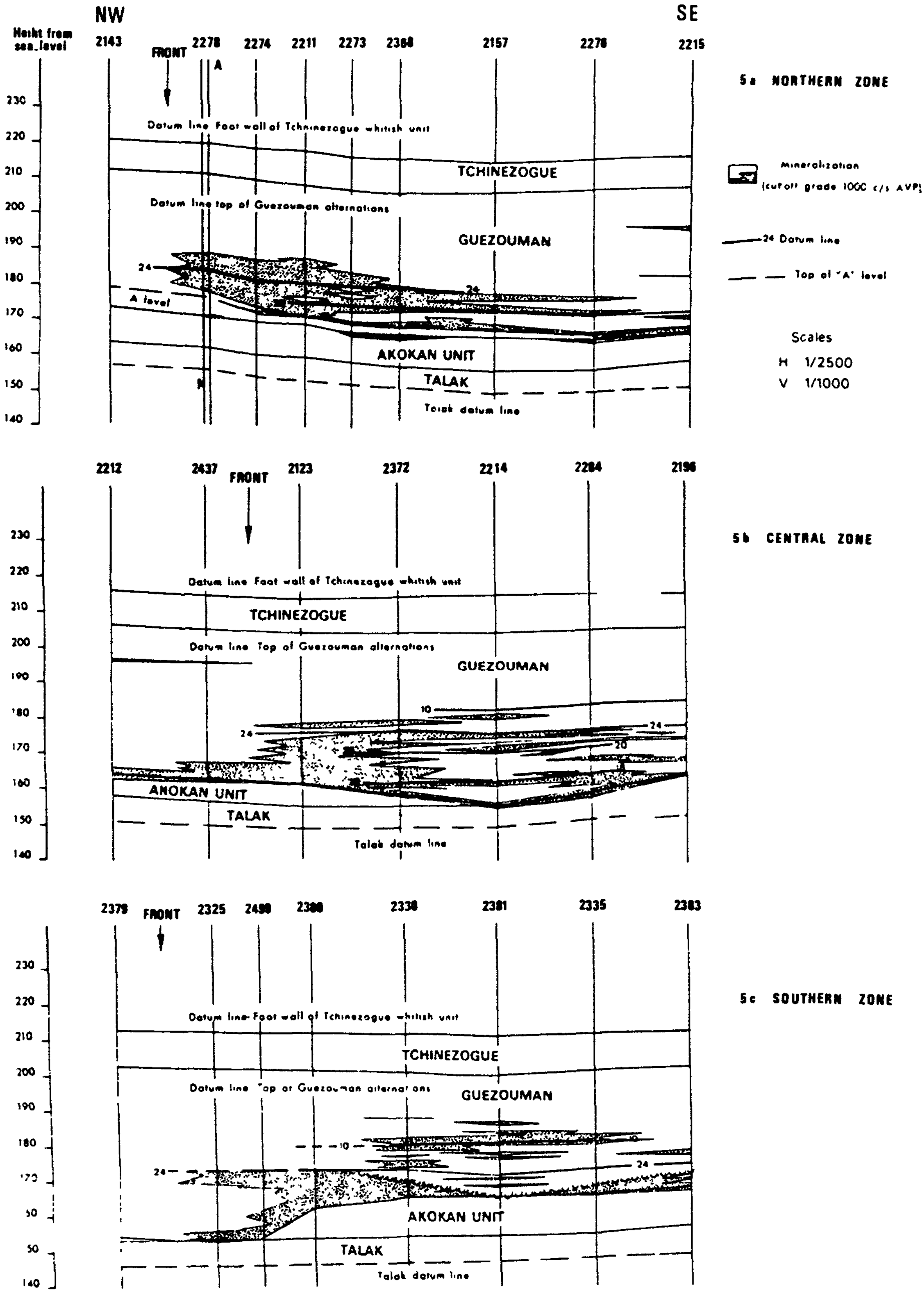


FIGURE 4 AKOUTA Structure contour map of the reference level





Figures 5 a.b.c
Schematic NW.SE Cross.sections

MS

3.2.1. General stratigraphy

Compared to the Guezouman, the Tarat Formation is more heterogeneous with coarse sandstones and well developed siltstone and shale levels (Fig.6). Its total thickness is highly variable ranging from 9 meters to 55 meters. In the Mining area the Tarat Formation is divided into two main sequences T1 at the base and T2 at the top. But, in some of the deepest scours of the main channel, a lower unit beneath T1, called T0, consists of fine-grained sandstones and mainly silstone and shale beds. This T0 unit is generally barren of uranium.

3.2.2. Depositional setting of the Tarat Formation

The Tarat Formation was deposited above the strongly eroded argillaceous Tchinezogue Formation. Control of the sedimentation by N-S, N 70° E and N 130° E basement faults is clearly shown by the structure contour map of the Tarat (Fig.7). In the SOMAIR open-pits, it can be observed that the sedimentation is very complex in detail and corresponds to a succession of sandstone lenses with intraformational discontinuities.

3.2.3. Structure

The comparison of the structure contour map of the base of the Tarat (fig.7) with the one for the Arlit Formation (fig.8) shows that the Tarat sedimentation filled a depression in the paleotopography. The basement structures do not appear clearly as faults in the sedimentary cover, but these tectonic directions have a strong influence on the distribution of the ore deposits.

The structure contour map of the base of the Arlit Formation (fig.8) shows the importance of the N 40° E synform structure where the mineralization has been protected.

3.2.4. Geometry of the mineralization

Uranium is widely distributed within the silstone and shale beds but, in the ore deposits, it invades all the interbedded sandstones (fig.9). In the Arlette ore body, for instance, mineralized sandstone has been found up to 20 meters thick. In the Tarat Formation, a roll-front type deposit has not been clearly established even where local remobilizations of mineralization have been observed showing apparent roll-front structures.

3.2.5. Uranium mineralogy

In the Tarat Formation, the high-grade ore is composed principally of microscopic black minerals : pitchblende and coffinite approximately in equal proportion, associated with pyrite and/or marcasite and coating the quartz grains in the sandstones. In the very high-grade ore, uranium minerals completely cement the sandstones. In the oxidized zones, as in Arlette for instance, the uranium minerals are tyuyamunite, francevillite and carnotite in association with iron oxides or kaolinite. In the siltstone and shales, uranium exists as organic complexes. No uranium minerals have been identified even in the very high-grade uranium siltone and shale ores. Other minerals like sphalerite and galena are often associated with the uranium minerals. Vanadium and molybdenum are present but in small amounts.

3.2.6. Uranium sources and ore deposit model

The mineralizations found in the Tarat Formation may have had the same source of uranium as those in the Guezouman Formation : Aïr basement erosion and leaching, or volcanic activity. Major preconcentrations were certainly penecontemporaneous with the sedimentation with preferential uranium precipitation where sediments have a high organic matter content. Stratiform-type orebodies were then formed during the early diagenesis. Later, structural deformations and ground water circulations locally remobilized the uranium and gave the orebodies their present shape : predominantly stratabound orebodies with local development of roll-type structures.
No isotopic dating of ore or host rock minerals has been done.

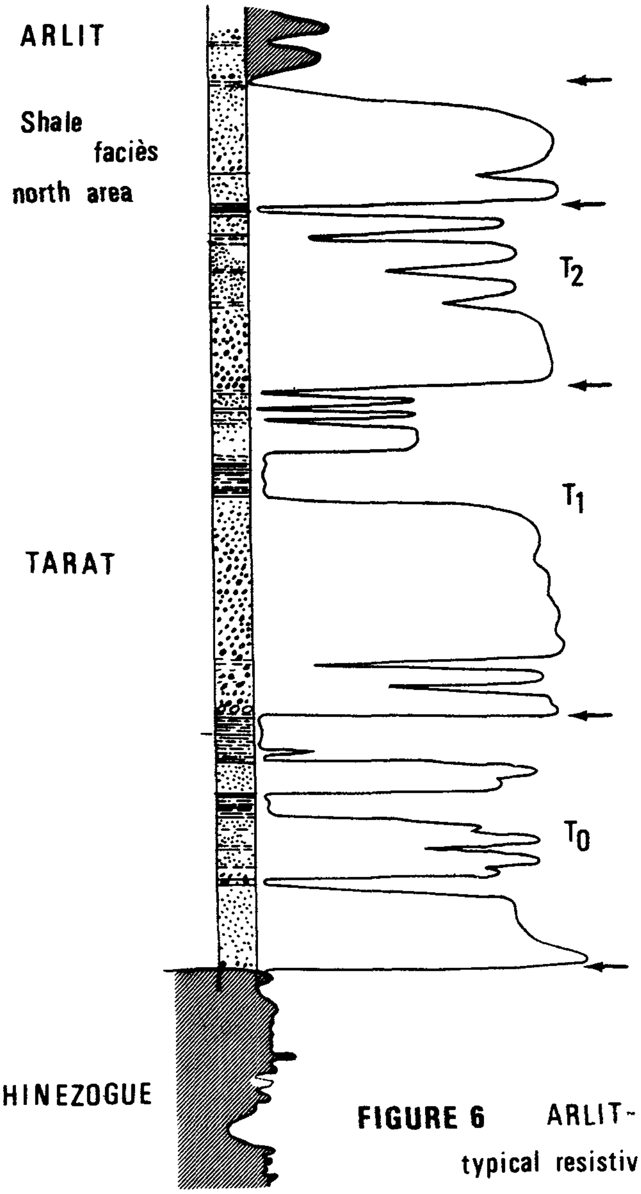


FIGURE 6 ARLIT- TARAT formation: typical resistivity curves

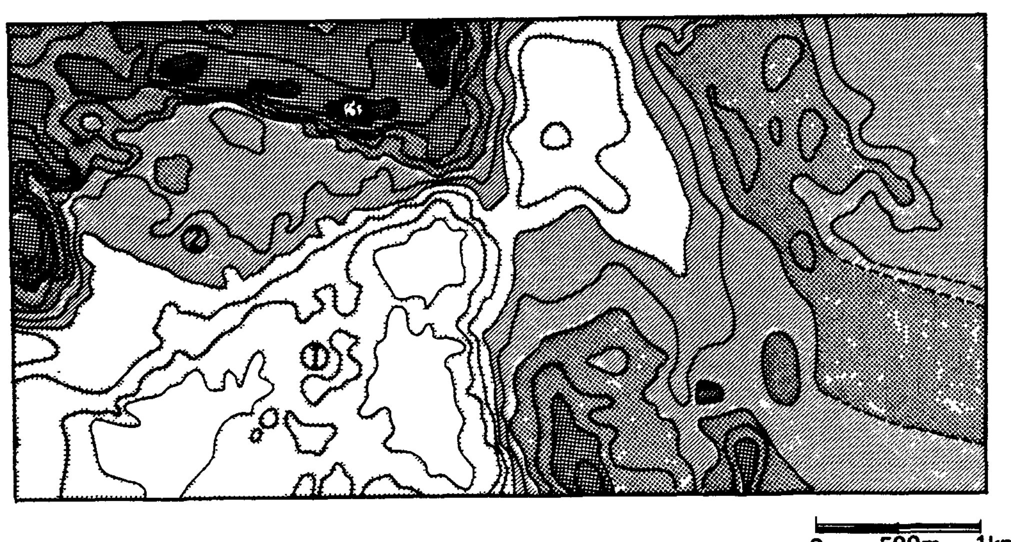


Figure 7 - ARLIT area: Isopach map of the TARAT formation

① ARLETTE
② ARIEGE
③ ARTOIS

<25 m
25 - 35 m
35 - 45 m
45 - 55 m
55 - 65 m
>65 m

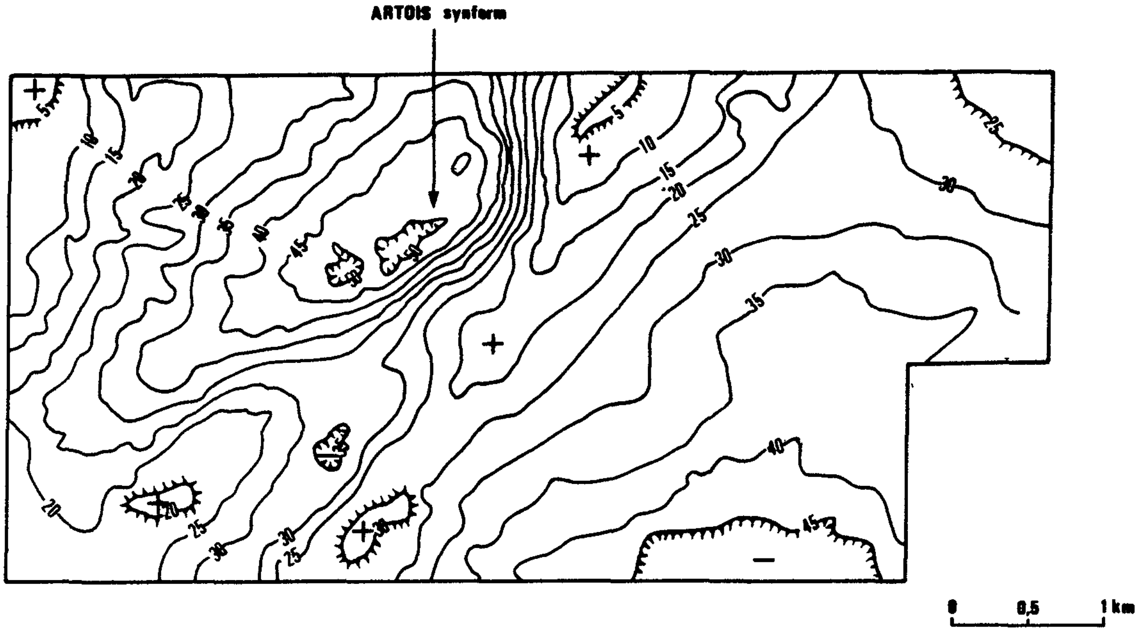


Figure 8 _ ARLIT area : structure contour of the Arlit formation

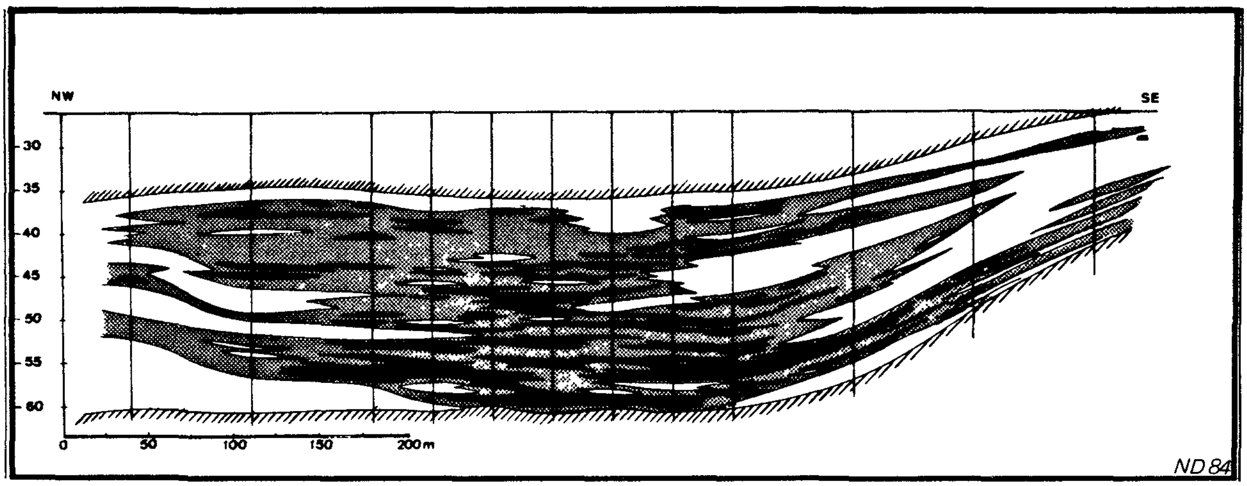


FIGURE 9 ~ ARLIT area : vertical cross-section of the ARLETTE deposit

Low grade ore zone — High grade ore zone

3.2.7. Characteristics of the Arlit deposit

Mineable reserves : 30 000 tons of U,
Average grade : 0.25% U,
Thickness : up to 20 meters,
Depth : 35 to 120 meters.

The Tassa N'Taghalgue ore bodies in the Tarat sandstones to the south west of Arlit, which have the same characteristics, are estimated to contain 20 000 tonnes of U.

4. MINERALIZATIONS IN THE JURASSIC FORMATIONS

The Imouraren uranium deposit is located about 80 km south of the Arlit deposits in the Jurassic Tchirezrine 2 Formation.

4.1. Stratigraphy

The Tchirezrine 2 Formation consists mainly of coarse feldspathic sandstones lying unconformably (local scouring) on the analcimolites of the Abinky Formation. The Tchirezrine 2 is overlain by the fine-grained sandstones of the Assaouas and the red argillites of the Irhazer (Cretaceous). The Tchirezrine 2 is comprized of fluviatile sediments including : coarse to very coarse heterogranular sandstones with cross-bedding at the base, medium to fine-grained sandstones, fine to very fine-grained analcimolitic sandstones, and analcimolitic argillites to analcimolites at the top (Fig. 10).

In this sequence, the analcimolites represent the same environment and have the same relative position as the shales in the Carboniferous sedimentary sequences. The sandstones generally contain about 80 % quartz grains, 3 to 4 % feldspar (microcline essentially), and rocks fragments of the Abinky or Tchirezrine 2 fine-grained sandstones reworked by scouring.

The sandstones are generally poorly cemented. Cement includes secondary silica, chlorite, spheroidal analcime and kaolinite-dickite. The analcimolites(rocks mainly composed of analcime) are of two types : 1) blue, grey or green analcimolites ; they are made up of spheroidal analcime with a white or green core and brown to pink cortex, scattered in a chloritic matrix, and 2) brownish massive analcimolites, which are made of yellowish spheroidal analcime in a brown hematitic matrix.

4.2. Paleogeography of the Tchirezrine 2 Formation

After the sedimentation of the Abinky Formation in a lacustrine environnement there were tectonic readjustments : a wide north-south trough developed, limited by the Arlit fault on the west, the Madaouela fault on the north and the Magagi fault on the south. This trough has been then filled up with fluviatile sediments of the Tchirezrine 2 (Fig. 11). The fluviatile system which is relatively simple in the northern and southern areas appears more complex and sinuous in the central area.

4.3. Geometry of the mineralization

The distribution of the mineralization at Imouraren is the result of the same controls already identified for the Arlit and Akouta deposits :

- a stratigraphic and sedimentologic control : the mineralization is preferentially related to the Tchirezrine 2 sandstones, especially to the heterogranular sandstones containing analcimolite pebbles ;
- a paleogeographic control : the mineralization occurs in the vicinity of the main channel, partly controlled itself by tectonic movements which occurred before or during the deposition of the Tchirezrine 2 ;
- a tectonic control : remobilization along faults have been found along E NE post-Tchirezrine 2 faults ;
- paleohydrogeological control : coalescences and discontinuities in the mineralization are the result of ground water circulation.

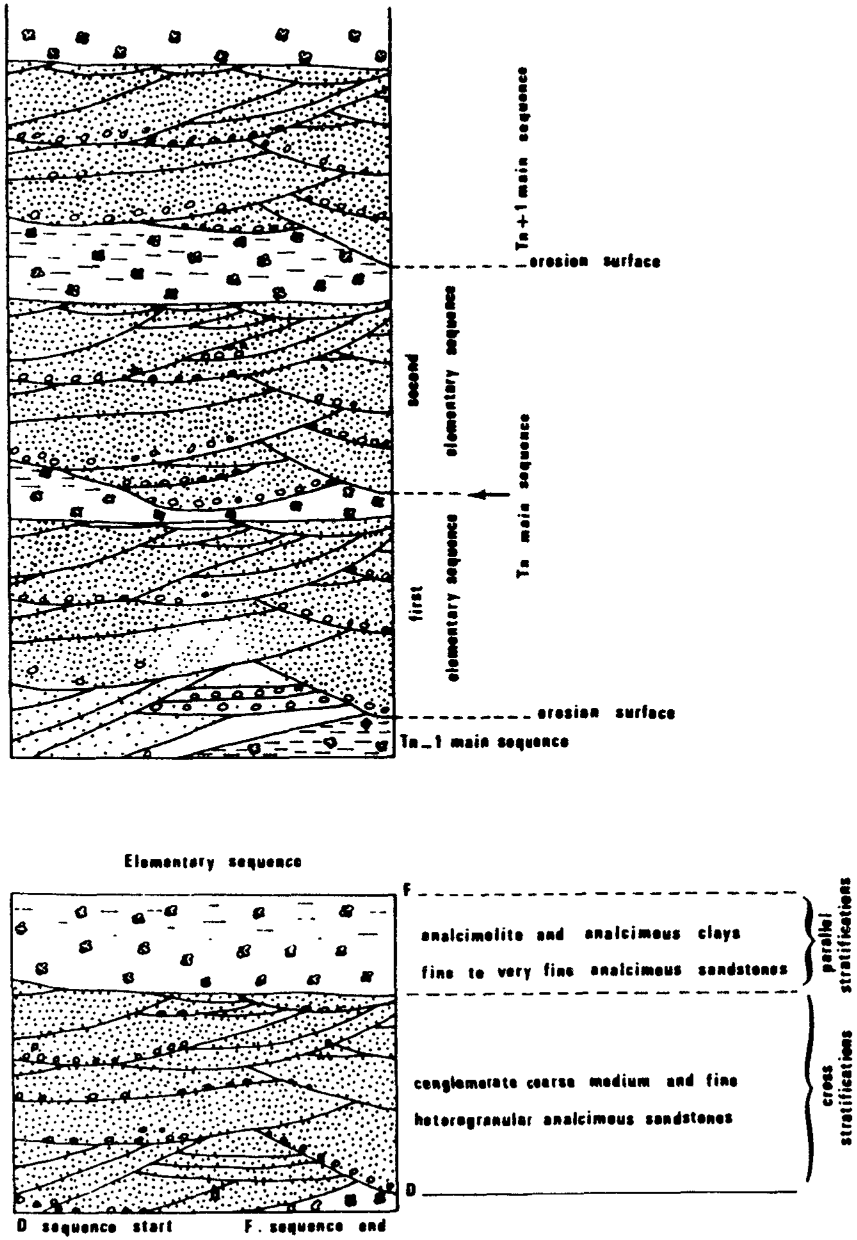


Figure 10

TCHIREZRINE 2 sedimentology

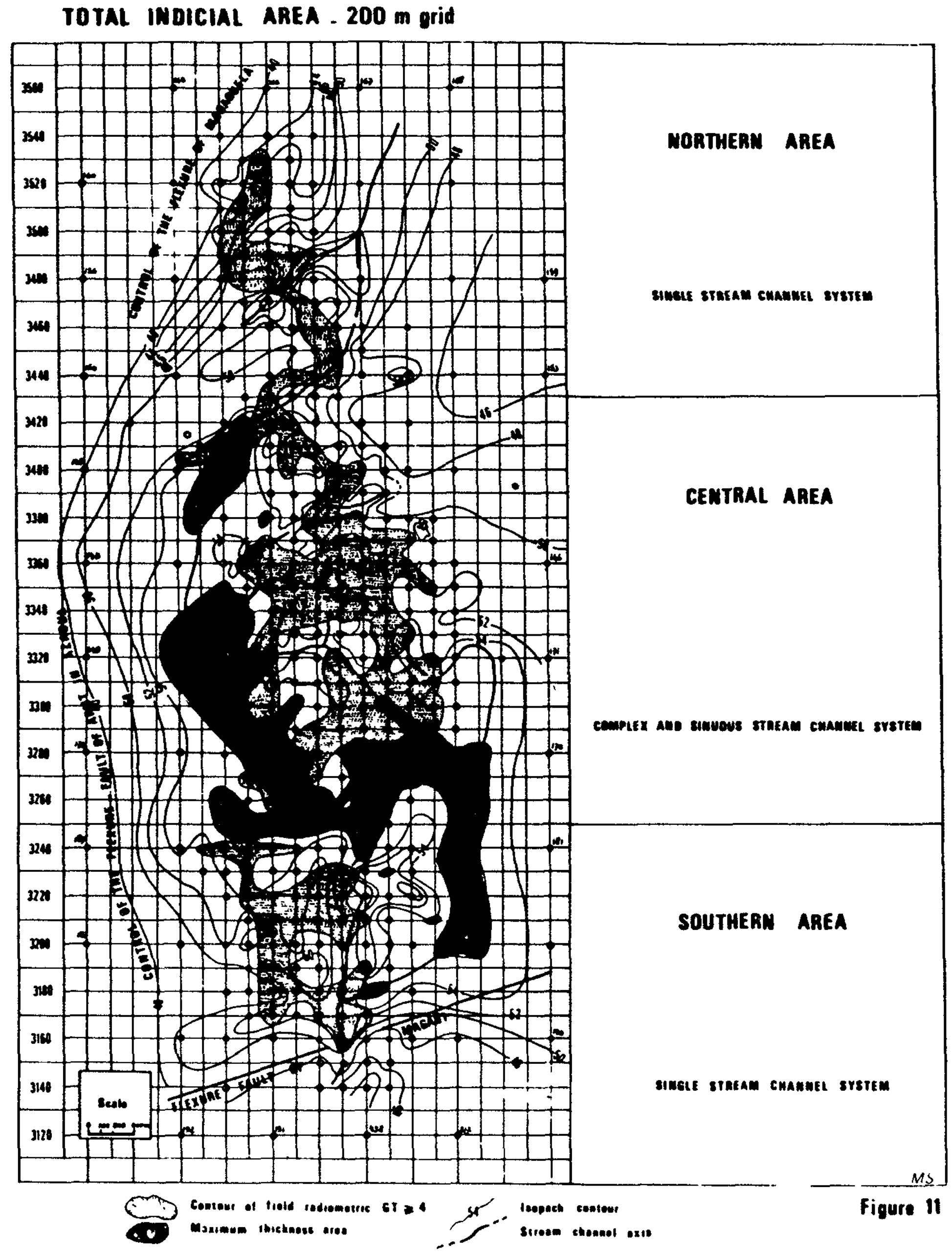


Figure 11

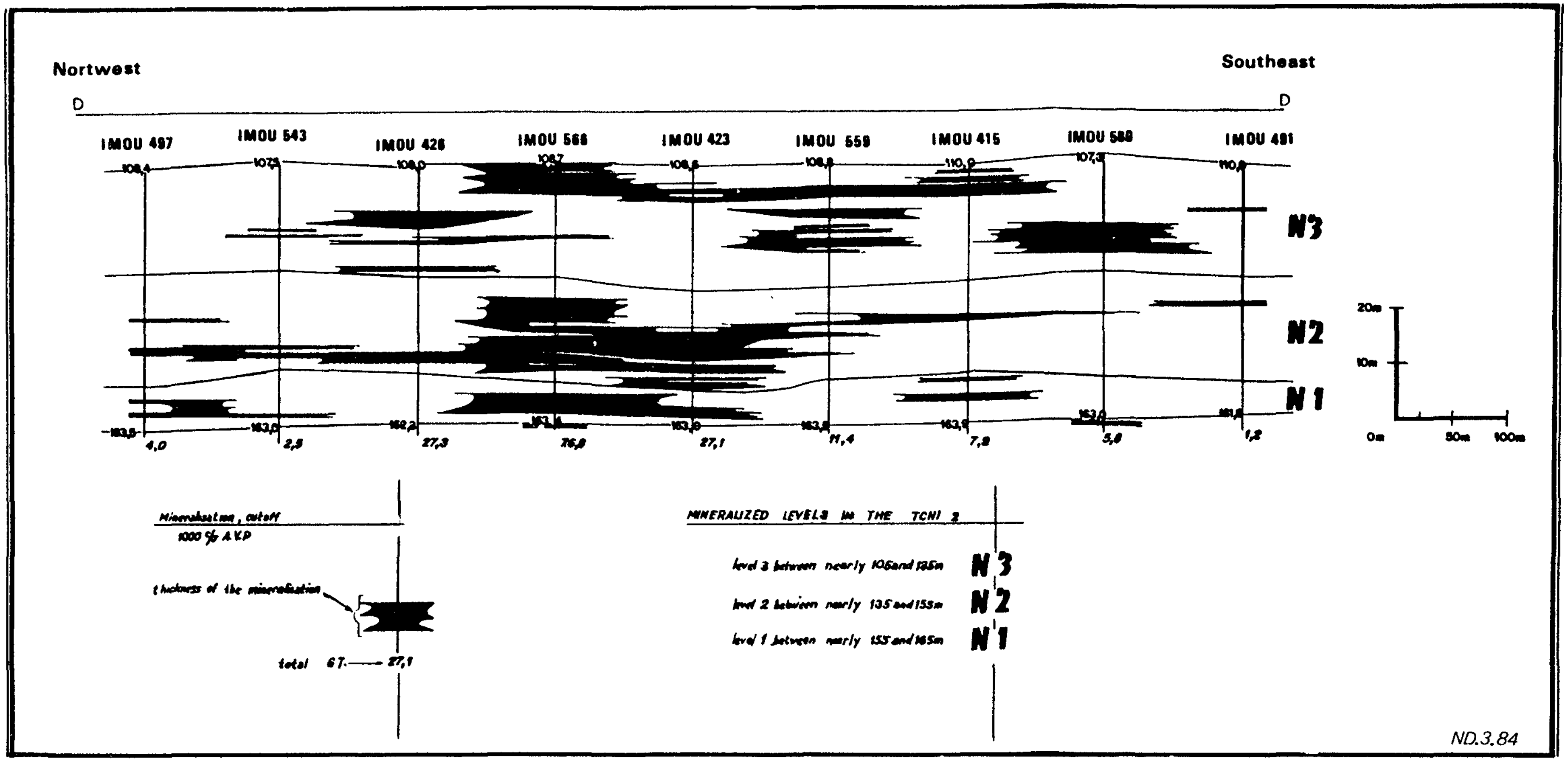


FIGURE 12 . Imouraren deposit N W – S E cross section

4.4. Uranium mineralogy

At Imouraren there is a marked difference with the Carboniferous orebodies ; the major part of the uranium appears in an oxidized environment in the form of hexavalent minerals. Some coffinite still exists in residual reduced zones associated with chalcocite and/or native copper, pitchblende in small amount and chalcopyrite.

In the oxidized facies, uranotile is the most abundant mineral. It forms either small aggregates with a radial fibrous structure or a continuous felty coating parallel to the stratification. Uranotile is commonly associated with chrysocolla and rarely with tenorite. Boltwoodite is associated, with uranotile, but in small quantity, and with the same habitat. Metatyuyamunite has also been found as microscopic crystals scattered in the kaolinite-dickite coating small fractures.

4.5. Other minerals

Besides the uranium and copper minerals, few other minerals have been found. Calcite is at the periphery of the orebody, collophanite in the cement of some sandpebbles, and sulphates as barite and gypsum.

4.6. Uranium sources and ore deposit model

The main source of uranium for the Imouraren deposit seems to have been the volcanic activity demonstrated by the abundance of analcime. Paragenetic studies favor a syngenetic uranium precipitation in a reduced sedimentological environment. The Imouraren orebody has been strongly oxidized and remobilized by ground water circulations. However, the presence of roll fronts has not been firmly established, and the orebody seems to be definitely stratabound (Fig. 12). No isotopic dating of ore or host rock minerals has been done.

4.7. Characteristics of the Imouraren deposit

- mineables reserves : 66 000 tons of U,
- average grade : 0.12% U,
- thickness : 2 to 40 meters,
- depth : 105 to 165 meters.

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GEOLOGICAL ENVIRONMENT OF URANIUM DEPOSITS IN THE BEAUFORT GROUP, SOUTH AFRICA

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Abstract

The sandstone-hosted uranium deposits of the Beaufort Group in the south-western Karoo are described. The sandstone is interbedded with mudstone and siltstone and the sedimentary sequence forms several megacycles of which the top three are economically the most important. Lithostratigraphic units are characterized by fossil assemblage zones. Several lithofacies can be recognized and the sandstone has all the characteristics of a fluvial depositional environment. Uranium is confined to calcareous pods and lenses which vary in size from less than one to several hundreds of cubic metres.

Coffinite and uraninite are the primary uraniferous minerals and are associated with carbonaceous debris and sulphides. Volcanic clasts and granitic detritus in interbedded mudstones, presumably released uranium and the ore-forming fluids migrated along permeable channels in the sandstone. The final site of ore-deposition was determined by sedimentological controls and the availability of a reductant.

1. INTRODUCTION

Radioactivity in the Beaufort Group was first reported in 1964 during the course of exploration for kimberlite pipes. Three years later radioactivity was also detected in the gamma-log of an exploratory hole for oil, drilled near the town of Beaufort West. Early in 1970, a private company embarked upon a uranium search throughout the world and selected a number of sedimentary basins, which show geological similarities to the Colorado Plateau region, as prime target areas. The Karoo basin was included and after a period of one year of carborne surveys, two uraniferous sandstone bodies were located west of Beaufort West. This initiated intensive aerial surveys and by the mid-seventies no less than twenty private companies as well as the Geological Survey of South Africa and the Nuclear Development Corporation of S.A. (Pty) Ltd. were actively engaged in uranium exploration and geological studies in the Karoo basin. Eventually, more than two hundred sandstone-hosted uranium occurrences were discovered of which Ryst Kuil, which is described below, is one of the more important ones.

The distribution of the Beaufort Group which consists of an alternating sequence of sandstone and mudstone, and the localities of the principal uranium occurrences are shown in Fig. 1. These occurrences are confined to the south-western part of the Karoo between Sutherland and Graaff-Reinet, hence the area treated in this paper was selected from this region (Fig. 2). A pediplain with low relief occupies the greater part of the area, with a plateau located towards the north and extreme west. This plateau is separated from the pediplain by a 500 m high escarpment. The climate is semi-arid and the region is sparsely populated, with the largest town, Beaufort West, having a population of 16 500.

2. LITHOSTRATIGRAPHY AND BIOSTRATIGRAPHY

The Beaufort Group of the Karoo Sequence is subdivided into the lower Adelaide and upper Tarkastad Subgroups, of which only the former is present in the south-western Karoo. The Adelaide Subgroup (Late Permian) attains a maximum thickness of 2 000 m and consists of the Abrahamskraal and Teekloof Formations (Fig. 3). The strata north of the escarpment are intruded by Early Jurassic dolerite sills and dykes.

Several upward-fining megacycles, up to 400 metres thick, have been recognized in the Beaufort Group [1]. Each megacycle consists of several sandstones in the lower portion and a mudstone-dominated sequence in the upper portion. From bottom to top, the sandstone-rich parts of the upper three megacycles have been named the Moordenaars sandstone, Poortjie Member and Oukloof sandstone. Most of the uranium occurrences are restricted to these three units.

In the area under review, four reptile assemblage zones are recognized [2] (Fig. 3). The correlation between these assemblage zones and the three top megacycles is a useful aid in delineating the lithostratigraphy and thus the uraniferous sandstone units. This is particularly true for the Aulacephalodon-Cistecephalus and Pristerognathus-Diictodon Assemblage Zone, associated with the Oukloof and Poortjie sandstones respectively. The Tropidostoma-Endothiodon assemblage occurs entirely within a thick mudstone unit and its zonal distribution thus indicates the absence of uranium-bearing strata. Since Dinocephalian

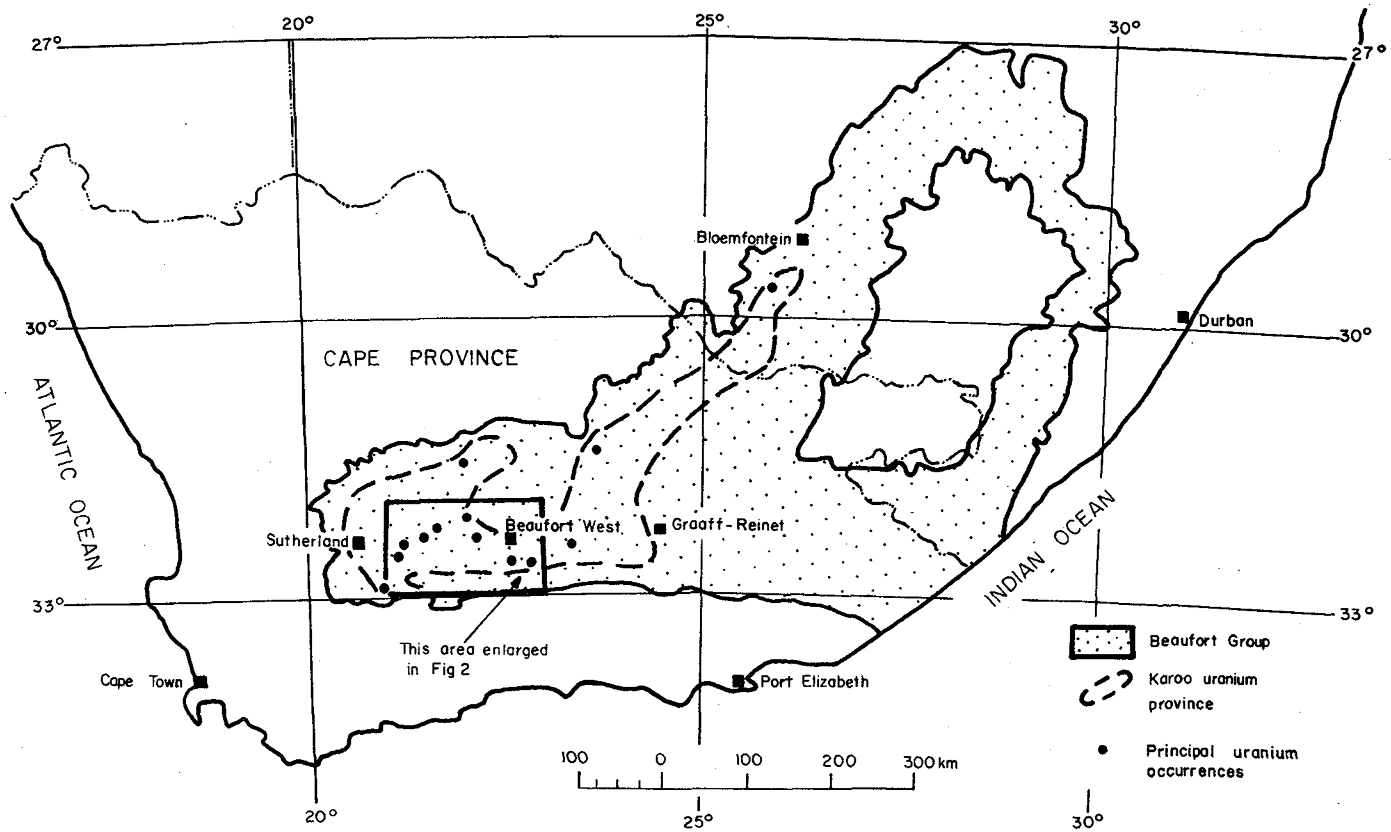

Figure 1. Distribution of the Beaufort Group and principal uranium occurrences in the Karoo uranium province

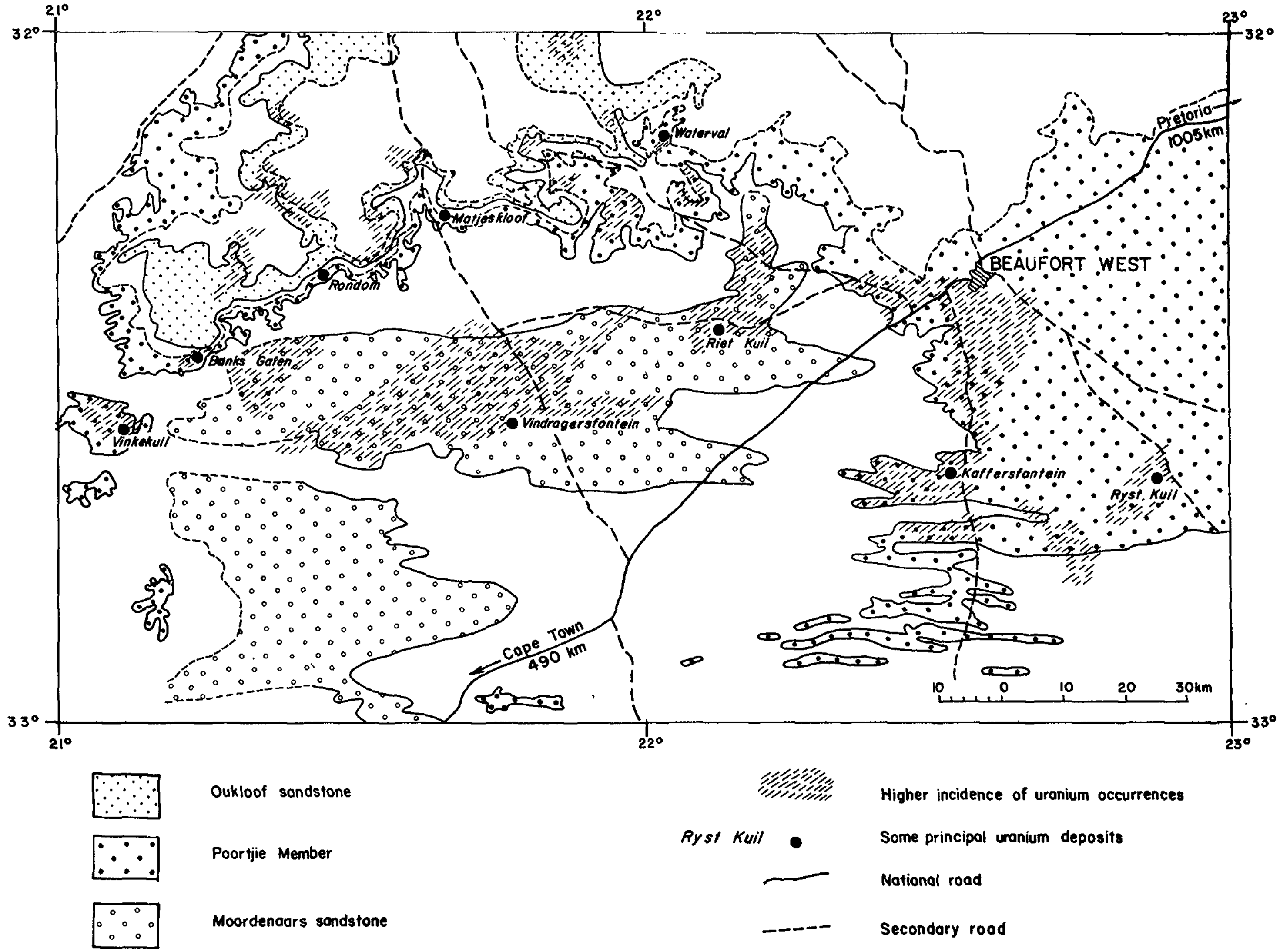

Figure 2. Distribution of uraniferous sandstones and uranium occurrences in the Beaufort West area

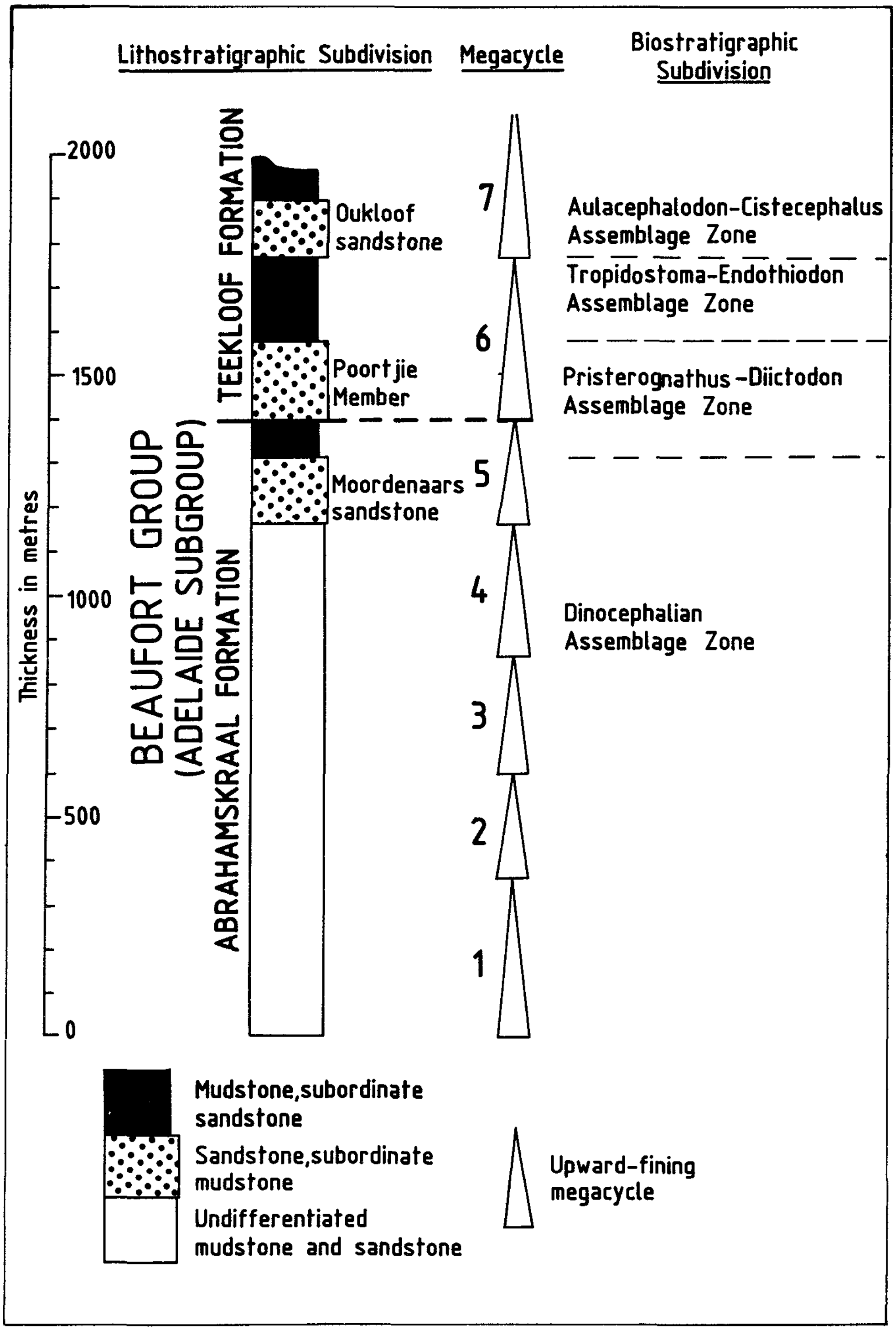

Figure 3. Lithostratigraphy and biostratigraphy of the Beaufort Group in the south-western Karoo (After [1] and Keyser and Smith [2]).

Assemblage Zone fossils characterize not only the Moordenaars sandstone but all the underlying Beaufort strata as well, these fossils can only be used to identify the Moordenaars unit where they occur in close proximity to the Pristerognathus-Diictodon Assemblage Zone fossils.

3. SEDIMENTOLOGICAL SETTING OF URANIUM MINERALIZATION

Uraniferous sandstones are between 1 and 60 metres thick and are interbedded with mudstone and/or siltstone in an approximate ratio of 1:3. Sandstones which are greater than 3 m thick, usually represent fluvial channel deposits, whereas thinner sandstones represent overbank deposits, e.g. crevasse splays, which accumulated in a mud-dominated floodbasin or playa-lake [1, 3]. Uranium mineralization is almost entirely confined to the fluvial channel sandstone and is best developed in the thicker sandstones [4]. The fluvial channel sandstones form discrete bodies, which can be up to 16 km long, 3 km wide and 60 m thick and their morphology is either ribbon or tabular. The sandstones are either unistorey or multistorey, with each storey representing the deposits of a single palaeochannel within the sandstone body. The sandstones can also be multilateral, as a result of lateral coalescence of palaeochannels, or composite, as a result of both lateral and vertical superpositioning of palaeochannels [1].

The base of both the sandstone bodies and individual palaeochannels within the bodies is erosional and gently undulose. Most of the sandstone bodies are multistorey as a result of successive channels occupying the same depositional site and reworking part of each underlying storey. Consequently, only the uppermost storey is usually complete [5]. Upward-fining sequences within the storeys are usually evident and the tops of the storeys are either abrupt or gradational. Turner [3] suggests that the abrupt contacts are related to low-sinuosity palaeochannels and the gradational contacts to high-sinuosity palaeochannels. Stear [1], however, associates the abrupt upper contacts with bedload palaeochannels and the gradational contacts with mixed-load palaeochannels.

The channel sandstones are fine- to very fine-grained and the lithofacies include intraformational conglomerate, trough cross-bedded sandstone, horizontally-bedded sandstone, planar cross-bedded sandstone, ripple cross-laminated sandstone, siltstone and mudstone.

Interpretations of the type of sedimentary deposits within the channel sandstone and the overall depositional environment are based on detailed studies of suitable outcrops and Markov chain analysis of lithofacies transitions. The following types have been recognized: channel lag, point bar, channel bar, sheet flood, scroll bar, chute bar, abandoned channel-fill, swale-fill and natural levee.

The ribbon-shaped sandstone bodies tend to occur within mudstone-dominated sequences whereas tabular-shaped sandstone bodies are located where the sandstone to mudstone ratio is the highest. Turner [3] and Le Roux [6] ascribed ribbon sandstones to deposition in high-sinuosity channels and tabular sandstones to deposition in low-sinuosity channels. Stear [1] , however, indicated that ribbon sandstones are generally straight and entrenched within mudstone, whereas tabular sandstones are unrestricted since there is a lack of stable, mud-dominated channel banks. Both morphological types contain bedforms which are related to lateral migration of the channel, e.g. lateral accretion surfaces, and to sheet-flooding of the channel, e.g. internal scour surfaces and horizontally-bedded sandstone. Lateral migration may have occurred in either high- or low-sinuosity channels whereas sheet-flooding may have taken place in straight, braided or low-sinuosity channels. Cole [5] showed that high- and low-sinuosity palaeochannels are present within the same sandstone body and that low-sinuosity palaeochannels are more numerous. Sheet-flood deposits tend to predominate over point bar deposits and the depositional processes probably consisted of high-regime ephemeral sheet-flooding and low-regime lateral migration [1].

The uranium occurrences within the channel sandstones form discrete pods and lenses, peneconcordant to the bedding. The pods and lenses can be isolated or stacked, and range in size from less than one cubic metre to maximum dimensions of several hundred metres long, twenty metres wide and seven metres thick [1, 3, 5]. They are usually restricted to the lower portion of the sandstone, and approximately fifty per cent or more of the ore was formed within the basal storey. The pods and lenses are elongated along the palaeochannel thalweg, which coincides with the thickest development of the sandstone [4]. The mineralization occurs preferentially within horizontally-bedded and/or massive sandstone, which was more amenable for mineralization where it is interbedded with mudstone or siltstone. The mineralized sandstone is predominantly very fine- to fine-grained, and is commonly associated with carbonaceous debris or other fossilized plant material.

4. MINERALOGY AND GEOCHEMISTRY

The sandstone is invariably immature and is in fact a type of lithic-feldspathic greywacke, containing quartz, feldspar and rock fragments set in a fine-grained matrix. A considerable amount of calcite can be present, particularly in some of the mineralized sandstones, along with organic material and minor amounts of disseminated sulphides [7, 8].

Quartz, the predominant detrital mineral, is usually fine- to very fine-grained ($<$0,25 mm in diameter) and constitutes between twenty and forty per cent of the sandstone. Feldspar consists of plagioclase and orthoclase in variable amounts. In unmineralized sandstone orthoclase is in the order of five and plagioclase about twenty per cent, whereas in mineralized sandstone, the amount decreases to two or three per cent for both feldspars. The rock fragments have a microgranular texture, which hampers microscopic identification, and their amount varies from less than five to thirty per cent [4, 9]. Two main periods of carbonate replacement took place: the first phase being a manganese-rich variety with minor calcium, whereas the later one is almost pure calcite [7]. The carbonate content in mineralized sandstone varies from two to thirty per cent and an increase of carbonate takes place at the expense of plagioclase.

Coffinite preponderates over uraninite, the only two primary uranium minerals present. Both minerals are very fine-grained and commonly intergrown with the coal macerals vitrinite, fusinite and semi-fusinite. They also replace the detrital matrix, carbonate cement and sulphides. Yellow and green secondary uranium minerals, which include torbernite, sabugalite and uranyl-arsenates, phosphates and silicates occur along joints, fractures and bedding planes in sandstone [1, 10].

Various sulphides are also associated with mineralized sandstone, of which molybdenite is economically the most important. Others are arsenopyrite, loellingite, pyrite, marcasite, pyrrhotite, sphalerite, tetrahedrite, tennantite, bravoite and chalcopyrite.

The discrete pods and lenses within channel sandstone are by far the most common uraniferous host rock. It is readily recognized in outcrop as a result of a thin surface coating of dark-brown MnO. This characteristic, locally known as "koffieklip", is an important ground-exploratory aid. The carbonate content of these pods and lenses is variable and there is a sympathetic relationship between the mass per cent $CaCO_3$ and

U_3O_8 as shown in Table 1.

% CaO	% CO_3	% MnO	ppm U_3O_8
1,87	1,10	0,17	< 20
11,44	3,75	2,01	181
22,08	10,75	2,25	1 148
21,84	12,70	2,66	1 100
1,56	0,98	0,16	< 20
0,93	0,58	0,12	< 20

TABLE 1. Partial chemical analysis of uraniferous pods and lenses (After Pretorius [7])

The second most common mode of occurrence of uranium is as secondary impregnations associated with iron oxides and hydroxides in bleached sandstone. Both Kübler [4] and Stear [1] consider these types of deposits as highly oxidised uraniferous calcareous pods and lenses.

Pretorius [7] concluded from detailed stream sediment sampling over uranium occurrences that the distribution of Zn, P and Co combined may be used as pathfinders in delineating uraniferous anomalous areas.

5. RYST KUIL – A SELECTED DEPOSIT

Detailed drilling by a company on Ryst Kuil and adjoining farms outlined a large area of subsurface uranium mineralization. The sandstone is light- to dark-grey, very fine- to fine-grained and interbedded with siltstone and mud-pebble conglomerate. Eighty-five per cent of the mineralization occurs in massive sandstone while fifteen per cent occurs in horizontally bedded sandstone [11]. The general composition is about one third each of quartz, feldspar and rock-fragments. The calcite content varies considerably and may be up to thirty per cent [12].

Structurally, the Ryst Kuil area consists of a series of shallow-dipping anticlines and synclines with the Ryst Kuil sandstone exposed along the flanks of the Ryst Kuil anticline. The outcrop width varies from 25 to 125 m and the calcareous pods or lenses, which host the uranium, occur within sandstone and are clustered along strike over several hundred metres. Individual pods or lenses may be up to 300 m in length [12]. The sandstone is up to 60 m thick and forms a composite body [1]. It comprises at least two major cycles of deposition and the mineralization generally occurs in the lower cycle, where the fluvial channel is at its thickest development. Ore continuity is directly related to the geometry of the sandstone but is also more extensive where shale interbeds are in contact with sandstone.

Coffinite is the principal ore mineral and is associated with urano-organic compounds, while uraninite is rare. The sulphides, which may be as high as 0,4 per cent, consist of arsenopyrite, pyrite, bravoite and molybdenite [1].

6. ORE GENESIS

Uraniferous ore-forming fluids presumably were derived either from volcanic tuff fragments, which were laid down contemporaneously with the fluvial sediments, and/or from detrital material transported from a granitic provenance. Martini [9] and Ho-Tun [13] reported volcanoclasts in sediments of the Beaufort Group in the south-western part of the Karoo basin, which on devitrification could have released uranium. Granite of the Namaqua-Natal metamorphic province in the north and north-west contains up to 350 ppm U, whereas granites south-west and south of the basin contain up to 30 and 3 000 ppm U respectively [14, 15, 16]. Age datings of zircon in uraniferous sandstone near Beaufort West, indicate an age of 1 050 Ma, which conforms with that of the last metamorphic event of the Namaqua-Natal province [17].

The most recent treatise on the migration of uraniferous fluids is by Stear [1], who considered that uranium was initially present in the interbedded mudstone within volcanic tuff fragments or was adsorbed onto clay minerals and organic particles. The clay minerals were derived from a granitic provenance and transported to the interchannel areas of the fluvial floodplain. The presence of uranium in siltstone and thermally metamorphosed mudstone of the Beaufort Group, as a result of dolerite intrusion, partially supports this contention [18, 19].

Dewatering of mudstone was assisted by evaporative pumping in a semi-arid, playa-lake environment, and the leached uranium was transported by groundwater, rich in carbonate and silica, which migrated towards, and eventually along, permeable channel sandstone bodies. The spatial distribution of mineralization to both specific sandstone bodies within the sedimentary sequence, and to specific sites within these bodies, was probably a result of the restriction of uranium-bearing groundwater to certain parts of the floodplain and selective penetration of the sandstone bodies. Precipitation of uranium within the sandstone was controlled by carbonaceous material and permeability differences as afforded by interfingering and intercalating mudstone and irregularities at the base of storeys [3, 4, 5]. The higher concentration of mineralization in the basal storey may be due to increased permeability differences caused by channel over-deepening and differential compaction of the sandstone body with respect to the underlying mudstone. Hydrogen sulphide, produced by anaerobic bacteria acting on carbonaceous debris, served as a reductant to precipitate U^{+4} from U^{+6} complexes.

7. CONCLUDING REMARKS

Most of the uranium occurs within the top three megacycles of the Beaufort Group in the south-western Karoo basin. Reptile fossils serve as a useful aid in deciphering the lithostratigraphy and thus potential uraniferous areas. The sandstone, which is in actual fact a type of lithic-feldspathic greywacke, has all the characteristics of a fluvial depositional environment.

Calcareous pods and lenses within sandstone are the most common host for uranium and a sedimentological control resulted in their spatial distribution. The uraniferous ore-forming fluids were presumably derived from either volcanic clasts and/or granitic detritus in mudstone and migrated towards, and along permeable channels in sandstone. Precipitation of coffinite, which preponderates over uraninite, took place when a suitable reductant was available.

Despite the fact that fluvial sandstones occur throughout the Beaufort Group in the entire Karoo basin, those in the Beaufort West area host by far the majority as well as the largest uranium deposits. This could be due to several factors, e.g. provenance, palaeoclimate, availability of reductant, and further research in this field is required.

The biostratigraphic concept and soil geochemical pathfinders in delineating target areas need to be extended outside the area under review.

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TECTONIC AND SEDIMENTOLOGICAL ENVIRONMENTS OF SANDSTONE-HOSTED URANIUM DEPOSITS, WITH SPECIAL REFERENCE TO THE KAROO BASIN OF SOUTH AFRICA

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Abstract

The principal tectonic and sedimentological settings for sandstone-hosted uranium deposits are described. Back-arc basins filled with post-Silurian, fluvial sediments bordering subduction zone magmatic arcs of calc-alkaline composition are considered favourable tectonic environments. The basins should be closed to prevent excessive oxidation of the sediments. Uranium deposits are concentrated near basin rims in the transition zone between uplift and basin subsidence, because of favourable sedimentary facies in those areas. Syn- and post-depositional deformation could have affected the localisation of uranium ore-bodies, while intrusive centres or uplifted arcs commonly have surrounding aprons of potential host rocks. Stratigraphic zoning is also related to source area tectonics and can be used to predict favourable sedimentary environments. Sedimentological processes had a direct influence on the permeability and carbonaceous matter content of sandstones and therefore have often controlled the localisation of ore-bodies.

INTRODUCTION

Although sandstone-hosted uranium deposits may occur in a wide range of tectonic and sedimentological settings, there are some environments that appear to be more favourable than others. This paper summarises some of the main tectonic and sedimentological environments in which sandstone-type uranium occurrences are found, with special reference to the Karoo basin of South Africa.

CHARACTERISTICS OF FAVOURABLE SEDIMENTARY BASINS

Fundamentally, two basic factors are required for the formation of a sandstone-hosted uranium deposit:

1) a suitable source of uranium
2) a favourable depositional environment in the host rock [1].

While most geologists agree that the majority of uranium ore-bodies in sandstone are of epigenetic origin, there is still considerable controversy as to the origin of the uranium itself. One school fervently advocates that the uranium was leached from adjacent tuffaceous sediments into the sandstones, or from pyroclastic material within the mineralised strata, and volcanic activity is indeed in most cases associated with these deposits. The other group holds that the uranium was derived from granitic and gneissic rocks in the source areas and was transported in the river water to be deposited syngenetically within the sediments, later to be remobilised and concentrated in favourable localities. This is based on the observation that most uraniferous sandstones were derived from Precambrian or younger granites that are commonly anomalous in uranium. There is no reason why the two so-called opposing theories could not be married, however, as the association of uraniferous sandstones with both granites and volcanics seems to be well established. This dual association may in fact be a valuable clue to the tectonic setting of many sedimentary uranium provinces.

Where two lithospheric plates collide, a continental margin magmatic arc can develop that is situated above an active subduction zone. In these regions anomalously high heat flow and geothermal gradients cause remobilising and partial melting of the older continental crust, which results in the transfer of uranium into the upper part of the crust. Where the basement rocks of the subduction zone are already anomalous in uranium, considerable enrichment of uranium can take place. These areas are generally zones of strong positive uplift and are also characterised by volcanic eruptions which can spread tuff for hundreds of kilometres in the downwind direction. Erosional debris from the uplifted calc-alkaline rocks and volcanics are carried into the back-arc basins, where the contained uranium can be remobilised and concentrated by circulating groundwater (Fig. 1). Back-arc basins of this type normally contain continental red-bed sequences, which are favourable geological environments for uranium mineralisation [2].

A possible example of this tectonic setting is provided by the Karoo basin of South Africa. During the Late Palaeozoic a subduction zone may have started to develop around the southern periphery of the continent on which the glacial Dwyka sediments had just been deposited [3]. Cordilleran-type fold mountains rose to the southwest, south and southeast during a series of tectonic pulses which reached a peak in the Triassic. The highlands probably consisted mainly of 1 050 m.y. old granites of the Namaqua-Natal basement complex underlying the Karoo sequence, as suggested by the ages of detrital zircons in the Permo-Triassic Beaufort sediments [4]. These granites are known to be anomalous in uranium and contain concentrations of elements such as molybdenum, copper and arsenic, similar to those associated with uranium deposits in the Karoo. Volcanic eruptions also released large amounts of ash into the atmosphere, as evidenced by the volcanic admixture of the Karoo sediments and the presence of discrete volcanic layers [5]. Basins to the east of the North and South American Cordilleras are further, classical examples of this type of setting.

The age of the magmatic arc and contemporaneous, associated sediments also seems to be important, as most occurrences of this association are of Late Palaeozoic to Mesozoic age. One possible explanation for this may be the advent of land plants in the Devonian. On erosion this vegetal matter could be concentrated locally within the sediments and play an important role in the mineralisation by creating a reducing environment. However, this does not preclude the possibility of finding significant Proterozoic uranium deposits of this type.

Within this broad tectonic environment, intermontane basins bordered by highlands of Precambrian or younger basement granites are also favourable areas. They normally contain thick fillings of Palaeozoic, Mesozoic and Cenozoic fluviatile sediments intercalated with tuffaceous layers. Ideally, the basins should be closed or partially closed with a limited drainage system, to prevent excessive oxidation of the sediments and to maintain a reducing environment in the zone of

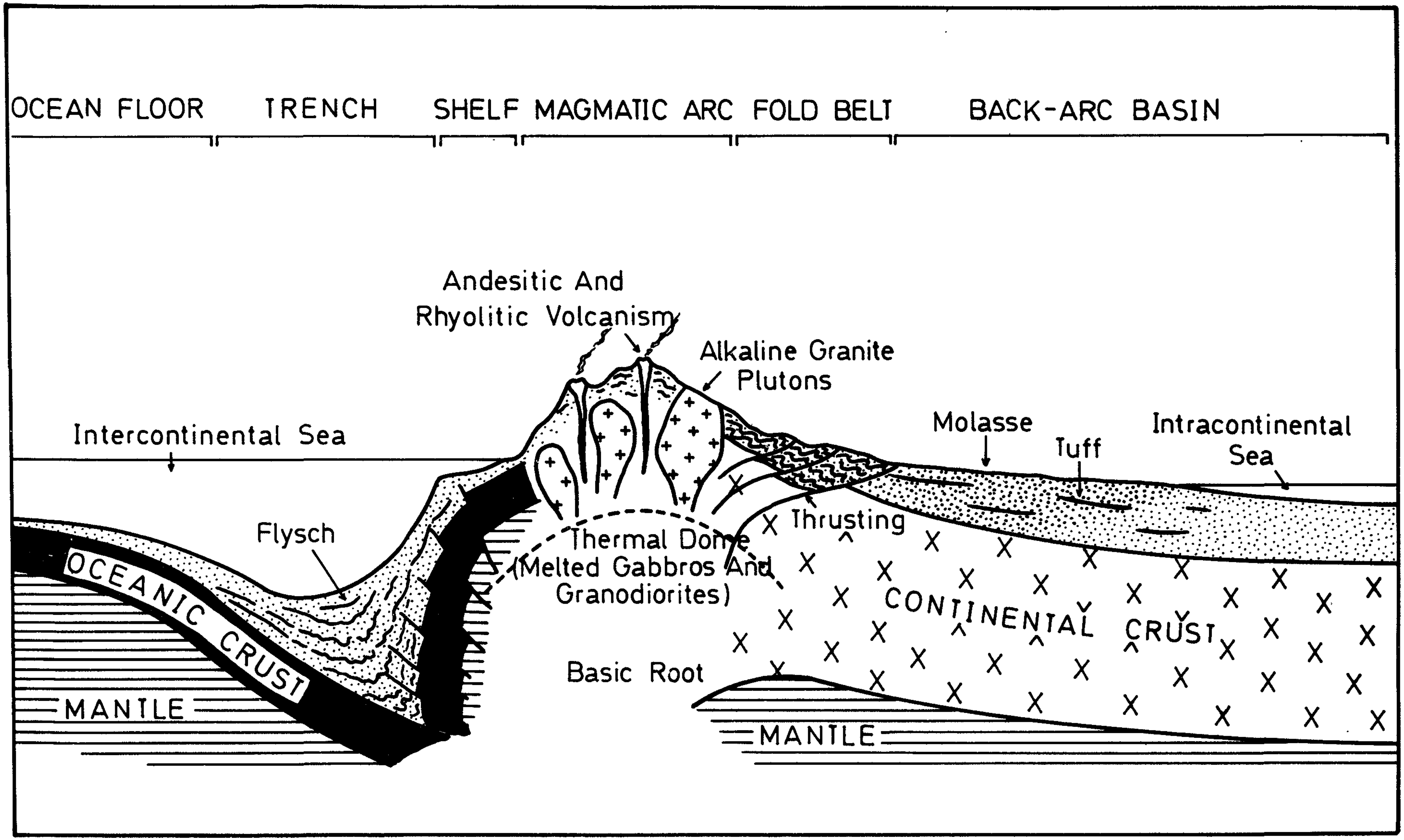

Fig. 1
Simplified model of Cordilleran-type mountain belt and back-arc basin

connate water [6]. The present-day rainfall should preferably be low to prevent further remobilisation of the uranium, as near-surface oxidation is normally a dispersive process, especially if the recycling is not in a preferred direction owing to local or regional geological factors (1).

Major sandstone uranium deposits seem to be concentrated near basin rims in the transition zone between basin and uplift, possibly because of facies changes from high- to low-velocity current deposits. Uranium is thus found mainly in the sandy sediments of the midfan facies, rather than in the conglomerate or silts of the proximal and distal facies respectively [6].

Apart from the source areas and tectonic settings discussed above, sedimentary basins surrounded by other potentially uranium-bearing source rocks can also be considered favourable. The latter include organic-rich black shales and regionally metamorphosed basement rocks, especially of the greenschist-amphibolite grade [7].

REGIONAL STRUCTURAL CONTROLS

Tectonic structures can affect the formation and localisation of uranium ore-bodies in several ways. Uraniferous districts are commonly located in belts around contemporaneous intrusive centres, uplifted arches or in grabens [8]. This may be due to the control of contemporaneous tectonics over sedimentation patterns and also to the effect of the resultant structures on groundwater migration. The trends of palaeochannels will be down the general palaeoslope of the basin, but the latter may have been interrupted locally by contemporaneous folding or igneous intrusions, diverting the courses of the palaeorivers. In the southern parts of the Karoo basin it appears as if southward-dipping monoclines and shallow synclines may have affected the trends of Permian river systems.

Post-depositional folding may have resulted in dips perpendicular to the elongation of sand bodies, which may have led to the concentration of groundwater flow along the downdip edge of the palaeochannel. In these zones the rate of flow is retarded by interfingering sands and muds, so that conditions ideal for the chemical reaction of uranium with reducing agents are created. Ore-bodies should therefore be found along this edge of the palaeochannel [1] (Fig. 2).

A similar situation may occur where the strata had a relatively high dip, so that migration of groundwater down the hydraulic slope was stratigraphically upward. Leaching of uraniferous strata or even pre-existing ore-bodies lower down may have resulted in the concentration of new ore-bodies along the basal contact of the first thick, impermeable horizon upward in the succession [9] (Fig. 3).

Fracture and fault systems may have been either positive or negative factors in the localisation of sandstone-hosted uranium deposits. Where these systems were highly permeable, groundwater flow could be either diverted away from some deposits, protecting them against leaching, or concentrated through others until only ghosts of the former ore-bodies remained. In some areas the uranium ore-bodies are seldom very far from fault zones and are commonly stacked up at different horizons along a fault. In this case the mineralisation was related to the introduction of solutions along the latter [7]. The presence of reductants, such as hydrocarbons escaping along the fracture from oil-bearing strata below, may also have been important. In other cases the fault zones may have been cemented, forming a barrier to fluid flow,

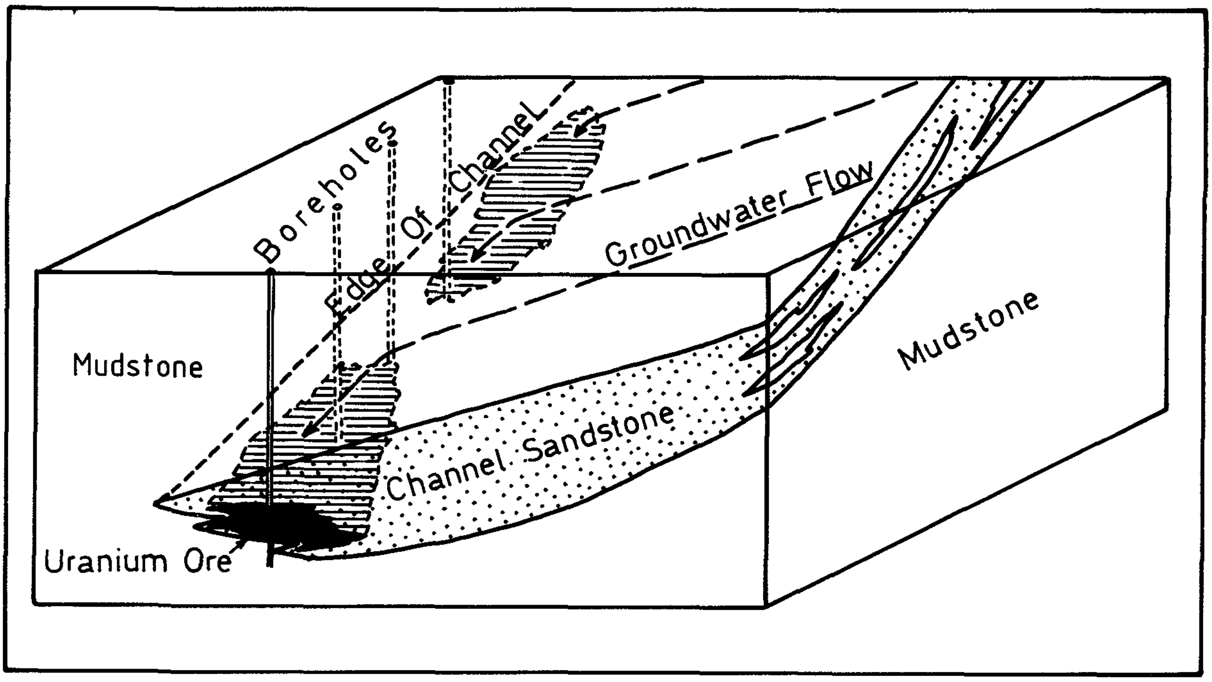

Fig. 2
Mineralisation related to groundwater flow along edge of channel in tilted strata

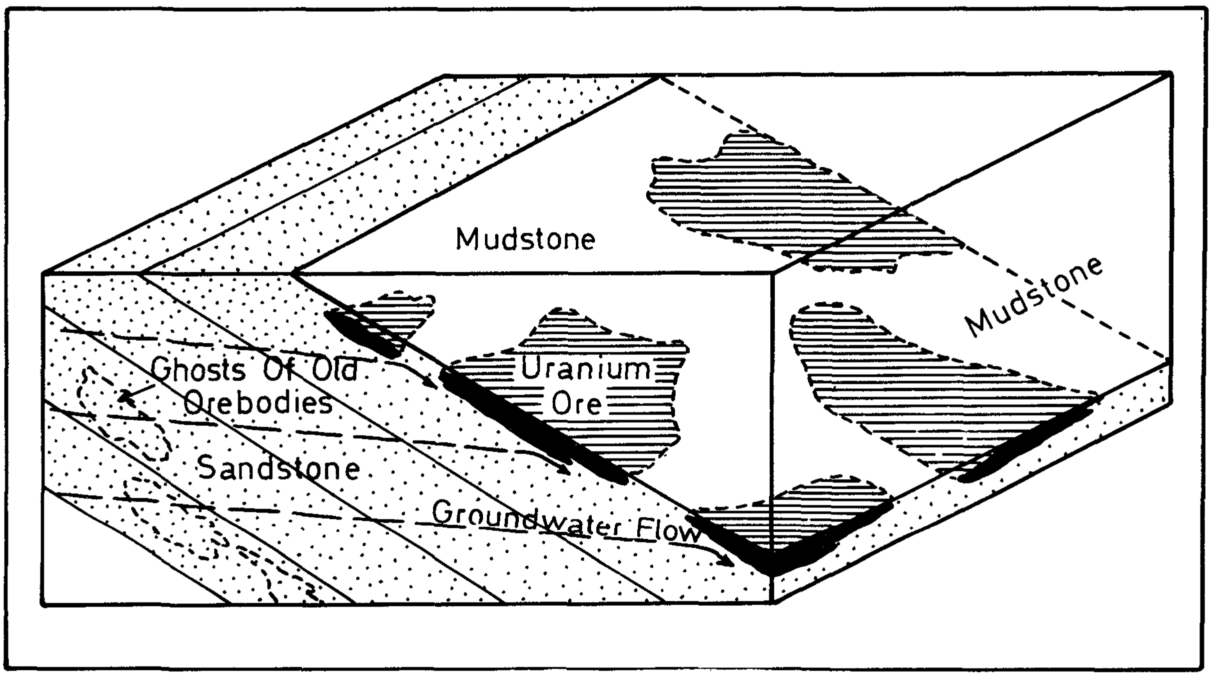

Fig. 3
Mineralisation related to groundwater flow along base of impermeable zone in tilted strata

or may have contained oxides or clay minerals capable of adsorbing uranium from solutions permeating the breccia. Regional fault systems in sandstone-hosted uranium provinces should therefore be identified on aerial photographs and examined in the field to determine their possible effect on groundwater migration. Similarly, regional unconformities could also have provided permeability systems along which uraniferous solutions entered suitable host sandstones, being especially important where they also formed traps for oil or gas.

STRATIGRAPHIC CONTROLS

Stratigraphic zoning often reflects the response of sedimentary patterns to tectonic events in the source areas, and can be used to identify or predict favourable depositional environments. Uplift and subsequent denudation of the source area will be expressed in the depositional basin by an upward-fining megacycle, commonly starting with braided river deposits grading upwards into meandering river sandstones and finally flood basin or lacustrine mudstones. Less pronounced uplift may have resulted in the megacyle starting with high-sinuosity river deposits at the base, which may constitute a less favourable zone for finding significant uranium deposits. In the Beaufort Group at least 5 megacycles have been identified, reflecting tectonic pulses gradually diminishing in intensity with time, so that the uppermost cycles are virtually devoid of uranium because of unfavourable facies. Midfan to distal braided river systems appear to host the majority of uranium deposits in the Karoo, as seems to be the case in the United States. According to Davis [10], 90 % of the uranium here occurs in fluvial sandstones of braided river origin on ancient alluvial fans.

As there is also a lateral variation in sedimentary environments with increasing distance from the source area, lateral facies changes will occur within a single chronostratigraphic unit, and this aspect should be investigated before eliminating certain stratigraphic zones as less favourable. In general, the megacycles will be most complete in the median or midfan zones of the basin, so that these regions should be examined first where possible (Fig. 4).

Favourable stratigraphic zones are generally at least 6 - 100 m thick, those with the largest volume of sandstone usually hosting the biggest ore deposits [6]. In areas of high present-day rainfall an impermeable cap rock is an added positive factor to protect the sandstone from excessive leaching.

Finally, palaeochannels commonly seem to have inherited the palaeodrainage pattern of underlying older channels, even though they were separated by thick mudstone intervals (Fig. 5). This is probably the result of subsidence of the thick channel sands into the subjacent muds, forming slight depressions on surface which were capable of diverting the courses of younger streams. This relationship may explain the vertical superposition of uranium ore-bodies as often encountered in boreholes.

SEDIMENTOLOGICAL ENVIRONMENTS

The role played by sedimentological environments in controlling the location, size, shape and grade of sandstone-hosted uranium deposits cannot be overemphasised. All the main factors affecting the formation of this type of ore-body are influenced by sedimentological processes. These factors include:

1) permeability
2) facies relationships
3) the presence of reductants and/or adsorptive compounds

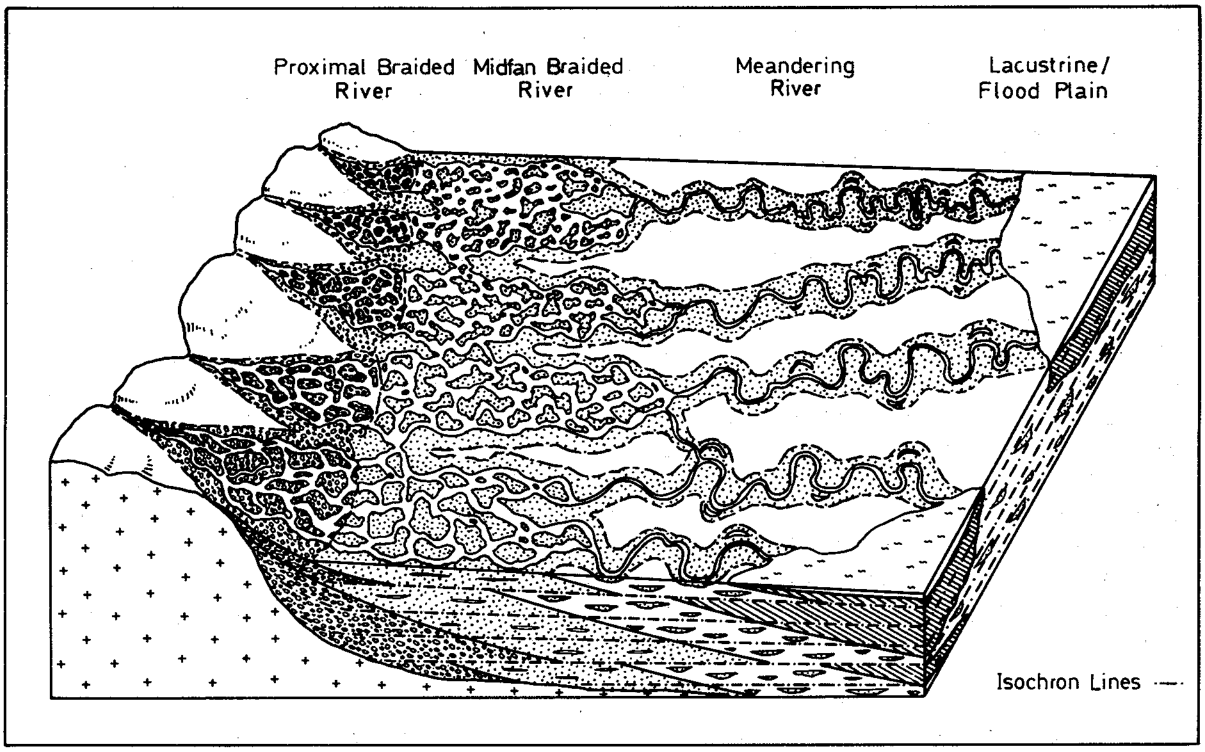

Fig. 4
Lateral and vertical relationships of source area and depositional environments

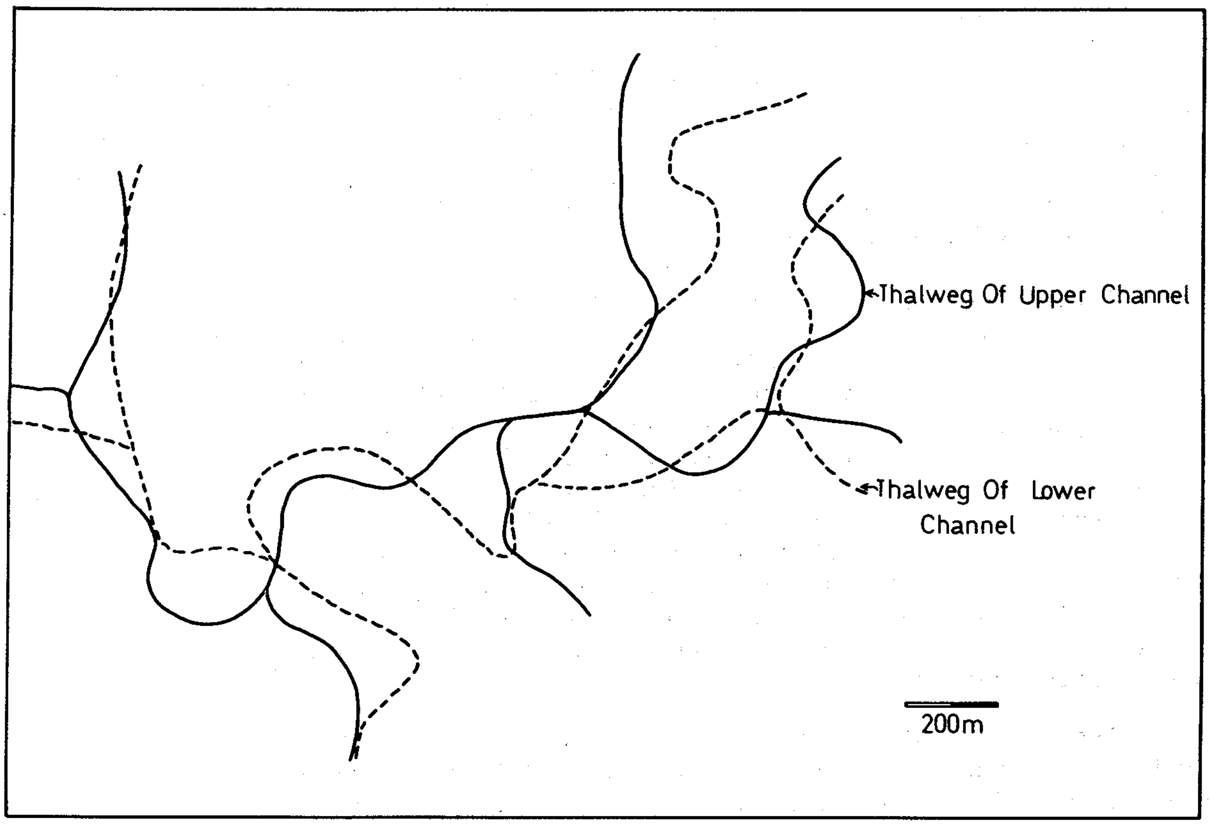

Fig. 5
Superimposed thalwegs of inherited channels in the South African Karoo

The permeability of sandstone lithosomes determines the extent and rate of migration of uraniferous solutions. Conditions favouring the entry of uranium-bearing solutions into the host sediments are necessary for the formation of a mineable deposit, but so are conditions preventing the exit of uranium from the host. The latter should therefore be neither too permeable, for then uranium will be leached out, nor too impermeable, in which case uranium will not be able to enter. In general, roll-type uranium deposits require better permeability than peneconcordant deposits.

The original permeability of a sandstone depended mainly on three factors, namely its texture, sedimentary structures and the presence of intraformational diastems. Secondary factors such as jointing, brecciation or cementation would also affect its properties as an aquifer. There is enough evidence to relate the primary permeability of a sandstone to sedimentation processes. The longer dimensions of sand grains align themselves parallel to current flow so that a good horizontal permeability in the palaeocurrent direction results [1]. Grain size is also influenced by current velocities, so that the basal parts of mesocycles in fluvial deposits are generally texturally more permeable than the fine-grained upper parts.

Sedimentary structures are equally important. Horizontal, commonly fissile-weathering bedding deposited in upper flow regime conditions normally constitute more permeable zones than cross-bedded cosets. Ripple lamination, on the other hand, generally developed in the finer-grained facies and can act as barriers to fluid flow [1]. Texture and bed-forms therefore combine to form permeable zones near the base of mesocyles which are deposited in upper flow regime conditions. These zones also contain most of the uranium deposits in the majority of sandstones in the Karoo. Intraformational diastems or erosion surfaces, resulting from channel avulsion and repossession, become more important for uranium mineralisation in well-cemented or very fine-grained sandstones, as they provide narrow passageways for fluid migration. They are normally overlain by either mudstone lenses, deposited in abandoned channels, or by upper flow regime deposits, such as mud-clast conglomerates or horizontally bedded sandstone. Again, these factors combine to create permeable zones at the base of mesocycles.

Interfingering facies relationships seem to have been a favourable factor for the localisation of ore deposits in many localities, by inhibiting the rate of groundwater flow so that mineralisation could take place [8]. This often resulted in mineralisation along the serrated, interfingering edges of channel sandstones and along intraformational diastems where fine-grained sediments abut against coarser-grained facies. An alternative explanation may be found in the adsorbing and ion-exchange properties of clay minerals within the mudstone, which could extract uranium from solutions migrating along the interface contacts. In many cases, however, ore pods show no relationship with areas characterised by an increase in vertical facies variation and are concentrated instead within channel zones, which commonly exhibit the least facies variation.

The importance of organic reductants and adsorptive compounds in epigenetic mineralisation has been stressed by many researchers, and they are indeed the chief agents of uranium concentration in sandstones. Carbonaceous material normally occurs as thin coatings or trash pockets on bedding planes and discontinuity surfaces or in disseminated form within the rock. This distribution is clearly controlled by sedimentological factors. During flood periods in a fluvial environment, vegetation growing on levees and elsewhere along river courses were swept along and deposited within the upper flow regime facies of the resultant mesocyle [11]. Where flood periods rapidly succeeded each other, the vegetation would have had little time to re-establish itself, with the result that subsequent mesocycles may contain little carbonaceous material. Plant remains seem to have accumulated in those areas where there was a sudden slow-down in current velocities, such as the inside of meanders or in the confluence areas of individual channels in braided rivers. Figure 6 shows a reconstructed braided river system in the Karoo, with the uranium ore-bodies located within the channel areas where there was a convergence of palaeoflow systems.

Proximal braided rivers normally have little carbonaceous matter, possibly because of too high current velocities which only resulted in the deposition of scattered tree trunks or larger pieces of flotsam. In beach deposits most of the carbonaceous content was winnowed out by wave action. Uranium deposits in these environments usually owe their existence to permeating sour gas from underlying oil reservoirs or other reductants. On the other end of the scale, low-energy swamp environments, characterised by carbonaceous shale deposits, are usually barren of uranium because of their relative impermeability to migrating uranium solutions [9].

In the Ambrosia Lake District of New Mexico, blanket-type uranium occurrences were deposited by viscous plant-derived oils called humates. The origin, transport and localisation of these humates are still not fully understood, but possible sources include paludal sediments in the vicinity of the ore deposits, decaying plant matter along the depositing river banks, plant debris within the host sandstones, and organic matter expelled by compaction from the lacustrine mudstone into the sandstone [12]. The humates formed undulating, tabular sheets which transect the local dip of the sandstone beds. They may have been derived by precipitation of humic or fulvic acids at the interface between two solutions, one containing the dissolved humic materials and another in which these substances were insoluble [13]. This interface may well have been palaeogroundwater tables [7, 14]. The uranium was possibly deposited simultaneously with the humates or subsequently by adsorption and reduction [9].

Having considered the factors affecting the general favourability of sandstones as uranium hosts, a short summary of potentially favourable depositional environments is necessary. Each environment produces a diagnostic arrangement of sand body geometry, sedimentary structures and textures, which govern the permeability and localisation of reductants within the lithosome. Arranged in order of decreasing favourability, the following depositional environments have been found to contain uranium deposits [7, 8]:

1) alluvial
2) lacustrine
3) paludal
4) marginal marine (lagoonal, littoral, shallow marine)
5) aeolian

Examples of uranium deposits in the alluvial environment include those of the Uravan Belt in Colorado and the Karoo deposits of South Africa. Uranium normally occurs in the midfan or distal facies of alluvial fans, where there is a facies change from coarse to medium or fine grain sizes. Braided stream channels appear to be more favourable

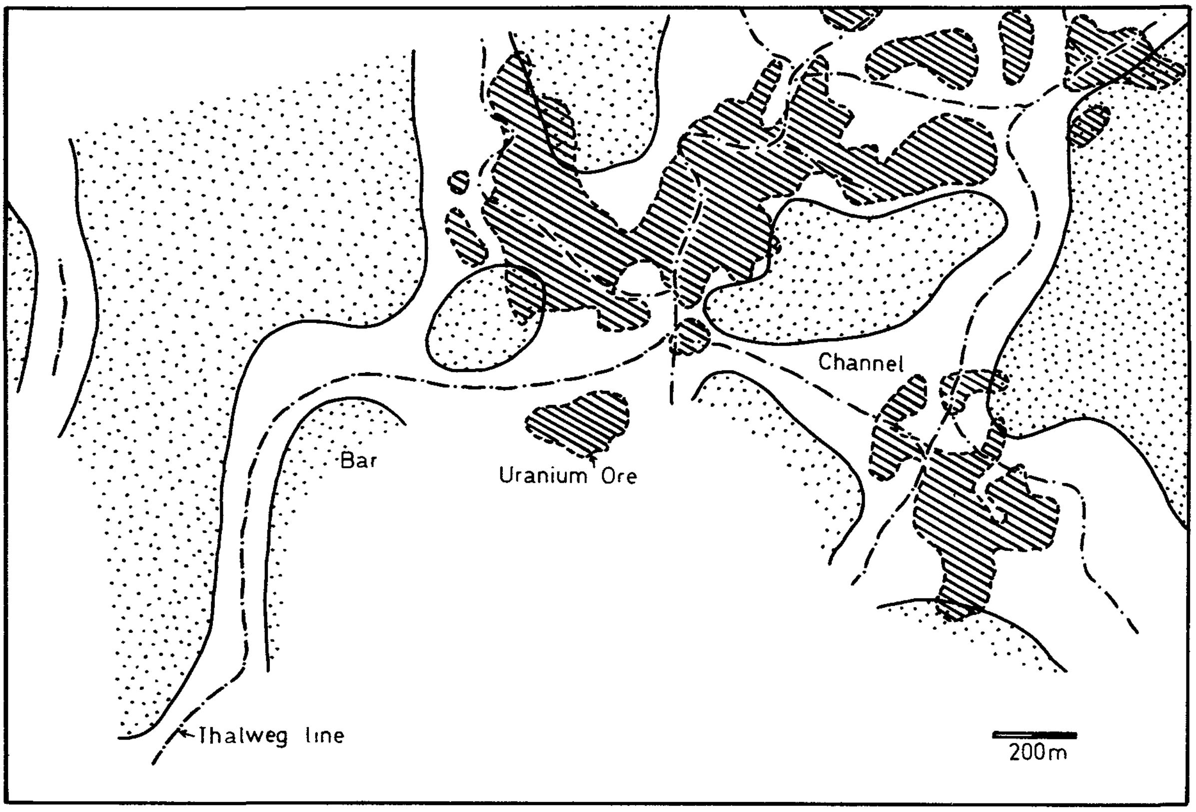

Fig. 6
Location of orebody in braided river system, South African Karoo

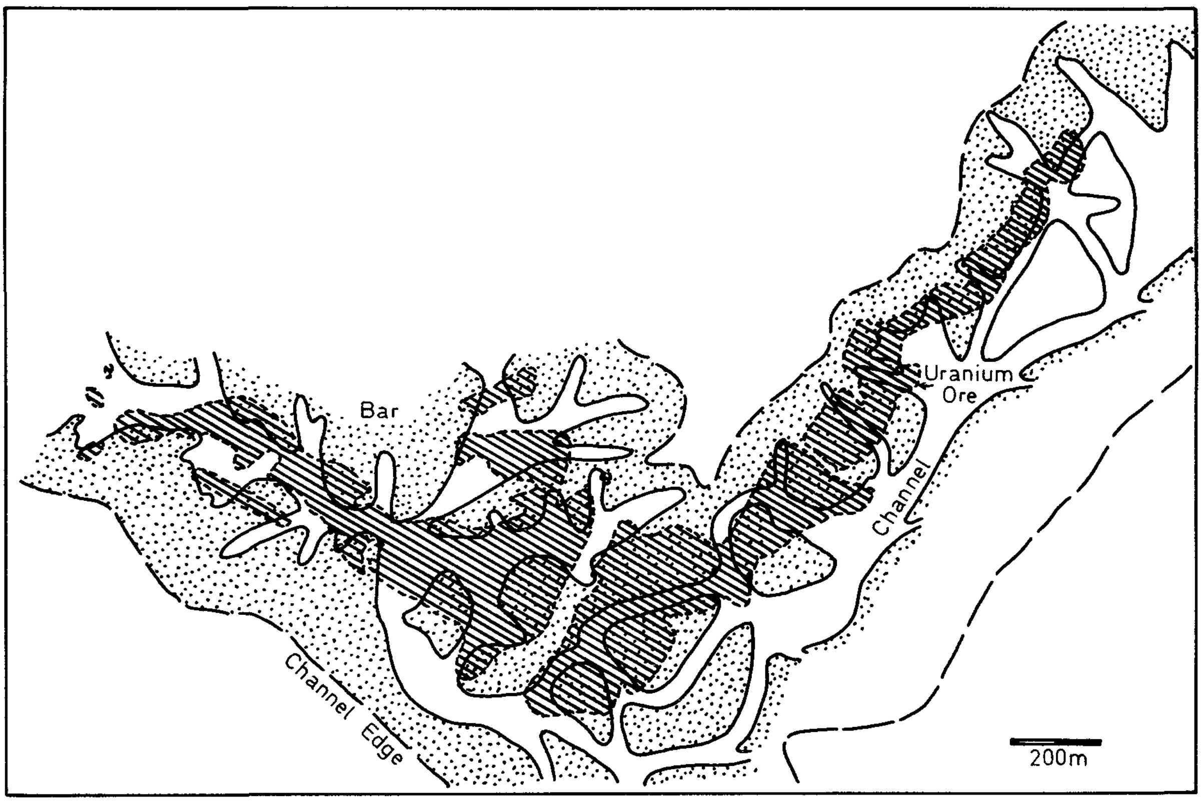

Fig. 7
Location of orebody in lacustrine delta, South African Karoo

in some areas than meandering river deposits, possibly because of the greater volume of sandstone involved. They normally form thick, tabular sands which may or may not display upward-fining mesocycles, and bed-forms deposited in upper flow regime conditions dominate over lower flow regime facies. This probably lends a greater permeability to these sandstones than is the case with high-sinuosity river deposits. The most favourable locales for uranium mineralisation in the braided river deposits of the Karoo were within the deepest parts of palaeochannels (Fig. 6), but embayments in the channel banks, the outside bank areas of channel bends and in the areas lateral to channels where the sandstones intertongue with levee, crevasse splay or flood basin mudstone deposits, were also important in other areas [15]. Point bar sands may be preferably mineralised in some regions. The favourability of these sub-environments appears to have varied from place to place, so that no hard-and-fast rules can be applied. Intraformational diastems and their associated channel-fill mudstone lenses, channel lag conglomerates containing carbonised tree fragments, and sedimentary structures of high velocity currents were usually favourable because of their high permeability and vegetal matter content.

Fluvio-lacustrine uranium-bearing sediments occur in the Chinle Formation of the San Rafael Swell in Utah [16] and in the Karoo basin [17]. In the latter case, the ore-body is located within the distributary channels and along subaerial or subaqueous levees of a lacustrine delta (Fig. 7). Here localised environments existed where organic material accumulated as algal mats and plant remains under reducing conditions, which acted as collectors of uranium from solution. This is supported by the observation of algal structures in coal accumulations and a linear relationship between phosphorus, uranium and organic carbon in the sediments.

In South Texas, paludal and lagoonal sediments are intercalated with fluvial channel, strand-plain and barrier-bar sandstones, providing aquifer restrictions which partly controlled uranium mineralisation in these sediments [7, 8].

An example of marginal marine strata which contains commercial uranium deposits, is the Jackson Group of the Gulf Coastal Plain in Texas. The uranium has here favoured the shoreward lagoonal sandstone [8].

Finally, in the aeolian sandstones of the Entrada Formation, uranium is believed to have been localised by some chemically favourable feature of the cement, or by the interface between a widespread reducing environment in a deep sandstone and an oxidising migrating fluid [8].

In conclusion, it may be stated that virtually any sandstone and a whole range of sedimentological environments can be hosts for uranium ore deposits, but that the following factors, especially in combination, are positive points in determining the favourability of any particular region:

1) Tectonic setting: back-arc basin adjacent to calc-alkaline magmatic arc
2) Age: post-Silurian
3) Sedimentological environment: fluvial or fluvio-lacustrine
4) Facies: midfan to distal braided river
5) Sandstone texture: medium to fine, permeable
6) Other characteristics: abundant plant material or other reductants/adsorptive compounds, intraformational diastems

There are of course many other factors that may control the localisation of uranium ore deposits, and the same principles may not be applicable to different sedimentary basins. However, continued research and comparison of different sandstone-hosted uranium provinces should gradually reveal the fundamental principles that controlled mineralisation in this type of environment, and may ultimately lead to improved exploration efficiency based on these genetic models.

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URANIUM OCCURRENCES AT AL AWAYNAT, SERDLES, LIBYA

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Since 1973, several uraniferous occurrences have been discovered along the western flank of Murzuk Basin, southwest Libya. These occurrences of uranium mineralization are found in sediments of Zarzaitine Formation of Permo-Triassic age. These sediments consist of siltstone, claystone, fine- to coarse-grained sandstone with minor microconglomerate interbeds deposited mostly in a continental environment. The Zarzaitine Formation disconformably overlies the shallow marine sediments of the Tiguentourine Formation of Late Carboniferous to Early Permian age and is unconformably overlain by the Taouratine Formation of Jurassic age.

The uranium mineralization occurs in two sandstone levels over a strike length of about 100 km extending north-south. The first level is exposed to the ground surface or close to it. Within this level, the uranium mineralization is associated with gray sandstone in the form of small disconnected bodies of 0.5 - 1 m thick having uranium contents varying between 37 and 5,000 ppm. These sandstone bodies commonly contain petrified wood logs and carbonaceous vegetal matter. Beta-uranophane, carnotite and tyuyamunite are the main uranium minerals identified in this mineralized level.

The second mineralized level occurs at a depth of 30-60 meters in a sequence of gray, medium- to coarse-grained sandstone confined between two impermeable siltstone beds. This level is characterized by the presence of coalified organic matter and pyrite. Uranium mineralization within this level occurs as small bodies, 1-2 m thick having uranium contents varying between 30 and 323 ppm with the higher concentration being recorded southward. No distinct uranium minerals have been identified in this level.

The Hoggar massif appears to be the most acceptable source for both the host rocks and the enclosing uranium mineralization.

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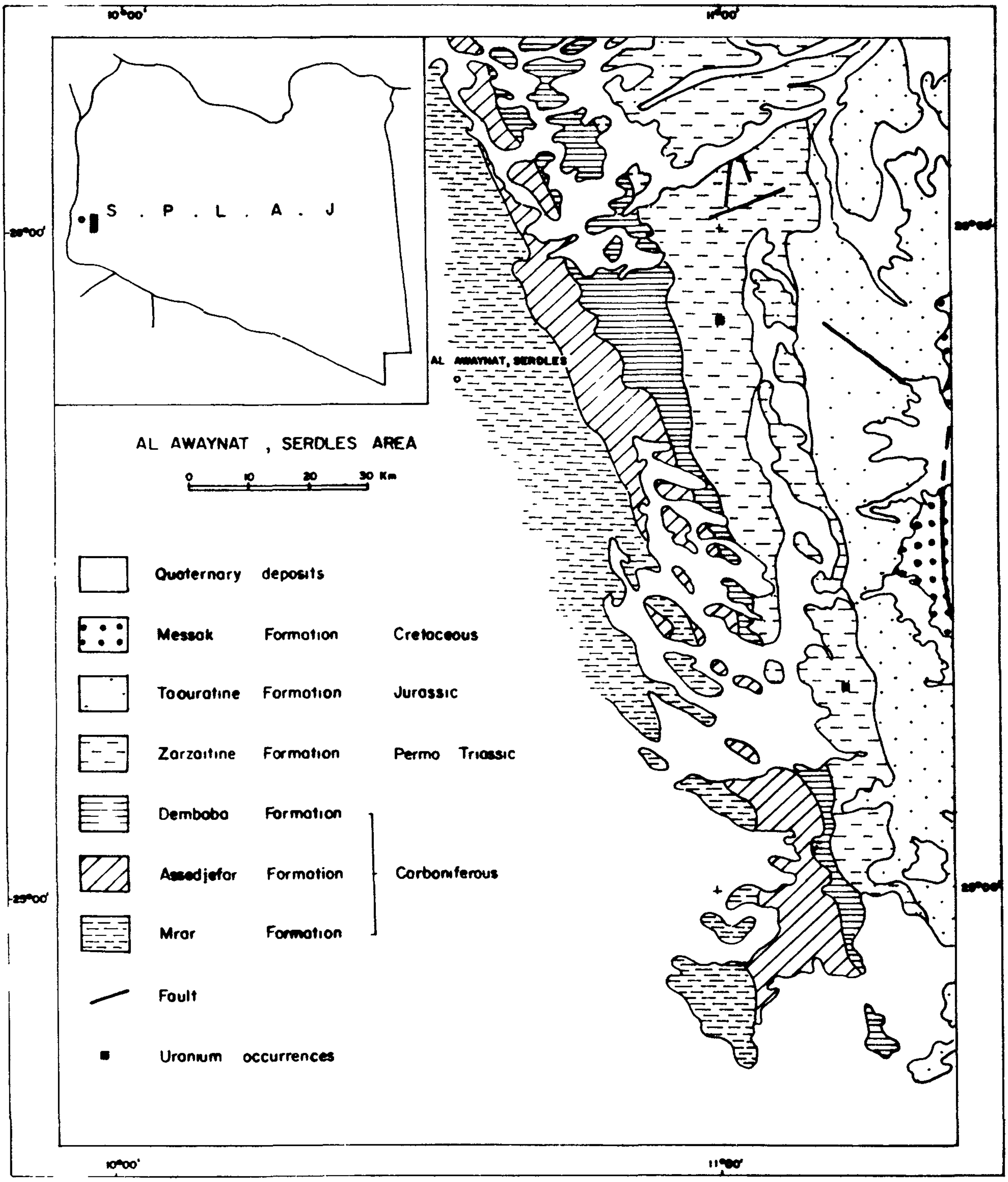
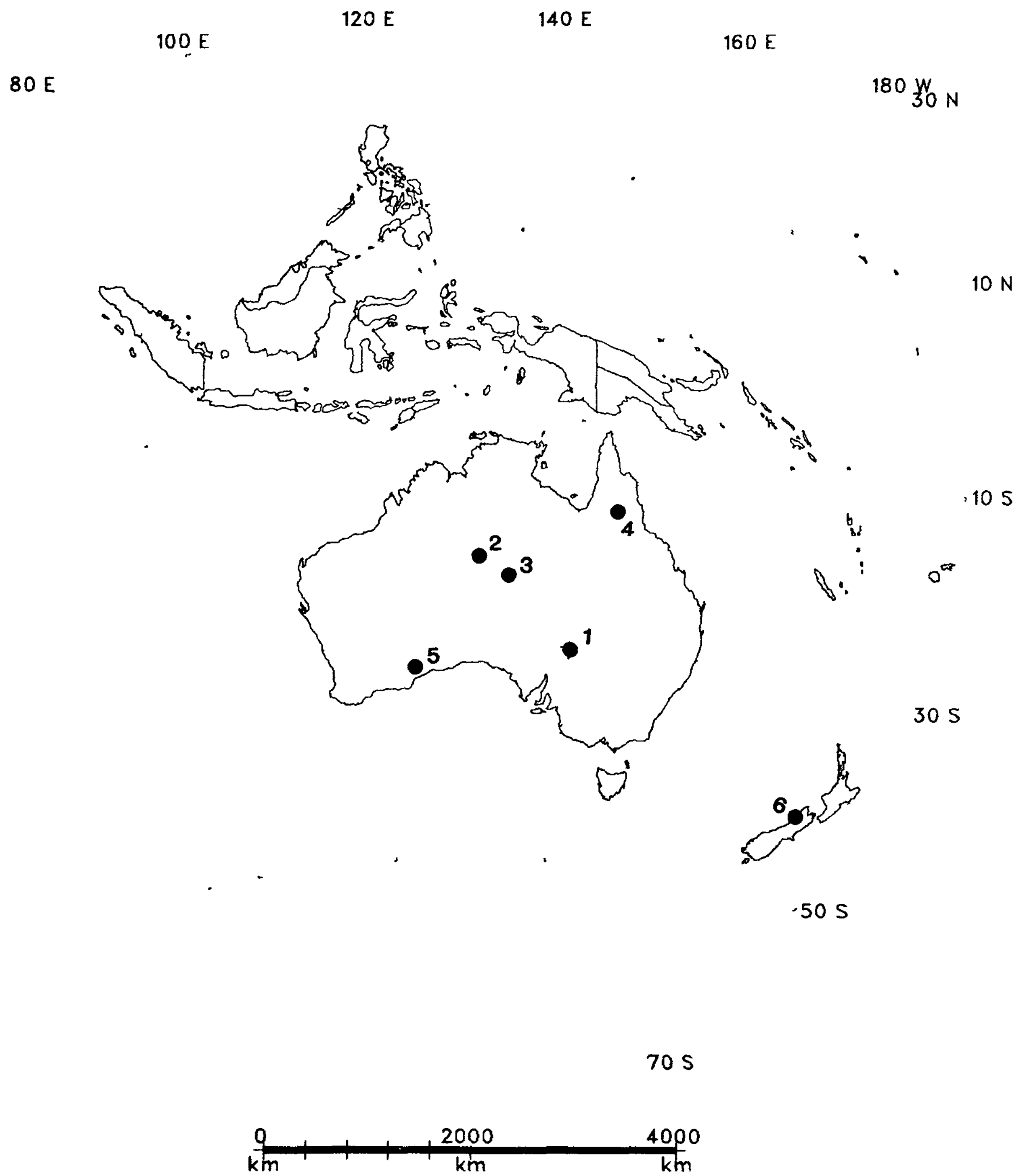


Location map of Al Awaynat, Serdles area

AUSTRALIA AND NEW ZEALAND

MAP AND INDEX LIST FOR SANDSTONE-TYPE URANIUM DEPOSITS IN AUSTRALIA AND NEW ZEALAND



AUSTRALIA AND NEW ZEALAND

Australia:

1. Beverley and other deposits, Frome Embayment, South Australia, Tertiary sandstone
2. Bigryli deposit, Ngalia Basin, Northern Territory, Carboniferous Mt. Eclipis sandstone
3. Angela deposit, Amadeous Basin, Northern Territory, Carboniferous sandstone
4. Maureen, Queensland, Permo-Carboniferous sandstone and siltstone
5. Victorian Desert, Western Australia, Tertiary sediments (approximate location)

New Zealand:

6. Lower Buller Gorge, South New Zealand, Cretaceous Hawks Crag

ORIGIN OF SANDSTONE-HOSTED URANIUM DEPOSITS, FROME EMBAYMENT, SOUTH AUSTRALIA

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Abstract

The formation of sandstone-hosted uranium deposits in the Frome Embayment of South Australia is largely a result of tectonic events possibly as old as the Archean. Uranium deposits of several types and ages in the region demonstrate the importance of uranium enrichment in the source area. Mobile zones around the Archean terrane of the Gawler block have been the locus of intermittent tectonic activity from Early Proterozoic to recent time. Vein-type uranium deposits in basement source rocks are concentrated in these zones, because they favor deep crustal partial melting and ascent of Na-rich granitic magmas and hydrothermal solutions. Relatively stable areas bordered by mobile zones, are important for the formation of sandstone-hosted uranium deposits because they act as platforms for terrigenous sedimentation from the surrounding, uplifted, uranium-rich basement rocks. Wet, subtropical conditions prevailing at the time of uplift aided rapid erosion and subaerial deposition of channel sands with intermixed organic detritus. Later uplift accompanied by erosion of the recently deposited sands in the headwater area caused increased recharge of oxygenated uraniferous ground water, which led to the formation of geochemical-cell roll-front type deposits like those in the Wyoming basins. Subsequent arid conditions helped preserve the deposits.

1. INTRODUCTION

Sandstone-hosted uranium deposits in the Lake Frome area of South Australia occur in a province having numerous uranium occurrences. Half the problem of explaining the sandstone-hosted uranium deposits is understanding the widespread uranium enrichment in the area as a whole. For this reason a large portion of this paper is devoted to the major tectonic events that have played a role in preparing a uranium-rich source terrane. The other half of the problem is the localization of uranium in geologic formations. This paper also describes the main sandstone uranium deposits in the Frome Embayment and their enclosing Tertiary sediments. These deposits are Beverley, Curnamona, Honeymoon, East Kalkaroo, and Yarramba. They are roll-type deposits that resemble those of Wyoming, U.S.A. I have taken generally accepted interpretations of the regional geology from the published literature and related these to the formation of the uranium deposits. Ages of geological time periods are from Palmer (1983).

Figure 1 shows the major tectonic elements in South Australia (Geological Society of Australia, 1971). The Frome Embayment is a physiographic unit that is a lobe of the Eromanga Basin and of the vast Great Artesian Basin of central Australia. Modern highlands bordering the embayment on the west, south and east are the Flinders, Olary, and Barrier Ranges, respectively. Geologically, the west, south and southeast margins of the embayment are bordered by Early and Middle Proterozoic metamorphic and igneous rocks of the Mt. Painter, Olary, and Broken Hill blocks and by Middle to Late Proterozoic metasediments of the Adelaide Geosyncline. The three Early Proterozoic blocks are collectively called the Willyama domain because of their similar lithologic and tectonic history (Glen et al, 1977; Rutland et al, 1981). The Willyama domain resembles and was part of the stable cratonic Gawler block of Archean to Proterozoic age. It is separated from the Gawler block by a belt of Middle to Late Proterozoic and Cambrian metasediments of the Adelaide Geosyncline and Arrowie Basin. Thin, less deformed Adelaidean sedimentary rocks also lap onto the Gawler block in the area known as the Stuart Shelf.

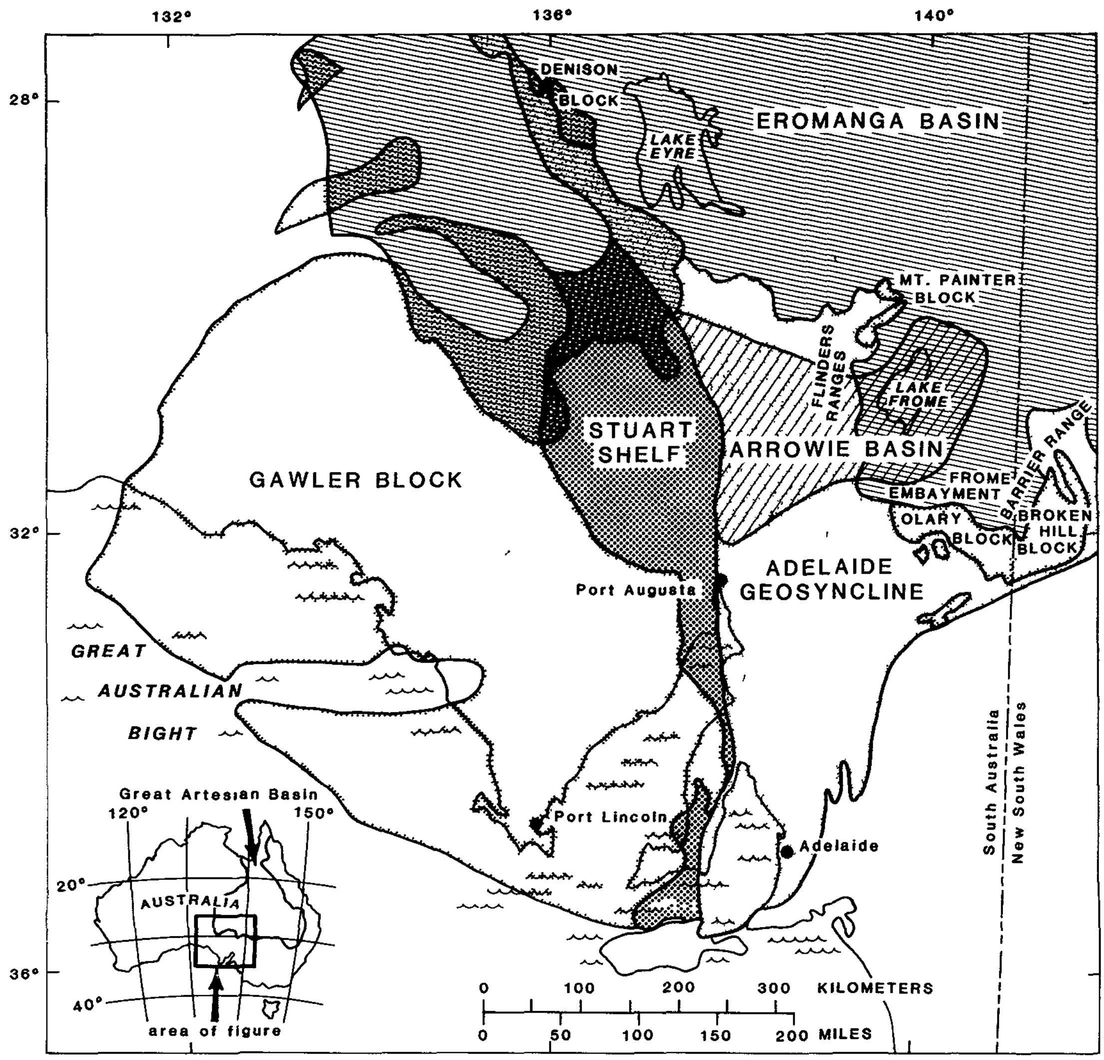

Figure 1. Tectonic and physiographic map of a part of South Australia including the Frome area. Based on the Tectonic Map of Australia and New Guinea (Geological Society of Australia, 1971).

The Lake Frome area has been part of several tectonic elements that have been active at different times. During Middle to Late Proterozoic time, the area was at the eastern margin of the Adelaide Geosyncline (Thompson, 1965, 1970; Parkin et al, 1969; Rutland et al, 1981). The Curnamona Cratonic Nucleus (Plumb, 1979; Rutland et al, 1981) or Willyama Nucleus (Freeman, 1966), corresponding in area to the Frome Embayment, was then a relatively stable block bordered by subsiding depositional belts and orogenic zones. Cambrian deposition was dominant in the Arrowie Basin centered west of Lake Frome in the area of the present Flinders Ranges (Daily, 1956, 1976; Dalgarno and Johnson, 1968; Wopfner, 1970, 1972; Youngs and Moorcroft, 1982). During the Early Ordovician Delamerian Orogeny, the Curnamona Nucleus acted as a relatively stable block. The Great Artesian Basin and Frome Embayment formed in Cenozoic time. The Eromanga Basin, which formed during the Triassic and Jurassic (Wopfner, 1970; Plumb, 1979; Habermehl, 1980), roughly corresponds in area to the Great Artesian Basin in South Australia, and its southern margin extended into the Frome Embayment.

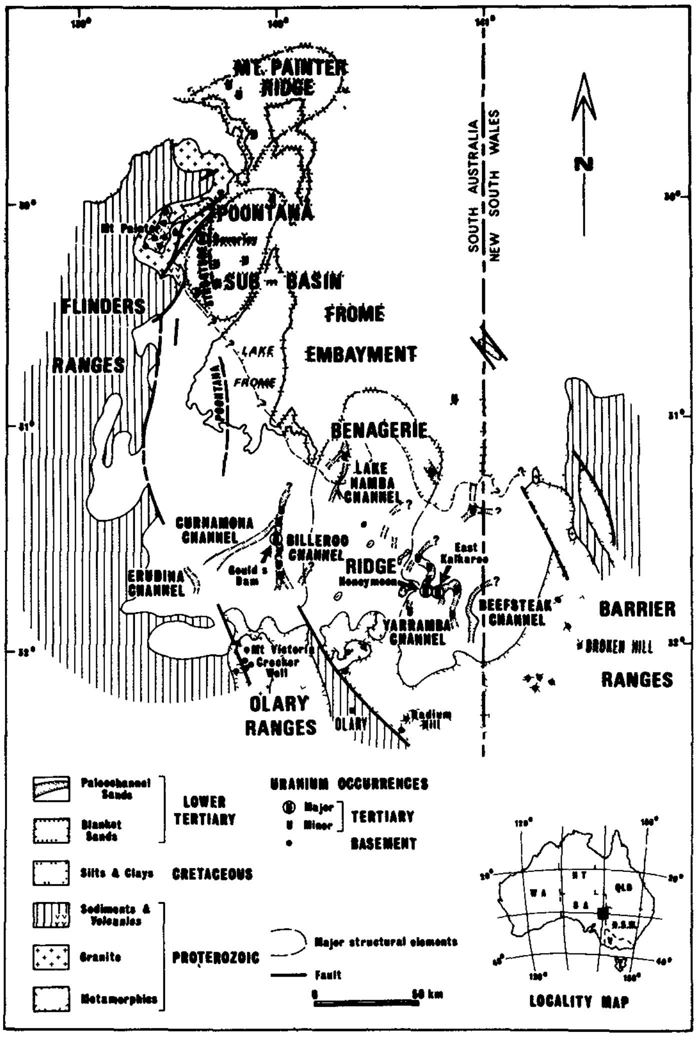

Figure 2. Geology and uranium occurances in the Frome Embayment and surrounding highlands. From Ellis (1980).

Uranium is widely distributed in the area around Lake Frome (Fig. 2; Ingram, 1974). It is associated with Middle Proterozoic adamellites and pegmatites in the Olary block (Dickinson et al, 1954; Campana and King, 1958; Blissett, 1975), with Middle to Late Proterozoic breccias and veins in the Mt. Painter block (Dickinson et al, 1954; Coats and Blissett, 1971, Youles, 1975), and with Tertiary fluvial channel sands in the Frome Embayment. The Goulds Dam, Honeymoon, East Kalkaroo, and Yarramba deposits are in Lower Tertiary channel sands in the southern part of the Frome Embayment (Brunt, 1978; Ellis, 1980) whereas the Beverley Deposit is in Upper Tertiary sands in the northwestern part of the embayment (Haynes, 1975; Callen, 1975b). Uranium is anomalously high in groundwater draining areas of basement rock around the embayment (Coats and Blissett, 1971; Johnson and Gow, 1975; Waterhouse and Beal, 1980).

2. STRATIGRAPHY AND TECTONIC HISTORY

2.1 Archean >2500 m.y.

The oldest rocks from the Gawler domain yield ages of 2600–2300 m.y. (Cooper et al, 1976; Webb and Thompson, 1977; Daly et al, 1978) for metamorphism and intrusion (Fig. 3).

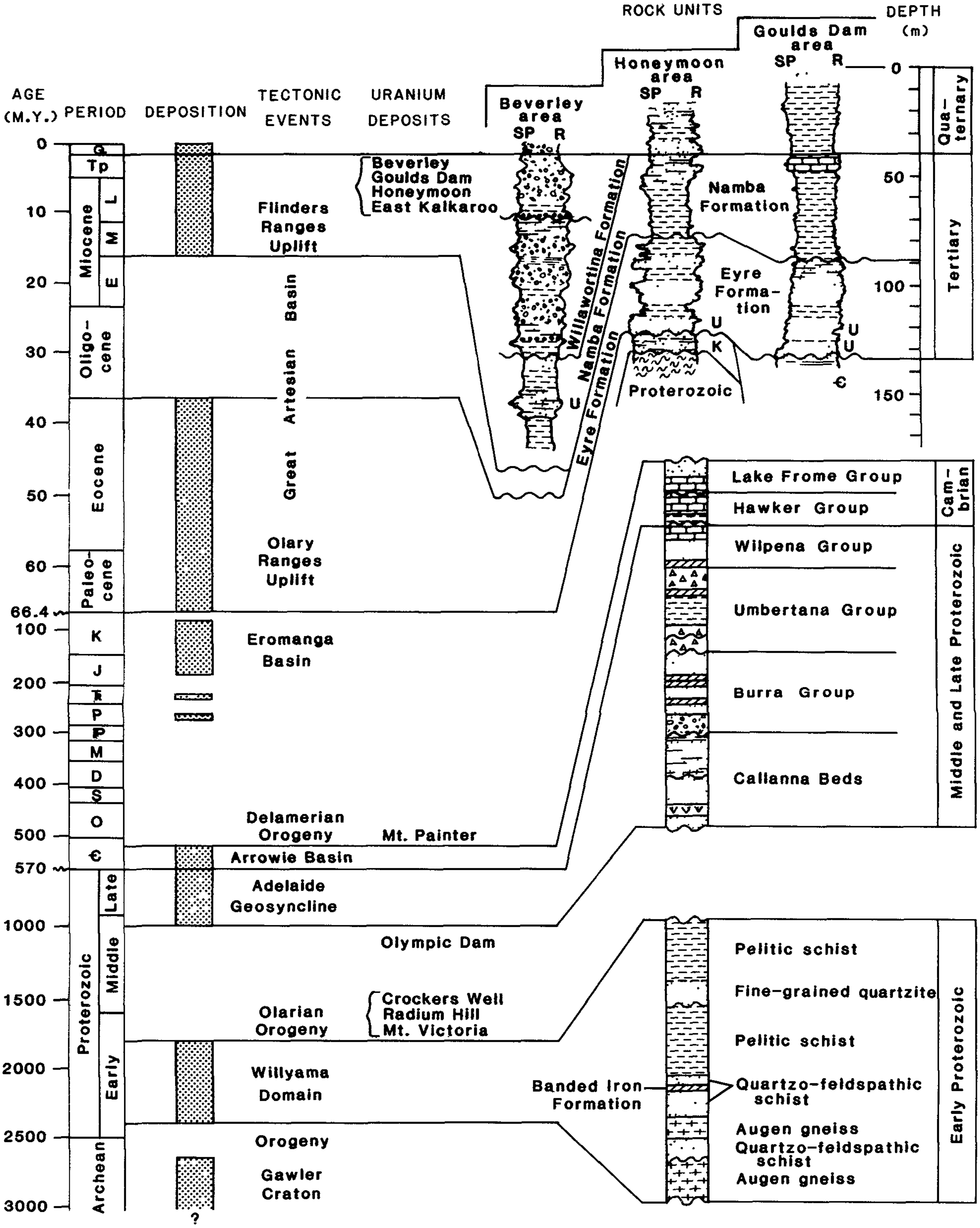

Figure 3. Summary of the geologic history of the Lake Frome region. Stratigraphic sections for the Early Proterozoic and the Middle Proterozoic to Cambrian are schematic. Tertiary sections from uranium-rich areas in the Frome Embayment are based on drill core logs of Callen (1975b), Callen and Tedford (1976), Brunt, (1978) and Ellis (1980). Ages of time periods are from Palmer (1983). U stands for uranium deposit.

Thus, the original sediments must be older. Although Archean ages have not been recorded for the Willyama domain, similarity with the Gawler domain suggests that it is also underlain by Archean basement (Thompson, 1970, 1975; Glen et al, 1977; Rutland et al, 1981).

2.2 Early Proterozoic 2500–1600 m.y.

Between about 2400 and 1800 m.y., sediments of the Willyama Domain were deposited (Rutland et al, 1981; Fig. 3). The Gawler domain and the Olary and Broken Hill sub-domains had basically similar Early Proterozoic depositional histories (Glen et al, 1977). Granitic augen gneiss underlies each sequence (Fig. 3). Overlying this possibly reworked basement are similar sequences of quartzite, metapelite, amphibolite, and banded iron formation (correlated with that of the Hammersley Group in northwest Australia). Calc-silicate rocks are more local. A link between the Mt. Painter and Olary blocks beneath the Frome Embayment is shown by Early Proterozoic felsic volcanics like those near Mt. Painter in a drill hole east of Lake Frome (Giles and Teale, 1979). Albite-rich layers in gneisses of the Olary sub-domain were important for later uranium localization. They may represent former felsic volcanic layers or evaporite deposits (Rutland, et al, 1981; Ashley, 1984).

2.3 Olarian Orogeny

Deposition of Early Proterozoic sediments was followed by a long period of deformation and metamorphism involving two major high-grade metamorphic events between 1800 and 1650 m.y. and a retrogressive event at about 1520 m.y. (Glen et al, 1977; Berry et al, 1978; Rutland et al, 1981). Widespread granitoids, including the Crocker Well adamellite or leuco-adamellite, host to the Crocker Well uranium deposits, were intruded at about 1580 m.y. (Ludwig and Cooper, in press). These events are collectively called the Olarian Orogeny (Glen et al, 1977), the Kimbian Orogeny (Parkin et al, 1969; Thompson, 1970, 1975; Thompson et al, 1976), or the Willyama Orogeny (Pidgeon, 1967; Shaw, 1968). The first metamorphic event is characterized by layer-parallel schistosity; the second metamorphic event produced tight folds having axial plane schistosity. Both deformations produced sillimanite-grade, granulite facies metamorphism at lower levels and lower grade metamorphism at higher levels. Migmatites and pegmatites are common especially in the Olary domain (Campana and King, 1958). Large scale recumbent folding suggests nappe structures, but only in the Willyama domain. The final event is characterized by shear zones, retrogressive metamorphism, and intrusion of late tectonic granites, including Rapikivi-type and porphyry (Coats and Blissett, 1971).

Glen et al (1977) suggest that the Olarian Orogeny represents compressional tectonics at an active continental margin, perhaps marked by a subduction zone. Early nappe structures, decreasing isotopic ages away from the cratons, shelf and basin facies, and metavolcanic rocks in the Broken Hill area suggest an active continental margin by analogy with tectonic zones such as the Penninic zone in the Alps (Glen et al, 1977). Conspicuously absent however are ophiolites or other possible fragments of oceanic crust.

Following the Olarian Orogeny, the Gawler and Willyama blocks diverged from their parallel paths. The Gawler block became a stable craton which occasionally received shallow water sediments and which was intruded by igneous bodies but which experienced no major orogenies for the rest of its history. In contrast, orogenic events in the Willyama domain continued with interruptions and changes in style into Early Ordovician time.

2.4 Middle and Late Proterozoic 1600–570

Following the Olarian Orogeny and a period of erosion, sedimentation resumed, this time in the long and relatively narrow Adelaide Geosyncline (Fig. 1). This event probably began between 1100 and 800 m.y. (Rutland et al, 1981). Sediments came from the west (Gawler block), north (Denison block), northeast (Mt. Painter block and Curnamona Nucleus), and east (Olary block) (Forbes and Coats, 1976). The rocks of the Adelaide geosyncline have been described by numerous authors including Glaessner and Parkin (1958), Campana and King (1958), Parkin et al (1969), Thompson (1970), Coats and Blissett (1971), Forbes and Coats (1976), Von der Borch (1980), and Rutland et al (1981).

The basal Callanna Beds (Fig. 3) consist of quartzite, carbonate, and mafic volcanic rocks, which represent fluvial to shallow marine deposition in restricted basins accompanied by tensional rifting (Rutland et al, 1981). A regional unconformity at the top of the Callanna Beds and their absence in the Olary region (Campana and King, 1958) suggest that the marginal areas of the Geosyncline, including the Mt. Painter and Olary blocks were uplifted and subjected to erosion before deposition of the overlying Burra Group. Burra Group sedimentation was similar to that of the Callanna Beds. Quartzites represent transgressions and regressions across a possible evolving continental shelf (Rutland et al, 1981). Arkosic rocks, deltaic features, primary dolomite and bedded magnesite suggest fluvial deposition into local evaporative basins (Rutland et al, 1981). In the Broken Hill area, sediments of this age are absent indicating either non-deposition or subsequent erosion.

The overlying Umbertana Group represents massive glacial and shallow marine sedimentation in a deepening basin. Whereas the Olary block had previously been a structural high, the Umbertana Group reaches 20,000 feet in thickness (Campana and King, 1958) in this area. Similarly its thickness is 18,000 feet in the Mt. Painter area (Coats and Blissett, 1971). Glacial striations and decrease in thickness of the Umbertana Group to the west and south suggest that the source area was to the northeast. The shallow marine conditions of the Umbertana Group were followed by the Wilpena Group representing an influx of clastics from the west.

Adelaidean sedimentation was marked by tensional tectonic activity. Two main episodes are recognized, an earlier period of relatively active rifting during deposition of the Callanna Beds and Burra Group, and a later period of quiet subsidence during deposition of the Umbertana and Wilpena Groups. The two episodes were separated by a very active rifting event during deposition of the glaciomarine Umbertana Group. During much of this time, shear zones developed in Early Proterozoic time were reactivated (Rutland et al, 1981), and sedimentary diapirs deformed the overlying sediments during deposition (Coats, 1965; Dalgarno and Johnson, 1968). Diapir trends are important markers of continued activity and structural weakness along ancient basement fault zones. These zones also favored igneous intrusion. Coats and Blissett (1971) consider that soda-granites intimately associated with diapirs were emplaced before the diapirs and are possibly the same age as the Callanna beds. Mafic dikes and plugs in the cores of diapirs (Dalgarno and Johnson, 1968) also indicate the favorability of these zones for intrusion of magma from deeper crustal levels. Areas marginal to the Adelaide Geosyncline, including the Curnamona Nucleus, were relatively stable cratonic blocks and structural highs.

2.5 Cambrian

Cambrian sedimentation took place in the same general area as Adelaidean deposition but in several north-northeast-trending troughs in contrast to the northerly trend of the Adelaide Geosyncline. One of these troughs, the Arrowie Basin (Fig. 1; Wopfner, 1970; Youngs and Moorcroft, 1982), was deepest, 14,000 feet, in the northern Flinders Ranges. Sediments consist of a transgressive basal sandstone overlain by thick carbonate and black shale and succeeded by sandstone and graywacke with interbedded dolomite (Daily, 1956, 1976; Dalgarno and Johnson, 1963; Freeman, 1966; Wopfner, 1970).

Cambrian time was essentially a continuation of the quiet downwarping that characterized the latter part of Adelaidean deposition. The Olary and Gawler blocks were structural highs (Wopfner, 1970, 1972; Daily, 1976). The uplift of these blocks relative to the Curnamona nucleus probably occurred by movements on pre-existing near-vertical faults.

2.6 The Delamerian Orogeny

The main orogenic event affecting Late Proterozoic and Cambrian sediments as well as already metamorphosed basement rocks was the Delamerian Orogeny, which extended from the Late Cambrian to the Early Ordovician (Fig. 3). Granites intruded in this event and metamorphic minerals give dates between 490 and 430 m.y. (Pigeon, 1967; Parkin et al, 1969; Coats and Blissett, 1971). These intrusive rocks include soda leucogranite, albitite, granodiorite, aplite, and pegmatite in the Mt. Painter area (Coats and Blissett, 1971) and granite dikes, granodiorite, and quartz-feldspar porphyry in the Olary region (Dickinson et al, 1954). Delamerian deformation caused folding and faulting in the deeper parts of the Adelaide Geosyncline and Arrowie Basin (Fig. 4) and resulted in the major fold structures affecting Late Proterozoic and Cambrian sediments (Webb, in Glaessner and Parkin, 1958; Glen et al, 1977; Rutland et al, 1981; Youngs and Moorcroft, 1982). The shelf areas adjacent to the Gawler and Curnamona blocks were only weakly deformed. Cambrian sediments on the Curnamona shelf were virtually undeformed (Wopfner, 1970; Daily, 1976; Youngs and Moorcroft, 1982). The major structural feature in the Frome Embayment was the uplift of a series of north trending horst blocks known as the Benagerie Ridge. Over the Ridge, Mesozoic sediments rest directly on Precambrian basement, whereas thick Cambrian sediments are on either side. The Benagerie Ridge affected Tertiary stream channels.

Delamerian fold structures reflect tectonic compression that varied in orientation along the fold belt (Fig. 4). The North and Central Flinders zones (Rutland et al, 1981) reflect squeezing between cratonic blocks including the Curnamona Nucleus on the northeast side. Compression from the southeast, which contributed to form the South Flinders zone, is due to some sort of mobile crustal unit that is poorly understood (Glen et al, 1977; Rutland et al, 1981). Delamerian folding is closely related to pre-Adelaidean basement retrograde schist zones, as are Adelaidean rift zones and diapir trends (Glen et al, 1977; Rutland et al, 1981). Igneous and hydrothermal activity occurred generally late in the orogenic episode and resulted in hydraulic fracturing, quartz-filled veins, and mineralization (Campana and King, 1958; Coats and Blissett, 1971; Lambert et al, 1982).

2.7 Late Paleozoic and Mesozoic

Late Ordovician through Triassic time was characterized by epeirogenetic activity in central Australia, but, with the exception of local glacial deposits in the Permian and coal beds in the Triassic, it was a period of nondeposition in the Frome area. The Eromanga Basin included the northern half of the Frome Embayment in the Late Jurassic and Cretaceous. Late Jurassic deposition was characterized by fluvial sands and conglomerates and lacustrine sands (Parkin et al, 1969, Wopfner, 1972). These units are now the principle artesian aquifers in central Australia. Continued subsidence and further transgression in the Cretaceous resulted in deposition of complexly interfingering marginal marine facies and widespread marine mudstones and clay.

2.8 Paleocene to Eocene

Tertiary sedimentation in the Great Artesian Basin and Frome Embayment was limited to two intervals, Paleocene-Eocene and Miocene-Pliocene. Intracratonic basins were covered by a thin (generally less than 500 ft) veneer of terrigenous fluvial conglomerates and sandstones and lacustrine lignites and lignitic clays (Parkin et al, 1969; Wopfner, 1972). Because of the gentle slopes that have persisted to the present, Tertiary sediments are generally not exposed at the surface. Consequently most available data comes from drill cores. Tertiary rocks in the Frome Embayment rest on Precambrian, Cambrian and Cretaceous rocks. In the Beverley area east of Mt. Painter, Tertiary sediments overlie Cretaceous shale and sandstone which are underlain by Proterozoic basement (Haynes, 1975). In the southern part of the embayment, Tertiary sediments lie directly on Cambrian shale, sandstone, and limestone and Proterozoic igneous and metamorphic rocks (Brunt, 1978).

Tertiary sediments are divided into three units, the Paleocene to Eocene Eyre Formation (Wopfner et al, 1974), the middle Miocene Namba Formation, and the middle Miocene to Pliocene Willawortina Formation (Wopfner, et al 1974; Callen, 1975b; Callen and Tedford, 1976). The Eyre Formation, host to uranium deposits in the southern part of the basin (Goulds Dam, Honeymoon, East Kalkaroo, and Yarramba deposits), consists mainly of widespread mature sand ranging from medium-grained to small pebble sized with polished irregular, subrounded grains commonly cemented by carbonaceous matter, pyrite, and marcasite. The Eyre also contains conglomerate, carbonaceous siltstone and

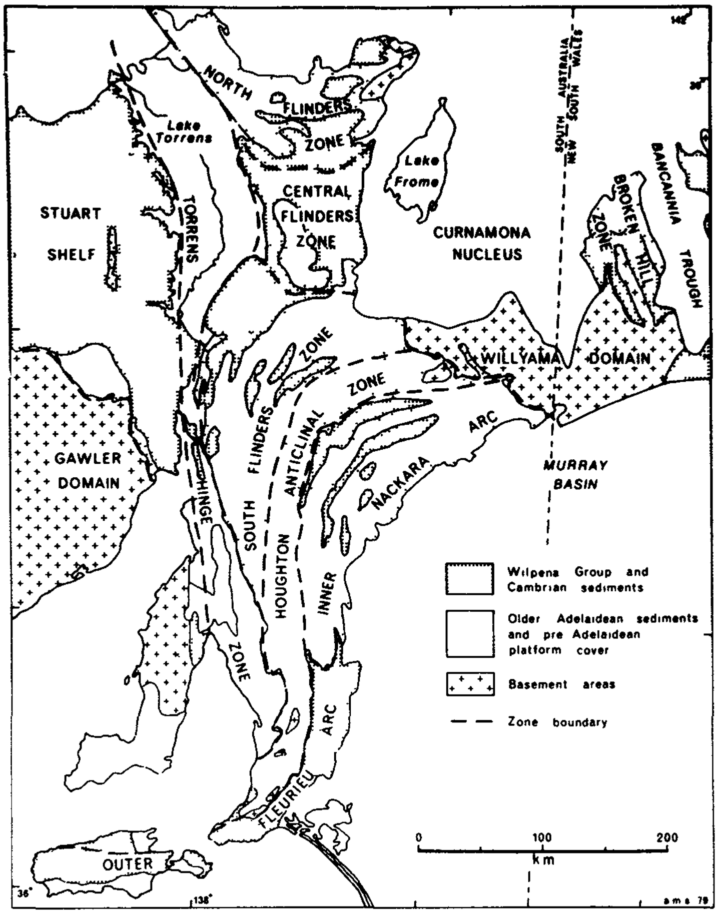

Figure 4. General geology of the Adelaide Geosyncline, Torrens Hinge Zone, and Stuart Shelf, showing the principal tectonic subdivisions of the Delamerian fold belt. From Rutland et al (1981).

lignite beds (Wopfner et al, 1974; Callen, 1975b). Silty claystone beds consisting primarily of kaolinite and montmorillonite are common. In the northern part of the basin, in the Beverley area, widespread, rounded, well-sorted blanket sands dominate the Eyre Formation (Fig. 2; Wopfner et al, 1974; Ellis, 1980). In contrast, in the southern part, the Eyre Formation consists of angular, micaceous, poorly sorted fluvial sands interbedded with clay and silt which were deposited in restricted areas in major stream channels (Brunt, 1978; Ellis, 1980). Some of the angularity of grains has resulted from alteration of quartz to clays by migrating pore fluids (Callen, 1975b).

The greater maturity of sediments to the north as well as the directions and gradients of the stream channels in the south indicate a source in the basement rocks of the Olary Ranges (Wopfner et al, 1974; Callen, 1975b; Brunt, 1978). During the early Tertiary, rivers changed from braided type to flood plain type with incised meanders, as the Olary highlands were worn down (Wopfner et al, 1974). The widespread blanket sands in the north may have been deposited as braided fans from a series of successive retreating scarps (Callen, 1975b). Their maturity suggests that Jurassic and Cretaceous rocks were the source (Brunt, 1978).

2.9 Oligocene to Miocene

The Eyre Formation is capped by a resistant quartzitic and opaline duricrust or "silcrete" representing a period of non-deposition and stable climate during Oligocene to Early Miocene (Coats and Blissett, 1971; Callen, 1975b) prior to deposition of the Namba Formation.

The middle Miocene Namba Formation consists of cyclic sand-silt beds, burrowed yellowish siltstone, light olive to black clay, bedded gypsum and dolomite, and crossbedded sandstone (Callen and Tedford, 1976). The cyclic sequences are composed from bottom to top of fine- to medium-grained crossbedded sandstone, parallel and cross laminated siltstone and fine sandstone, dolomite and calcite beds, and tough dark gray clay having scattered pockets of fine to coarse grained sandstone. Gypsum and brown chert nodules and manganese coatings on sand grains are common. The Beverley uranium deposit is in crossbedded sandstones of the upper part of the Namba Formation (Callen and Tedford, 1976; Fig. 3).

Sedimentary features in the Namba indicate lacustrine and fluvial depositional environments. During middle Miocene time, the Frome Embayment was largely covered by a deep to shallow, thermally stratified lake fed by large rivers (Callen and Tedford, 1976). Expansions and contractions of the lake are shown by interfingering of three facies, fluvial channel sands, fossiliferous beds that indicate fresh or brackish water, and carbonate and gypsum beds demonstrating hypersaline conditions (Callen, 1975b). The distribution of channel sands in a dominantly clay sequence suggests a meandering river system (Callen and Tedford, 1976).

The middle Miocene to Pliocene Willawortina Formation overlies and intertongues with the Namba. It consists of coarse, poorly sorted sand, clay and conglomerate. Carbonate occurs as nodules and beds (Callen and Tedford, 1976). This formation resulted from uplift of the Flinders Ranges. Fanglomerates and coarse clastic deposits of the Willawortina west of Lake Frome are evidence of rapid uplift in the early stages of this event (Callen and Tedford, 1976). Callen and Tedford (1976) suggest that reducing, sub-water table conditions of the Namba Formation were followed by oxiding conditions by means of deposition of sediments above the water table.

The present topography is largely a result of major Pliocene uplift of the Flinders Ranges. Pre-existing faults bordering the Flinders Ranges, and to a much lesser extent around the Benagerie Ridge, were active during this time. The Olary Ranges, uplifted in the early Tertiary, continued quietly to erode without further uplift in the late Tertiary.

2.10 Quaternary

The Quaternary Period is characterized by stable conditions and deposition of terrigenous sediments, principally eolian sands, fluvial sands and conglomerates, and lacustrine clays (Firman, 1970; Draper and Jensen, 1976; Callen, 1976; Callen and Tedford, 1976). Lacustrine clays are generally beneath the areas of modern-day lakes. Quaternary lakes covered a larger area than their modern counterparts (Callen and Tedford, 1976). Conglomerate and sandstone occur as alluvial fans and outwash around the Flinders, Olary and Barrier Ranges bordering the Frome Embayment. Some minor Quaternary uplift is indicated by tilted beds, mesas, and stream incision into gravel deposits (Horwitz, 1962; Ker, 1966; Forbes, 1972).

3. CENOZOIC CLIMATE AND HYDROLOGY

3.1 Climate

Abundant plant matter, lignitic beds, absence of feldspars, and evidence from spores suggest that the Paleocene and Eocene climate was subtropical with high humidity and rainfall (Wopfner et al, 1974; Callen, 1975b, 1976). Semi-arid or seasonally arid climate in the Oligocene is suggested by the formation of silcrete at the top of the Eyre Formation (Wopfner et al, 1974).

The middle Miocene Namba Formation represents deposition in a warm temperate to subtropical climate punctuated by arid periods (Callen and Tedford, 1976). Grasslands and forests covered the landscape, as determined by pollen analysis.

Uplift of the Flinders Ranges in the Pliocene time was accompanied by drying of the lake and increased aridity up to the present (Callen, 1975b). Today the Lake Frome area is arid having an average annual rainfall of 17 cm (7 in) and variations between 2 and 50 cm (1 and 20 in) (Haynes, 1975). Ephemeral streams cause much sheet flooding and gullying together with transport of large amounts of detritus during rare periods of heavy rainfall. Average high and low temperatures are 28 and 15°C (82 and 59°F) in January (summer) and 13 and 4°C (55 and 39°F) in July (winter) (Forbes, 1972). Vegetation types are mallee (eucalyptus thickets), low-layered woodland and shrub steppe (Forbes, 1972).

3.2 Hydrology

On the basis of stream channel and sediment transport directions, surface and shallow groundwater flowed mainly to the north from the Olary Range in lower Tertiary time. The orientation of stream channels shows that the Benagerie Ridge formed a slight structural high and diverted northward flowing streams toward the east and west parts of the basin. Gradients of the paleochannels today, thought to be similar to the original gradients, range from 0.49 to 2.4 m/km (Brunt, 1978; Ellis, 1980).

Uplift of the Flinders Ranges in the late Miocene and Pliocene caused increased surface and groundwater flow east toward the basin. Oxidizing groundwater gradually replaced earlier reducing conditions in sandstone beds (Callen and Tedford, 1976). Modern surface drainage and shallow groundwater flow follows roughly the same paths as those established in the late Tertiary, i.e., from the west and south toward Lake Frome (Draper and Jensen, 1976; Waterhouse and Beal, 1980). There is little drainage from the Barrier Range to the east. The lake is covered with water only during abnormally wet periods; much of the time it is dry.

Aquifers include sandstone strata of Jurassic, Cretaceous and Cenozoic age (Ker, 1966; Waterhouse and Beal, 1980). Groundwater in each aquifer converges on Lake Frome. Upwelling and discharge of ground water, especially on the eastern edge of the lake, is shown by "mound springs" composed of carbonate and quartz precipitates up to 60 cm high and 2 m in diameter (Draper and Jensen, 1976). Jurassic aquifers receive recharge from the Great Dividing Range east of the Great Artesian Basin and supply artesian water to most of the Basin including the northern half of the Frome Embayment. Because this mountain range was uplifted in late Tertiary time (Plumb, 1979), it is probable that the westerly groundwater flow in Jurassic aquifers began at this time also. Presumably groundwater in Cretaceous aquifers follows similar paths but little is known about them. Groundwater in Cenozoic sediments, mainly stream gravels and sands, flows east and north from the Flinders and Olary Ranges respectively. Because the Tertiary sediments have little outcrop area, their recharge must be primarily through overlying Quaternary sands and gravels.

Uranium is concentrated in groundwater entering the basin from the Flinders and Olary Ranges but is virtually absent from the same water discharging into Lake Frome. Radioactive, ^{222}Rn-rich water discharging at Paralana Hot Springs east of Mt. Painter (Coats and Blissett, 1971) has U_3O_8 concentrations from 180 to 6800 ppb, but U_3O_8 in water east of the Mt. Painter block decreases from 80–330 ppb near the block to less than 10 ppb near the north end of Lake Frome (Draper and Jensen, 1976). In the southern part of the basin near the Honeymoon deposit, groundwater is also radioactive (Waterhouse and Beal, 1980). Water from wells in the Broken Hill Inlier average 25 ppm U_3O_8 (Johnson and Gow, 1975). In contrast, Lake Frome water shows a maximum of about 5 ppb (Draper and Jensen, 1976). Dissolved uranium, derived from the weathering of Proterozoic basement rocks, apparently is precipitated in the sediments before it reaches Lake Frome. This fact and the existence of radioactive disequilibrium in the Beverley deposit suggest that uranium is being deposited today (Callen, 1975a).

4. URANIUM DEPOSITS

4.1 Uranium in Basement Rocks

Uranium anomalies are widespread on the eastern margin of the Gawler Domain and in the Willyama Domain (Ingram, 1974). Shows and small deposits occur in the Cleve and Port Lincoln areas west of Spencer Gulf (Johns, 1975; Thompson; 1975), in the Adelaide Hills (Dickinson, et al, 1954), near Thackaringa in New South Wales (Johnson and Gow, 1975), in the Denison block northwest of Mt. Painter (Reyner, 1955; Blissett, 1975), in the Mt. Painter area (Dickinson, et al, 1954; Coats and Blissett, 1971; Blissett, 1975; Youles, 1975), and at numerous places in the Olary block including Crockers Well and Radium Hill (Dickinson et al, 1954; Campana and King, 1958; Ashley, 1984). Of these, only the Radium Hill deposit has been mined (Joint, 1980). In contrast to these small occurrences, the Olympic Dam deposit in the northern part of the Stuart Shelf is a massive concentration (Roberts and Hudson, 1983). Uraninite, coffinite, brannerite, davidite, and thorian brannerite are the main primary uranium minerals. These minerals are associated with sodic felsic gneiss, sodic granitoids, and hydrothermal veins and breccia. Uranium was deposited in shear and breccia zones. Metamorphism reaches sillimanite grade in most areas of uranium enrichment in the Willyama domain, although the Olary block was more metamorphosed than the Mt. Painter block. Small shows of uranium are most abundant in high-grade metamorphic areas (K.R. Ludwig, personal communication). At Crockers Well, uranium appears to have been concentrated first in soda-rich volcanogenic sediment, now high-grade sodic gneiss, and later in magmatic segregations during cooling of soda-rich granitoids anatectically formed from the gneiss (Ashley, 1984). This accounts for the close association of uranium with soda-rich rocks (Whittle, in Dickinson et al, 1954). Middle Proterozoic host rocks at Olympic Dam are unmetamorphosed but were deposited in an active rift graben (Roberts and Hudson, 1983).

Ages of uranium mineralization in basement rocks range from possibly Early Proterozoic to Late Ordovician. The Radium Hill and Mt. Victoria deposits may have ages anywhere between 1800 and 1500 m.y. (Ludwig and Cooper, in press), which corresponds to the Olarian Orogeny. Initially obtained discordant apparent ages of 1730 (Dickinson et al, 1954) and 1500 m.y. (Campana and King, 1958) reflect at least one later event that redistributed the ore minerals (Ludwig and Cooper, in press). The association with shear zones suggests that mineralization took place near the end of the Olarian Orogeny. The age of the Crockers Well deposit was first thought to be about 580 m.y. (Campana and King, 1958), however Cooper (1973) and Ludwig and Cooper (in press) have shown that the true age is close to 1580 m.y. This age and the association with basement shear zones suggests that this deposit also formed late in the Olarian Orogeny. The Olympic Dam deposit is thought to be Middle Proterozoic in age (Roberts and Hudson, 1983). Uranium mineralization at Mt. Painter is syngenetic with Late Ordovician hydrothermal activity and brecciation late in the Delamerian Orogeny (Coats and Blissett, 1971; Lambert et al, 1982). However, Youles (1978) suggested that the Olympic Dam and Mt. Painter deposits might be correlative and about the same age as the Umbertana Group.

4.2 Deposits in the Yarramba Paleochannel

Tertiary stream channel systems that host uranium deposits in the Frome Embayment are the Yarramba system east of the Benagerie Ridge and the Curnamona-Billeroo system west of the ridge (Fig. 2). The Honeymoon, East Kalkaroo, and Yarramba deposits are in the Yarramba paleochannel; the Goulds Dam deposit is in the Billeroo paleochannel. All these discoveries resulted from exploration based on analogy with sandstone-type deposits in western United States (Brunt, 1978).

Deposits in the Yarramba paleochannel were described by Brunt (1978), and the following summary is from his description. Reserves of the Honeymoon and East Kalkaroo deposits are estimated at 1700 tonnes U at 0.22 per cent U and 800 tonnes U at 0.13 per cent U, respectively. Reserve estimates for the smaller Yarramba deposit have not been reported. Exploratory drilling has revealed 40 km of sinuous channel from 1.5 to 6 km wide and as much as 55 m deep. The paleochannel is overlain disconformably by upper Tertiary clay and silt at a depth of about 70 m below the present surface. Channel sands are generally light yellowish gray to orange, fine to medium grained, moderately well to poorly sorted, subangular to subrounded, clayey with muscovite and traces of limonite. Three sand units are separated by light grey to white silty, kaolinitic clay with small but variable sand content. The main uranium deposits are in the basal sand unit which is the least mature, least well-sorted, coarsest grained and highest energy of the three units. Basement geology and paleotopography greatly influence the channel morphology, and significant changes in orientation are seen depending on whether the channel was scoured in Cretaceous mudstone or Proterozoic shale, phyllite, schist, or granite.

Ninety percent of the paleochannel is anomalously radioactive. Only thick continuous sand units are barren. Uranium concentrations are at the interfaces between reduced carbonaceous, pyritic gray sands and yellow to orange limonitic, oxidized sands.

In detail the redox front consists of four zones, 1) yellow limonite zone, 2) orange limonite zone, 3) ore zone, and 4) seepage zone, distinguished on the bases of intensity and hue of limonite staining, abundance of iron disulfides, abundance of carbon, presence of presumed humic matter coating quartz grains, and gamma-ray log character. These zones are based on the work of Rubin (1970).

The nose of the roll front is farther down the channel than has been explored. Present deposits represent remnants or offshoots that the roll front left behind. The Honeymoon and East Kalkaroo deposits are on the outside curve of a meander; the Yarramba deposit is immediately up stream from a tributary junction. Local permeability variations strongly affect distribution and concentration of the uranium.

Brunt (1978) proposes the following sequence of events leading to the formation of these deposits. 1) Paleocene uplift of the Olary block exposed uraniferous rocks and initiated incision of stream channels. 2) Sand, organic matter and uranium mineral detritus deposited in the channels resulted in a reducing, alkaline, and uraniferous environment in the sand layers shortly after deposition. 3) Diagenetic pyrite precipitated in areas of carbon accumulation with the aid of sulfate-reducing bacteria. 4) Miocene clay was deposited over the channels preventing later upward groundwater leakage from the channels. 5) Late Miocene and Pliocene uplift and more arid climate allowed recharge of slightly alkaline, oxidizing groundwater into the headwater areas of the channels and resulted in a geochemical cell moving down the channels concentrating and precipitating uranium.

4.3 Goulds Dam Deposit

The Goulds Dam Deposit, and the Billeroo paleochannel in which it occurs, was described by Ellis (1980), whose observations are summarized here. Reserves are estimated at 1400 tonnes of U having an average grade of 0.09 per cent U. The Curnamona-Billeroo channel system was incised into flat-lying, red-brown siltstone and interbedded gray-green mudstone and some minor limestone of Middle Cambrian age. The channel has been defined by drilling along 40 km of its length. The width ranges from 5 to 8 km (averaging 6 km) and the depth of channel-fill sediments is about 45 m. About 85 m of Miocene and Quaternary sediments, mostly clays, overlie the channels.

Channel sediments consist of as many as five sand units separated by clay layers. Clay layers are discontinuous, and in many places two separate sand units merge into one. Sands are light gray, yellow, and orange, fine to coarse grained, subangular to subrounded, poorly to well sorted and quartzose with variable amounts of muscovite, kaolinite, magnetite, tourmaline, and pyrite. The basal sands, in which the uranium is concentrated, are the most coarse grained, most angular and least well sorted. Thus the energy of deposition and the maturity of the sediments decreases upward. The sedimentary environment, characterized by a slightly sinuous to straight channel, numerous longitudinal bars, and marginal overbank muds, indicates a braided stream.

The same mineralogical and geochemical zones are observed here as in the Yarramba paleochannel. The control on roll-front geometry by variations in transmissivity of the sands is particularly well shown in the Billeroo channel. Four roll fronts follow four sand units. Ore rolls have traveled farthest in the most transmissive sands. In places, where a clay layer is missing and two sandstone beds merge into one, the roll in one sandstone bed has penetrated the other sandstone bed and moved both up- and down-dip from the point of penetration. Uranium is concentrated both at the noses of the rolls and at the margins. The Goulds Dam deposit is at the channel margin just upstream from the confluence of the Curnamona and Billeroo channels.

The geological development leading to ore formation is virtually identical to that in the Yarramba paleochannel deposits (Brunt, 1978; Ellis, 1980).

4.4 Beverley Deposit

Haynes (1975) and Callen (1975a, 1975b) described the Beverley Deposit. Estimated reserves are 13,400 tonnes U of which 9300 tonnes having an average grade of 0.20 per cent U are recoverable. The deposit is 16 km east of of the Flinders Ranges in argillaceous sand lenses of the middle Miocene Namba Formation. These beds lie unconformably upon Cretaceous marine shale and sandstone. About 60 m of argillaceous sediments, including local coarse clastics with boulders, overlie the middle Miocene sands. The sands were probably deposited in meandering stream channels, in a low-gradient littoral area dominated by flood plain and lacustrine silts and clays. Heavily bioturbated sands may represent offshore lacustrine sand bars (Callen and Tedford, 1976).

Uranium mineralization is in sandstone lenses within a dominantly clay sequence. Underlying clay layers are carbonaceous whereas the host sand lenses and the overlying clay layers are not. Individual sandstone bodies in the 50 km^2 area of anomalous radioactivity have widths from 100 to 900 m and are 1 to 20 m in thickness. Uranium is commonly in the lower part of a lens but in places is distributed throughout the lens. The form is tabular rather than roll shaped (Callen, 1975a). Uranium was probably derived from detrital uraniferous material from the Mt. Painter block to the west. The deposits probably developed during the Pliocene uplift when uraniferous ground water probably recharged the Tertiary sand lenses through overlying Pleistocene gravels. Groundwater flow was confined by the sand lenses. The fact that underlying blanket sands are not mineralized is probably due to the lack of "focusing" and convergence of the groundwater flow (Sanford, 1983) in these relatively homogenous, widespread sands. The geochemistry of uranium precipitation was probably similar to that in the channel sands of the southern Frome Embayment.

5. TECTONIC HISTORY AND THE URANIUM CYCLE

5.1 Development of the Source Area

Uranium deposits are found in favorable rocks of several ages from Early Proterozoic to Tertiary. Like Archean terrane and areas underlain by Archean rocks elsewhere in Australia, the Gawler domain is a rich source for uranium. Deposits are absent in the stable central and western part of the domain but are in tectonically active zones on the eastern margin. The uranium deposits are also temporally related to tectonic and igneous activity. The Radium Hill and Crockers Well deposits formed toward the end of the Olarian Orogeny in ductile shear zones. The Olympic Dam deposit appears to have formed during or shortly after deposition of sedimentary breccias from a nearby, rapidly rising, fault-bounded block (Roberts and Hudson, 1983). Deposits near Mt. Painter formed during explosive hydrothermal activity in the latter stages of the Delamerian Orogeny. Uranium localization in vein-type deposits appears to be controlled by Olarian shear zones that were remobilized during every successive tectonic event. The retrograde schist zones in Early Proterozoic basement, the folding and faulting in overlying Late Proterozoic metasediments, the emplacement of diapirs in Late Proterozoic to Cambrian time, the belts of high grade metamorphism, the explosive hydrothermal activity in the Early Ordovician, the late Tertiary uplift, and the concentrations of pegmatite and hydrothermal veins all mark persistant zones of crustal weakness. The localization of vein-type uranium deposits along these zones is probably due to the ease of movement of soda-rich granitic magmas and hydrothermal fluids along them.

Uranium deposits in metamorphic and igneous rocks tended to occur in the later stages of compressional events, such as the Olarian and Delamerian Orogenies. In contrast, uranium deposits hosted by sandstone and sedimentary breccia formed where block faulting and rapid uplift caused terrigenous clastic sedimentation.

The development of the Australian craton in general shows accretion outward from original Archean crustal blocks (Fisher and Warren, 1975; Rutland, 1976; Plumb, 1979; Rossiter and Fergusson, 1980; Rutland et al, 1981). However, uranium does not show outward belts of progressively younger deposits corresponding to outward accreting terranes. Rather, uranium deposits of all different ages are concentrated in the mobile belt around the original crustal block and thus uranium appears to stay in roughly the same geographical area but migrate vertically through time.

5.2 Uranium Transport and Deposition in the Frome Embayment

Detrital material shows that basement rocks were exposed to weathering during the late Tertiary. Groundwater derived from Willyama domain rocks today was probably uranium-rich in the Tertiary as it is today. Uranium probably precipitated out on the way to the Tertiary ancestor of Lake Frome, as it does today. Paleochannels and sediment source indicators show that groundwater flow was in roughly the same directions during Tertiary time as it is today.

While other basins formed at different times in the same area and received sediments from the same uraniferous source rocks, the Frome Embayment was the one basin that was most strictly a continental basin. The Adelaide Geosyncline, the Arrowie Basin, and the Eromanga Basin were all dominantly marine and thus unfavorable for sandstone-hosted uranium deposits.

Dispersed flow of uraniferous groundwater must be focused in a small area for an ore deposit to form (Sanford, 1983). In the Frome area, groundwater recharge was "focused" by transmissive channel sands sealed above and below by much less permeable rocks. Formation of the deposits at or immediately upstream from tributary junctions and river bends also suggests preference for points of convergent flow upstream from obstacles to flow as discussed by Sanford (1983). Perhaps the reason why no significant uranium deposits are found in the lower Tertiary "blanket sands" is that uranium-bearing groundwater remained dispersed, while in the overlying channel sands and sand lenses the groundwater was forced to converge in the most transmissive zones.

Organic matter deposited with the sediments was probably the ultimate cause for uranium precipitation. Sulfate-reducing bacteria and oxidation of diagenetic pyrite probably also played a role in ore deposition.

Preservation of the ore was made possible by increasingly arid conditions and a stable tectonic environment from the end of the Tertiary to the present. Reducing conditions below the water table fixed uranium.

5.3 Summary of Controls on Uranium Ore Formation

The following events led up to the eventual deposition of uranium in Tertiary stream channels in the Frome Embayment:

1. Archean basement rocks may have provided the initial concentrations of uranium.

2. A mobile zone at the border of the Archean craton was the site for deposition of possibly uranium-rich volcanogenic sediments that were later metamorphosed and partially melted in the Willyama domain. These metasediments later became basement rocks and host to widespread uranium deposits in the Willyama domain. This mobile zone was reactivated in every subsequent tectonic event.

3. Deformation, metamorphism, anatexis, and late intrusion of soda-rich granites in the Olarian Orogeny led to further concentration of uranium in the source area, this time in Proterozoic rocks.

4. Subsidence and sedimentation during Adelaidean rifting covered and preserved existing uranium deposits. Rifting also favored emplacement of soda-rich granitoids.

5. Late Proterozoic and Cambrian deposition was terminated by the Delamerian Orogeny which reactivated old zones of weakness and, in its later stages, resulted in hydrothermal breccia and a new generation of uranium deposits in the source area.

6. Minor uplift and gentle subsidence persisted from Late Ordovician through Cretaceous time. Uranium deposits were preserved without change.

7. Tertiary uplift along old shear zones in the Willyama domain initiated a period of erosion of the uraniferous basement rocks.

8. The Curnamona Nucleus, originating in Proterozoic time, remained relatively stable through the present and provided a platform for Tertiary intracratonic, terrestrial deposition from source areas in surrounding structural highs.

9. Marine basins dominated from Proterozoic through Mesozoic time. Intracratonic basins completely surrounded by highlands did not form until the Tertiary when the present craton was essentially completed.

10. Rapid Tertiary uplift in highland areas caused braided as well as meandering river deposits at the margins of the Frome Embayment. Channels scoured in Proterozoic to Cretaceous basement rocks were filled with sands. Sand lenses also formed in offshore lacustrine bars.

11. The climate in early to middle Tertiary time was relatively wet, and temperate conditions encouraged growth of vegetation deposited with channel sands.

12. Humid conditions and abundant runoff aided weathering of source rocks and transport of uranium in solution and possibly in detrital fragments.

13. Less permeable clays deposited on top of sand-filled channels together with impermeable underlying rocks sealed later groundwater movement in the channels and assisted in concentrating the flow of uraniferous groundwater.

14. Detrital organic matter and sulfate-reducing bacteria produced diagenetic pyrite which led to uranium reduction and precipitation.

15. Late Tertiary uplift increased recharge of oxygenated uraniferous groundwater in the Tertiary sands and caused movement of geochemical cells that precipitated and concentrated uranium.

16. Uranium deposits formed at or just upstream from tributary junctions and bends in the paleo-channels where groundwater flow may have been obstructed.

17. Preservation of the sandstone-hosted uranium deposited was facilitated by increasingly arid conditions from the Pliocene to the present and by relatively stable tectonic conditions which preserved reducing conditions below a stable water table.

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PART III

GEOCHEMICAL AND GEOPHYSICAL ASPECTS

HYDROGEOCHEMICAL AND STREAM SEDIMENT SAMPLING FOR URANIUM IN THE SANDSTONE ENVIRONMENT

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Abstract

Sandstone terranes commonly host uranium occurrences in the western United States. In addition, because sedimentary terranes, particularly shales and immature, not well cemented sandstone, contribute more sediment and soluble material than do plutonic, volcanic, or metamorphic terranes they are an excellent regime for hydrogeochemical and stream-sediment prospecting. Because of higher conductivity, and hence higher uranium content, of waters draining such environments the sampling need not be as precise nor the analytical detection limit as low as in other terranes to yield a successful survey. Nevertheless, reasonable preparation and care of the samples is recommended: (1) The water samples should be filtered through 0.45 μm membranes and acidified to a pH of less than 1. (2) Because the adsorption of uranium by organic material is so significant it is recommended that the reasonable finest stream-sediment fraction, <90 μm , be used. In the case of dry streams with significant aeolian contamination, the 500-1000 μm size fraction is best. (3) A multi-element study be made because (a) the greatest expense in a hydrogeochemical survey is usually field related so once the samples are collected relatively little additional cost is incurred to determine other economic metals, and (b) many elements (such as organic C, Fe, PO_4, conductivity, etc.) are useful in the data reduction towards the elimination of false anomalies.

INTRODUCTION

The concentration of most trace and minor elements in natural water is typically controlled by the source rocks feeding sediment into the drainage basin. Sedimentary terranes, particularly those containing immature sandstones and shales, generally contribute more sediment and soluble material than do plutonic, volcanic (except for tuffs), or metamorphic terranes. An example of this can be seen in figure 1 where Bear Creek (at Morrison, Col.), draining small uranium occurrence in the Precambrian crystalline rocks, is compared to two sites on the San Miguel River draining uranium-bearing sandstone terrane (Uravan Mineral Belt). The uranium concentrations of water from crystalline rocks ranges from 0.1 μg/ℓ (ppb) to 3 μg/ℓ as compared to water from the sedimentary terrane (sandstones and shales) which ranges from 0.4 μg/ℓ to 8 μg/ℓ (San Miguel River at Naturita) or 1 μg/ℓ to 20 μg/ℓ (20 km downstream along the San Miguel at Uravan where more uranium-bearing terrane has been drained than at Naturita). These concentrations are also dependent on the topographic terrain, such that areas with steep relief and short water to rock residence time will always have lower trace element concentrations than low relief terrains of the same source rock. The soluble material entering the drainage network from a carbonate terrane is significantly greater than that from sandstone or shale, but the average uranium concentration of limestone is sufficiently low so that their uranium contribution to the hydrosphere is much less than a sandstone terrane. Because plutonic, metamorphic, and most volcanic terranes are more resistant to erosion than sedimentary terranes due to their generally better cementation and welding, they commonly occur in high relief terrain, and produce lower level uranium concentrations in the hydrosphere. As a result hydrogeochemical and stream-sediment prospecting are better for the location of sandstone uranium deposits than for any other type of uranium occurrence.

Geochemical exploration for uranium applies the known geochemical properties of uranium to mineral exploration. The objective is to locate aureoles of uranium concentrations, or those of its pathfinder elements (table 1), sufficiently above normal background to be identified as anomalies. The anomalies may represent mineralization. Although the elements shown in table 1 are frequently associated with uranium deposits they only occasionally occur with uranium in hydrogeochemical or stream-sediment dispersion halos. For sandstone deposits arsenic is the only element which consistently correlates with uranium in the hydrosphere [1].

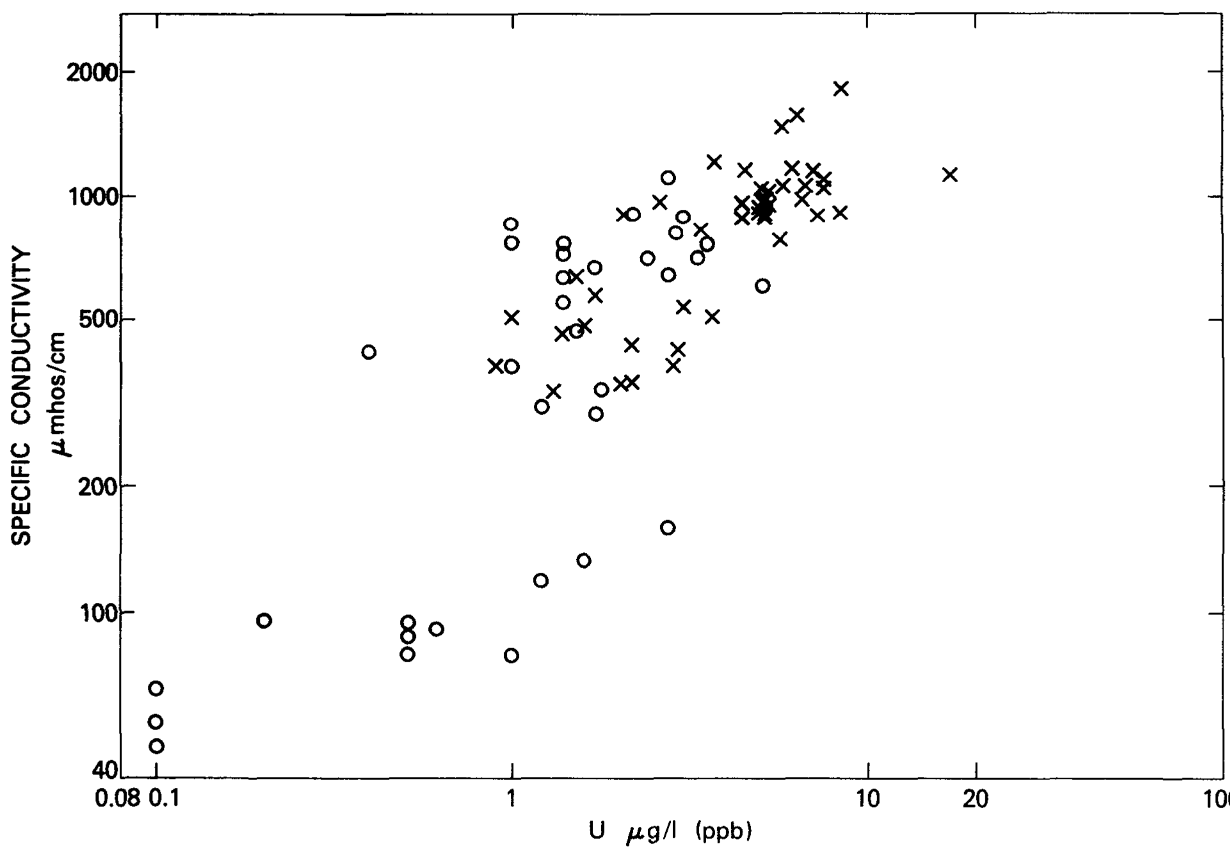

Figure 1. Uranium concentration versus specific conductance (proportional to total dissolved solids) for the San Miguel River at Naturita, Colorado (o) and Uravan, Colorado (x), both draining uranium-bearing sandstone terrane (Uravan Mineral Belt) in contrast to Bear Creek at Morrison, Colorado which drains uranium-bearing Precambrian crystalline terrane (vein-type deposits such as the Idledale Mine). Each point represents a different sampling date; each stream was sampled in different months over a period of several years.

Table 1.--Pathfinder elements commonly associated with uranium deposits (modified associated with uranium deposits (modified from [2])

PATHFINDER ELEMENT	TYPE OF DEPOSIT
Se, V, Mo, As, Cu	U; sandstone type
Rn, Ra	U; all types
Cu, Bi, As, Co, Mo, Ni	U; vein type

Two of the most commonly used sampling media in geochemical exploration for uranium are water and stream sediments. Because water and stream sediments evaluate different parts of the geologic terrane, both should be utilized simultaneously in a geochemical survey. In general, stream sediment anomalies indicate near-surface uranium deposits whereas surface water, because of ground water contributions through seeps and springs, also shows expression of buried uranium deposits.

Water: The application of water sampling to geochemical exploration is based on the high solubility of uranium in the oxidized 6+ valence state. The concentration of uranium in oxidizing ground water tends to reach a value roughly proportional to the uranium concentration in the rocks through which it flows. As ground water flows it tends to converge in streams and lakes so that, in general, a systematic sampling of surface waters allows detection of hydrogeochemical dispersion halos of buried uranium deposits. U^{6+} is not coprecipitated during the precipitation of common minerals such as carbonates, sulfates and chlorides. Once uranium has dissolved in surface water the dispersion aureole is stable and persistent for many kilometers. Uranium has a high solubility over a large pH range due essentially to the formation of stable and soluble complexes of uranyl ions with the anions in natural waters (carbonate, sulfate, and chloride). Uranium is extremely insoluble, however, when in its reduced 4+ valence state.

The concentration of most trace and minor elements in natural water fluctuates widely in relation to changes in environmental conditions. For instance, in the more temperate Eastern United States the average uranium concentration in water is <0.1 μg/ℓ (ppb) whereas in the more arid Western United States the average uranium concentration is >0.1 μg/ℓ. This is due largely to dilution of streams by greater rainfall in the Eastern United States, but also, in part, to the larger area buried by sandstones in the Western United States. Although temperate climatic zones, such as the eastern United States, favor the development of stable and easily detectable hydrogeochemical aureoles, dilution by rain water can be so acute as to "swamp-out" the anomaly or push the concentration of uranium below the lower detection limit. Semi-arid climatic zones are in some respects ideal because (1) surface water flows for at least a significant part of the year and a sizeable percentage of this water is contributed by ground water rather than by rain water; (2) the uranium concentrations are sufficiently high so as to minimize contamination and analytical problems. Desert climates preclude the formation of a regular stream network--the water table is normally deep and ground-water movement is dominantly vertical--both of which prevent the formation of hydrogeochemical aureoles. In tropical climates the bedrock is generally deeply weathered and leached, making the detection of hydrogeochemical aureoles difficult. In cold climates, water circulation occurs mainly at the surface where accumulation of organic matter limits the formation of aureoles. This is due to the formation by the organic matter of a cap impermeable to oxidation, keeping the uranium in the insoluble 4+ state, as well as permitting the organic matter to adsorb what uranium may have been in solution. Climatic conditions for the various climatic zones themselves vary greatly throughout the year (see fig. 1 for variation in uranium concentration throughout the year), so the importance of prior evaluation of the geologic and climatic environment should not be underestimated.

Stream Sediments:

Uranium occurs in stream sediments not only in detrital minerals, but also as an adsorption product. Because uranium is insoluble in the reduced 4+ valence state the most effective concentration of uranium in stream-sediments is organic material. Under oxidizing conditions the following processes may produce a stream-sediment aureole of U at the expense of a hydrogeochemical aureole:

1. The precipitation of insoluble uranium minerals such as phosphates, arsenates, and vanadates,
2. The precipitation of uranium by insoluble hydroxides, such as those of Fe and Mn, and
3. The precipitation of uranium by organic matter.

Nevertheless, the removal of uranium from solution by adsorption and (or) precipitation is, in most cases, is not sufficient to deplete the waters to the extent that they are no longer good geochemical prospecting tools. Stream sediments do not appear to have sufficient opportunity to adsorb significant amounts of uranium, even from high uranium waters, in moderate-to-high-gradient terrains [1, 3]. Yet, the adsorption of uranium by high organic-bearing stream sediments may commonly result in large uranium anomalies.

SAMPLING DESIGN

The sampling design, along with careful sampling, is perhaps the most critical part of an exploration program. If the sampling design is in error the entire program becomes irrecoverable, whereas if the data interpretation is erroneous the results can still be reinterpreted.

Geochemical surveys can be divided into two main groups, reconnaissance and detailed, each requiring different sample design. Reconnaissance surveys are applied to large areas from hundreds to tens of thousands of square miles and are relatively cheap and fast. Detailed surveys are used to focus on small parts of the reconnaissance area identified as favorable from the reconnaissance survey. Uranium deposits, particularly in sandstone environments, are much more difficult to isolate on a reconnaissance level because of their generally small size and discontinuous nature, than are the larger more massive base- or ferrous-metal deposits. Water and stream-sediments are the most useful samples in a uranium reconnaissance-survey. Water sampling is climatically restricted, whereas stream-sediment sampling is possible under most climatic conditions. Although samples if stream sediments from areas of at least moderate rainfall are preferred, sediments from dry stream beds are frequently the only geochemical medium available to evaluate arid regions. Both of these media, as well as rocks and soil, can be used in a detailed survey. Water sampling is a powerful tool because of the high solubility of uranium when in the oxidized 6+ valence state.

Water surveys can be of two types: (1) surface water and (2) ground water. Ground-water survey data should not be combined with those of surface water as the two water types have distinctly different chemical and physical properties; ground water tends to have higher contents of dissolved components. Nevertheless, it is often useful to run both types as simultaneous studies. Ground water is a more reliable evaluator of the geologic terrane than is surface water, but it has many drawbacks. It is largely inaccessible in many regions because there are no wells. When wells are available they rarely yield a good geographic or geologic distribution, but rather are usually restricted to localized areas tapping the same horizon. Well water also has the disadvantage of contamination, particularly from metals used in pipes supplying the water. Consequently, surface water yields a broader distribution of sampling sites and with careful sample design can yield excellent results. Cold water seeps and springs as well as hot springs, although technically ground water, can be very useful in a surface water study because of their subsurface information and ease of accessibility as compared to wells.

Sample design for surface waters is of the utmost importance. In areas of moderate to high rainfall sampling of all perennial streams should be done during the time of year of lowest precipitation. This maximizes the contribution from ground water, which carries the information concerning buried uranium deposits. In areas of abundant intermittent streams, sampling should be done when precipitation and snow runoff are low, but still sufficient for minimum discharge in the streams. The entire area should be sampled as closely in time as possible in order to avoid fluctuations in stream discharge and thus permit comparison of all samples. Figure 1 demonstrates why this is necessary. Each of the three stream sites sampled at various months over several years demonstrate the large monthly fluctuation in uranium content; the data for each site span more than one order of magnitude, which in some areas exceeds the data spread between background and anomaly. Monthly stream discharge records are kept for most drainages in the United States by the United States Geological Survey and should be helpful in determining the time of year to sample.

The exact sampling density and particular regions to concentrate on must be determined by the geologist familiar with both the geologic terrane and the topographic terrain in consideration of the total budget and the previously available geologic, geophysical, and geochemical data. Site accessibility must always be kept in mind when designing the sampling program. Some sites can take as much as a day to reach, so their value, in exchange for 10 sites which might otherwise have been reached, must be carefully evaluated.

Sampling should be restricted to either first- or second-order streams; streams of the same size should be sampled. Samples should represent a catchment area of no more than 12 square kilometers. Streams that are less than 2 km long from their headwaters to the sampling point are ideal. In some regions of poorly developed drainage, catchment areas of 50 square kilometers drained by 1- to 8-km-long streams, are not unusual. In this case a lower sample density, sometimes as low as 1 sample per 50 square kilometers will have to be acceptable. As a generalization, the larger the stream being sampled, the more extensive the mineralization must be to have a significant effect on the trace-element content of the water or stream sediments. For detailed surveys a sample density greater than one sample per kilometer of stream length is preferable. Every confluence is sampled, with sample sites located just above the stream junction far enough upstream to avoid contamination of the sediment from flooding of the adjoining drainage.

Stream Sediments:

Collecting the very fine fraction (fig. 2) is more important in stream-sediment sampling for uranium than in sampling for the ferrous or base metals. This is due primarily to three factors: (1) the extreme solubility,

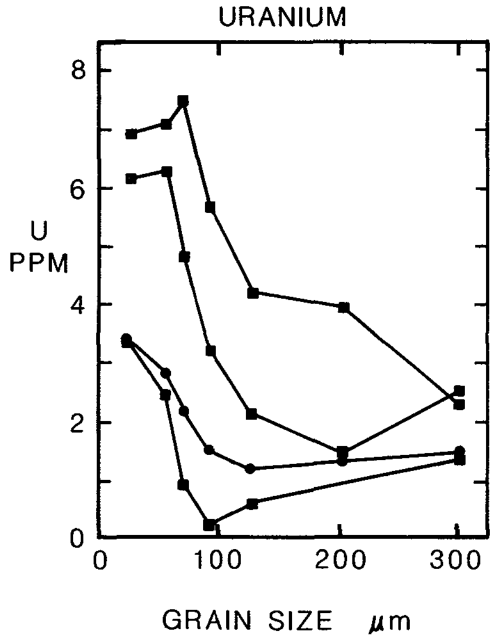

Figure 2. Uranium is primarily concentrated in the less-than-90-μm size fraction (less-than-170 mesh) [4]

under oxidizing conditions, of such common uranium minerals as uraninite and pitchblende, hence, a paucity of detrital uranium minerals in the sediment which could be medium- to coarse-grained; (2) the high adsorption capacity of organic material and iron and manganese oxides for uranium in solution; and (3) the original fine-grain size and low resistance to physical weathering of most uranium minerals, particularly the common secondary minerals such as carnotite and tyuyamunite. Consequently, only the finest material, less than 88 μm (170 mesh), should be submitted for analysis. Rarely, uranium minerals do occur as large detrital grains in the very coarse fraction, greater than 200 μm. If the geologist believes this to be true in an area, then this greater-than-200-μm fraction should be submitted for analysis. This is more a problem in crystalline terranes, where detrital uranium minerals such as brannerite may be prevalent, than in sandstone terranes where the uranium minerals tend to be finer grained and more readily oxidized into a soluble state. Here adsorption by organic material and iron oxides plays a more important role, underscoring the necessity of using the finer-size fraction of the stream sediment. Figure 2 illustrates the tendency for uranium to concentrate in the extremely fine fraction; the break in slope toward high uranium concentration occurs at 90 μm. This tendency is exceptionally pronounced in streams rich in organic material. Figure 3 [5] shows that the leachable uranium is concentrated in the finest fractions, whereas uranium in zircon, as well as in other noneconomic resistate minerals, is not. Using such a fine fraction necessitates a large sample, sometimes as much as 5 pounds. In high-energy streams sufficient fine material is sometimes difficult to locate, but if the stream is searched thoroughly, downstream from and under large rocks, sufficient material can be obtained.

Dry stream-sediment sampling is more complicated due to the problem of eolian contamination. Scraping off the top few millimeters only removes the contamination from the last windstorm, so another solution to the problem is necessary. Despite the contention from some geologists that the less-than-88-μm (170 mesh) size fraction, in contrast to the more standardly used less-than-177-μm (80 mesh) size fraction, contains more eolian contamination, the contrary is true. Figure 4 shows that a higher wind velocity is required to begin transport of the silt- and clay-size particles than the fine and very

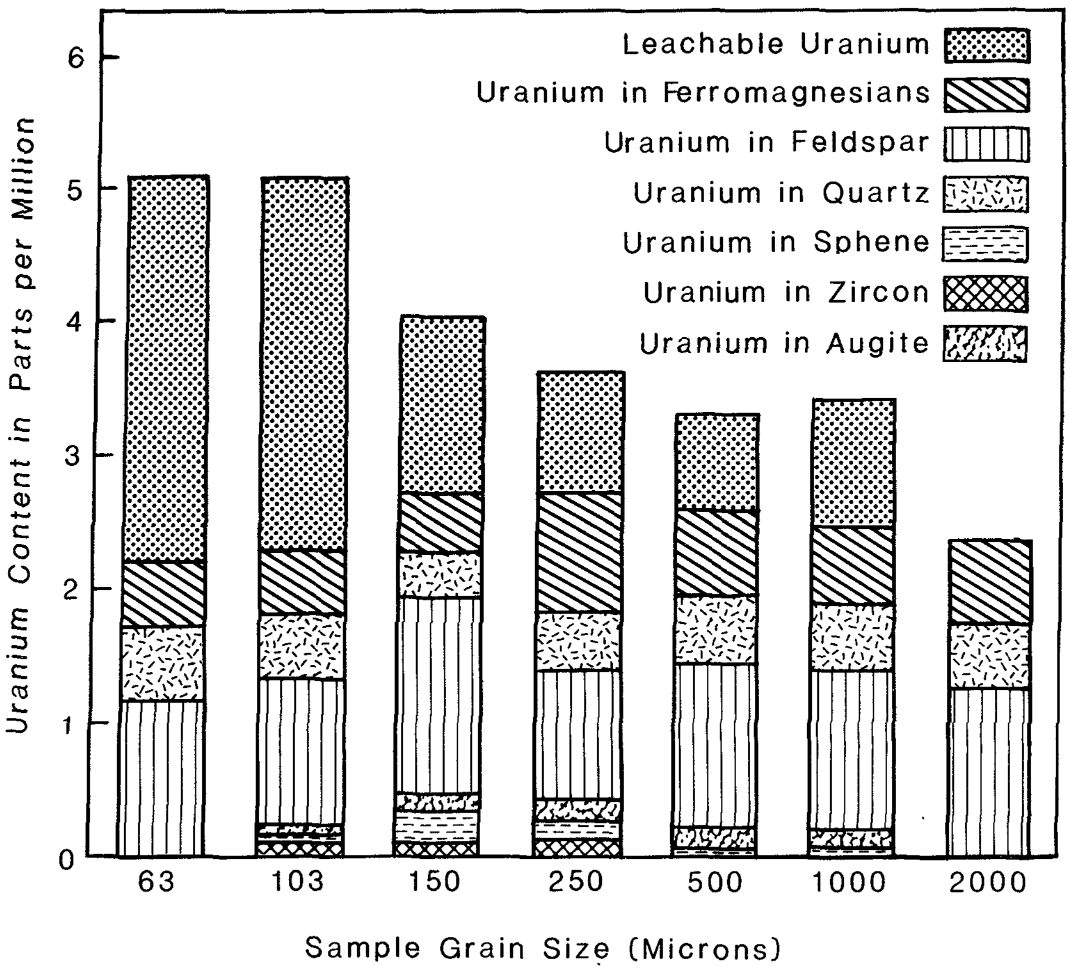

Figure 3. The distribution of uranium between mineral phases in various size fractions of stream sediments from the Tertiary sandstone and lacustrine beds of the Walker River Basin, Nevada [5].

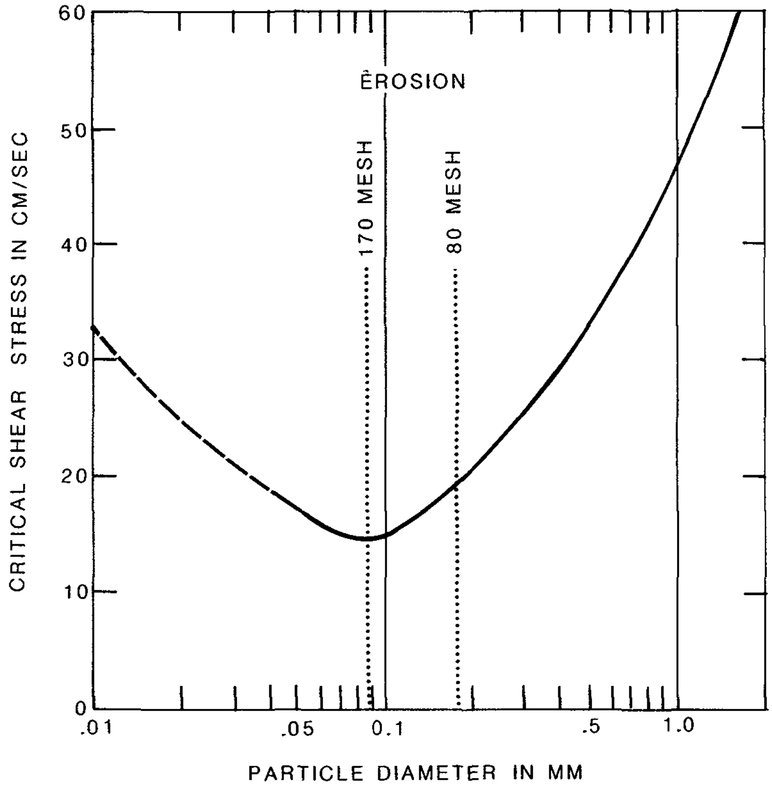

Figure 4. Variation of the threshold shear stress in air, required to move a grain, with grain size [6].

fine sand. This is because the clay- and silt-size particles are (1) held down more by cohesive forces than are sand-size particles and (2) they are smaller and therefore not affected as much by eddy currents of turbulent flow. Hence, the less-than-177-μm (80 mesh) size fraction contains a greater percentage of material located in the trough of the curve (fig. 4) than does the less-than-88-μm (170 mesh) size fraction. Nevertheless, both size fractions are readily transported by the wind and to avoid eolian contamination a coarse size such as greater-than-500 μm (35 mesh) and less-than-1000 μm (18 mesh), coarse sand, has been recommended by D. L. Leach [5] for sampling in arid environments. Figure 3 demonstrates that for these sediments once the size fraction is coarser than 250 μm there does not appear to be any significant change in uranium concentration until 1000 μm is reached. Although this size fraction may not yield the greatest percentage of extractable uranium (fig. 3) it minimizes the more serious problem of eolian contamination in arid environments. Besides, due to the paucity of organic matter in arid regions, uranium does not appear to be as severely enriched in the fine fraction of the stream sediments as it is in more temperate areas (compare figs. 2 and 3).

Because of eddy currents, large physical and chemical inhomogeneities in the sediments within the channel, and migration of the active channel from the center of the stream, sampling cannot be restricted to one part of the stream. For the most representative sample, a composite sediment sample should be collected in a zigzag course across the channel beginning downstream and moving upstream along a length equivalent to on the order of ten times the width. Several grams of sediment should be taken along each segment of the path length to form the composite sample. Only the active sediments, those that are still being moved, should be sampled.

Water:

Problems of sample inhomogeneity are only minor with water sampling compared to stream-sediment sampling. Filtration is recommended to overcome the problem of concentration changes in solution due to leaching or adsorption of elements from the suspended fractions during storage; acidification is recommended to minimize loss of ionic species onto the container. Although these effects are minimal for clear water, they are not for turbid water, where filtration becomes essential for reproducible uranium determinations. If at all possible the collection of turbid water should be avoided. This is not always possible particularly in sandstone terranes where streams commonly run turbid.

The variation in uranium concentration between a filtered (F) and an unfiltered (UF) sample (both unacidified) can be seen in figure 5. In addition to turbid samples, those with low concentrations of uranium (less than 0.04 μg/ℓ) appear to have minor problems with inconsistent uranium concentration between UF (later laboratory F) samples and field-F samples.

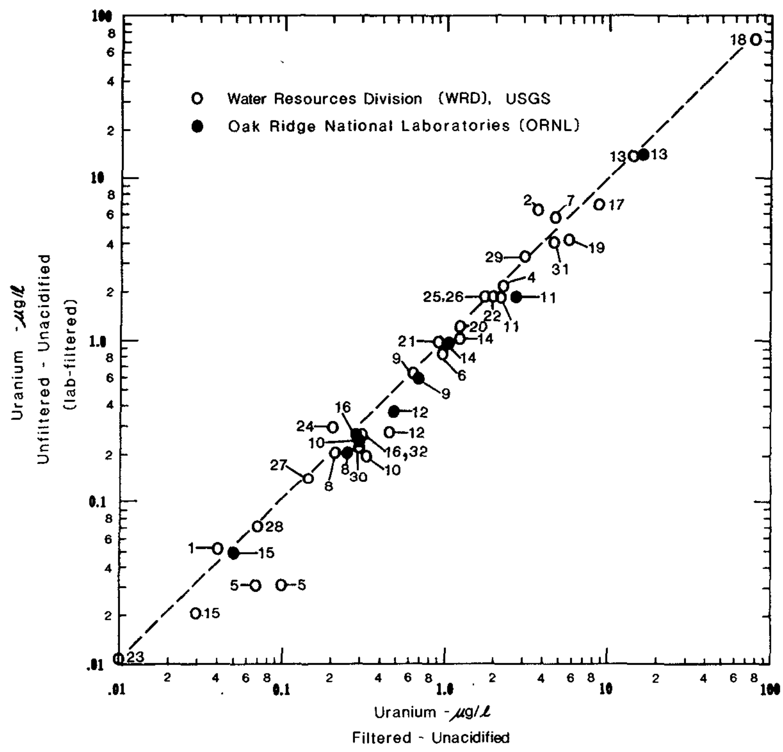

Figure 5. Uranium variation between filtered-unacidified and unfiltered-unacidified samples. The "unfiltered" samples were later filtered in the laboratory as compared to the "filtered" samples which were filtered in the field. Line represents the array of points where both sample types have equal uranium concentrations. A comparison of results on the same samples (number indicates sample site) by Oak Ridge National Laboratories (o) and the U.S. Geological Survey (o) provides an estimate of the precision of fluorimetric determinations.

Because uranium concentrations below 0.1 μg/ℓ are rare in water draining sandstone and shale terranes, this is not a major concern in these areas unless they are in a high gradient terrain. It appears from figure 5 that filtering might not be necessary, but an additional problem is revealed by the unacidified (UA) versus acidified (A) data shown in figure 6 (all samples are F). Many of the UA samples with uranium concentrations of less than 0.5 μg/ℓ show a significant loss in uranium content as compared to the A samples. This is most likely due to adsorption by the polyethylene container of small amounts of uranium (probably on the order of less than 0.1 μg/ℓ) from the UA samples, whereas in the A samples the large hydrogen ion preferentially occupies the available exchange sites on the container walls. This adsorption effect is insignificant for higher concentrations of uranium, hence the insignificant difference between A and UA samples for uranium concentrations greater than 0.5 μg/ℓ. Thus, the samples should be acidified. Acidification of UF samples should be avoided. With the exception of three turbid samples the A-UF samples show a significant increase in uranium content (fig. 7)--a result of the lower pH allowing dissolution of a substantial amount of the uranium from the suspended material, which is later filtered out in the laboratory.

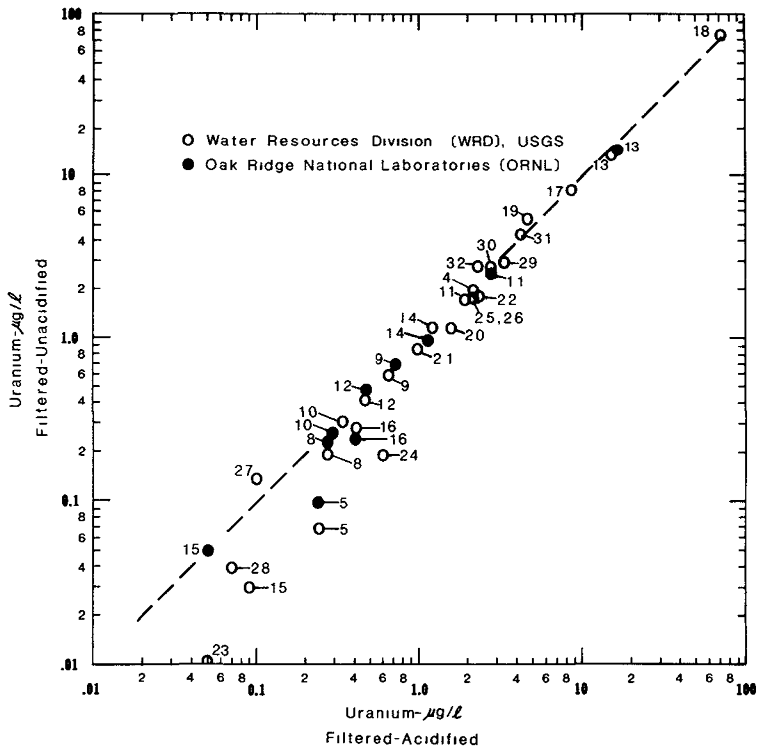

Figure 6. Uranium variation between filtered-acidified and filtered-unacidified samples. The "unfiltered" samples were later filtered in the laboratory as compared to the "filtered" samples which were filtered in the field. Line represents the array of points where both sample types have equal uranium concentrations. A comparison of results on the same samples (number indicates sample site) by Oak Ridge National Laboratories (o) and the U.S. Geological Survey (o) provides an estimate of the precision of fluorimetric determinations.

Samples UF in the field and later F in the laboratory tend to either gain or lose uranium depending upon whether or not they were A. If UF-A samples are used, most of the uranium, both dissolved and suspended, will end up in the filtrate, although this is not always true and depends upon the nature of the suspended material. Due to these inconsistencies, for most uranium exploration a total leachate is not desired. Following such a procedure would result in the uranium content being totally dependent upon the quantity of suspended sediment in the stream. Sediment content is positively related to the surface runoff. A heavy rain upstream could thus result in more inconsistent changes in the uranium concentration of UF-A samples than would F-A samples.

Although F-A, F-UA, and UF-UA samples exhibit similar analytical results at concentrations higher than about 0.5 μg/ℓ, at lower uranium concentrations F-UA and UF-UA samples tend to lose some of their uranium to the polyethylene container and to the suspended material. Thus, it is recommended that F-A samples be taken, especially for lower values of uranium. Because anomalous uranium in water associated with nonsandstone uranium deposits is occasionally as low as 0.5 μg/ℓ and background must be determined in order to establish the anomaly threshold, values below 0.5 μg/ℓ are important and need to be considered for deposit types other than sandstone. If a stream is clear, particularly in areas where helicopters are necessary and time is critical, it might be preferable not to filter (the sample should then not be acidified).

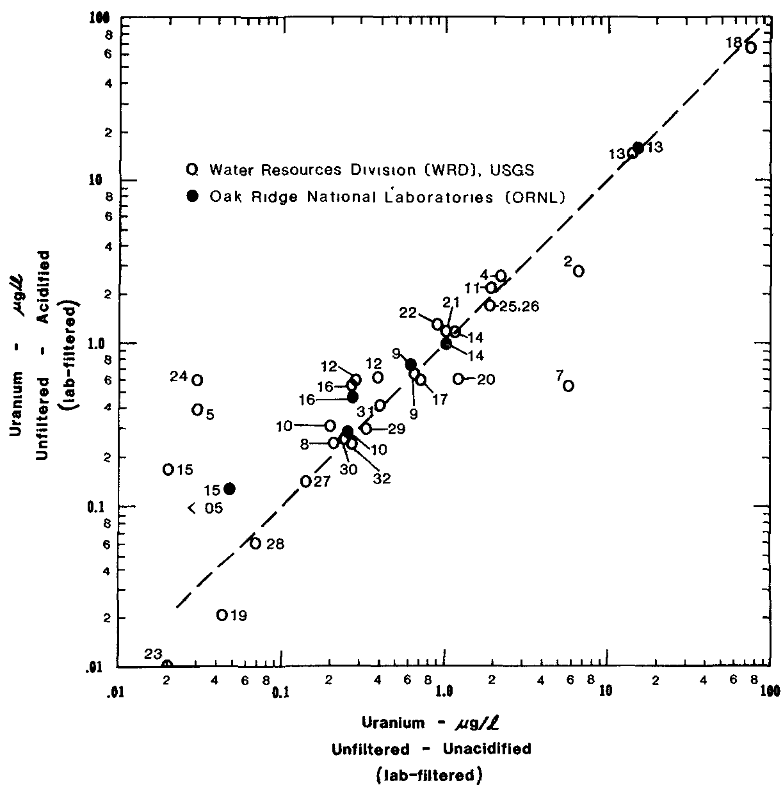

Figure 7. Uranium variation between unfiltered-unacidified and unfiltered-acidified samples. The "unfiltered" samples were later filtered in the laboratory as compared to the "filtered" samples which were filtered in the field. Line represents the array of points where both sample types have equal uranium concentrations. A comparison of results on the same samples (number indicates sample site) by Oak Ridge National Laboratories (o) and the U.S. Geological Survey (o) provides an estimate of the precision of fluorimetric determinations.

In such circumstances, the entire study area must be treated the same, and the assumption is then made that a proportional quantity of suspended material is carried in each stream. This is not usually true and unless the suspended material is negligible either some insignificant anomalous values will result or some may be overlooked.

Samples should be filtered through 0.45-µm millipore filters into polyethylene containers. Passage of the water through the membrane must be accelerated by exterior pressure; if quantities of less than 50 ml of water are necessary (the volume of water is dependent upon the analytical method) then a plastic syringe, commercially available for water sampling, is adequate. Larger volumes may require a bicycle pump or a small nitrogen tank.

Acidification should be done using ultra pure nitric or hydrochloric acid. The sample should be acidified to a pH of approximately 1; low-ion pH paper is adequate to test the degree of acidification. A set volume of acid cannot be used because commonly a large variation in total dissolved solids occurs from one sample to the next.

Water samples should be analyzed as rapidly as possible following collection. A recent study (fig. 8) does show though that if the sample is filtered and acidified and a note is made of the original water level in the container, samples can apparently be stored in excess of a year. Figure 8 shows the comparison of samples originally analyzed in 1978 compared to analyses made in 1981 by the same laboratory on water from the same sample.

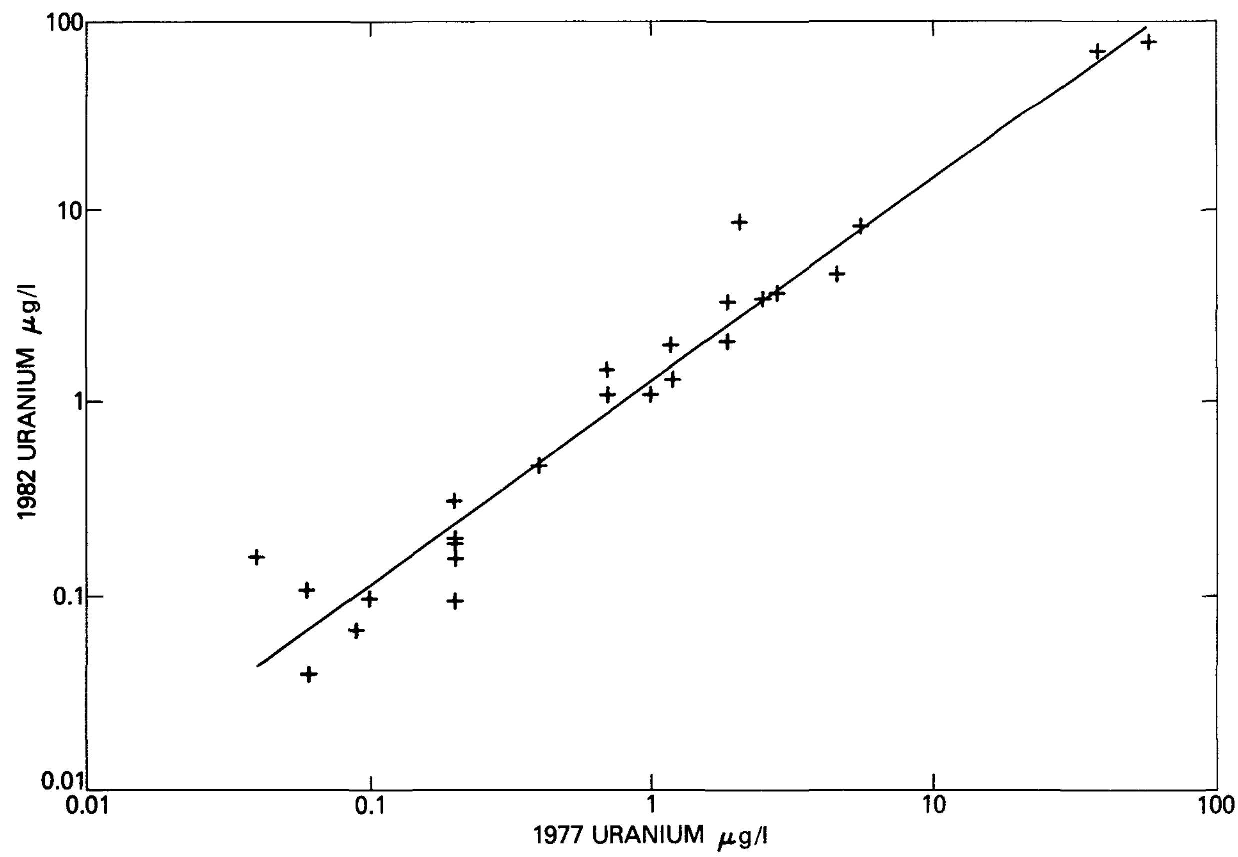

Figure 8. Comparison of U determinations made in 1977 against ones made in 1982 by the same laboratory on water from the same sample. Note the minor increase in uranium concentration which is probably a result of some evaporation of water from the sealed container (particularly prevalent in a dry climate such as that in Denver, Colorado where the samples were stored).

The minor increase in uranium concentration in 1981 is probably due to some evaporation of water from the sealed container, which could have been corrected had the original level been noted.

Conductivity (proportional to the total dissolved-solids in the water) measurements, are essential for a reliable uranium surface-water survey. Evaporation of surface water may greatly increase the uranium concentration, or a sudden rain may dilute it (fig. 1). This becomes a significant problem when a large geographic area is studied that requires more than a few days of sampling. In this situation variation in evaporation and rainfall affect the resultant uranium concentrations. The use of conductivity measurements to normalize the uranium concentration minimizes those effects. An example of fluctuating uranium concentration with changing discharge can be seen in table 2 for the Rio Ojo Caliente, New Mexico. These fluctuations were minimized by normalizing the uranium concentration by conductivity (last column, table 2). Hence, conductivity is the most important parameter needed in addition to uranium; its measurement can greatly increase the effectiveness of surface waters as an exploration tool by minimizing the external influences of evaporation and dilution.

Table 2.--Samples collected at different times from the Rio Ojo Caliente near Ojo Caliente, New Mexico

[1977 was a dry year, hence the low discharge during the month of May which typically has high discharge]

Date	Discharge	Uranium	Conductivity	$\frac{\text{Uranium}}{\text{conductivity}} \times 100$
July 23, 1975	15 ft^3/sec	16 μg/ℓ	715 μmhos/cm	2.2
May 19, 1976	109	3.3	235	1.4
May 5, 1977	9.2	30	1,100	2.7

Although field measurements of pH are useful for research studies their value in uranium exploration is questionable. No significant correlation between pH and uranium has been observed for streams studied throughout the United States [7]. This lack of correlation is probably because the pH in surface water is rarely outside of the range of 6-8.5; this entire range falls within the same uranium species solubility field on the Eh-pH diagram of Hostetler and Garrels [8]. Thus, strictly for surface-water uranium exploration purposes, pH has no applicability in surface water unless there is reason to suspect that the pH is outside the 6-8.5 range. Nevertheless pH measurements are essential for ground-water studies, particularly where modern thermodynamic techniques are used to interpret the data. If possible, pH values should be determined; the measurements should be made in the field with a pH meter. pH paper, even low-ion paper, is not adequate because the total dissolved solids content in most natural water is so low that the results are rarely close to the true pH value.

Eh measurements in surface water have proved to be unreliable as well as useless to exploration. No correlation has been found between field Eh measurements and uranium concentration in surface water. Due to the constant oxidation of the platinum electrode by the oxidizing surface water, reproducible results are difficult to achieve. Consequently, the time-consuming Eh measurements are not recommended for surface-water uranium exploration.

A composite water sample should ideally be taken in one round-trip traverse across the stream, although most streams are sufficiently mixed that inhomogeneities are not a problem. For details on water and stream-sediment sampling see Wenrich-Verbeek [9]. Spring- and well-water samples should be taken as close to the point of issue as possible, before the water passes through any manmade softening or demineralizing devices. Water from pumped wells should be allowed to run for at least several minutes before sampling until the temperature stabilizes, so that standing water in the system has a chance to be flushed out.

ANALYTICAL METHODS

Stream Sediments:

Uranium concentrations in stream sediments can be determined by delayed neutron activation or by fluorimetry following an acid leach on the sediments. Delayed-neutron activation is not as frequently used because of the limited availability of nuclear research reactors. It has the additional disadvantage of giving uranium concentrations as total uranium; this includes uranium tied up in such resistate minerals as zircon and samarskite, which are not amenable to present milling circuits in the United States. The advantage is the reproducibility and the knowledge that no uranium has been overlooked. If a multi-element analysis is also made, delayed-neutron activation can be most useful in evaluating the mineral species, and hence the geologic terrane supplying the uranium.

Fluorimetry analysis on an acid leach of the stream sediments has the advantage for exploration that it provides a total uranium content of the more leachable uranium and not that in the resistate minerals, which are of no economic significance. Its disadvantage is that a question remains as to exactly which minerals were dissolved and whether there was total dissolution of each phase. Also, some of the more resistate uranium minerals, such as brannerite, may not be leached and a possible deposit might be overlooked.

A good geochemical exploration program should have a multi-element analysis. Furthermore, with the bulk of the exploration cost going toward field sampling it is inefficient to omit analyses for other potential economic elements. In addition to these elements, determinations of organic carbon, Fe, and Mn are desirable for detection and removal of false anomalies. This is particularly true of organic carbon, which has such a strong affinity for the adsorption of uranium that samples taken from organic-rich pools within the stream often give anomalous uranium concentrations. These false anomalies can be removed if the organic carbon content has been determined. Determination of Fe and Mn serves the same function although their affinity for uranium is significantly less than that of organic carbon, so much so that they frequently do not have a significant correlation with uranium [10]. Although uranium is also believed to be adsorbed onto clays, a significant positive correlation between Al and U is has not been observed [10]. Elements correlating with uranium vary considerably among different geologic terranes. Those elements that generally correlate with total uranium in stream sediments are Th, Nb, Y, Ce, Yb, P, Li, Se, and Mg. Elements frequently correlating with uranium in sandstone terranes are As, Cu, Be, C, P, Se, Si*, Sr*, and Th (*=a negative correlation). Elements such as Th, Nb, Y, Ce, Yb and Zr are present with uranium in the resistate minerals and are therefore useful only for uranium determined by delayed-neutron activation and generally are not important pathfinders in sandstone terrane. For instance, a large Zr enrichment with the uranium is indicative of a concentration of zircon in the sediments but not particularly indicative of uranium deposits. The elements As, Se, Mo, Cu and V are commonly thought of as associated with U in ore deposits. This association is principally in sandstone uranium deposits, and hence, explains the lack of consistent correlation of most of these elements with uranium in stream sediments draining volcanic and metamorphic terranes. The Mg and Li correlation with U may be due to the presence of smectite clays (Glanzman, R. L., written commun., 1979), particularly in volcanic terranes.

Water:

Water samples may be analyzed for uranium by any of the following four methods: (1) extraction or direct fluorimetry, (2) neutron activation, (3) Scintrex[1] uranium laser analyzer, and (4) fission track. In the past, fluorimetry has been the most commonly used method. (1) Determination by direct fluorimetry enables detection of uranium to 0.4 µg/ℓ, but the more expensive and time-consuming extraction fluorimetry has a lower detection limit of 0.01 µg/ℓ. Unfortunately, extraction fluorimetry frequently requires one liter of water. Because many sandstone terranes provide uranium concentrations in water in excess of 0.4 µg/ℓ , extraction fluorimetry is may not always be necessary in this environment. (2) Neutron activation is generally more costly and requires the availability of a high flux nuclear research reactor. This method does have two distinct advantages: (a) a 0.01-µg/ℓ detection limit, and (b) no problem with loss of uranium into the container walls, because the entire container is irradiated. (3) The Scintrex[1] uranium analyzer has the advantage that it requires a small sample (although the sample must be filtered) and also the sample can be analyzed immediately (in the field). Its disadvantages are a higher detection limit (advertised at 0.05 µg/ℓ) and the initial cost of the instrument. If greater than 5000 samples are to be analyzed, the instrument may become cost-effective. Although this is a field instrument, the laser beam can be knocked out of alignment if jarred excessively. (4) Fission track has the disadvantage of requiring a nuclear research reactor and the track counting can be time-consuming unless an automated procedure is adapted. Nevertheless, this method is commercially available and has a detection limit of 0.01 µg/ℓ. Fission-track determinations of uranium give additional information on the location of the uranium in water. If the tracks are disseminated, the uranium is dissolved in solution whereas if they are in clumps the uranium is in the fine suspended material.

No matter which method is chosen a detection limit on the order of 0.05 µg/ℓ is essential in sandstone terrane and 0.01 µg/ℓ in nonsandstone unless there is good evidence that most water in the study area has more than 1 µg/ℓ of uranium. Background values requiring a detection limit significantly lower than the average concentration for the region; must be established anomalies with values between 0.1 and 1 µg/ℓ are not uncommon.

As with stream sediments, additional parameters are useful and necessary for the elimination of false anomalies in hydrogeochemical surveys. Because uranium is believed to complex with CO_3, HCO_3, PO_4, SO_4 and F ions, analytical determinations of alkalinity (or HCO_3 or CO_3), PO_4, SO_4 and F should be made. Phosphate is also important because uranium contained in phosphate fertilizers may be contaminating the water in agricultural areas.

Uranium in surface water most commonly correlates with the following cations: Ca, Mg, Na, K, Ba, B, Li, As. Although determinations of the major elements Ca, Mg, Na and K are of no particular use to exploration, determinations of Ba, B, Li and As are. Arsenic in particular, is the only element commonly associated with uranium ore deposits that has a similar enough solubility to uranium to consistently correlate with it in surface water. This correlation may possibly also be due to a complexing of uranium with arsenic in solution. The correlation of Li and Mg with uranium is probably due to the association of smectite clays and uraniferous tuffs or tuffaceous sediments in the aquifer system. Because tuffaceous sediments are occasionally good uranium hosts these elements are also important pathfinders for sandstone uranium deposits.

[1]Use of brand names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

DATA INTERPRETATION

Geochemical exploration does not search directly for ore but rather for anomalies. If an anomaly is located it may indicate: (1) ore, (2) subeconomic accumulations of minerals, or (3) concentration of elements not representing mineralization, that is, a false anomaly due to secondary geochemical processes, sampling or analytical errors, or contamination. Although the use of a statistical analysis greatly helps in the interpretation of anomalies, a thorough knowledge of the geology and hydrology is the foundation for reliable interpretations.

The first step in data interpretation is the establishment of uranium background for a given area, sample type, or geologic terrane. Generally the modal value is considered to be the normal abundance or background value. Before the mode can be determined it must be established whether or not the data is normally or lognormally distributed. Most geochemical data are lognormally distributed. The "less than" data should not be ignored in the statistical analysis because valuable information is lost, resulting in a higher mean value. The qualified, or "less than" data should be replaced, for purposes of statistical analyses, with a carefully selected arbitrary value that is less than the qualified value. If over half of the data for a particular element is qualified then that element should not be used in the statistical analysis. Subsequent to this, the anomaly threshold value, the upper limit of background, also needs to be established. Values above the threshold are considered anomalous and worthy of careful scrutiny. The regional threshold and the local threshold are usually different, as can be seen from figure 9. Care must be taken not to mix populations, especially

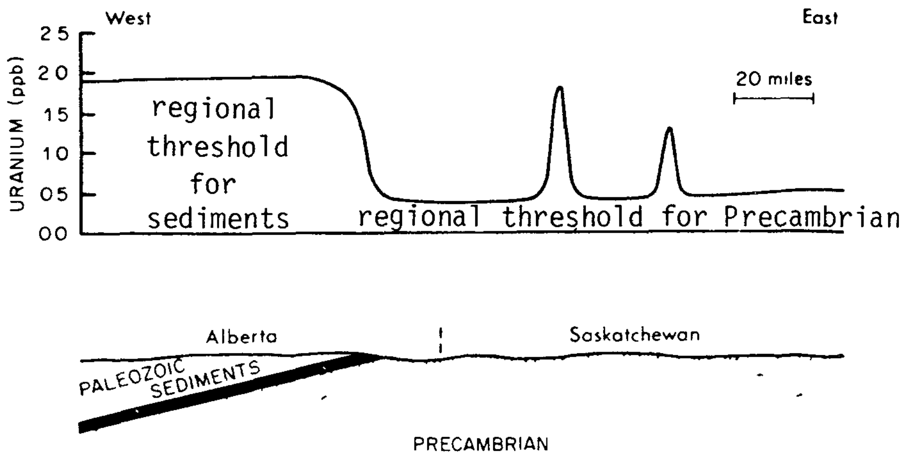

Figure 9. The regional threshold can be quite different for different populations of data such that the anomalies for one region can be swamped out by the regional threshold for another if the populations are not separated (modified from Levinson [2]).

where one regional threshold is significantly higher than another and can obscure anomalous values if the populations are mixed (fig. 9). Cumulative-frequency plots can assist in isolating different populations. Determination of the anomaly threshold can be somewhat subjective. A number of rules have been proposed, although the two most commonly used are: (1) samples that contain amounts of elements twice background, or more, are anomalous [11]; and (2) samples that contain amounts of elements more than two standard deviations above the mean are anomalous [12]. The latter definition is the most commonly used anomaly threshold in geochemical exploration, but the use of the mean value permits the anomaly threshold to be sensitive to extreme values; that is, one extreme value could force the anomaly threshold so high that no other data is anomalous.

The last step in data treatment is an attempt to eliminate false anomalies, sampling errors, and the like. Heterogeneity in stream sediments introduces false anomalies due to the varying proportions of such constituents as organic matter, oxides, and carbonates, all of which have different fixation properties for uranium. In stream sediments the parameter most commonly causing false anomalies is organic carbon. A simple ratio of uranium to organic carbon can be used in place of the raw uranium data to eliminate false anomalies caused by high uranium content in some samples due to adsorption of uranium by large amounts of organic matter. A more ideal method is to use a weighted sum computed as a sum of all the above parameters plus uranium. If uranium was determined by delayed-neutron analysis the elements Th, Nb, Y, Ce, Yb and Zr may be added to the weighted sum in order to eliminate anomalies caused by large volumes of resistate minerals in the stream sediments.

Similar problems also result in false anomalies for hydrogeochemical data. As mentioned previously, fluctuating discharge may cause false anomalies. These may be eliminated by dividing uranium by conductivity (and multiplying by 100 or 1000 to make the number less cumbersome). If a stream drains a limestone terrane the uranium value will be higher because there is more carbonate for uranium to complex with; these anomalies may be eliminated by dividing by alkalinity, CO_3, or HCO_3. A stream entering an agricultural region may suddenly increase in uranium concentration due to uranium in fertilizers; dividing by PO_4 will minimize this problem. A multi-element analysis combining these parameters as well as other complexing elements such as F and SO_4 is the best method for isolating true anomalies and eliminating variability due to environmental factors. Dall'Aglio [13] shows an excellent example of multi-element analysis of water samples. In his weighted sum he uses Ca, Mg, Na, K (conductivity measurements may be substituted for these four elements), HCO_3 (alkalinity or CO_3 may be substituted), SO_4 and Cl. Fluorine, and particularly PO_4, should be added to this list.

Because water and stream sediments evaluate different parts of the geologic terrane, both should be utilized simultaneously in a geochemical survey. Determining anomalous areas solely on the basis of the raw data is difficult and leads to false anomalies, as discussed above. Multi-element statistical analysis is a powerful tool for data interpretation which should be applied to hydrogeochemical and stream-sediment surveys.

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GASEOUS EMANATIONS ASSOCIATED WITH SANDSTONE-TYPE URANIUM DEPOSITS

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Abstract

Helium and radon are two gases produced by the radioactive decay of uranium. Field studies show a dispersion of these gases from an orebody but models quantifying the relationship of the gases to the ore are difficult to derive. This is due to variables such as size and grade of ore, distribution of radioactive daughters, porosity and permeability of host rock, and the geologic, hydrologic and structural settings which influence the concentration of the gases. Helium has a greater dispersion than radon, which is limited by its short half-life before radioactive decay. Both gases can be useful in identifying sandstone environments that may have the potential for hosting uranium deposits.

1. INTRODUCTION

Radon and helium are two gases that are characteristic of uranium deposits. These gases are produced by natural radioactive decay of the parent uranium atom: radon (Rn) is the seventh member of the decay series, and helium (He) is produced in 8 successive steps as the product of alpha particle emission (Table I). In the search for uranium deposits, one technical approach is to analyze for other elements commonly associated with uranium in the hope that they may provide a larger dispersion halo, ultimately indicating the target. Noble gases, because of their chemical and physical characteristics and their relative ease of measurement, are ideally suited for this technique. This paper discusses the unique characteristics of radon and helium and demonstrates both theoretically and by field measurement how those gases are associated with uranium in sandstone-type uranium environments.

2. HELIUM AND RADON CHARACTERISTICS

Helium and radon are members of the chemically inert noble gas family of elements. Naturally occurring helium is composed of two isotopes, helium-4 and the million times less abundant helium-3. Helium-3 is the decay product of tritium which is formed mainly by cosmic-ray nuclear reactions. In this paper, only helium-4 will be discussed. Helium-4 is produced from the alpha particles emitted during the radioactive decay of uranium-238 and uranium-235, and thorium-232. It is a nonradioactive atom with an atomic weight of 4. The mole fraction in the atmosphere is only 5.2×10^{-4} percent, due to escape to space from the top of the atmosphere. The production rate is about 3×10^{12} atoms per year per gram of U-238 in equilibrium with the daughter products. The production rate of helium from Th-232 is about 75 percent of this figure and that from U-235 only about 4 percent.

Naturally occurring radon is composed of three isotopes, Rn-222, -220, and -219, produced by alpha decay from a radium parent. Radon is also monatomic but unlike helium, is radioactive with half-lives of 3.8 days for Rn-222, 56 seconds for Rn-220, and 4 seconds for Rn-219.

TABLE I. NATURAL RADIOACTIVE DECAY SEQUENCE OF URANIUM-238. EIGHT ALPHA PARTICLES (α) ARE EMITTED DURING THE SOURCE OF THIS DECAY. β IS THE BETA PARTICLE DECAY. y = YEAR, d = DAY, m = MINUTE, s = SECOND

Isotope	Mode of decay	Half-life
U-238	α	4.5×10^{9} y
Th-234	β	241 d
Pa-234	β	1.2 m
U-234	α	2.5 y
Th-230	α	7×10^{4} y
Ra-226	α	1620 y
Rn-222	α	3.8 d
Po-218	α	3 m
Pb-214	β	27 m
Bi-214	β	20 m
Po-214	α	1.6×10^{-4} s
Pb-210	β	22 y
Bi-210	β	5 d
Po-210	α	138 d
Pb-206	--	stable

The mole fraction of radon in the atmosphere is 6×10^{-18} percent and the production rate of radon-222 from 1 gram of U-238 in equilibrium with all the daughter products is about 4×10^{11} atoms per year. Radon-220 and -219 production from 1 gram of Th-232 or U-235 in their respective decay series is about 30 percent and 600 percent compared to that for Rn-222 from U-238. The production rate is a function of the half-life ratio. In natural crustal environments, the concentration of U-235 is 138 times less than U-238 whereas Th-232 may be 3-4 times more abundant than U-238. The contribution of radon from U-235 is therefore minor. Because of radioactive decay, radon does not have the potential to accumulate as does helium; for example, Rn-222 in equilibrium with U-238 is decaying at the same rate it is being produced, about 1.4×10^{4} disintegrations per second per gram of U-238.

3. CONTROLS OF HELIUM AND RADON DISTRIBUTION

The actual amount of helium and radon present in the geologic environment, such as a sandstone formation, depends on a number of factors. The most important are the amount of parent nuclide present, the emanation rate at which the gas is released from its sources, and the diffusion and transport efficiencies of the system being considered. On any scale, local or regional, it is difficult to determine a background flux for helium and radon because of the great number of variables involved. The flux can be defined as the amount of gas crossing the soil-atmosphere boundary per unit time. For helium, which does not decay, both crustal and mantle generated gas can contribute to the flux. For radon, the half-life restricts the volume of material that can contribute gas to the flux because of the limited distance the atom can migrate before it decays. Influencing the diffusion and transport are local geology, rock types, faults, joints, fractures, hydrology, porosity, permeability, and environmental effects, such as farming, urbanization, as well as exploration and mining activities. The rate of emanation not only depends on material type and crystalline structure but also varies in response to changes in physical forces, such as pressure and stress.

This latter response has been observed in seismically related studies [1,2]. It is possible that even a change in the hydrostatic force related to seasonal variations of water availability could modify the emanation rates of minerals.

The concentation of parent nuclides is governed by chemistry. Equilibrium for the complete uranium or thorium decay series is nearly impossible to maintain on a geologic time-scale because the different chemical affinities of the elements in a decay series cause separation and disequilibrium. Helium, in the form of an alpha particle, is generated 6, 7, or 8 times in a decay series. About 50 percent is produced in the first part of the decay series when half-lives are measured in 10^5 to 10^9 years, and the other 50 percent when half-lives are measured in seconds to 10^3 years. Chemical separation of parents in the shorter time period is less likely to be a dominant factor. Radon is produced from only one decay-series event, the alpha-particle decay of radium. The half-life of radium-226 is of the magnitude of 10^3 years, and there is sufficient time for it to be partially chemically separated from the earlier members of the decay series . Radon, therefore, can correctly be considered as an indicator of its parent, radium. Helium very likely is also a indicator of radium because nearly half of its production occurs relatively rapidly and subsequent to radium disintegration within the decay sequence.

Although the problem of flux determination is very complex, it can be dealt with best on a local scale. Models can be developed for the flux of helium and radon in the vicinity of uranium deposits by setting boundary conditions and making practical assumptions about the relationship of the ore to the host rock.

4. MODELS FOR GAS TRANSPORT

Various models have been developed to describe the transport mechanism through overburden and the surficial expression of gases associated with a uranium orebody or other subsurface source. For helium in sedimentary rocks, Newton and Round [3] present models based on classical diffusion and exclude mechanisms such as migration in bubbles or fluid flow. In fact, they point out that diffusional rates are exceeded by general sedimentation rates and they further acknowledge that migration in flowing water is more significant than diffusion even if the flow rate is only 0.3 m per year. Their models are based on the diffusion equation (Fick's Law):

$$\frac{\delta c}{\delta t} = D \frac{\delta^2 c}{\delta x^2}$$

where D is the diffusion coefficient, $\frac{\delta c}{\delta t}$ is the rate of change in concentration with time at distance and $\frac{\delta c}{\delta x}$ is the concentration gradient at a fixed time. Diffusion is considered to occur in the X direction only.

Golubev and others [4] present a three-layer model involving migration in waters. They point out that the discrepancy between actual helium measurements and migration solely by diffusion can be reduced by considering water migration. Tugarinov and Osipov [5] compare the flow of helium from uranium deposits to the helium background generated by granites; they consider the helium generation and classical diffusion model of Grammakov and others [6] but include the influence of geologic structures, such as faulting, in controlling the rate of helium migration and further consider the dispersion of radioactive minerals around the main ore body. Turgarinov and Osipov [5] summarize the total helium in a given zone as follows:

$$\Sigma \text{ He} = \text{He}_1 + \text{He}_2$$

where He_1 is the contribution of helium from deep sources such as the mantle, local granite massifs, the rock or sediment enclosing the ore, and the geochemical aureoles around the orebody; He_2 is helium formed from the alpha decay in the ore itself.

Pereira and Adams [7] present a discussion on the accumulation rate of helium in sedimentary strata. Although primarily directed to show that helium accumulation in large reservoirs is possible without invoking nearby zones of anomalous uranium and thorium, their treatment of generation, emanation, and migration demonstrates how sedimentary strata can accumulate helium. Pogorski and Quirt [8] suggest that water is a critical factor in accumulation, whether that water fills the pore spaces or exists only as a thin film around mineral grains. The tendency of sedimentary rocks to accumulate gases is the key to producing a gaseous signature for a uranium orebody and explains why in calculations derived from simple models showing gas emanation from an orebody just above the background rate, as in the case of helium by Martin and others [9], a significant concentration in soils or soil gas might still be produced within a fraction of geologic time.

Radon transport models have also been developed and are generally analogous to the helium models. With radon migration, the consideration of radioactive decay enters into the models. Tanner [10,11] presents excellent reviews of radon migration. He states that radon-222 can migrate only several meters by diffusion before the concentration becomes negligible. Various concentrations of radon in sandstone, based on assumed diffusion coefficients and emanation rates are used in models developed by Lampley and Wells [12] and Kraner and others [13]. Experimental values for generation and emanation rates are given by Pearson [14] and Wilkening and Hand [15]. A review of this literature is provided by Rubin [16], who tabulates the best diffusion coefficients for various models from many that are proposed in the literature. Tanner [10] suggests that diffusion and other migration mechanisms be combined into one term dealing with total transport.

Generalized field observations indicate that radon is frequently measured in anomalous concentrations at much larger distances from a radioactive source than can be accounted for by simple-diffusion models [17]. A steady-state diffusion model developed by Jeter and others [18] predicts radon detection several tens of meters from the radioactive source. Mogro-Campero and Fleischer [19] propose the theory of subterrestrial fluid convection as a means to transport radon hundreds of meters before it is diminished by radioactive decay. Soonawala and Telford [20] present a more comprehensive model that involves both diffusion and convection and apply it to complex multi-dimension source and multilayered overburden models. They conclude that geochemical dispersion of uranium and radium might be the explanation for observed detection at long distances from an orebody. That suggestion appears to be correct and has been documented by Stieff and others [21], who measured the radon and radium gradients from a known uranium orebody. Further, a model that includes uranium and radium dispersion for the radon distribution associated with a uranium orebody is consistent with the thorough model developed by Tugarinov and Osipov [5] for helium.

Dyck [22] presents a very generalized but accurate picture for the dispersion of helium, radon, radium, and uranium from a uranium orebody in which uranium and radium are chemically dispersed to some distance from the ore, and helium and radon are further dispersed as a result. Helium is shown to have a greater dispersion but lower intensity than radon.

From the foregoing discussion, various factors have been identified as being important in controlling the distribution of the radioactively produced gases associated with orebodies in sandstone. In summary, these are concentration of the ore (parent and daughter nuclides), 3-dimensional geometry of the ore, dispersion of radioactive minerals into the host rock, transport rates of the gases, and the accumulation and retention abilities of the host rock.

5. ANALYSES OF THE GASES

There are several standard analytical techniques used to measure helium and radon concentrations. For helium, a mass spectrometer is commonly used, which has the sensitivity to resolve the small concentration differences, about 1 part in 10^8, typically found in soil and soil gas. These spectrometers have been developed and used by Goldak [23], Dyck and Pelchat [24], and Reimer and others [25], the latter refined so it is a field-transportable unit. A gas chromatograph could be used for higher helium concentrations, about 1 part in 10^5, that might be found in some natural gases or dissolved in some waters. Radon measurements are usually made either with a scintillometer sensitive to alpha particles or with solid-state electronic or film detectors. The latter have an advantage of acting as time-integrators for radon detection especially useful in areas of low radon concentrations. Various methods of sample collection are used depending on the type of sample to be analyzed. For soil gas, a probe can be pounded or drilled into the ground and a gas sample withdrawn; water can be placed into a degassing chamber and a gas sample extracted. Time integrators usually are emplaced in a hole that had been dug at the sampling location and are retrieved later.

It is interesting to note that the products being analyzed to determine helium and radon concentrations are more closely related than might at first be evident. Alpha particles are, of course, helium nuclei. In the case of radon detection, the techniques are looking specifically at the rate of helium production from radon decay. Total helium concentrations are the reflection of the net accumulation and current equilibrium of helium from radon and all other alpha disentegrations.

6. FIELD OBSERVATIONS

Two field studies are presented to demonstrate the relationship of helium and radon to uranium ore in sandstone.

The first study is a helium and radon survey of water and soil gas in the vicinity of a low-grade uranium deposit. This deposit, located in Weld County, Colorado, was discovered by exploratory drilling and was being considered for recovery by insitu leaching techniques [26]. The host rock is the Laramie Formation of Late Cretaceous age and consists of alternating beds of gray mudstone and gray carbonaceous, pyritic sandstone. Uranium is concentrated along solution fronts in the sandstone. The orebody studied occurs in the lower part of the Laramie Formation at a depth of about 70 meters. The Laramie is conformably overlain by a sequence of light-colored conglomerate, sandstone and mudstone 15-20 meters thick. Ground water and surface water flow is to the south-southeast parallel to the dip. The water table is shallow, ranging from 3-12 meters, depending on local topographic relief. Wells for domestic use are generally 25 meters deep.

Several 15-centimeter-diameter wells had been drilled into the orebody to test the ground water response to large-scale pumping operations that would be associated with solution mining. These wells, in addition to some outlying domestic and livestock supply wells were sampled for radon and helium. Soil-gas helium survey and soil-gas radon were surveyed in the surrounding vicinity of the ore deposits. Water samples from the pipes (in the case of pumped wells) were collected in one-liter plastic containers, filled to 75 percent capacity, and then sealed. The containers were then vigorously shaken for 30 seconds to allow the head-space air to equilibrate with gases from the water. After allowing the containers to stand for 2 minutes, gas samples were withdrawn into hypodermic syringes through an air-tight septum on the container cap and stored for subsequent helium and radon analysis. Soil-gas samples were collected in hypodermic syringes from a hollow probe that had been pounded into the ground to a depth of 1 meter. Helium analyses were performed within hours of sample collection using the mobile, helium-mass spectrometer assembled by the U. S. Geological Survey. Radon analyses were performed immediately after sample collection using a battery-powered alpha scintillometer equipped with a closed, evacuated phosphor cell [27].

The well locations are shown in Figure 1, and Table II shows a comparison of the helium and radon concentrations. Both helium and radon show high concentrations in the vicinity of the ore deposit but helium remains higher in areas where the host rock was sampled whereas radon concentrations are

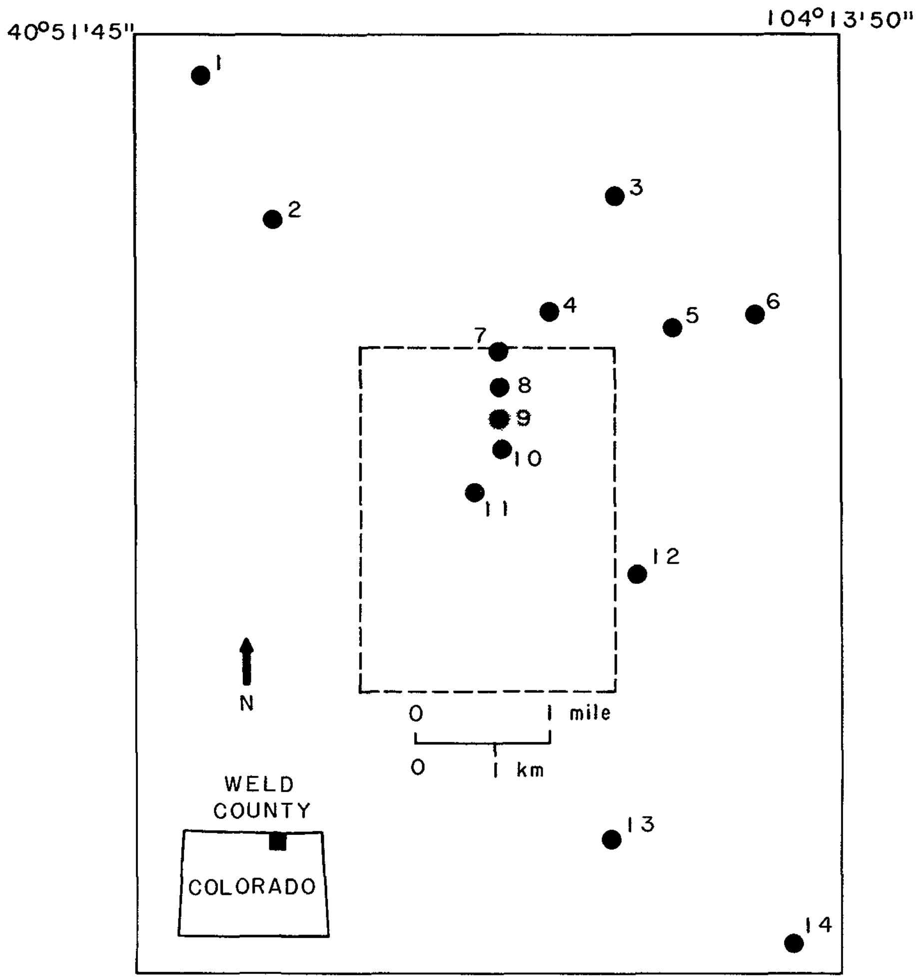

Figure 1
Map of ground water sampling locations in Weld County, Colorado. The sample location numbers are referenced to Table 2, where the helium and radon concentrations are reported. The cross-hatched area is the location of the uranium ore. Present-day ground water flow is toward the south-southeast. Dashed rectangle is enlarged in Figure 2.

TABLE II. HELIUM AND RADON CONCENTRATIONS OF WELL WATER IN THE VICINITY OF THE WELD COUNTY, COLORADO, URANIUM DEPOSIT. BOTH GASES HAVE HIGHER CONCENTRATIONS IN THE WELLS THAT INTERESECTED THE OREBODY; BOTH WERE LOWER IN THE DOMESTIC WELLS AND LOWEST IN THE STOCK SUPPLY WELLS.

Sample Number	Helium ($cm^3 He/cm^3 H_2O x 10^{-9}$)	Radon (counts/min)	He/Rn (relative)	Well depth (meters)
1	4,200	60	70	25
2	6,400	70	91	30
3	8,000	60	133	25
4	400	10	40	5
5	2,400	20	120	5
6	13,000	120	108	10
7	7,600	80	95	80
8	11,600	250	46	80
9	12,200	640	19	80
10	8,400	500	17	80
11	11,200	460	24	80
12	12,200	210	58	75
13	3,000	80	37	10
14	32,200	100	322	25

dramatically lowered. Figures 2 and 3 show the results of the Weld County helium and radon soil gas surveys, respectively. The concentration of helium in the soil gas is higher in the immediate vicinity of the orebody than the background samples on the perimeter of the area. A pattern is revealed that indicates dispersion in the direction of ground water flow. The radon distribution shows discrete highs located immediately above the orebody but no dispersion pattern as for helium. It is possible that some radon highs might be in response to surface contamination from drill cuttings spread around the well site even though care was taken in sampling to avoid obvious drilling sites

A second survey compares helium and radon in the vicinity of the Lamprecht deposit located in south Texas. The host rock for this deposit is the Oakville Sandstone of Miocene age. The sandstone is overlain by 70-90 meters of clay and cemented sandstone. The strata dip 3 degrees to the southeast. As in the case of the Weld County deposit, the ore is below the water table but in contrast it is overlain by a more impermeable material. Ground water flow in the vicinity of this deposit is generally towards the southeast. At the time of this survey, this deposit was being recovered by underground leaching. A series of wells had been drilled in a line perpendicular to the trend of the orebody to monitor ground water chemistry. These wells and several domestic and stock-supply wells were sampled for helium and radon. Only soil-gas helium was analyzed. Sample collection and analysis procedures were the same as described for the Weld County survey.

Figure 4 shows the location of the wells sampled and Figure 5 shows the results of the helium soil gas survey. The soil gas survey reveals only one area of higher helium concentration. The one region of high helium, although spacially related to one defined ore body, may be an artifact caused by local thinning of the cemeted sandstone, which is known to occur in this area. The results of the water analyses are presented in Table III. Both helium and radon concentrations are very anomalous in the vicinity of the monitoring wells numbers (1, 2, 3, and 4 on fig. 4). These concentrations may be anomalously high due to effects of solution mining. Outlying shallow wells

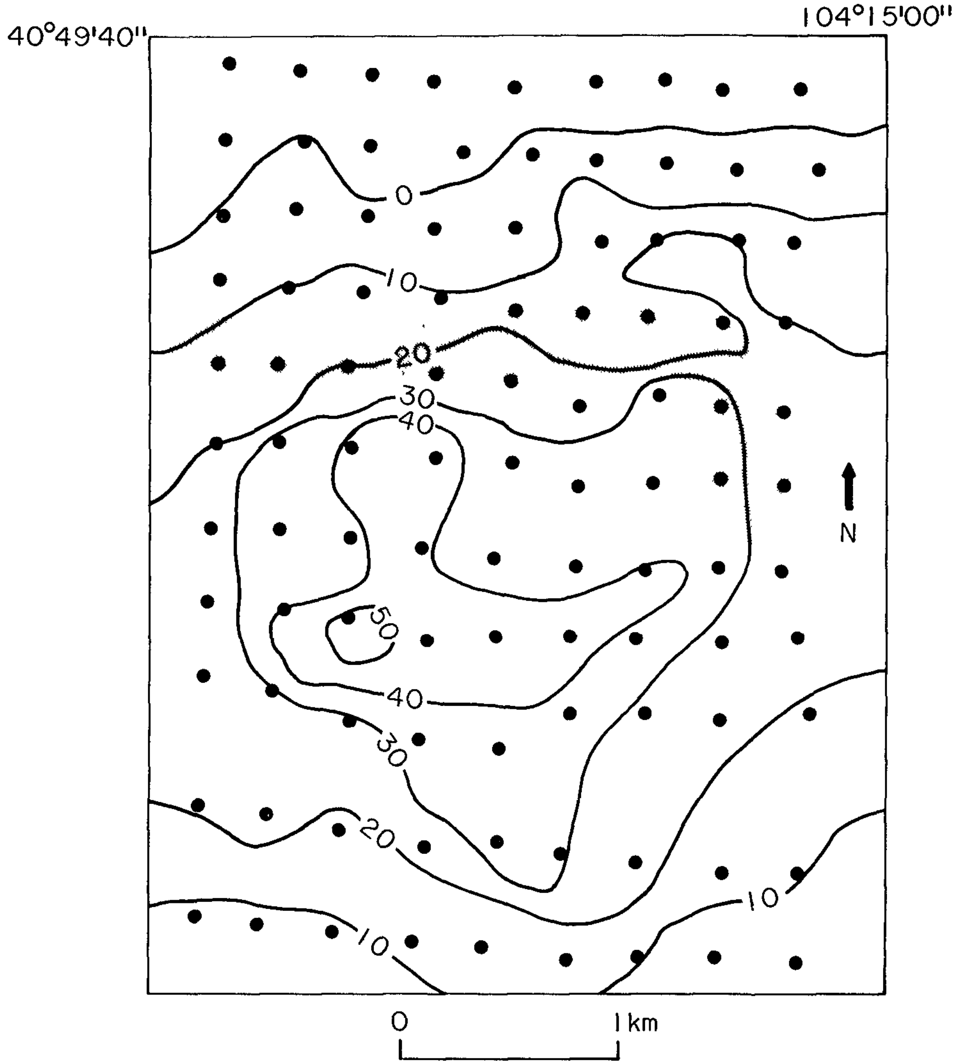

Figure 2
Contour diagram of soil gas He concentrations for the Weld County, CO study. Dots = sample localities and the contour interval is 10 ppb. He concentrations are with respect to air at 5240 ppb. The maximum He concentrations are dispersed 1-2 km in the direction of ground water flow away (S-SE) from the uranium orebody (cross-hatched area).

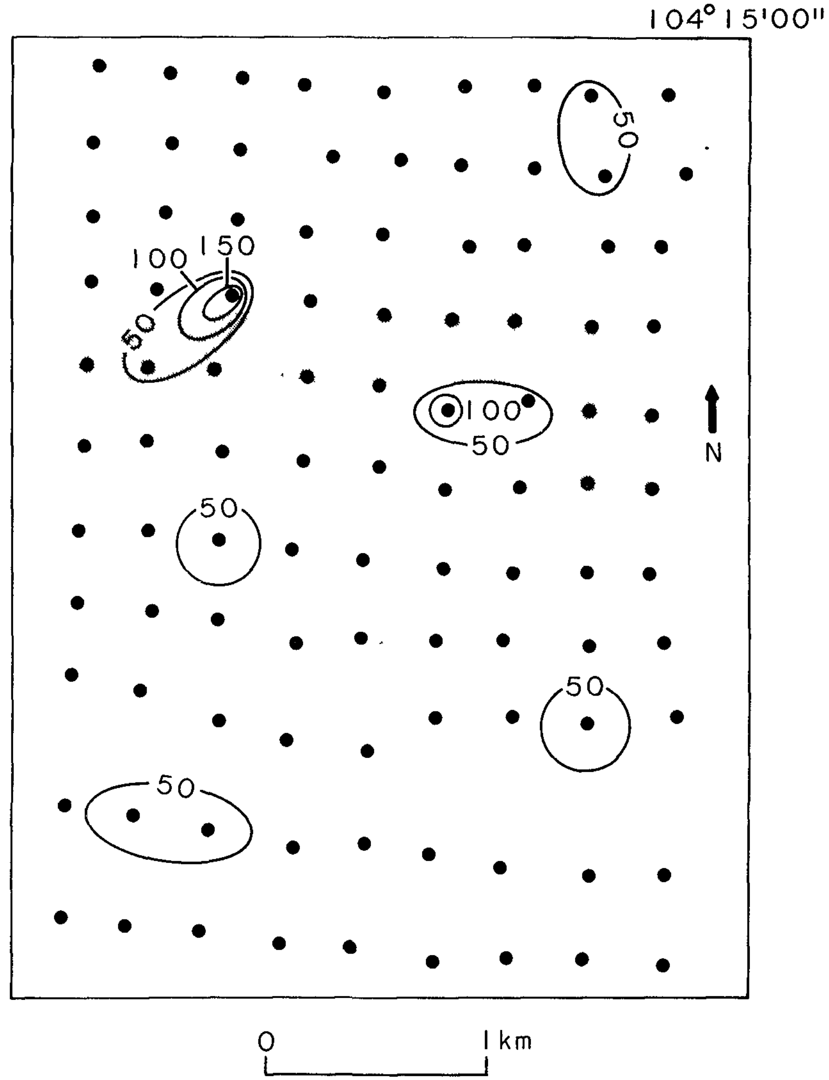

Figure 3
Contour diagram of radon soil gas concentrations for the Weld County, CO study. Dots = sample localities and the contour interval is 50 disintegrations/min. Areas of high radon concentrations are few, but the highest values are over the uranium orebody (cross-hatched area).

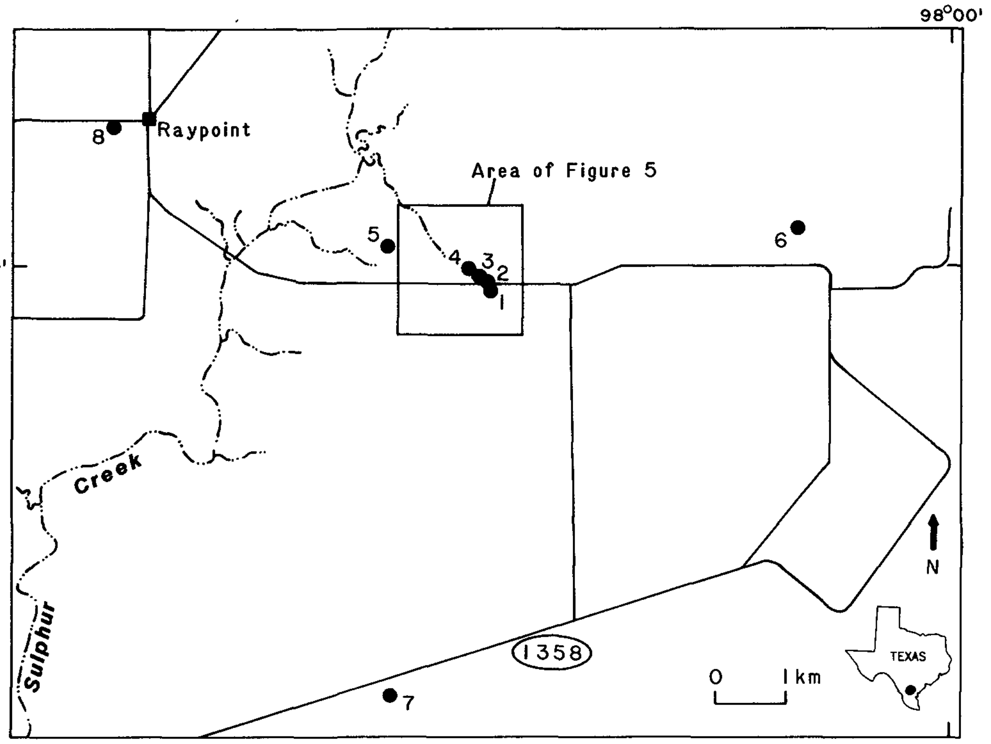

Figure 4
Map showing well locations in Live Oak County, Texas. Sample locality numbers are referenced to Table 3, where the helium and radon concentrations are reported.

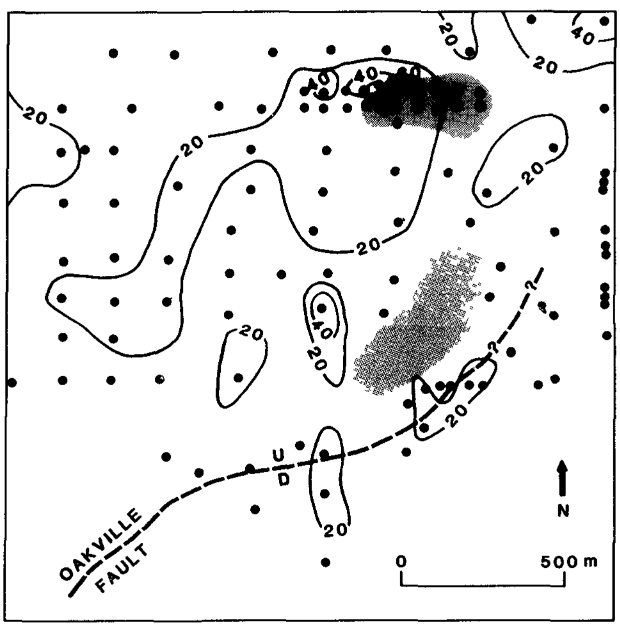

Figure 5
Contour diagram of a soil gas helium survey in Live Oak County, Texas. Dots represent the sample localities and the contour interval is 20 ppb. Helium concentrations are with respect to air at 5420 ppb. Stippled areas are uranium ore at depths of 70-90 m. The highest helium concentration is spatially related to the northern-most occurrence uranium ore.

TABLE III. HELIUM AND RELATIVE RADON CONCENTRATION AND RATIOS OF GROUND-WATER SAMPLES COLLECTED IN THE VICINITY OF THE LAMPRECHT URANIUM DEPOSIT, LIVE OAK COUNTY, TEXAS

Sample Number	Helium $cm^3 He/cm^3 H_2O \times 10^{-9}$	Radon (counts/minute)	He/Rn (relative)	Well depth (meters)
W1	950	1,600	0.059	90
W2	1,720	15,100	0.11	90
W3	630	120,000	0.005	90
W4	810	1,000	0.81	90
W5	710	30	2.36	70
W6	55	320	0.17	20
W7	1,050	80	1.62	160
W8	50	80	0.63	20

(numbers 6 and 8 on fig. 4) show low radon concentrations and helium concentrations only slightly higher than the expected values for water in equilibrium with air. Outlying wells intersecting the Oakville Formation (numbers 5 and 7 on fig. 4) have higher helium concentrations but their radon concentrations are about the same as those of the shallow wells.

These case studies present data that can be explained by the general theories that have been presented discussing gas migration from an orebody in a sandstone environment. Both helium and radon are extremely anomalous in the immediate vicinity (within meters) of the orebody; radon concentrations diminish quickly with distance while helium concentrations decrease more slowly and are disseminated for a greater distance (kilometers). Ground water and the permeability of the overlying rock are shown to have a significant influence on the near-surface gas distribution of these two study areas.

7. SUMMARY

The complex interactions of all natural variables including geologic, hydrologic, and meteorologic factors, make it nearly impossible to develop a single model that adequately characterizes the noble gas distribution associated with sandstone uranium deposits.

The qualitative theories are valid even though estimates of single parameters, emanation rate for example, may vary by a factor of 5 or more. Parameters such as concentration and distribution of ore and subgrade ore, local structure, permeability and porosity of host rock and overburden are also important influences on the dispersion of the gases. Field studies confirm the dispersion of gases from the ore deposit with helium having a much greater range than radon in areas where the deposit is below the water table. Where the deposit is above the water table, theory would predict that dispersion would be less for both gases. With the understanding of basic models already in hand and with future research, one of the most promising applications for noble gas surveys is in estimating the uranium resources and reserves of an area. This can be an excellent supplement to the use of the gases as an indirect detection method for uranium.

ACKNOWLEDGEMENTS

This discussion of helium and radon gas associations with uranium deposits has been made possible by the efforts of many people who participated in and supported the U.S.G.S. helium-detection development program. Specific appreciation for the uranium applications, from which sampling, analytical, and background data usages have been widely adopted by industry, is due to W. I. Finch and T. W. Offield. I thank Alan Roberts and Joel Leventhal for their review of this manuscript.

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INDUCED POLARIZATION AND ELECTROMAGNETIC FIELD SURVEYS OF SEDIMENTARY URANIUM DEPOSITS

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Abstract

Induced polarization (IP) and electromagnetic (EM) geophysical surveys were made over three areas of sedimentary uranium deposits in the western United States. The EM techniques were sometimes useful for investigating general structural settings, but not for finding uranium deposits *per se*. IP techniques were useful to help pinpoint zones of disseminated pyrite associated with the uranium deposits. In one case no clear differences were seen between the IP signatures of oxidized and reduced ground. Spectral (multi-frequency) IP showed no particular advantages over conventional IP for exploration applications. A sediment mineralization factor is introduced comparable to the "metal factor" used to detect porphyry copper mineralization.

1. INTRODUCTION AND LITERATURE REVIEW

Smith [1] and Smith, Cady, Campbell, Daniels and Flanigan [2] reviewed the pre-1976 literature on non-radiometric geophysical methods for uranium exploration. Note that uranium minerals have no unusual magnetic or electrical properties comparable to the high magnetic susceptibilities of iron deposits or high electrical conductivities of massive copper sulfide deposits. Consequently non-radiometric geophysical methods are all "indirect" and highly dependent on particular geologic setting; at best they can only help define favorable areas for uranium deposits. Our review of recent literature on the use of electromagentic (EM) and induced polarization (IP) methods for uranium exploration shows that these methods generally made use of the following types of characteristics of uranium deposits:

(1) Favorable lithologic units for uranium mineralization can have sufficient electrical contrasts with their host rocks to constitute a viable geophysical target. Examples are EM and IP methods used to locate graphitic horizons in the Athabaska basin, Canada [3-6], and EM methods used to locate channels in Tertiary sediments [7-9].

(2) Geological structures associated with some types of uranium deposits can sometimes be detected geophysically [10-16].

(3) Processes by which uranium is concentrated may also localize associated minerals (e.g., authigenic sulfides) that have detectible electrical properties [17-21]. Similarly, these processes may also result in geochemical alteration halos (e.g., the classic oxidized and reduced terranes). Smith, Kalliokoski

and Nash [6] showed that the IP properties of graphites are changed by alteration associated with some uranium deposits in Athabasca basin, Canada. Commercial contractors have reported a case where reduced and oxidized ground near a roll-front was detected by resistivity and IP measurements [22]. Smith, Cady, Campbell, Daniels and Flanigan [2]; Scott and Daniels [23]; Daniels and Scott [24]; Daniels, Scott, Blackmon and Starkey [25]; Scott and Daniels [26]; and Thompson [27] all report cases in which borehole IP surveys made in well-logging or surface-to-hole configurations have indicated possible uranium mineralization. These investigators agree that sulfide minerals, probably pyrite or marcasite, are the principal source for the observed higher IP responses near uranium deposits. The investigations show that these minerals occur near uranium roll-fronts, offset somewhat in the direction of reduced ground, and that they often can be detected when present in quantities as low as 0.2 to 0.5 weight percent.

In the remainder of this report, we describe some surface EM and IP studies we have made over sandstone-type uranium prospects in the Western United States (Fig. 1).

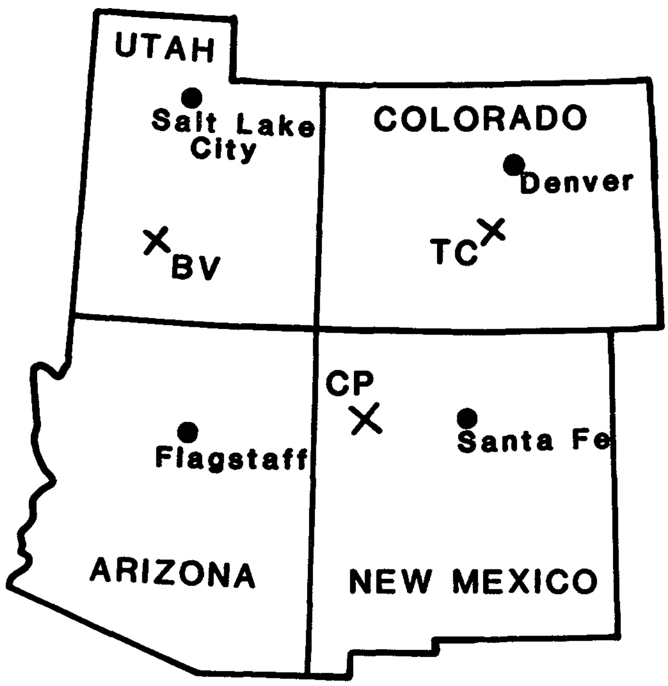


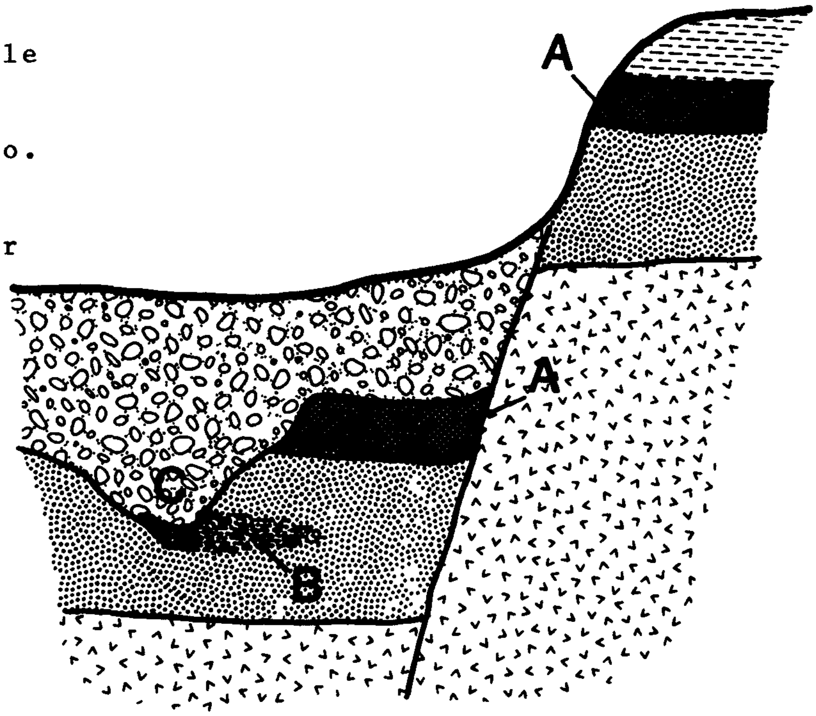
FIG. 1 Locations of the geophysical surveys described in this report. TC = Tallahassee Creek, BV = Beaver Valley, CP = Crown Point

2. SIROTEM AND SPECTRAL IP STUDIES: TALLAHASSEE CREEK AREA, COLORADO

The Tallahassee Creek, Colorado, uranium district lies along the southern edge of the Thirtynine Mile volcanic field, which was active in Oligocene time. Extensive post-late Eocene faulting in this area had caused a number of graben valleys, filled with sedimentary rocks and separated by horsts of

Precambrian bedrock [28]. Uranium as uraninite and minor secondary uranium minerals occurs in podiform lenses in the sediments filling the grabens, and also where altered zones in the Precambrian wall rocks pass into the graben sediments. It is possible, but not proved, that the uranium deposits derive from devitrification of tuffs and other volcanics of the Thirtynine Mile volcanic field [29,30]. Dickinson [29] shows that the Hansen deposit, a major prospect in the area containing about 12,000 metric tons of uranium, is located just outside a meander of a paleostream channel which had cut windows through such a tuff unit (Fig. 2). A possible role of geophysics in such a setting, therefore, is to help trace such buried stream channels.

FIG. 2 Sketch showing the setting of a possible type of uranium deposit from the Tallahassee Creek district, Colorado. Uranium leached from volcanic tuff A is deposited in pods B near paleostream channel C. Simplified from Dickinson [29].



In the summers of 1980 and 1981 the U.S. Geological Survey made geophysical measurements near Tallahassee Creek, Colorado. Induced polarization, Slingram frequency-domain EM, and Sirotem (GeoEx Pty. Ltd. Trademark)[1] time-domain EM measurements were made on profiles passing directly over uranium mineralization, as defined by drilling. Spontaneous polarization, total-field magnetics, and surface spectrometric gamma-ray measurements were also made at selected sites. These last three techniques showed no significant anomalies, however.

[1] Trade names and model numbers of equipment used in the surveys are given for the sake of complete description. This citation does not constitute endorsement by the U.S. Geological Survey.

The profile shown in Figure 3 was made far from crystalline rocks, on sediments which filled a wide, deep graben. Drilling here by Cypress Exploration Co. had indicated uranium-mineralized sediments at about 45 m depth. The deposit was thought to be podiform, with maximum lateral extent of about 150 m. Like other small pods in the area, this body was not considered economic at the time, though projected construction of a uranium mill at the nearby Hansen uranium deposit might have made it so. (Plans for the mill were later shelved.)

Figure 3a shows results from the Sirotem time-domain EM survey, made using coincident square loops, 61 m on a side. (Survey procedures using the Sirotem system are described by Busselli [31].) Heavy vertical bars indicate locations of two uncased drillholes where uranium was found. The calculated apparent resistivity is plotted vertically below each measurement site for a total of 6 channels. Each channel reflects response measured by the receiver loop during an interval of time after current in the transmitter loop has been turned off. The time index shown is at the center of the interval for its channel. Because responses at later times generally reflect conditions at greater depths, they are plotted deeper on the profile figure.

The EM profile of Figure 3a shows a buried zone of relatively high resistivity to the right of the boreholes, and possibly another such zone, less clearly defined, to their left. The deep low-resistivity zone at Station 2 is a one-station anomaly, and so is regarded as unestablished; multiple repeats of the measurements at this station, however, all showed this feature. This profile can be interpreted to show a lower-resistivity stream channel cut into a higher-resistivity unit. This interpretation has not been tested, however; further drilling at the site was stopped due to falling uranium prices.

Figure 3b shows results at this same site of the spectral IP survey. The survey was made using a dipole-dipole configuration with 61-m dipoles. The data was collected using a ZERO GDP-12 (Zonge Engineering & Research Organization Trademark) and following procedures outlined in the ZERO manual. The pseudosection shows Phase Difference between GDP-12 frequencies 4 (1.0 Hz) and 1 (0.125 Hz), divided by phase at frequency 1. Phase Difference is a measure of IP response which is used in spectral IP surveys; it is somewhat analogous to PFE (percent-frequency-effect), the IP measure used in conventional frequency-domain IP surveys. Relatively high Phase Difference values are seen on the figure near the borehole where uranium was found. As mentioned, such enhanced IP response is common near roll-front uranium deposits. Thus the above result may argue that oxidation-reduction processes could have been involved in forming this deposit.

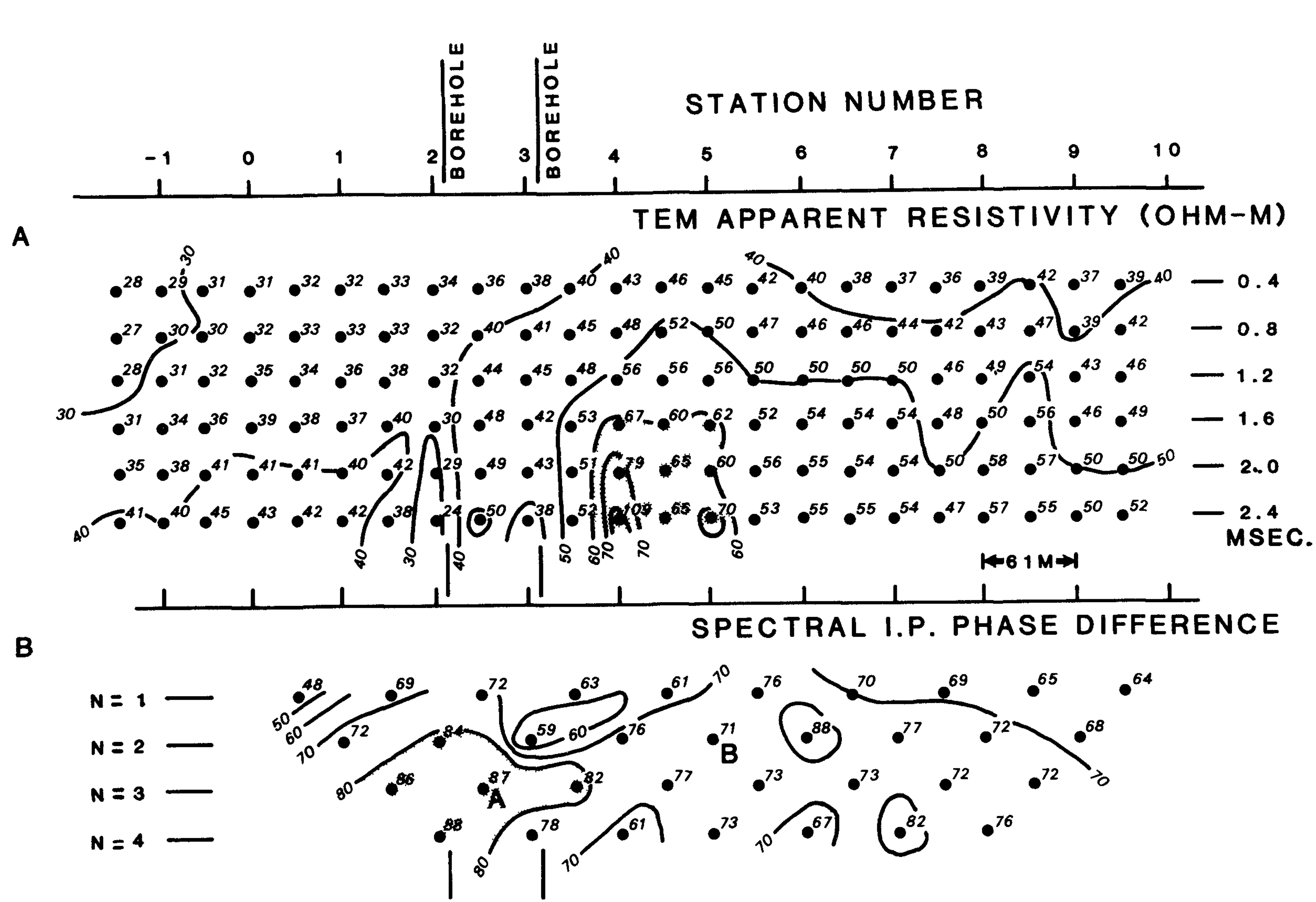


FIG. 3 (a) Profile showing apparent resistivity over a small uranium deposit in the Tallahassee Creek district, Colorado. The data was collected using a Sirotem time-domain EM system with square coincident loops 61 m on a side. Heavy vertical bars show positions of nearby boreholes with uranium minerals. (b) Pseudosection showing spectral IP Phase Differences along the same profile. The data was collected using a ZERO GDP-12 with a dipole-dipole array and 61 m dipoles. A and B are the locations of the IP spectra shown in Fig. 4.

Figure 4 shows complete spectral IP signatures at two places on the profile; A, a "mineralized" location and B, a "background" location (these locations are shown on Fig. 3b). There are clear differences between the two signatures, though the reasons for these differences are unknown. If enough spectral measurements were available for statistical correlations, composite signatures might suggest appropriate spectral IP indexes that could be used for empirical detection of favorable areas for uranium mineralization. Using the drill, such measures could be checked and refined so that spectral IP might become a powerful exploration tool. Such a strategy probably would be site-specific; it is not known whether signatures from one area would apply in another.

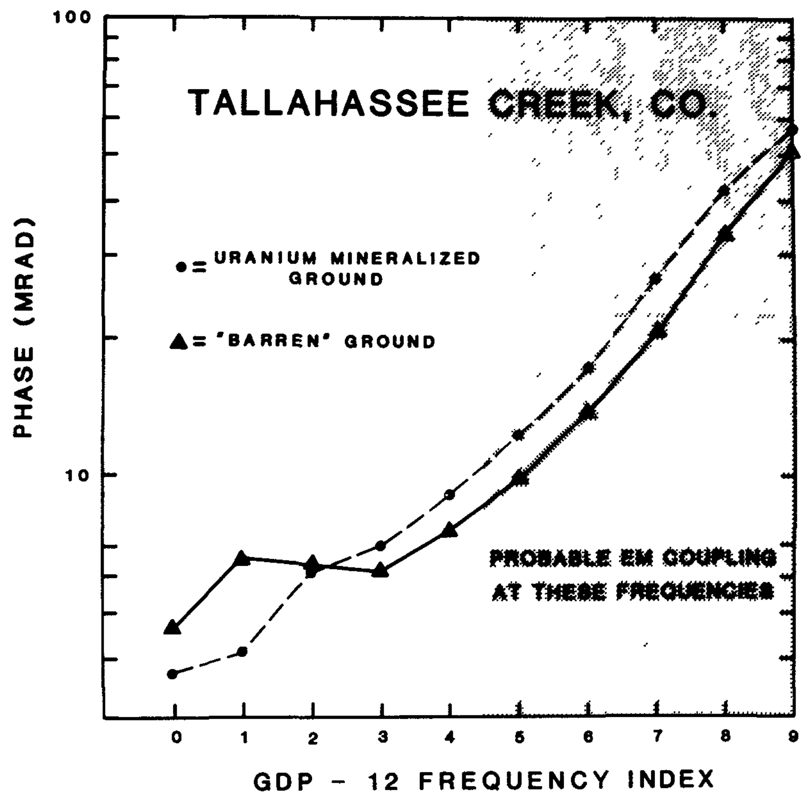


FIG. 4 Spectral IP signatures at two locations on the profile shown in Fig. 3, indicating differences between "mineralized" ground (Location A) and "barren" ground (Location B). Signal frequency f is 2 to the power n-4, where n is GDP-12 index (e.g., n=0; f=0.0625 Hz). The upward slopes of the curves for frequencies greater than frequency 4 are thought due to EM coupling, and not to IP properties of the ground. The differing slopes for low frequencies, however, may be due to real geologic differences between the two sites.

3. IP SURVEYS; CROWN POINT, NEW MEXICO

Numerous sandstone-type uranium deposits are found in Mesozoic formations of the San Juan basin, Arizona-New Mexico [32]. Figure 5 shows a resistivity profile near Crown Point, New Mexico, which passes over a uranium deposit that had been drilled by private industry [33]. The data was obtained by Phoenix Geophysics Inc. under contract to the U.S. Geological Survey using the dipole-dipole configuration with 122 m dipoles. Using the filtering scheme of Fraser [34], the original pseudosection array of values was reduced here to a single resistivity index which varies along the profile. This profile shows higher resistivity values over ground which drilling indicates is uranium mineralized.

The Crown Point data presents us with a dilemma, however. A conventional rule-of-thumb ([35], p. 203) states that the typical depth of penetration for dipole-dipole surveys is of the order of one electrode interval (here, 122 m), while the reported depth of uranium deposits in this area is between 500 and 600 m. This particular survey therefore should not detect the reported uranium deposits. Yet eight additional survey lines, spaced approximately 2 km apart and each using 122 m dipoles, all showed comparable features which correlated with each other and with the extension of known uranium mineralization. Either there is a remarkable coincidence here; or the modern generation of geophysical gear is far outperforming rule-of-thumb expectations; or there is a halo of some sort extending up into the shallow sediments overlying the uranium mineralized zones. We favor the latter explanation. Note that similar geophysical effects have also been observed over deep oil fields [36, 37], though it seems unlikely that the same mechanism (whatever it is) could be acting in such different cases.

Figure 6 shows IP effects along a portion of the same line as Fig. 5. The contractor's report included standard plots of percent-frequency-effect (PFE), apparent resistivity, and the so-called "metal-factor", a normalized ratio of the two (see Sumner [35] for a fuller discussion of these terms). Metal factor is an empirical index developed for exploration for porphyry copper deposits in the southwestern United States. Relative to the surrounding ground, such deposits have high PFE and low resisitivity; the ratio of the two therefore tends to enhance measurements having both favorable characterisitics. Earlier U.S. Geological Survey work on uranium roll-fronts ([2], [23-27]) showed signatures that contrasted with those of porphyry copper deposits, however. The uranium minerals that occur in roll-front deposits represent only one of several groups of minerals that precipitate from ground-water solutions because of redox reactions in sandstone aquifers. Near the roll-front, but down hydrologic gradient from it, pyrite and/or marcasite are commonly precipitated. If sulfides occur in sufficient quantity they give rise to PFE anomalies. At such sites, a somewhat higher resisitivity is often measured, possibly because other ground-water precipitates plug interstices in the sandstone aquifer, retarding both hydraulic and electrical conduction.

If a roll-front is characterized by the above processes, then metal factor is a poor index to use to help find it. A better index would emphasize measurements having both relatively high PFE's and resistivities. Here we used the product of these two quantities. Figure 6 compares metal factor and PFE-resistivity product. In this area it appears that the PFE-resistivity product does a better job of highlighting (halos above the) favorable ground, as indicated by boreholes.

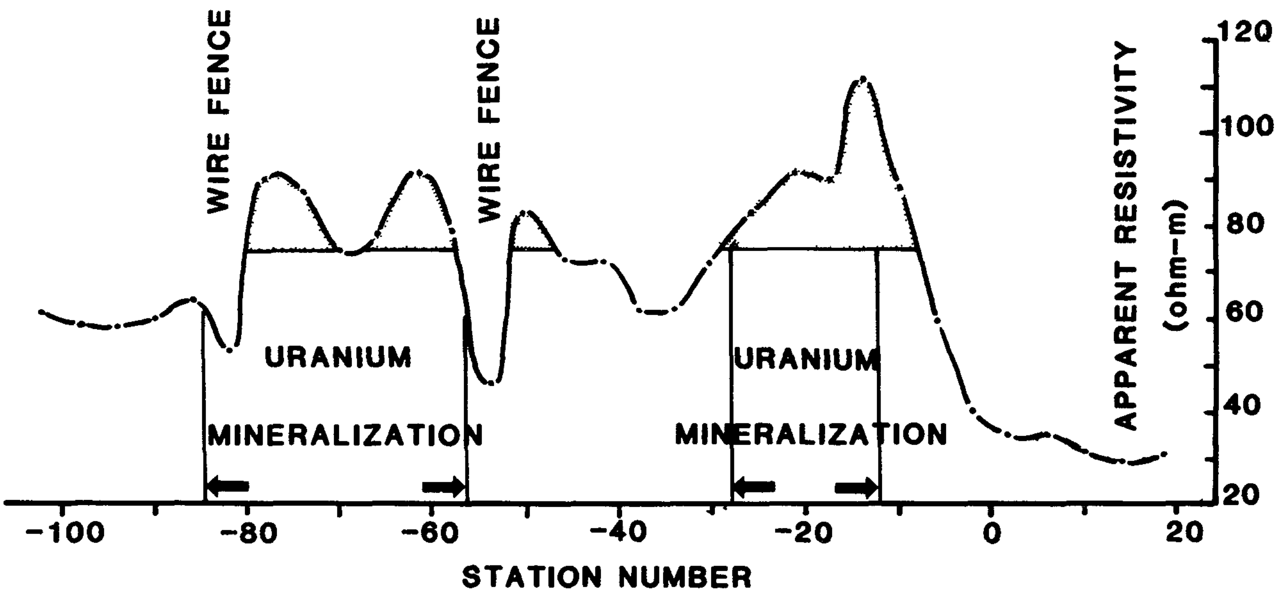


FIG 5. Apparent resistivity profile passing over two zones of uranium mineralization near Crown Point, New Mexico. The dipole-dipole configuration with 122 m dipoles was used to collect this data. Wire fences crossing the profile give local lows which should be disregarded. Apparent resistivities above about 75 ohm-m (shaded) appear to mark the zones of uranium mineralization here.

4. SPECTRAL I.P.; BEAVER, UTAH

The Beaver basin, Utah, has existed since mid-Miocene time, and may have acted as a sump for uranium leached from volcanics of the nearby Marysvale volcanic field [38]. Some geophysical field work was done by the U.S. Geological Survey in the Beaver valley in 1980 and 1981 on property leased by Spenst Hansen Associates, but to date no mines have been developed there [39], [40].

Figure 7 shows results from a study in the Beaver area which attempted to distinguish oxidized and reduced ground using spectral IP. The unit measured is a porous conglomerate beneath the Joe Lott Tuff Member of the Mount Belknap Volcanics. Logistical considerations limited measurements to two sites about 6.4 km apart; at one site the conglomerate unit was red in color (oxidized) and at the other it was brown (reduced). Magnetic and VLF electromagnetic measurements around the two sites showed that each area was homogeneous. Spectral responses were measured using the ZERO GDP-12 system in a dipole-dipole configuration with 15.2 m dipoles and n=1. There are no clear differences between the two spectra. We conclude that spectral IP cannot distinguish oxidized from reduced ground in this area. In turn this implies that spectral IP cannot be used here to bracket locations of possible roll-fronts which may occur between

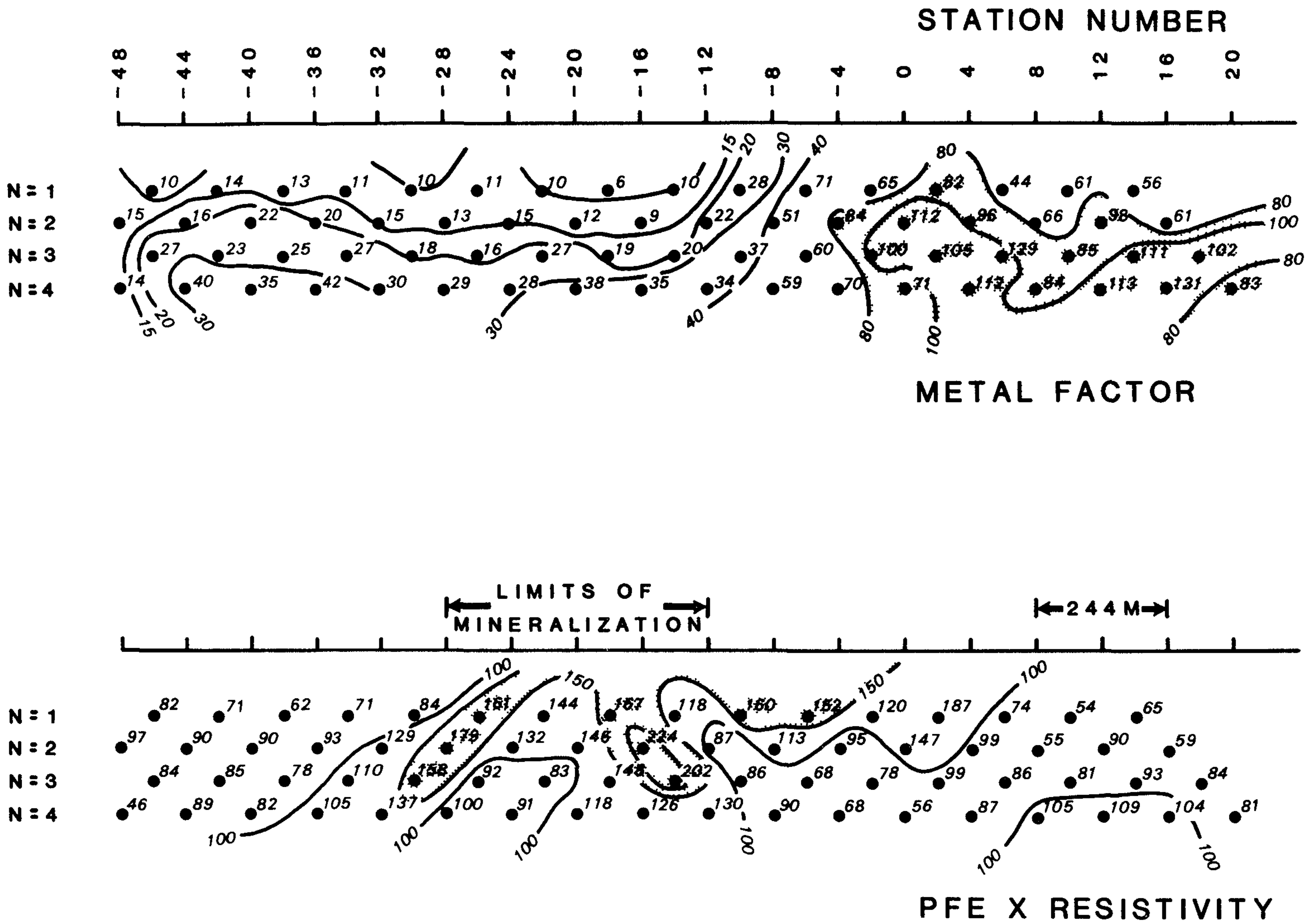


FIG. 6 IP pseudosections of conventional two-frequency (0.1, 1.0 Hz) IP data from the Crown Point uranium district, New Mexico. Dipole-dipole configuration was used with 122 m dipoles. The top pseudosection shows metal factor and the bottom pseudosection shows PFE-resistivity product, introduced in the text. Heavy horizontal bar shows limit of horizontal extent of uranium mineralization, as determined by boreholes.

oxidized and reduced ground. Note, however, that we have shown that both conventional and spectral IP may help locate roll-fronts that occur within the limits of the IP profile.

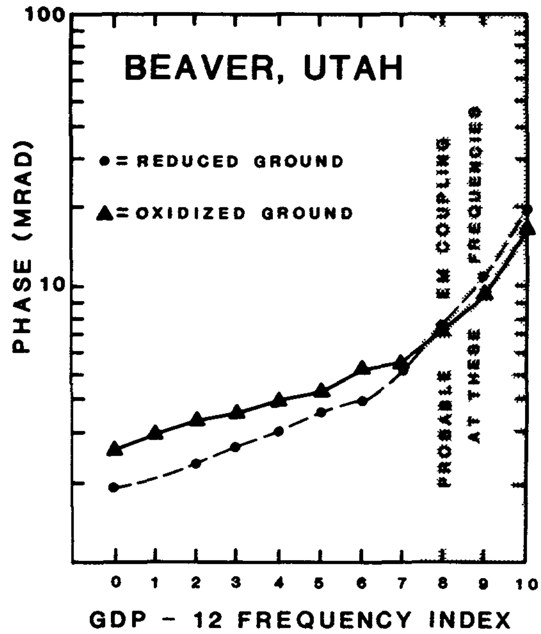


FIG. 7 Spectral IP signatures of oxidized and reduced portions of a porous conglomerate unit near Beaver, Utah. The upward slopes of the curves for frequencies greater than frequency 7 are thought due to EM coupling, but the signatures at lower frequencies probably reflect true IP properties of the conglomerate unit. The two curves are so similar that it appears difficult to distinguish the two types of ground using spectral IP alone.

5. SUMMARY

On the basis of this and other work, we have come to some tentative conclusions regarding EM and IP geophysical work in exploring for sandstone-type uranium deposits. First, although rocks near such deposits often have a somewhat lower electrical conductivity than other rocks in the area, the effect is minor and is easily masked by other structural and petrological variations, so that EM is not likely to be useful for direct detection of mineralized ground. This conclusion is in strong contrast to geophysical experience in the Athabasca basin, Saskatchewan, where rocks near unconformity-vein uranium deposits have a much higher electrical conductivity than other rocks in the area, and where EM is a very successful exploration tool. For sandstone-type uranium deposits, however, it appears that EM is mainly useful for delineating structures in the rocks (e.g., buried stream channels) which may affect the location of the deposits.

Second, both conventional and spectral IP techniques hold strong promise for finding possible sandstone-type uranium deposits, principally through their capability to detect associated pyrite or other chargeable minerals. In hole-to-hole or hole-to-surface borehole configurations, the IP method can be sensitive to sulfide concentrations as small as 0.2 weight percent [27]. Because they typically average the chargeability properties of larger blocks of ground, surface IP techniques require somewhat larger sulfide concentrations for detection. Conventional (non-spectral) IP techniques are often adequate to localize sedimentary uranium deposits. The PFE-resistivity product appears to enhance the signature of such deposits to a modest degree. Using spectral IP, it is possible that better uranium-mineralization indices could be devised, involving algebraic combinations of spectral IP responses at key frequencies. In the single instance where we tried it, we found no way to distinguish oxidized from reduced ground using IP measurements alone.

Acknowledgments

We thank Cypress Exploration Co. (now part of AMOCO Minerals Co.) for allowing access to company properties in the Tallahassee Creek, CO, area; special thanks goes to Fred Grigsby for all his help during our sometimes-hectic work schedules there. We also thank the Navajo Indian nation for arranging access to their land in the Crown Point, N.M. area, and C. G. Cunningham, Jr. of the U.S. Geological Survey and Spenst Hansen of Spenst Hansen Associates for many helpful discussions on the Beaver Valley, UT, area.

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PART IV

SUMMARY MODELS

GEOLOGIC ENVIRONMENTS FOR BASAL-TYPE URANIUM DEPOSITS IN SEDIMENTARY HOST ROCKS

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Abstract

Basal-type uranium deposits are characterized by economic concentrations of unusual primary minerals such as ningyoite, francevillite, saleeite and uranocircite. These deposits occur within unconsolidated Tertiary fluvial sediments that overlie or are adjacent to major fault zones or graben structures within igneous and metamorphic massifs. Host sediments, which comprise a fining upwards sequence of conglomerates, sandstones and mudstones containing abundant organic material as well as iron sulphides and/or iron oxides, generally occupy paleovalleys within the basement complex. Cover rocks are, with few exceptions, intermediate to basic volcanics representing Tertiary continental volcanism; the volcanics often contain intercalated sediments. Basement complexes consist of intermediate to felsic intrusive and metamorphic rocks which have generally undergone a multiphase history of intrusion or metamorphism and an important period of extensional tectonism. The high density of fracture zones within the basement complexes and the high degree of fracture interconnectivity results in significant groundwater-rock interaction to produce bicarbonated, uraniferous groundwaters. The compositional makeup of many basal-type uranium deposits can be explained by preferential availability to groundwater leaching of such elements as Ca, Mg, K, Ba, Pb, P and V within the basement complexes.

The genesis of this type of deposit requires a thorough understanding of the inter-relationships between the source of ore-forming elements, mechanisms of migration, paleoclimatology, environment of deposition and preservation. The entire ore-forming process is initiated, promoted and preserved by favourable tectonic events of which the most important appear to be extensional tectonism and regional uplift.

1. INTRODUCTION

Basal-type uranium deposits may be considered as a specific class of sandstone-type uranium deposits. In the author's terminology, however, they form a small class of groundwater infiltration-type uranium deposits. Their general characteristics and geological settings suggest that they are transitional between basinal, 'sandstone-type' deposits, and surficial uranium deposits, such as the uraniferous calcrete-gypcrete deposits. The term basal-type was first proposed by Katayama et al. (1) to describe Japanese uranium deposits in fluvial basal sediments overlying Cretaceous-Tertiary intrusive complexes. Since then, many uranium deposits of this type have been found throughout the world, the major ones of which are shown in Fig. 1, together with an outline of potential areas in which others may be found. General features characterizing this type of uranium deposit may be summarized as follows:

1. Deposits occur in basal units of fluvial continental sediments overlying previously uplifted igneous or metamorphic basement complexes.
2. Mineralization is spacially associated with fault zones, small grabens and major tectonic lineaments in the basement complexes.
3. Ore deposits are capped by impermeable volcanic and/or sedimentary units.

TABLE 1 MAJOR CHARACTERISTICS OF THE PRINCIPAL BASAL-TYPE URANIUM DEPOSITS

DEPOSIT	AVERAGE GRADE (%U)* AND TONNAGE (TONNES U)	MINERALOGY	HOST ROCKS	COVER ROCKS	BASEMENT	TECTONICS
Blizzard, B.C., Canada	0.18;4040 (7)	Ningyoite, saleeite, autunite, pyrite, organics, limonite	Miocene-Pliocene sst, mdst, cglm	Pliocene basalts	Jurassic-Cretaceous-Eocene Qtz Mnzn, Grdr; Hrnb Mnzn	Extensional (pre ore), uplift (post ore); deposit underlain by major fault zone
Tyee, B.C., Canada	0.031; 850 (7)	Ningyoite, marcasite, organics	Miocene-Pliocene cglm, minor mdst	Pliocene basalts	Jurassic-Cretaceous-Eocene Qtz Mnzn, Grdr; Hrnb Mnzn	Extensional (pre ore), uplift (post ore); major fault zone underlying deposit
Cup Lake, B.C., Canada	0.042; 420+ (7)	?, pyrite	Miocene-Pliocene sst, mdst, cglm	Pliocene basalts	Jurassic-Cretaceous-Eocene Qtz Mnzn, Grdr; Hrnb Mnzn	Extenional (pre ore), uplift (post ore); extension of Blizzard fault zone
Haynes, B.C., Canada	0.017; 340+ (7)	?, pyrite	Miocene-Pliocene cglm-sst-mdst	Pliocene basalts	Jurassic-Cretaceous-Eocene Qtz Mnzn, Grdr; Hrnb Mnzn	Extensional (pre ore), uplift (post ore); probable underlying fault zone
Sherwood, Wash., U.S.A.	0.075; 4820 (9)	Uraninite, coffinite, $U-PO_4$, organics, pyrite	Eocene Sanpoil cglm	Sanpoil andesites (Eocene) Columbia basalts (Miocene)	Loon Lake Qtz Mnzn (Cretaceous)	Extensional (pre ore), uplift (post ore); major fault zone underlying deposit
Juniper, Cal., U.S.A.	0.3-0.5; ? (16)	Uraninite, coffinite, organics, autunite	Miocene Relief Peak cglm, carbonaceous sst, slts	Relief Peak andesite, slst, mdst (Miocene)	Cretaceous Sierra Nevada Batholith (grdr)	Pre and post ore faulting
Stanley, Idaho, U.S.A.	Many small deposits some averaging 0.20-0.3% (14)	Uraninite, coffinite, $U-PO_4$, organics, coal, pyrite	Oligocene-Miocene cglm, tuffaceous sst, mdst, slts; carbonaceous beds	Oligocene-Miocene Challis Volcanics (andesite, basalt, latite)	Cretaceous Idaho Batholith (grdr, qtz mnzn)	Intermittant extensional tectonics and uplift
Hansen, Colorado, U.S.A.	0.068; 10200 (13)	Uraninite, coffinite carbonaceous material	Eocene Echo Park alluvium	Thirtynine Mile andesite (Oligocene)	Precambrian granodiorite	Graben formation later uplift; deposit within Echo Park Graben
Picnic Tree, Colorado	0.068; 850 (13)	Uraninite, coffinite carbonaceous material	Oligocene Talahassee Creek cglm	Thirtynine Mile andesite (Oligocene)	Precambrian granodiorite	Graben formation later uplift; deposit within Echo Park Graben
Ningyo-Toge, Japan	0.043; 2132 (5) (5 deposits)	Ningyoite, uraninite coffinite, pyrite, organics	Miocene cglm, arkose ssts	Andesite and mudstone (Miocene)	Mesozoic-Paleogene granites	Extensional tectonics and uplift; fault zones underlying deposits
Tono, Japan	0.046; 5100 (5) (4 deposits)	Uraninite, coffinite pyrite, organics	Miocene cglm, arkose ssts	Andesite and mudstone (Miocene)	Mesozoic-Paleogene granites	Extensional tectonics and uplift; fault zones underlying deposits
St. Pierre, France	0.15; 1700 (20)	Francevillite, tyuyamunite, autunite, limonite, organics	Oligocene sst	None, Miocene basalts removed	Biotite granite (Hercynian)	Extensional, uplift; deposit located over Bordier Nord fault zone
Antisarabe, Madagascar	0.10; 85-130 (23)	Uranocircite, organics	Plio-Pleistocene fluvial-lacustrine seds	Plio-Pleistocene Vlccs (partially removed)	Precambrian gneiss, granite	Graben formation, uplift
Sebinkarahisar, Turkey	0.04; 300 (24)	Autunite, torbernite uranocircite, limonite organics	Eocene sst-cglm	Miocene basalts	Mesozoic granite	Extensional tectonics, uplift
Koprubasi Deposits, Turkey	0.03-0.06; 3400 (22) (7 deposits)	Autunite, uraninite, pyrite, jarosite, waylandite, siderite	Miocene cglm, sst mdst	Upper Miocene lmst-slst	Precambrian gneiss	Extensive block faulting; deposits adjacent to fault zones in basement

* Numbers in brackets correspond to references at end of text.

4. Mineralization is often exotic, comprising economic concentrations of such rare minerals as ningyoite $(Ca_{2-x}U_x(PO_4)_2 \cdot nH_2O)$, saleeite $(Mg(UO_2)_2(PO_4)_2 \cdot 8\text{-}10H_2O)$, francevillite $((Ba,Pb)(UO_2)_2(VO_4)_2 \cdot 5H_2O)$, uranocircite $(Ba(UO_2)_2(PO_4)_2 \cdot 8H_2O)$, and uraniferous waylandite, zeolites, apatite, calcite and clay minerals.
5. To date, recognized basal-type deposits are all of Tertiary age (See Section on Pre-Tertiary Deposits).

Major characteristics of the principal basal-type uranium deposits are given in Table 1. It should be noted that with the exception of the Japanese and Canadian deposits researchers who have worked on many of these deposits have not described them as being of basal-type (or sandstone-type). They have been collated by the author as representative of this class of deposit because they exhibit the main features mentioned above. Thus basal-type deposits have been described from Japan (1-6), Canada (7), United States (8-18), France (19-21), Turkey (22) and Madagascar (23). Only the salient characteristics of this deposit type can be given in the present review and the reader is, therefore, refered to the above mentioned references for more detailed information.

2. UNDERLYING BASEMENT COMPLEXES

Basal-type uranium deposits occur in Tertiary continental sediments overlying (a) Jurassic-Cretaceous-Tertiary igneous complexes (e.g., Tono and Ningyo-Toge areas of Japan, Figs. 2 and 3; Okanagan Highlands Intrusive Complex, British Columbia, Canada, Fig. 4; Loon Lake Batholith, Washington, U.S.A., Fig. 5; and the Idaho Batholith, Idaho, U.S.A., Fig. 6), (b) Paleozoic igneous and metamorphic complexes (e.g., Central Massif, France, Fig. 7 and 8) and, (c) Precambrian igneous and metamorphic core complexes and massifs (e.g., Tallahassee Creek area, Colorado, U.S.A., Fig. 9; Menderes Massif, Turkey, Fig. 10 and Ankaratra Massif, Madagascar, Fig. 11).

All of these igneous and/or metamorphic basement complexes have been uplifted during pre-Tertiary times as a result of specific orogenic events, such as the Laramide orogeny in the North American Cordillera and the Hercynian orogeny in Europe. Uplift and exposure of these basement segments was attended by extensive block faulting and fracture development leading in many cases to highly irregular horst and graben landscapes (See Figs. 5-11). During specific Tertiary periods of tectonic quiescence or gradual uplift these landscapes became paleosurfaces on which fluvial-lacustrine sediments hosting mineralization developed.

Basement complexes composed entirely of igneous intrusive bodies are dominated by rocks of felsic compositions, such as biotite granite (Tono and Ningyo-Toge, Japan, Figs. 2 and 3 and Ussel granite, France, Fig. 8), porphyritic quartz monzonite-granodiorite-syenite (e.g., Okanagan region, British Columbia, Canada, Fig. 4), two mica granites (e.g., Loon Lake Batholith, U.S.A., Fig. 5: Central Massif, France, Fig. 7). The metamorphic rocks comprising some of these complexes are dominated by biotite gneiss, micaschists and migmatites (e.g., Central Massif, France, Fig. 7; Tallahassee Creek area, Colorado, U.S.A., Fig. 9; Menderes Massif, Turkey, Fig. 10 and Ankaratra Massif, Madagascar, Fig. 11).

All of the basement complexes outlined in Figs. 2-11 and Table 1 contain primary uranium deposits in the form of one or more of (a) pitchblende-bearing vein and shear zones (e.g., Central Massif, France; Idaho Batholith, U.S.A.), (b) uraniferous pegmatites (e.g., Ankaratra Massif, Madagascar; Okanagan Highlands Intrusive Complex, Canada), contact metasomatic uranium deposits (e.g., Loon Lake Batholith, U.S.A.) and (c) uraniferous sulphide-bearing stockworks (e.g., Okanagan Highlands Intrusive Complex, Canada).

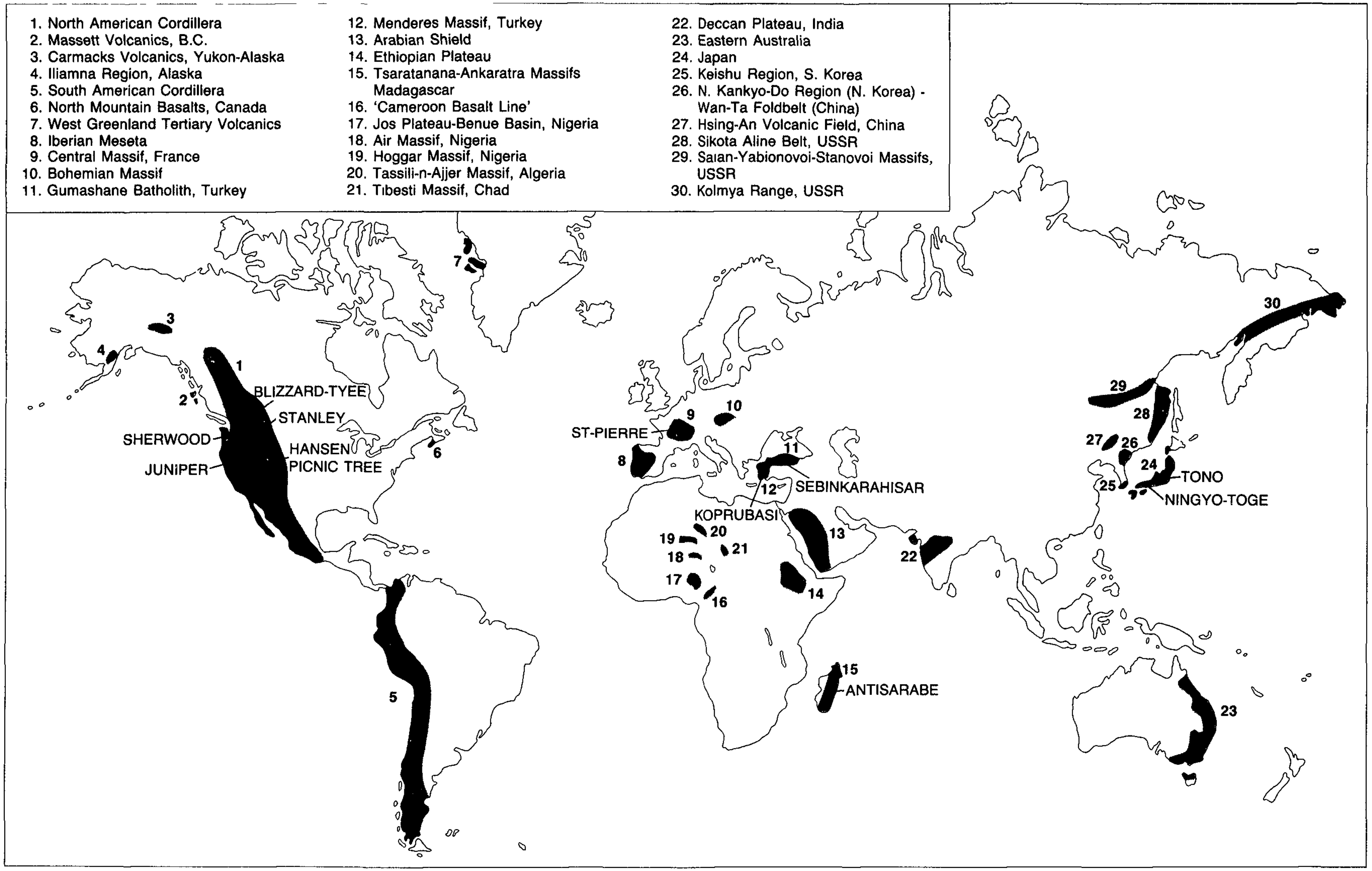

Figure 1 Principal basal-type uranium deposits and regions of potential mineralization (shaded).

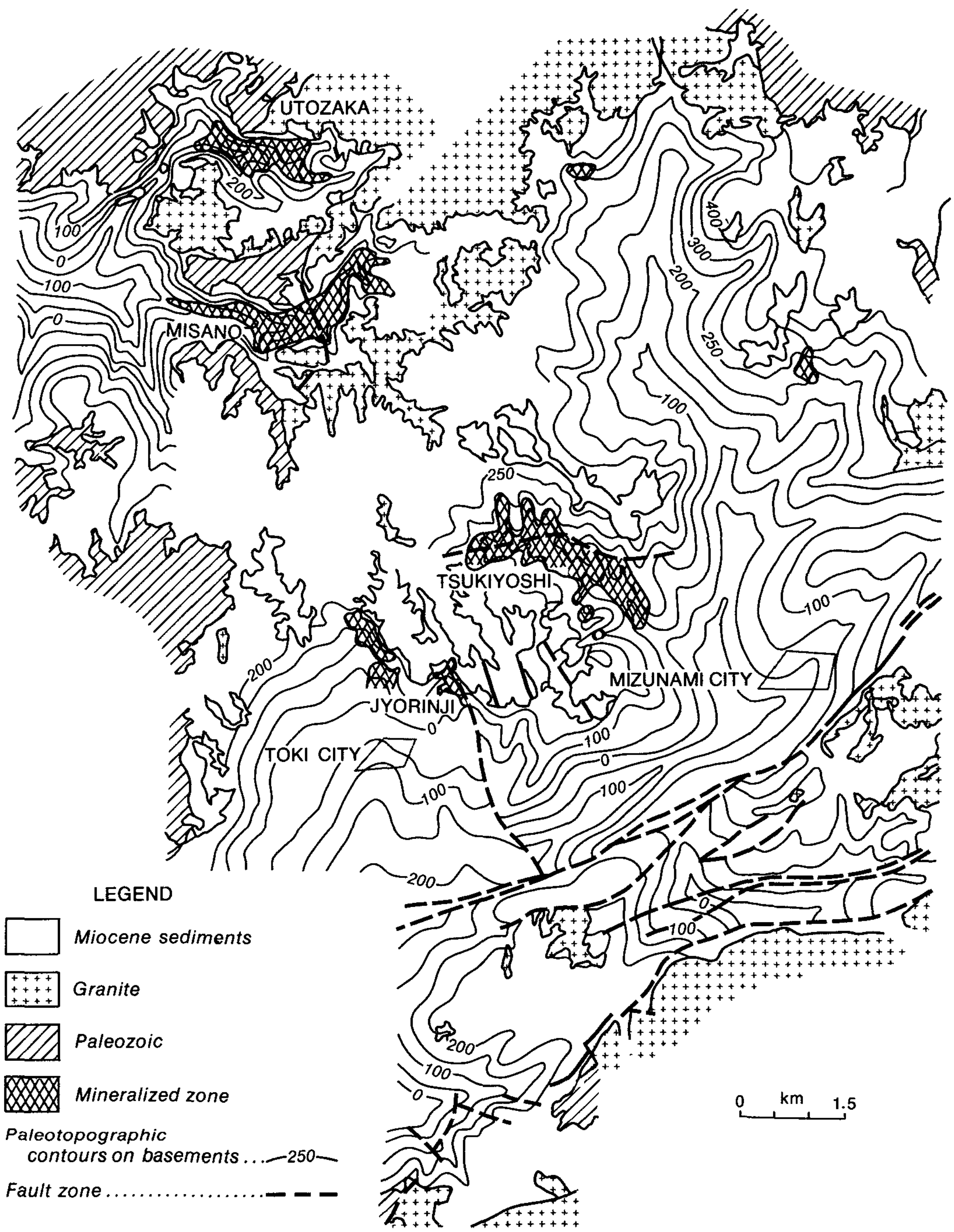

Figure 2 Basal-type uranium deposits and regional geology of the Tono district, Japan. After Katayama et al. (1).

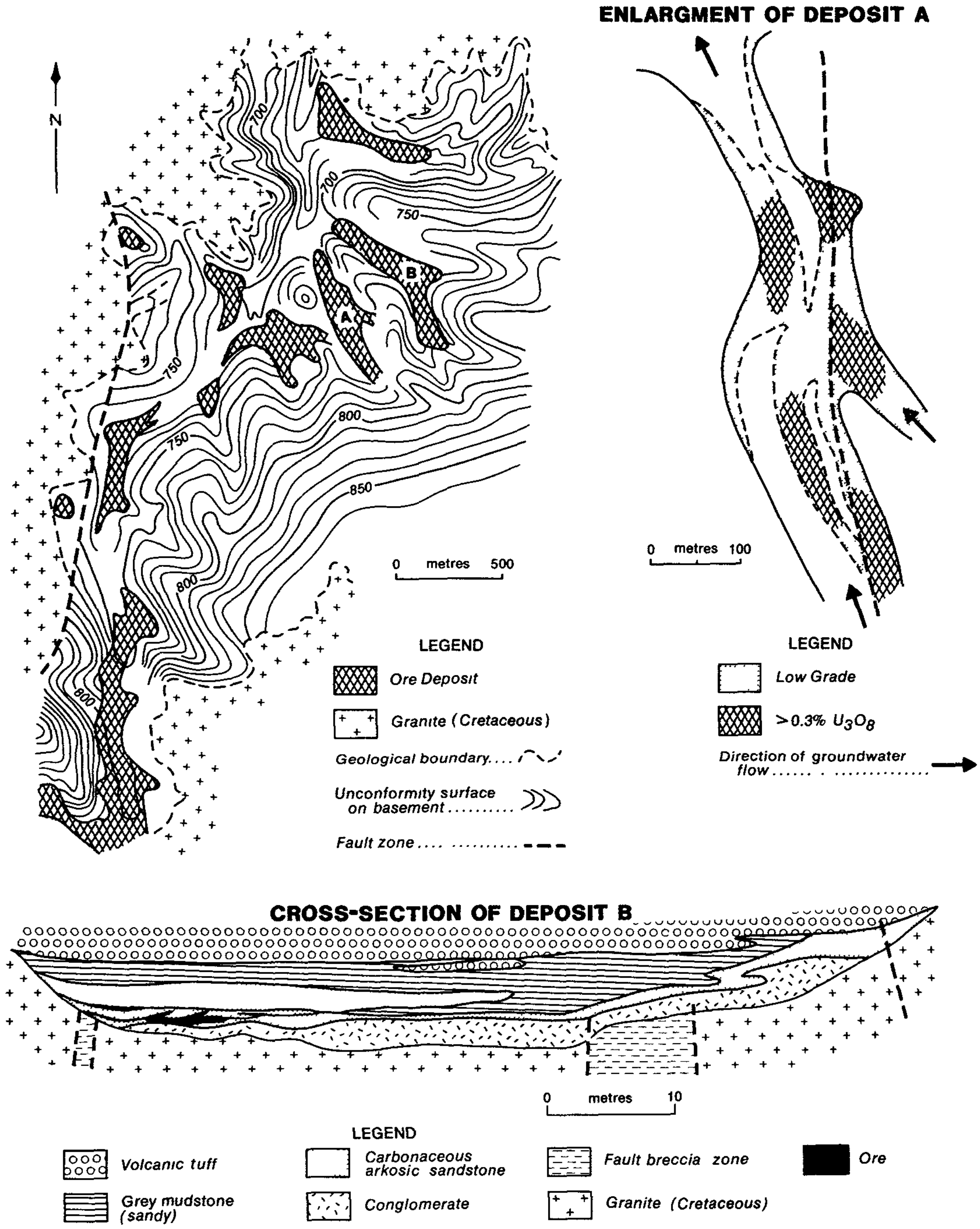

Figure 3 Kannokura uranium deposits, Ningyo-Toge region, Japan. After Takase (25).

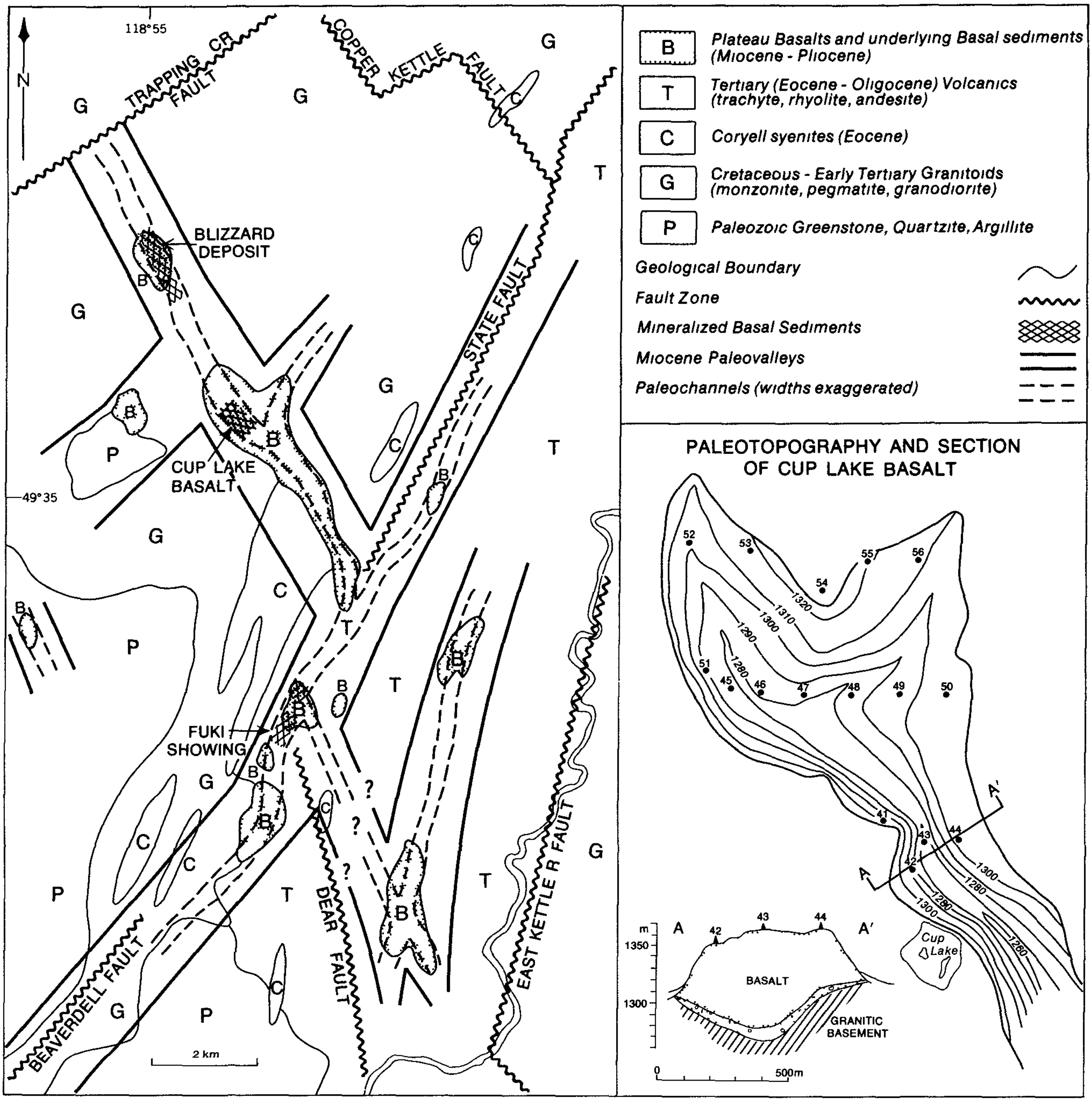

Figure 4 Geologic setting of the Blizzard basal-type uranium deposit and associated uranium occurrences, British Columbia, Canada. After Boyle (7).

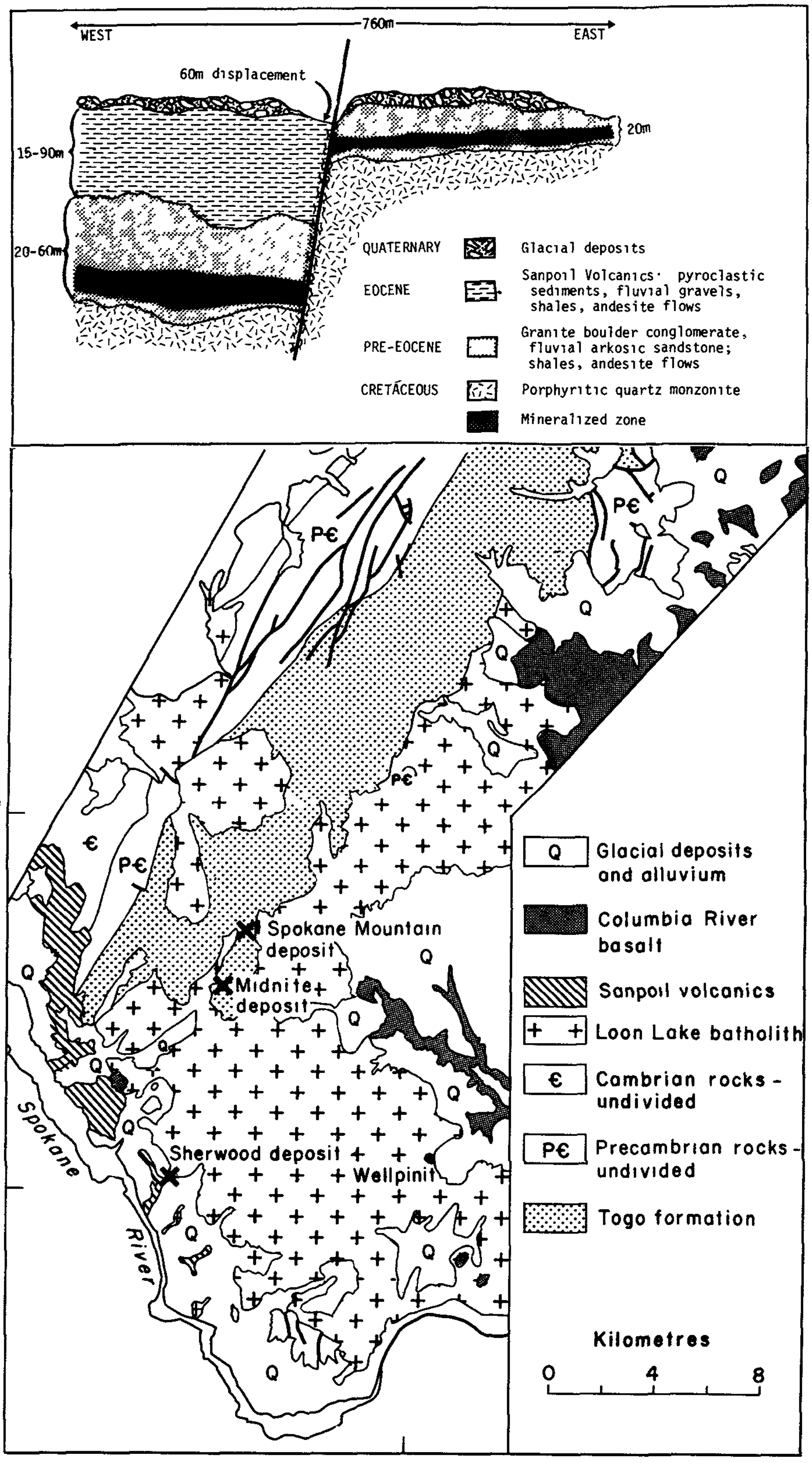

Figure 5 Geologic setting of the Sherwood basal-type uranium deposit and contact metasomatic deposits (Midnite, Spokane Mountain), Loon Lake Batholith area, Washington State, U.S.A. After Milne (8) and Nash and Lehrman (26).

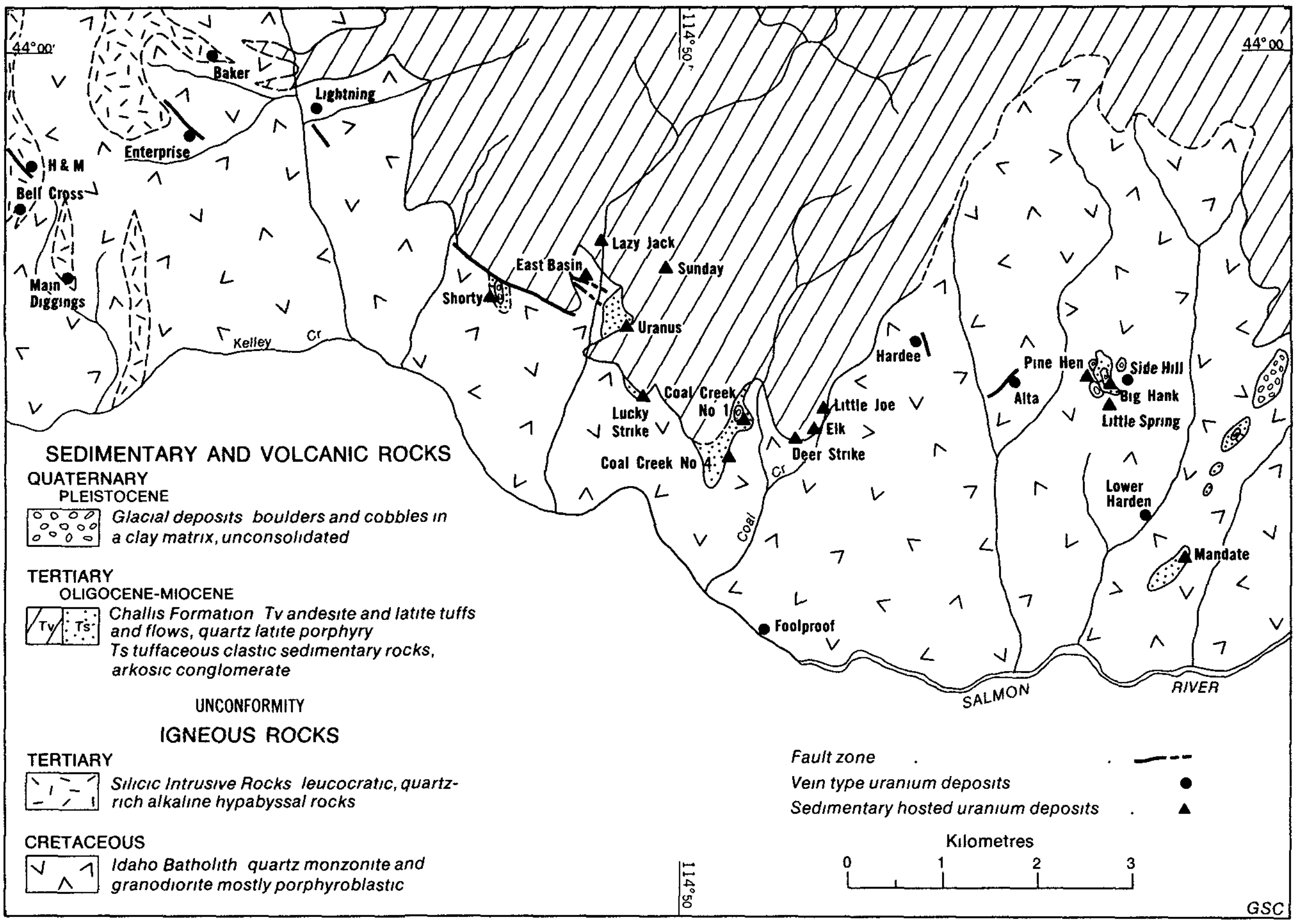

Figure 6 Geologic setting of basal-type and vein-type uranium deposits in the Stanley area of the Idaho Batholith, Idaho, U.S.A. After Kern (14) and Choate (15).

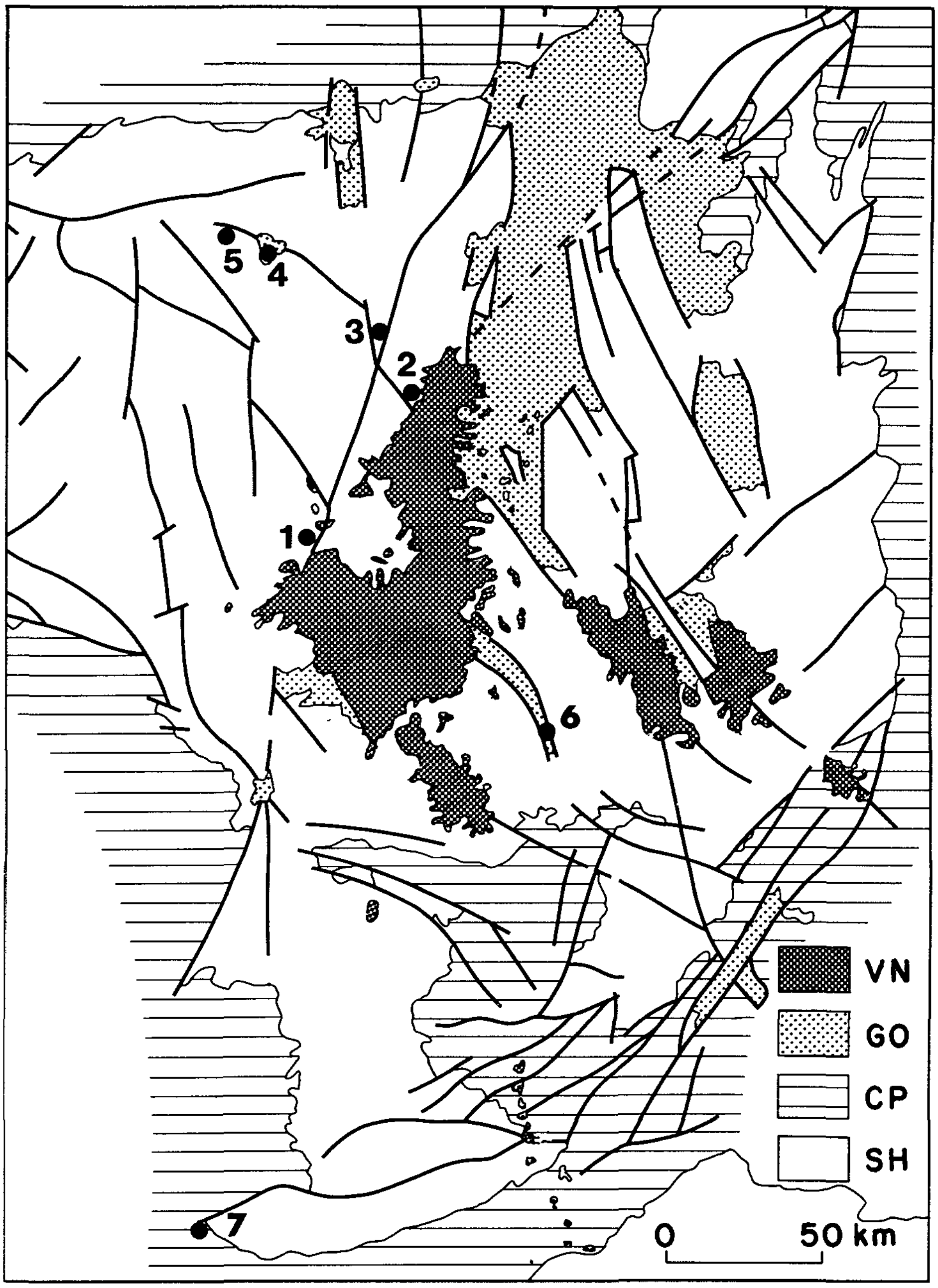

Figure 7 Geologic setting of basal-type uranium deposits on the Central Massif of France. 1. St. Pierre, 2. Olby, 3. Pontaumur (Rochemand), 4. Gouzon, 5. Chaux Maillat, 6. Mont Albert, 7. Laurcegais. VN - Neogene Volcanics; GO - Oligocene sedimentary basins; CP - Peripheral Paleozoic-Mesozoic formations; SH - Hercynian Basement Complex. After Carriou (19), Carre (20) and Charrier (27).

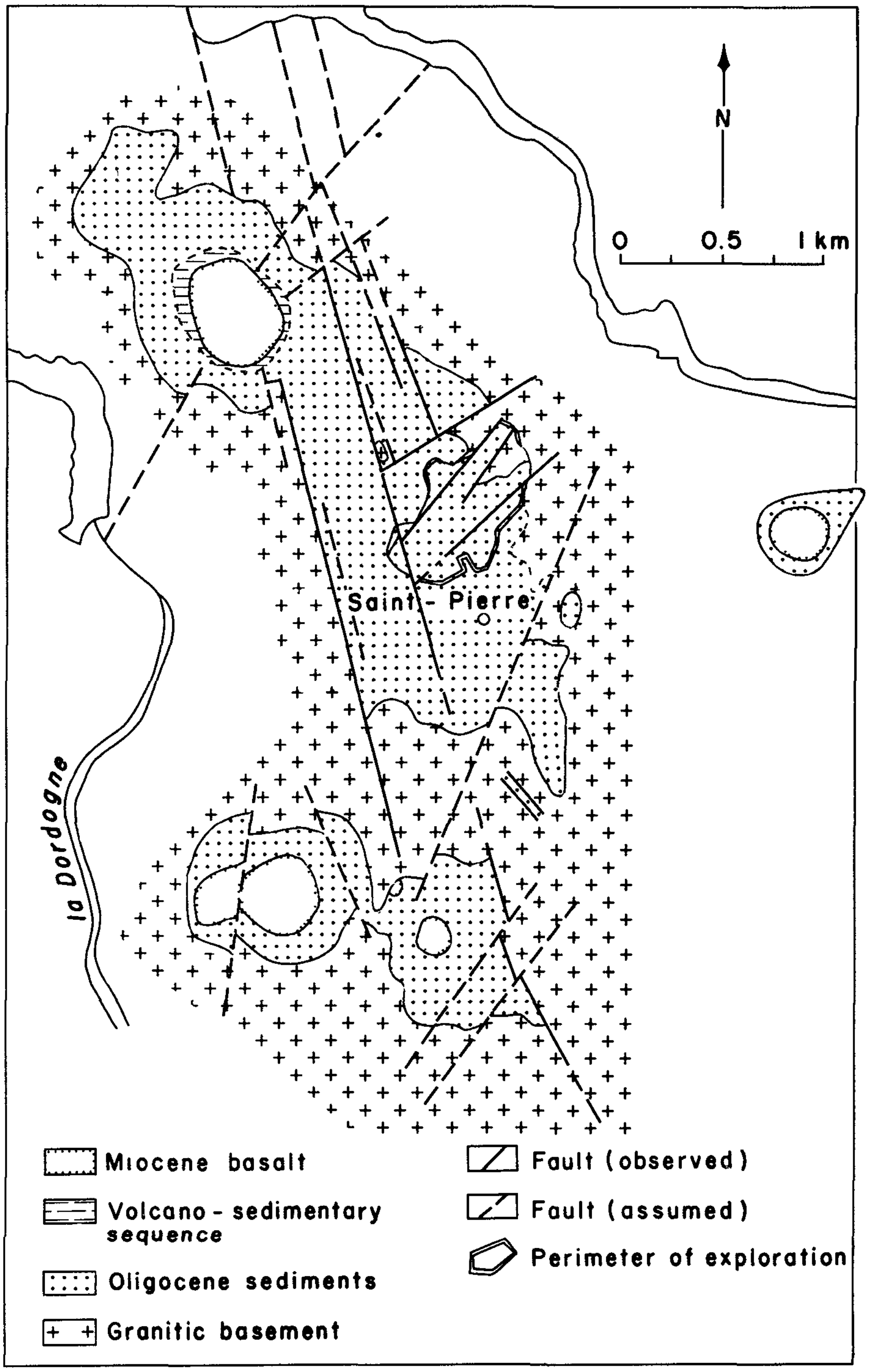

Figure 8 Geologic setting of the St. Pierre basal-type uranium deposit, Central Massif, France. After Carre (20).

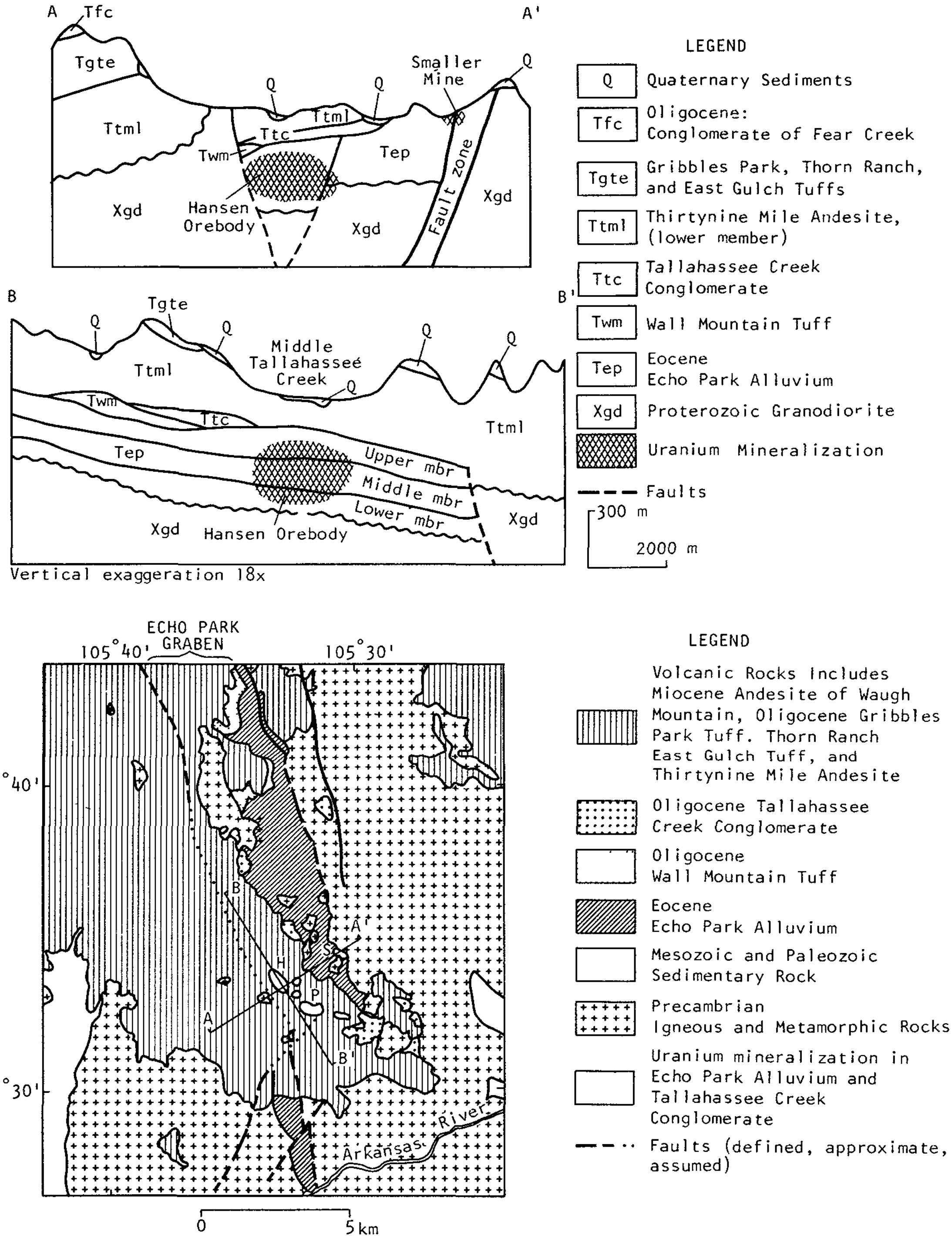

Figure 9 Geologic setting of basal-type uranium deposits (Hansen, Picnic Tree, Smaller), Tallahassee Creek area, Colorado, U.S.A. After Dickinson (13).

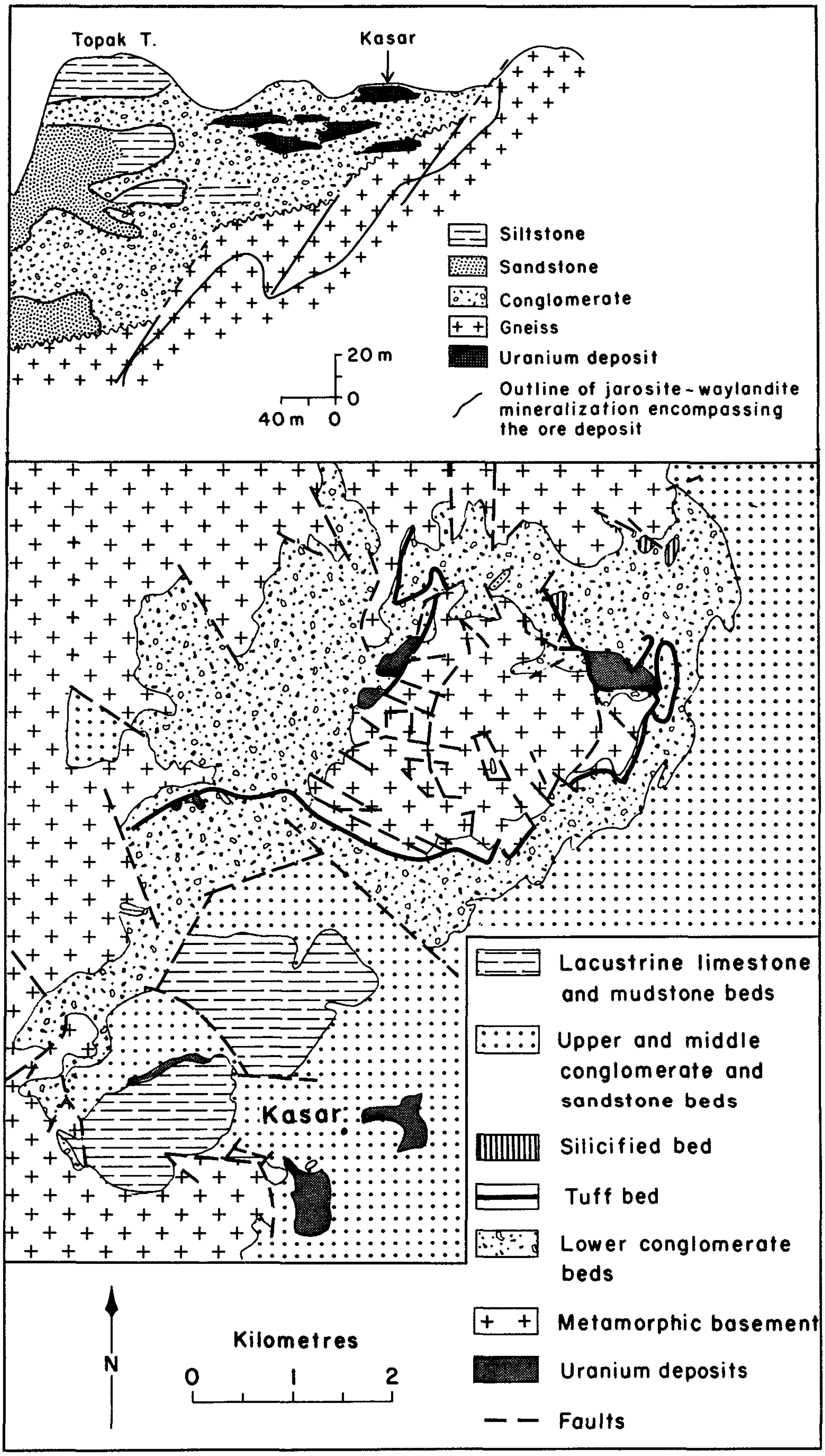

Figure 10 Geologic setting of basal-type uranium deposits, Menderes Massif, Turkey. After Yilmaz (22).

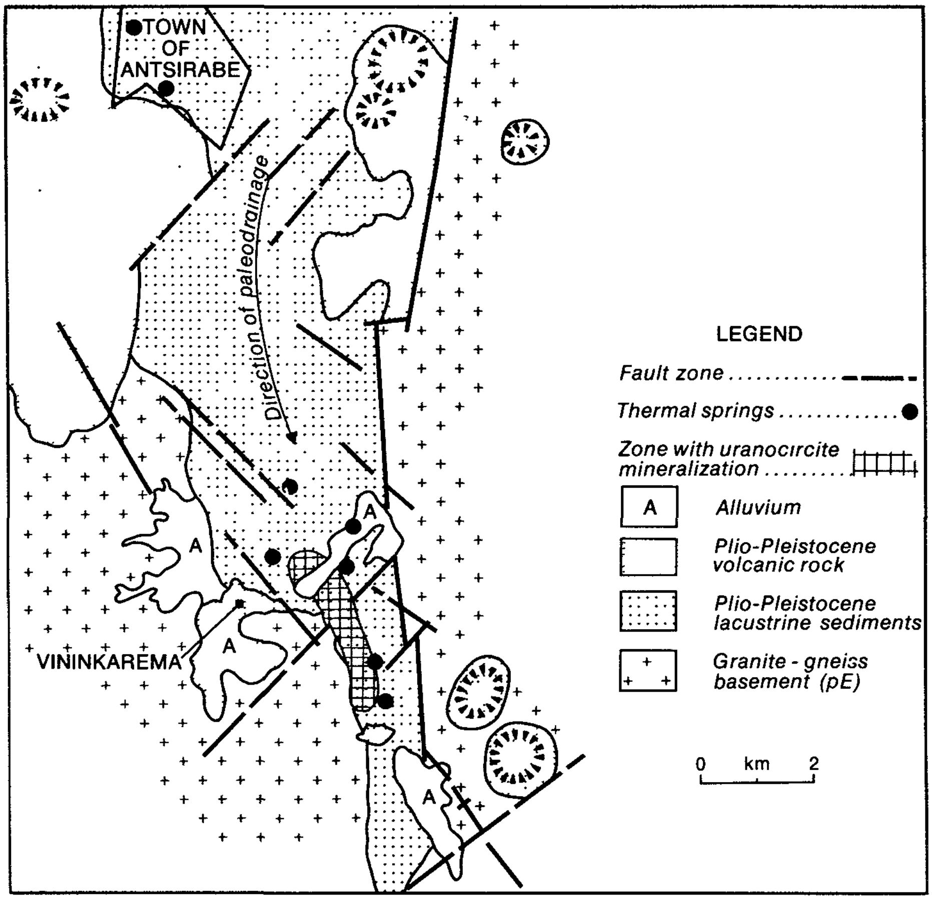

Figure 11 Geologic setting of the Antisarabe basal-type uranium deposit, Madagascar. After Premoli (23).

3. HOST ROCK STRATIGRAPHY

Tertiary sediments hosting basal-type uranium deposits on igneous and metamorphic massifs consist of a fining upwards sequence of fluvial conglomerates-sandstones-mudstones and lacustrine clays. Erosion of highland areas on the massifs has led to the formation of sediment-filled Tertiary paleovalleys and basins. Many of these paleovalleys overlie large fault zones or grabens (Figs. 7, 8, 9, 11). Sediments within these paleovalleys rarely exceed a few hundred meters in thickness and are on average only 50-100 meters thick.

In all cases the basal sedimentary unit is a conglomerate containing angular, subangular and rarely rounded cobbles and boulders of basement lithology in a kaolinite dominated matrix. In many cases (e.g., Blizzard deposit, Fig. 4, ref. 7) this conglomerate represents a reworked fault breccia. Organic material and iron sulphides may occur in these conglomerates (e.g., Tyee deposit, Canada; Tono and Ningyo-Toge deposits, Japan, and Sherwood deposit, U.S.A.), but commonly these rocks are devoid of these materials (e.g., Blizzard deposit, Canada and Koprubasi deposits, Turkey). The conglomerates are overlain by sandstones which are generally arkosic but may occasionally be tuffaceous. These rocks generally contain abundant organic matter, iron sulphides, limonite, ilmenite-magnetite and waylandite-jarosite; all compounds which are active 'catalysts' in precipitating uranium. Mudstones, which are often highly carbonaceous, are intercalated with the sandstones and generally succeed them further up in the sedimentary sequence.

These rocks generally act either as aquicludes or aquitards to groundwater flow, channelling uraniferous waters into the more pervious sandstones and conglomerates.

Generally rocks hosting basal-type uranium deposits consist of a single fining-upwards sequence of fluvial sediments. In the Tallahassee Creek area of the U.S.A. (Fig. 9), however, two erosional events have led to the formation of the basal Eocene Echo Park Alluvium formation and a downcutting Oligocene Tallahassee Creek channel conglomerate (Fig. 9). Both these units are mineralized, but together they can be considered as a basal sedimentary assemblage of 200-300 meters in thickness underlying volcanic cover rocks (Thirty-Nine Mile Andesite).

4. COVER ROCKS

Uraniferous basal sediments developed on igneous and metamorphic massifs are generally covered by impervious rock units consisting of (a) a single volcanic unit such as the Plateau Basalts of Southern British Columbia (Fig. 4), (b) lacustrine sediments (e.g., certain deposits in Ningyo-Toge and Tono regions, Japan, Figs. 2 and 3 and Koprubasi, Turkey, Fig. 10), or (c) interbedded volcanic-sedimentary sequences (e.g., Ningyo-Toge region, Japan, Fig. 3; Sherwood deposit, U.S.A., Fig. 5; and Tallahassee Creek area, U.S.A., Fig. 9). These cover rocks have played an important role in the preservation of basal-type uranium deposits, especially in areas which have experienced later uplift and erosion (e.g., Okanagan Region, Canada and Sherwood deposit, U.S.A.). In some areas, however, cover rocks have been completely stripped off exposing basal uranium deposits to weathering processes and erosion (e.g., St. Pierre deposit, France, Fig. 8; Koprubasi deposits, Turkey, Fig. 10 and Antisarabe deposit, Madagascar, Fig. 11).

5. MINERALIZATION

Basal-type uranium deposits form in sediments at, or just above, basement unconformities, typically in fluvial paleochannel structures occupying major fault zones or small grabens (See Figs. 2-11). In a few cases deposits occur at distances of 20-30 meters above the unconformity. In these situations groundwaters upwelling from the basement complex have probably been channelled by impervious sediments (mudstones, siltstones) into higher horizons, or else, as is common in some deposits, the lower units of the basal sediments are devoid of the precipitating agents required to form ore (i.e., organic matter, pyrite, limonite); such agents not being added to the sedimentary sequence until late in the erosion cycle. Dimensions of these deposits vary greatly (See Figs. 2-11), the Blizzard deposit which is one of the largest of this deposit type averages 120 m in width, 1,600 m in length and 15 m in thickness (7). Average ore grades in the various deposits rarely exceed 0.2% U, and the largest tonnage to date is that of the Hansen deposit, Tallahassee Creek area (Fig. 9) at 10,200 metric tonnes U (13).

To date about eleven styles of basal-type uranium mineralization have been described. They are summarized below together with representative deposits and references.

1. Ningyoite + pyrite and/or marcasite + organics: Ningyo-Toge deposits, Japan (2,4,6); Tyee deposit, Canada (7).
2. Uraninite ± coffinite + pyrite and/or marcasite + organics: Tono deposits, Japan (1,4); Sherwood deposit, U.S.A. (8,9); Stanley deposits, U.S.A. (14,15), Juniper deposit, U.S.A. (16); Hansen, Picnic Tree deposits, U.S.A. (11-13).
3. Coffinite + organics: Tono deposits, Japan (1,4).
4. Saleeite + autunite + ningyoite + limonite + pyrite + organics; Blizzard deposit, Canada (7).

5. Francevillite + tyuyamunite + autunite + limonite: St. Pierre deposit, France (20).
6. Uranocircite ± autunite ± torbernite: Antisarabe, Madagascar (23), Jorinji deposit, Tono district, Japan (1); Sebinkarahisar deposits, Turkey (24).
7. Uraniferous zeolites: Tono deposits, Japan (1,4).
8. Uraniferous apatite: Nakamaruke, Noto, Nakajyo deposits, Japan (4).
9. Uraniferous clays: Olancha deposit, U.S.A. (18).
10. Uraniferous waylandite-jarosite + organics: Koprubasi deposits, Turkey (22).
11. Uraniferous calcite + siderite + pyrite: Misano deposit, Tono district, Japan (4).

Organic materials occurring in these deposits may comprise coal, vitrain, carbonized wood, organic humates and relatively fresh wood, twigs and leaves. Precipitation of uranium occurs as a result of various organic and inorganic reduction mechanisms as well as sorption processes on minerals such as zeolites, clays, apatite, calcite, waylandite, jarosite and limonite.

Other than uranium, there are no elements which are consistantly enriched in basal-type deposits. Many, but not all, deposits display significant enrichments in phosphorus, chiefly present as ningyoite, saleeite, autunite, uranocircite and phosphuranylite. Certain deposits are enriched in V (e.g., St. Pierre, France), As (e.g., Stanley deposits, Idaho, U.S.A.; Sherwood deposit, Washington State, U.S.A., Ningyo-Toge and Tono deposits, Japan) and other metals, such as Se, Mo, Pb, Zn, Cu, and Ba (7,15,20).

6. RELATIONSHIP OF MINERALIZATION TO BASEMENT STRUCTURE

Perhaps the most striking feature of basal-type uranium deposits is their close spacial association with basement structure. The Blizzard (7; Fig. 4), Tyee (7; table 1) Tsukiyoshi (3,4; Fig. 2), Kannokura (25; Fig. 3), Sherwood (8; Fig. 5), Stanley (14; Fig. 6), Smaller (11; Fig. 9) and many other deposits are located in paleochannel sediments directly overlying major fault zones in basement complexes; the St. Pierre (Fig. 8), Hansen (Fig. 9), Picnic Tree (Fig. 9) and Antisarabe (Fig. 11) deposits occur in basal sediments occupying small fault bounded graben structures, and the Koprubasi deposits (Fig. 10) overly en-echelon fault zones along the peripheral borders of uplifted segments of the Menderes Massif.

On a regional tectonic scale, the disposition of basal-type uranium deposits on the Central Massif of France (Fig. 7) serves to demonstrate the close association between mineralization and basement structures.

Possible associations between basal-type uranium deposits and mineralized lineaments or trends in basement complexes can be seen in the Loon Lake Batholith (Fig. 5) and Idaho Batholith (Fig. 6) areas of the western United States. In the Loon Lake Batholith region, the Sherwood deposit is situated along a possible mineralized lineament (Midnite Trend) characterized by metasomatic uranium deposits (Midnite and Spokane Mountain, Fig. 5), which are localized along the base of a linear roof pendant of Precambrian Togo phyllites. Erosion of this mineralized roof pendant may have supplied the necessary uraniferous groundwaters to form the Sherwood deposit. In the Stanley area of the Idaho Batholith (Fig. 6), vein-type uranium deposits have a similar strike to that of the structurally controlled uraniferous paleochannel deposits underlying the Challis volcanics (15).

7. GENESIS

The genesis of basal-type uranium deposits requires a thorough understanding of the inter-relationships between source of ore-forming elements, mechanisms of migration, paleoclimatology, environment of deposition and preservation.

Results of research on the genesis of basal-type uranium deposits in Canada (7), Japan (1,3,4,6), the United States (11,12,15), and Turkey (22) overwhelmingly support an igneous or metamorphic basement source for ore-forming elements. Cited as evidence for this are the barren nature of basal sediments on older rocks overlying and surrounding basement complexes (6,7); the close association of mineralized paleochannels with basement structures (1,3,4,7, 11,12, 15,20); the lack of widespread occurrence of suitable volcanic source rocks (7,22); the lack of variation in uranium content between oxidized and unoxidized barren basal sediments (7,22), and the presence of structurally controlled uraniferous groundwaters with long residence times in the basement complexes (4,7).

For the St. Pierre deposit on the Central Massif of France (Figs. 7 and 8), Carre (20) proposes a basement leaching model but suggests that much of the uranium may have been derived from a Pre-Oligocene ferralitic paleosol, which contains high concentrations of U (up to 55 ppm). Other regions containing basal-type uranium deposits are not, however, characterized by lateritic paleosols rich in uranium, and Carre (20) does not present evidence to show that uranium has been leached from the ferralitic profile during the time of ore formation. Considering the fact that the intrusive basement rocks of the Central Massif (biotite granite, two-mica granite, episyenite) have high average uranium contents (5-30 ppm), contain accessory uraninite, and have structurally controlled primary uranium mineralization, it would be difficult not to consider them as an excellent source of labile uranium.

The Tallahassee Creek district of Colorado, U.S.A. contains a number of basal-type uranium deposits (Hansen, Picnic Tree, Dickson-Snooper, Sunshine, Smaller, Thorne). Dickinson (13) suggests that the overlying andesitic to rhyolitic Wall Mountain Tuff unit of the Thirty Nine Mile volcanic field was the source of uranium for these deposits. This unit, however, was heavily eroded before formation of the ore-bearing Tallahassee Creek conglomerates (See Fig. 9), and its relevance as the principal source of uranium is, therefore, questionable. Jensen (10), MacPherson (11), and Babcock (12) have shown that ore deposits in the Tallahassee Creek area occur where mineralized groundwaters were able to gain access to poorly sorted, carbonaceous-rich sediments by way of steeply dipping faults or shear zones in the Precambrian basement.

Favourable tectonic events, of which the most important appear to be extensional tectonism and regional uplift, play an important role in initiating, promoting and preserving basal-type uranium mineralization. Ore formation is initiated by regional uplift, block faulting and unroofing of the basement complex and development of a fluvial continental erosional landscape. Precipitation of ore is promoted by an important period of tectonic quiescence coupled with a structural fabric capable of sustaining well developed intermediate and regional hydrological regimes. Preservation is attained by the extrusion of continental volcanic cover rocks or the development of an overlying sedimentary lacustrine facies.

Information on the climatic conditions during time of ore formation of basal-type deposits is sparse. Although much more research is required on this subject it would appear from available evidence that these deposits can form in most environments with the exception perhaps of cold arid (tundra) regions.

Depending on the chemical composition of the basement rocks, ore-forming groundwaters will contain variable concentrations of (K, Ca, Mg) - U - (V, P, SiO_2) - (Ba, Pb), thus resulting in formation of the unusual minerals (ningyoite, saleeite, francevillite, uranocircite, etc.) which characterize these deposits.

8. PRE-TERTIARY DEPOSITS

Uranium deposits recognized by most geologists as basal-type and described in the present review are all of Tertiary age. However, processes leading to their formation do not indicate temporal constraints on their occurrence. Difficulties in recognizing older basal-type uranium deposits probably lie in their fragile existence in unconsolidated sediments and the fact that they may be greatly altered or recast into other deposit types during subsequent periods of deformation. The Precambrian uranium deposits of the Franceville Basin in Gabon (Mounana, Bayindzi, Oklo etc.) occur in a basal carbonaceous conglomerate-sandstone-phyllite sequence at or just above a Lower Proterozoic granitic basement complex (28), and it seems possible that these were originally basal-type deposits, especially since they are associated with block faulting in the basement complex. Likewise, the Carboniferous St. Hippolyte deposits of France (Thannenkirch, Warik, Teufelsloch and Schaentzel), which occur in a basal arkose-sandstone-black schist sequence within small graben structures on the Vosges granitic basement complex, may also be considered as basal-type (29). Although a great deal of research is required, it is conceivable that many unconformity-type uranium deposits may have originally been basal-type deposits.

9. CONCLUSIONS

Basal-type uranium deposits constitute a single unique class of groundwater infiltration-type uranium mineralization. The present review generalizes the important features of this deposit type and the examples shown in Figs. 2-11 and Table 1 collectively demonstrate the variety of geological settings in which these deposits may occur. Both the genesis and geological environments of formation of basal-type uranium deposits are reasonably well understood as a result of a number of detailed studies (1,3,4,7,15,20,22). In view of the fact that most basal-type uranium deposits found to date are exposed at surface or occur under very shallow cover, the incorporation of genetic and geological features mentioned above in an exploration program is paramount if deposits under thicker and more extensive cover rocks are to be found. The association of these deposits with basement structures (faults, grabens) is so universally consistent that geophysical and photogeological techniques of detecting or extending such structures under regions of extensive cover rocks (e.g., Tertiary volcanic fields) should be mandatory in any exploration program. Basal-type uranium deposits are generally found in fluvial paleochannel structures on basement complexes and shallow seismic methods may, therefore, be useful in mapping such structures under thick cover rocks.

Regions with the greatest potential for basal-type uranium deposits are generally characterized by uplifted segments of felsic intrusive or biotite gneiss, mica-schist metamorphic basement rocks that have undergone extensive fracturing and block faulting and that have experienced at least one period of Tertiary erosion followed in some cases by continental volcanism. A number of areas with these characteristics are shown on Fig. 1.

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DATA-PROCESS-CRITERIA MODEL FOR ROLL-TYPE URANIUM DEPOSITS

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Abstract

Roll-type uranium deposits occur in reduced sandstones along linear, crescent-shaped oxidation-reduction boundaries. Roll-type deposits have been particularly important sources of uranium in the United States, but deposits are also known in South America, U.S.S.R., Australia, and other countries. Economic deposits commonly contain a few to more than 25 million pounds U at mining grades between 0.10 and 0.25 percent U.

A data-process-criteria (DPC) model for roll-type uranium deposits, based largely upon published deposit geologic characteristics (data) and interpretations of their causative geologic processes, is presented. From the data and process interpretations, geologic characteristics (recognition criteria) have been selected that are most useful and reliable in the exploration for and evaluation of roll-type uranium occurrences. All criteria require field observations and include considerations of regional geologic setting (geometry, size, and composition and erosion of uplifts and basins), structure, stratigraphy, and characteristics of the potential host sandstone, including dimensions, depositional environment, lithology, reductants and alteration.

This model is applicable to resource evaluations and exploration in any sandstone environment, but particularly in intermountaine basins. The use of genetic or process interpretations promotes the identification of previously unrecognized criteria and greater confidence in (a) the selection of recognition criteria and (b) in assigning relative importances to the favorability of each criterion. The use of only field-observable geologic characteristics as recognition criteria insures greatest reliability in exploration, evaluation, and resource studies.

1. INTRODUCTION

Roll-type uranium deposits in sandstones and related permeable sediments have been important to world uranium production and reserves, particularly in the United States. This deposit type accounts for about 29 percent of United States uranium production [1] and 40 percent of reserves producible at $50 per pound U forward cost [2]. Many roll fronts contain uneconomic grades and tonnages of uranium. Economic deposits exploitable by open pit or underground mines or in-situ leaching generally contain between one and 25 million pounds U at grades between 0.10 and 0.25 percent U.

This paper identifies recognition criteria that are judged to be the most reliable and important geologic characteristics of roll-type deposits, for purposes of exploration, regional resource studies, and the evaluation of prospects.

These criteria are based on the numerous published descriptions of roll-type deposits in sandstones and the companion studies of the chemical, physical, and hydrologic processes that produced the deposit characteristics. The recognition criteria are the final step in a data-process-criteria (DPC) model and provide a basis for the subsequent development of exploration and evaluation models that are designed for the idiosyncrasies of particular exploration/evaluation programs and regions.

The format of this paper is abbreviated from the data-process-criteria model developed by the senior author for use with distinct types of mineral deposits [3]. Many of the concepts presented herein were developed as part of the Prospector consultation system [4]. This approach to deposit modeling uses empirical data from example deposits together with process interpretations (identification of geologic processes that produced the deposit characteristics) to select previously identified and new recognition criteria that are most reliable and useful in exploration and evaluation. Space limitations permit no systematic review of the geologic characteristics of roll-type deposits and only a brief review of the processes involved in ore formation. The description, importance, and means of recognition of the recognition criteria are presented in greater detail.

2. DEFINITION OF ROLL-TYPE DEPOSIT

Roll-type deposits are epigenetic accumulations of uranium and other components (pyrite, marcasite, calcite, vanadium, selenium, molybdenum, etc.), in the matrix of reduced sandstones and other permeable sediments along the interface (roll front) between pervasively reduced and pervasively oxidized sandstone. The reduced sandstone occurs down hydrologic gradient from the oxidized (altered) sandstone (Fig. 1). The reduced sandstone is commonly buff, gray, gray-green, or black due to disseminated carbonaceous material (generally detrital plant debris), and/or pyrite, which may be of either a diagenetic (i.e., Wyoming Basins) or an introduced (i.e., South Texas) origin. The oxidized sandstone is pink-red (hematite), yellow/orange (limonite), or white/gray due to the removal of iron and alteration of feldspar. The uranium-bearing zone cuts across stratigraphy, but uranium distribution may locally reflect sedimentary features. The orebodies are broadly crescentic in cross section, and elongate and sinuous in plan along the roll-front interface. Different alteration types for major roll-type districts in intermontaine basins in the United States are shown in Figure 2. Alteration associated with the roll-type deposits of the Texas Coastal Plain are similar to those associated with deposits in the Powder River Basin.

The classical roll-type deposits of the United States occur in intermontaine basins such as the Wind River (including the Gas Hills District), Shirley, Powder River (including Kaycee area), and Great Divide (including Crooks Gap District) Tertiary Basins of Wyoming. Somewhat related roll-type deposits occur in South Dakota (Black Hills), Nebraska, Colorado (Weld County), and Wyoming in Mesozoic sandstone below the angular unconformity at the base of the Tertiary volcaniclastic sediments. These subsequent roll-type deposits were formed by uraniferous waters that moved from the oxidized Tertiary sediments down into the carbonaceous and/or pyrite-bearing older sandstones [5].

The deposits of South Texas are also roll-type deposits, but the reductant is introduced sulfide in most formations. The so-called tabular or Salt Wash-type deposits of the Colorado Plateau were not formed by the same chemical processes as the roll-type deposits, and are not included in this class. The uraniferous humate deposits of the Grants Region, New Mexico, are not roll-type deposits, although younger roll-type deposits have locally impinged on and redistributed the primary uraniferous humate mineralization.

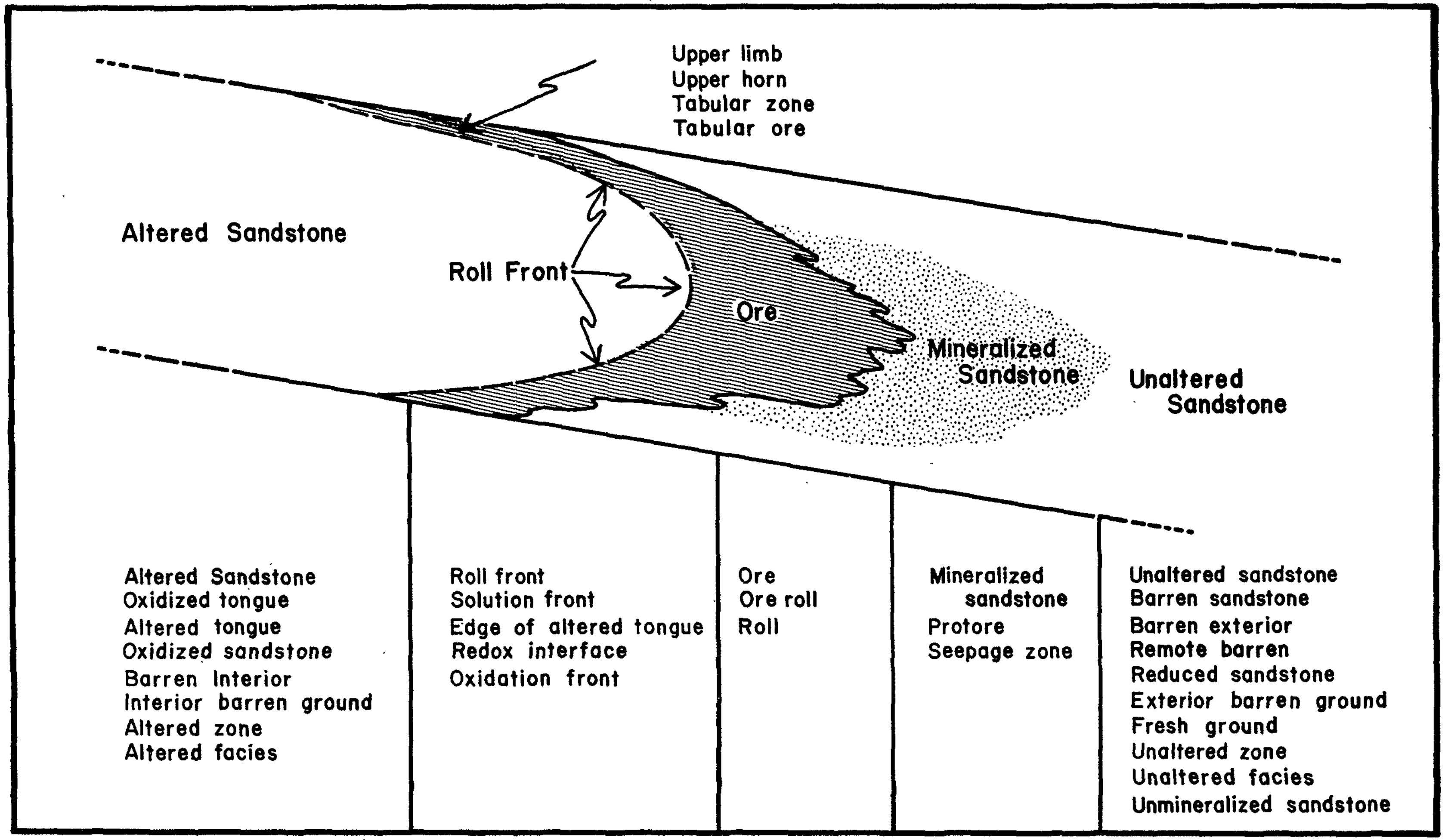

Figure 1. Schematic cross section of a roll front illustrating the various terms used to describe features of roll-type uranium deposits [5].

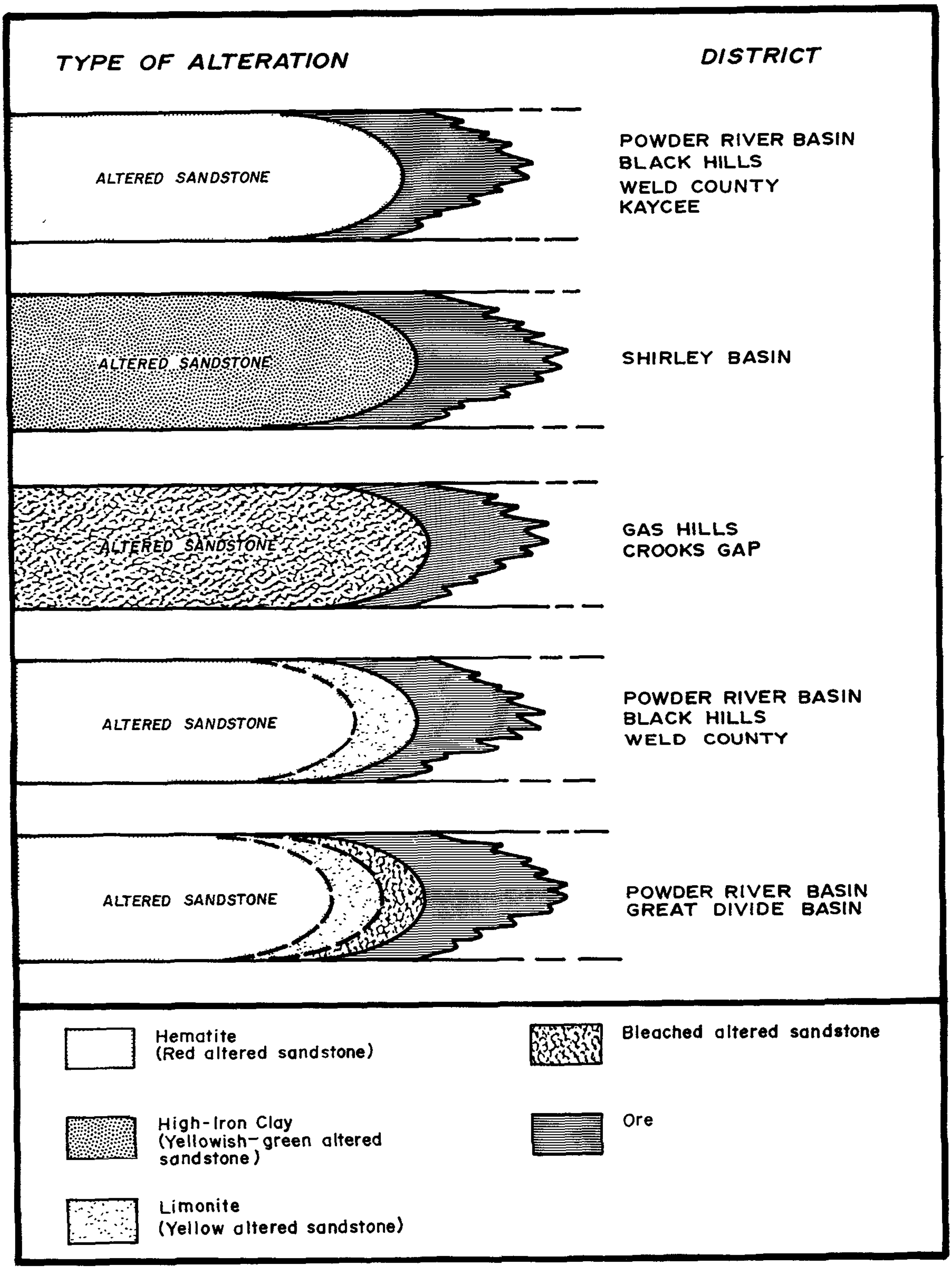

Figure 2. Simplified cross sections across the edges of altered sandstone tongues showing the most common types of alteration present in some uranium mining districts in Wyoming, Colorado, and South Dakota [5].

3. PREVIOUS STUDIES

Numerous descriptions of roll-type deposits have been published. The most complete description of a single roll-type district is that of Harshman [6]. The geologic data, process interpretation, and recognition criteria for the major roll-type districts were compiled by Harshman and Adams [5] and Adams and Smith [7]. Important descriptions of roll-type deposits in the Wyoming Basins of the United States include Harshman [8][9], Melin [10], Sharp et al [11], Sharp and Gibbons [12], Bailey [13], King and Austin [14], Mrak [15], Fischer [16], Langen and Kidwell [17], Dahl and Hagmaier [18], Rackley [19], Sherborne et al [20], and Gaschnig [4]. The roll-type deposits of South Texas have been described by Eargle and Weeks [21], Galloway et al [22], and Goldhaber et al [23]. Roll-type deposits in Australia have been described by Callen [24], Haynes [25], and Brunt [26].

4. PROCESS INTERPRETATION

Important aspects of the chemical and physical processes related to the formation of roll-type deposits have been discussed by many authors, in some cases prior to the recognition of this subtype of sandstone uranium deposit [27], [28], [29], [30], [31], [19], and [32]. The most important processes, based both on these interpretive studies and deposit descriptions (see Previous Studies), are summarized below.

4.1. Deposition of Host Sandstone -- Sandstones of favorable characteristics (see Recognition Criteria) were deposited, most commonly in continental fluvial depositional environments.

4.2. Reduction of Host Sandstone -- Sandstones became pervasively reduced through diagenetic alteration of detrital plant debris and the formation of pyrite, or through introduction of hydrocarbons and sulfides from other formations.

4.3. Deposition of Uraniferous Source Rock -- Oxidized, uraniferous, volcaniclastic sediments accumulated in hydrologic continuity with the host sandstones. Volcaniclastics were either younger than the host sandstones, or the latter were deposited simultaneously or continuously following the deposition of the volcaniclastics. Volcanic debris altered in the formation waters, releasing uranium to the ground water. Uraniferous, granitic basement rocks may have provided uranium for some roll-type deposits.

4.4. Sustained Ground-Water Flow -- The oxidizing, uraniferous ground water derived from the alteration of volcaniclastic sediments, driven by a regional hydrologic gradient and sediment compaction, moved into the reduced host sandstones, displaced the reducing ground water, and formed an oxidation-reduction roll-front boundary. As the oxidizing ground waters advanced through the aquifer, they oxidized iron to hematite and limonite and themselves became reducing. The oxidation-reduction roll front, therefore, also advanced down hydrologic gradient but at a slower rate than ground-water flow, controlled by the oxidizing capacity of the introduced ground water and the reducing capacity of the host rock. Uranium dissolved in the oxidizing ground water precipitated directly down gradient from the roll front due to its substantially lower solubility in reducing ground waters. For the major deposits, ground-water flow remained stable for thousands of years, during which many roll fronts propagated several miles down dip. Roll fronts associated with introduced reductants may have experienced a reintroduction of reductants, leaving the roll front entirely within reduced sandstones.

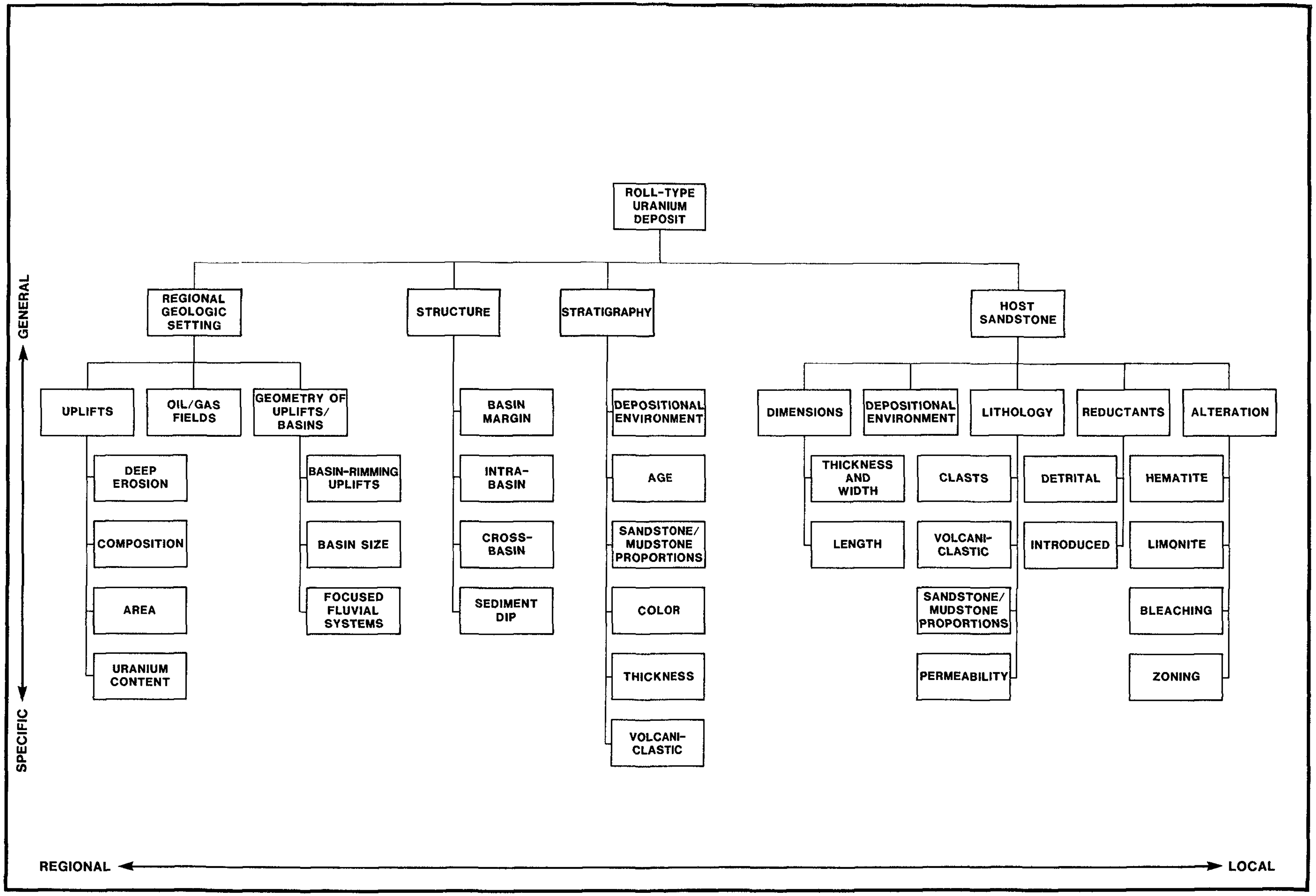

Figure 3. Recognition criteria net for roll-type uranium deposits.

5. RECOGNITION CRITERIA

Recognition criteria are those field-observable, geologic characteristics of a mineral deposit type that are judged to be the most reliable and important for exploration, evaluation, and resource studies based upon a process (genetic) interpretation of all data for examples of the deposit type. Many recognition criteria have historically been used in prospecting and empirical exploration. Process interpretation, however, improves confidence in and indicates the relative importance of each criterion, and commonly identifies important criteria not previously recognized.

To be most useful, recognition criteria are chosen for two characteristics. First, when the criterion is present or favorable, the chances of a deposit being present are significantly increased. The more significantly the presence of a criterion increases the chances for a deposit, the more sufficient that criterion is for identifying favorability. Second, when the criterion is absent, or unfavorable, the chances of a deposit being present are significantly decreased. The absence of a highly necessary criterion (i.e., a sandstone for a sandstone uranium deposit) virtually eliminates favorability for a deposit. Some recognition criteria are both highly necessary and sufficient; hence, they are particularly useful. By using only criteria that significantly increase and/or decrease favorability, one avoids collecting and processing geologic observations that are not useful.

Recognition criteria for roll-type deposits have been selected to cover the range from regional to local scale, presented from left to right in Figure 3. This range of detail corresponds to the evolution of most exploration programs, from regional to more detailed observations. Criteria for roll-type deposits progress from characteristics of the regional geologic setting to the detailed characteristics of the host sandstone (Fig. 3).

Recognition criteria also range from inclusive, general observations at the top of Figure 3 to more specific observations at the bottom. For example, the regional geologic setting is comprised of three criteria, two of which (uplifts and geometry of uplifts/basins) have yet more specific defining criteria. In practice, field observations are made only for the most specific, terminal criteria, which then collectively define the favorability of the intermediate criteria above them. The heirarchical arrangement permits a limited number of specific criteria to be combined to evaluate the favorability of a higher level criterion. For example, the favorability of lithology is defined by four criteria. The favorability of lithology is then combined with favorabilities for sandstone dimensions, depositional environment, reductants, and alteration, each determined from their specific criteria, to determine the favorability of a host sandstone. This approach avoids the simultaneous evaluation of 31 terminal criteria to evaluate the favorability for a roll-type deposit.

The relative importances of geologic criteria have historically been subjectively assessed by prospectors and exploration geologists in their heads. In this data-process-criteria model, each criterion is defined and its importance to the favorability of the next higher criterion, both when present and when absent, is estimated. This more systematic and explicit approach to the development of predictive deposit models seems warranted by rapidly expanding regional and mineral deposit data bases, increasing recognition of the variability of ore-forming processes, and the search for more obscure deposits. Although estimates of importance are subjective, the reader has the benefit of these judgements, which he can validate against his own experiences.

The importance of each terminal criterion to the favorability of the criterion above, is estimated by asking two questions. First, when the criterion is present or "perfectly favorable", how suggestive is it that the next higher criterion is favorable? Conversely, when the criterion is absent or perfectly unfavorable, how unfavorable is that for the next higher criterion (i.e., how necessary was the favorability of the criterion to the favorability of the next higher criterion). In this manner, estimates of the importance of all terminal and intermediate criteria to the favorability of the criteria above them have been made and are summarized in Table 1.

No wholly satisfactory method has been developed for evaluating the favorability of an area for a particular deposit type using data for its recognition criteria. The most logically and numerically rigorous approach yet developed is Prospector [4], the advantages of which are currently offset by the complexity, inflexibility, and cost of its models. For this roll-type model, we propose a more subjective, informal evaluation of favorability, based on the following guidelines:

1. The purpose of recognition criteria is to develop sufficient confidence to make a decision and initiate action (terminate a program, estimate a resource, acquire land and drill, etc.).

2. The level of confidence in an evaluation depends on the information available. Highest confidence results when data are available for many criteria, including all those of high sufficiency and necessity.

3. The level of confidence required varies with the decisions to be made. The user subjectively determines what constitutes sufficient data for his evaluation.

4. The absence of any highly necessary criterion results in low favorability.

5. The presence of all highly necessary and highly sufficient criteria results in high favorability.

6. The absence of no highly necessary criteria and the presence of only some highly necessary and moderately sufficient criteria results in intermediate favorability.

7. Insufficient information (low confidence) for criteria of moderate and high importance results in indeterminate favorability.

The favorability of each criterion is defined and its importance to the favorability of the next higher criterion are presented in Table 2. Also included is a statement of the criterion's significance and the means by which its characteristics are recognized.

6. CONCLUSIONS

The favorability of a region or a prospect for a roll-type deposit can be evaluated with geologic data for 31 recognition criteria. The criteria are equally applicable to regional exploration reconnaissance, resource studies, or prospect evaluation. The criteria and favorability are best evaluated subjectively by experienced mineral deposit geologists.

For roll-type deposits, as for other deposit types, negative or necessary criteria are more common than are strongly positive or sufficient criteria; i.e., there are more criteria to kill a project than to advance one. Provided the negative criteria are faithful to the data and process interpretation, they effectively eliminate unworthy projects early and promote more promising projects. Also, the importance or sufficiency of criteria when present increases as the criteria become less regional and more local in scale; the importance or necessity of criteria when absent is generally high throughout the scale range (see Table 1).

The preparation of a data-process-criteria (DPC) model improves the likelihood that important criteria have been identified and new criteria will be developed. The simple, explicit format invites communication, peer review, and model improvement. The identification of the most important and reliable criteria improves the focus and efficiency of exploration. Above all, a DPC model is to be used as a point of departure for improving the model and developing new criteria, not as a conclusion to be applied as a cook book.

Table 1. Summary of intermediate and terminal recognition criteria for roll-type uranium deposits.

Intermediate Criterion	Importance to Favorability When Lower Criteria Are: Present (Sufficiency)	Absent (Necessity)	Terminal Criterion	Importance to Favorability If Present (Sufficiency)	If Absent (Necessity)
Regional Geologic Setting	Low	Moderate-High			
Uplifts	Moderate	Moderate			
			Deep Erosion	Moderate	Moderate
			Composition	Moderate	High
			Area	Moderate	Moderate-High
			Uranium Content	Low-Moderate	Low
			Oil/Gas Fields	Low	Low-Moderate
Geometry of Uplifts/Basins	Moderate	Moderate-High			
			Basin-Rimming Uplifts	Moderate	Moderate-High
			Basin Size	Moderate	High
			Focused Fluvial System	Moderate	Moderate-High
Structure	Low-Moderate	Moderate-High	Basin Margin	Moderate	Moderate
			Intra-Basin	Low-Moderate	Low-Moderate
			Cross-Basin	Moderate	Low-Moderate
			Sediment Dip	Moderate	High
Stratigraphy	Moderate-High	High	Depositional Environment	Moderate	High
			Age	Low	High
			Sandstone/Mudstone Proportions	Low	High
			Color	Low	High
			Thickness	Low	High
			Volcaniclastics	Moderate-High	High
Host Sandstone	High	High			
Dimensions	Low-Moderate	High			
			Thickness and Width	High	High
			Length	Moderate-High	High
			Depositional Environment	Moderate	High
Lithology	Moderate-High	High			
			Clasts	Moderate	High
			Volcaniclastics	Moderate	Moderate
			Sandstone/Mudstone Proportions	Low	Moderate
			Permeability	Low	High
Reductants	Low	High			
			Detrital	Low-High [1]	Low-High [1]
			Introduced	Low-High [1]	Low-High [1]
Alteration	High	High			
			Hematite	High	High
			Limonite	Moderate-Low	Low-Moderate
			Bleaching	Low	Low
			Zoning	High	High

[1] Importance depends on whether the deposit type is of the detrital or introduced reductant type.

Table 2. Recognition criteria for roll-type uranium deposits arranged by scale of observation (see Fig. 3).

	Importance to Favorability: If Present (Sufficiency)	Importance to Favorability: If Absent (Necessity)
I. Regional Geologic Setting		
1. Uplifts		
Tectonic uplifts in the vicinity of exploration areas are important as a source of (a) host sediments, (b) strong surface and ground-water hydrologic systems, and (c) possible uranium from granitic or other basement rocks. Important characteristics of the uplifts include the following:		
a. Deep Erosion -- exposure of relatively old rocks in the core of the uplift is favorable.	Moderate	Moderate
Significance -- old rocks in the core of the uplift suggest significant uplift and erosion that would have contributed to a strong hydrologic system and coarse sediments.		
Recognition -- geologic maps and literature with ground checking as necessary.		
b. Composition -- large areas of quartzofelspathic rocks within the uplift are most favorable. Shales and other rocks that erode to fine-grained and chemically unstable sediments are unfavorable.	Moderate	High
Significance -- source for coarse, stable, clasts for permeable host rocks.		
Recognition -- geologic maps and literature to identify granites, quartz monzonites, quartzofelspathic gneisses, and possibly some coarse clastic sediments (sandstones and conglomerates); ground verification may be necessary.		
c. Area -- large areas (500 to 1,000 square miles) of exposed crystalline basement are most favorable.	Moderate	Moderate-High
Significance -- large areas indicate major uplifts that may have provided abundant sediments and a strong hydrologic system.		
Recognition -- geologic maps and field reconnaissance, as necessary (note smaller outcrops should be pursued if they result from partial cover by younger sediments).		
d. Uranium Content -- anomalous concentrations (greater than 5-10 ppm U_3O_8) of uranium in crystalline basement rocks of the uplift are somewhat favorable.	Low-Moderate	Low
Significance -- anomalous uranium concentrations indicate the availability of uranium for ultimate concentrations in roll-type deposits.		
Recognition -- airborne and ground radiometric surveys and assays of rocks for uranium and thorium (an indicator for original uranium concentrations where surface leaching has occurred).		
2. Oil/Gas Fields	Low	Low-Moderate
Basins containing oil and/or gas fields are somewhat more favorable as they are capable of providing reductants for otherwise oxidized sandstones.		
Significance -- reduced sandstone is required for roll-front formation and most host sandstones contain detrital and diagenetic reductants. Oil and gas fields provide a possible reductant source for those potential host sandstones that were oxidized at deposition and which are now cut by faults, or may enhance diagenetically reduced sands.		
Recognition -- oil and gas production data.		
3. Geometry of Uplifts/Basins		
a. Basin-Rimming Uplifts -- basin surrounded by uplifts is most favorable.	Moderate	Moderate-Low
Significance -- basin with surrounding uplifts tends to receive more sediments and to develop a strong, easily defined sedimentary system with well-developed potential host sands and a strong ground-water flow (basins with only two or even one adjacent uplift should be pursued as other criteria may be favorable).		
Recognition -- geologic maps and literature and some subsurface stratigraphic data to identify fluvial systems.		
b. Basin Size -- basins in the range of 10 miles by 30 miles are most favorable. Significantly smaller basins are unfavorable as are significantly larger basins, unless they have sub-basins or focused fluvial systems.	Moderate	High

Table 2 continued

	Importance to Favorability	
	If Present (Sufficiendy)	If Absent (Necessity)
Significance -- well-developed sands and high ground-water flow are favored by intermediate-sized basins, smaller basins tend to have poorly developed sands and low ground-water flow; large basins tend to have dispersion sediments and dispersed, low ground-water flow. Recognition -- geologic maps or airphotos and ground reconnaissance.		
c Focused Fluvial System -- the convergence and focusing of multiple streams from rimming uplifts into and through a basin is most favorable. Multiple streams entering and leaving the basin is less favorable. Significance -- focused sedimentation tends to produce thicker and more continuous sands (widths of miles and lengths of hundreds of miles) with potential for high ground-water flow to produce high-grade, large deposits, favorable sands may extend through and well beyond the basin. Recognition -- geologic maps and literature, field observations, stratigraphic drilling and correlations.	Moderate	Moderate-High
II. Structure		
1. Basin Margin Faults and folds that are parallel to the basin margin, and that produce linear contacts separating uplifted crystalline basement rocks from basin sediments are favorable. Significance -- basin margin structures commonly produce significant relief between uplifted crystalline basement and the adjacent basin, favorable for the deposition of coarse clastics and strong ground-water flow, faults can introduce reductants into potential host sands. Recognition -- geologic maps and satellite or airphoto imagery and magnetic/gravity maps to detect basement structures.	Moderate	Moderate
2. Intra-Basin Faults, broad folds and lineaments reflecting probable basement structure are most favorable Strong folds and faults are unfavorable. Significance -- basement structures active during sedimentation focus sedimentation and tend to develop thicker and more continuous sand bodies, faults may introduce reductants into potential host sands. Recognition -- geologic maps, satellite and airphoto imagery, field reconnaissance, and gravity and magnetic surveys to detect basement structures.	Low-Moderate	Low-Moderate
3 Cross-Basin Structures that project into the basin from surrounding areas are favorable, but the favorable areas are not necessarily coincident with the structures. Significance -- structures may produce sand thicks and high ground-water flow and may introduce reductants into the potential host sandstones. Recognition -- geologic maps and literature and satellite and airphoto imagery, structures indicated by lineaments, color alteration, offsets in basement and sediments contacts, and magnetic maps.	Moderate	Low-Moderate
4 Sediment Dip Dips in the range of 1-3 degrees are favorable, dips significantly greater are unfavorable Significance -- dips of 1-3 degrees are sufficient to maintain strong ground-water flow necessary for deposit formation, steep dips may indicate flushing of the aquifer and destruction of deposits. Flatter dips may produce insufficient flow for the formation of significant deposits. Recognition -- geologic maps, airphoto interpretation, and field reconnaissance.	Moderate	High
III Stratigraphy		
1. Depositional Environment Fluvial sediments composed of mixed sandstones and mudstones are most favorable (generally braided streams and meander belt depositional environments). Thick sequences of dominantly pebbles and boulders (proximal fan environment) and siltstones and mudstones (mudflat environment) are generally unfavorable. Significance -- sediments deposited in the central portions of the fluvial system generally produce excellent aquifers, interbedded with mudstones that focus and constrain ground-water flow, both favorable for roll-front formation. Recognition -- subsurface electric logs and core, outcrop investigations and possibly literature.	Moderate	High

Table 2 continued.

	Importance to Favorability	
	If Present (Sufficiency)	If Absent (Necessity)
2. Age	Low	High

Tertiary sediments are most favorable in the United States. Older sediments, particularly where in contact or previous contact with overlying Tertiary sediments, may contain roll fronts, but these deposits are generally less favorable.

Significance -- Tertiary sediments account for most of the roll-type uranium production and reserves, roll fronts in older sediments, below these Tertiary sediments, tend to be smaller, lower grade, and are generally less amenable to *in situ* leaching methods.

Recognition -- geologic maps and literature and age dates.

	If Present (Sufficiency)	If Absent (Necessity)
3. Sandstone-Mudstone Proportions	Low	High

A stratigraphic sequence of approximately equal proportions of interbedded, moderately thick (25-100 feet) sandstones and mudstones is most favorable. Thick sequences of dominantly shale or sandstone are unfavorable.

Significance -- interbedded, thick sandstones and shales produce the most favorable balance of well-developed aquifers and bounding aquitards for roll-front formation.

Recognition -- geologic literature, field examinations, and subsurface logs.

	If Present (Sufficiency)	If Absent (Necessity)
4. Color	Low	High

Light to dark gray reduced sediments (excluding the effects of surface oxidation) with or without minor oxidized horizons, are most favorable. Dominantly or exclusively oxidized sediments are unfavorable unless introduced reductants are possible or likely.

Significance -- reduced sandstones are capable of reducing uranium from oxidized ground waters to form roll fronts. Oxidized sediments are incapable of precipitating uranium from ground water, unless reductants are introduced, hence are unfavorable.

Recognition -- dark, drab colors of reduced sediments are easily recognized and confirmed by the presence of pyrite and carbonaceous material or bitumin; bright red-yellow colors of oxidation are also easily recognized (differentiation between depositional, oxidized sediments and epigenetic oxidation related to roll-front formation is discussed under Alteration).

	If Present (Sufficiency)	If Absent (Necessity)
5. Thickness	Low	High

Several hundred feet of interbedded sandstones and shales are favorable. Thin sequences may contain small uneconomic deposits.

Significance -- thick sequences of interbedded, well-developed sands and shales offer the best opportunity for strong, prolonged ground-water flow to form large, high-grade deposits.

Recognition -- literature, airphoto interpretations, ground reconnaissance, and subsurface data.

	If Present (Sufficiency)	If Absent (Necessity)
6. Volcaniclastics	Moderate-High	High

Volcaniclastic-rich sediments within the stratigraphic pile are very favorable. Most favorable are several hundred feet of oxidized bentonitic shales and siltstones interbedded with reduced sandstones. The absence of volcanic-rich sediments is very unfavorable unless it can be demonstrated that the host sediments were in hydrologic contact elsewhere with volcaniclastics or uraniferous basement rocks.

Significance -- all important roll-type uranium deposits occur in stratigraphic sequences containing, or adjacent to, thick, volcanic-rich sediments. It is likely that the volcanics were the principal source of uranium in the roll-type deposits.

Recognition -- literature, geologic maps, and field investigations for "popcorn weathering" of bentonite, silica cement in and adjacent to siltstones and shales; glass shards, devitrification, and authigenic clays in thin sections.

IV. Host Sandstone

1. Dimensions

	If Present (Sufficiency)	If Absent (Necessity)
a. Thickness and Width	High	High

a. Thickness and Width -- favorable sands (generally composite channel sands with high hydrologic continuity) should be more than 100-feet thick and channel systems should be at least a few miles wide (many are several miles wide). Thinner sands are unfavorable but may grade into thicker sands.

Significance -- significant deposits form only in larger sand bodies with potential for high ground-water flow; smaller sands may contain smaller and/or lower grade deposits.

Table 2 continued.

	Importance to Favorability	
	If Present (Sufficiency)	If Absent (Necessity)
Recognition -- oil well logs and core, stratigraphic drilling, field observations and possibly literature.		
b Length -- the most favorable channel systems extend from 20 to as much as 100 miles from the uplifts. Shorter channel systems are less favorable	Moderate-High	High
Significance -- longer channel systems transmit more ground water, hence provide the opportunity for larger, higher grade deposits.		
Recognition -- oil well and water well logs, stratigraphic drilling, field observations, and possibly literature.		
2. Depositional Environment	Moderate	High
Sandstones deposited in braided stream depositional environments are most favorable, meander belts and proximal fans are less favorable.		
Significance -- braided streams, and to a lesser extent meander belts, produce major channels of stacked sands necessary for major hydrologic systems. Discontinuous meander sands and dominantly overbank mudstone sections do not provide the necessary ground-water flow.		
Recognition -- depositional environments interpreted from oil well logs, stratigraphic drilling, field mapping, and literature.		
3 Lithology		
a. Clasts -- arkosic to subarkosic sediments are most favorable. Sands with pure quartz are less favorable, and sands with abundant lithic clasts (shale, carbonate, volcanics, etc.) are unfavorable.	Moderate	High
Significance -- arkoses and subarkoses contain stable clasts (feldspar and quartz), which will retain sediment permeability. These sediments also suggest derivation from nearby uplifted basement rocks that would be favorable for high ground-water flow and a possible uranium source.		
Recognition -- literature, hand-speciman study, and possibly thin sections.		
b. Volcaniclastics -- presence of volcaniclastic material deposited in the sands and in interbedded mudstones is very favorable. Its absence is moderately unfavorable	Moderate	Moderate
Significance -- the presence of volcanic material indicates that a source for uranium existed in hydrologic continuity with the potential host sandstone. Its absence does not rule out potential for the sand if volcaniclastic material is present elsewhere in hydrologic continuity with the sand.		
Recognition -- "popcorn weathering" texture of interbedded mudstones in outcrop, identification of shards, authogenic bentonite, etc., in thin section.		
c. Sandstone-Mudstone Proportions -- approximately 25-60 percent interbedded siltstone and mudstone within the host sand is most favorable.	Low	Moderate
Significance -- interbedded, fine-grained sediments within the sandstone (a) somewhat retard ground-water flow and prevent flushing of uranium, (b) reflect depositional environments where reductants and fine-grained sediments accumulate, and (c) focus fluid flow. All these factors are favorable for the formation and stabilization of higher grade roll fronts.		
Recognition -- oil well logs, stratigraphic drilling, and possibly field mapping and literature.		
d. Permeability -- Medium-grained, well-sorted sands with negligible matrix cement are most favorable. Poorly sorted and fine-grained sands, and those with abundant cement (authigenic clays, calcite, silica, etc.) are unfavorable.	Low	High
Significance -- high permeability is essential for the formation of major roll-type deposits. Poorly sorted, fine-grained, and matrix-cemented sands have low permeability and are unfavorable.		
Recognition -- drill cores and electrical logs and field examinations are most important; literature may be useful, but should not be relied upon, selected thin sections should be used to confirm hand-specimen and outcrop observations.		
4 Reductants		
Roll fronts form only when oxidized ground water flows into reduced sandstones. Detrital plant debris and associated diagenetic pyrite are the most common reductants. Introduced reductants may be superimposed on primary reductants or may reduce previously oxidized sandstones.		

Table 2 continued.

	Importance to Favorability	
	If Present (Sufficiency)	If Absent (Necessity)
a. Detrital -- plant debris, present as logs to fine-grained trash is favorable. Pyrite, derived from sulfate reduction in the presence of the carbonaceous material, is always present in greater or lesser amounts, and is an important reductant. Significance -- reductants must be present in the host sand for roll fronts to form. Recognition -- hand-specimen and microscope examination of sandstones to identify plant material and the associated pyrite.	Low-High	Low-High
b. Introduced -- hydrocarbons, humate material, or sulfides may have been introduced into sandstone and are favorable for roll-front formation. Significance -- introduced reductants, commonly derived from organic-rich underlying sediments (commonly oil- and gas-bearing) provide adequate reducing capacity for roll-front formation. Recognition -- the absence of detrital plant debris, evidence of former, widespread sediment oxidation, and the local presence of "mobile" reductants (hydrocarbons, amorphous humates, and pyrite) identified in hand specimen and by microscope, identify sediments as containing introduced reductants.	Low-High	Low-High
5. Alteration The movement of an oxidation-reduction boundary through a reduced sandstone produces diagnostic types of alteration within the sandstone. These alterations differ somewhat between districts, and they can generally be differentiated from surface oxidation. The important alteration types include the following.		
a. Hematite -- light, pinkish to reddish sandstone is an extremely favorable alteration. The presence of only reduced sands, or sands with more earthy or blotchy limonitic or hematitic surface oxidation, are very unfavorable. Significance -- hematitic alteration is the most common and widespread alteration associated with roll-type deposits. It forms by the movement of oxidizing waters through reduced, iron-bearing (mostly pyrite with some contribution from carbonaceous material and silicates) sandstone. Uranium-bearing roll fronts occur at the boundary between oxidized (usually hematite) and reduced sands. Recognition -- the soft, bright pink to reddish color of roll front-related hematitic alteration is easy to discern from the dull earthy hematitic alteration of redbeds oxidized at the time of deposition. The particularly favorable hematitic color is due to very fine-grained hematite crystals on detrital grains, which can be seen under high magnification (100x) in thin section, and which are in sharp contrast to clots of hematite found by the oxidation of iron-bearing detrital grains.	High	High
b. Limonite -- bright to dull yellow/orange limonitic sandstone is a favorable criterion, particularly when it grades into "bleached" sandstone down hydrologic gradient or hematitic alteration up hydrologic gradient. The presence of limonitic sands over a broad area (several hundred feet) is more likely due to surface oxidation of a recent age and is, therefore, unfavorable or uninformative. The absence of limonitic alteration is also uninformative, as many roll-type districts have little or no limonitic alteration. Limonitic sands of unknown extent and unassociated with other alteration types are mildly encouraging and warrant additional exploration. Significance -- limonitic alteration occurs in several, but not all, roll-type districts. Since it is the most common alteration produced by surface oxidation, its habit and distribution are important to determining its favorability for a roll-type deposit. Recognition -- bright to dull yellow/orange coloration uniformly distributed throughout the sandstone on clasts and fine-grained matrix material. Spotty limonitic blebs are more likely the result of surface oxidation of iron-bearing clasts or matrix sulfides, and are less favorable.	Moderate-Low	Low-Moderate
c. Bleaching -- white to buff alteration up dip from oxidation-reduction boundaries is less common than hematite and limonite alteration. Bleaching alone is of low importance, and is difficult to interpret. The absence of bleaching is also of low importance to favorability. Significance -- this type of alteration has been mapped in several districts; hence, it may be useful in drilling out roll-type deposits. Recognition -- bleaching differs between districts, and it can be most easily confused with unaltered sands down dip from roll fronts. Feldspar may be altered to clay in bleached zones, whereas unaltered sandstone should contain some carbonaceous material and/or pyrite. Some bleached zones are due to re-reduction behind a roll front, hence, themselves may contain a late stage of pyrite.	Low	Low

Table 2 continued.

	Importance to Favorability	
	If Present (Sufficiency)	If Absent (Necessity)
d. Zoning -- where all of the alteration types are present, they occur in the sequence bleaching-limonite-hematite up hydrologic gradient away from the oxidation-reduction boundary. When two or more of these alterations are found in this sequence, it is very favorable for a roll-front occurrence. The occurrence of only hematitic alteration is also favorable, but the occurrence of bleaching alone is unknown. The occurrence of only limonitic alteration suggests surface oxidation, and is, therefore, unfavorable. Significance -- alteration zoning is characteristic of most roll-type districts; hence, the zoning is very useful in exploration drilling. Zoning that is not compatible with the hydrologic gradient suggests processes other than roll-front formation, and may be very unfavorable. Recognition -- the recognition of the individual alterations was discussed above. Recognition of the zoning requires outcrop and drill-hole data and information on the ground-water flow directions in the sandstone aquifer.	*High*	*High*

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SANDSTONE-TYPE URANIUM DEPOSITS – SUMMARY AND CONCLUSIONS

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1. INTRODUCTION

The similarity of most of the deposits described in this volume is striking even though they occur in sandstone host rocks ranging in age from Carboniferous to Tertiary and on every continent outside the polar regions. Exceptions are mainly those in older Phanerozoic, Ordovician and Devonian, rocks where the form of uranium is syngenetic and closely related to carbonaceous black shale, and, therefore, not typical of sandstone-type uranium deposits. Dominant occurrence in Silurian and younger host rocks reflects the initial and continued development of vascular land plants. Another strong principle developed in most well-studied districts is that the timing and geochemical character of the mineralizing process were closely related to the diagenesis of the host rock. Geologic environments of the uranium deposits consist of distinctive sets of tectonic and sedimentary-depositional systems, all of which have some common threads of favorable geologic processes. It is hoped that this volume has sharpened our understanding of the deposit's "home environment" that will aid future exploration for these resource-important sandstone-type uranium ores.

All of the papers in this volume contributed to this summary so that specific references to papers are limited.

2. GEOGRAPHIC DISTRIBUTION

Although geographic distribution of sandstone-type uranium deposits is widespread, this project resulted in a clearer understanding of deposit distribution, particularly because of compilation of the continent-distribution maps placed at the beginning of each descriptive section. In the previous IAEA project, it was noted that the known distribution was essentially limited between latitudes 60° S. and 50° N. [1]. A recent discovery of a significant deposit in Death Valley, Alaska [2], at latitude 65° N. indicates that continental basins near and above the Artic Circle should not be overlooked.

3. TECTONIC ENVIRONMENT

The tectonic environment of sandstone uranium districts was particularly important in the development of favorable host sandstone formations, and the tectonic styles varied widely as summarized in table 1.

Table 1.--Distribution of sandstone-type uranium deposits relative to tectonic style of sedimentary basins

I. Platform and intracratonic basins

A. Geologic age--Carboniferous, Permian, Jurassic, Cretaceous
B. Geographic range--Argentina, Brazil, Niger, South Africa, U.S.A.
C. Deposit form--tabular

II. Intermontane basins

A. Geologic age--Tertiary
B. Geographic range--Australia, U.S.A.
C. Deposit form--roll-front

III. Graben and regional extensional basins

A. Geologic age--Permian, Triassic, Tertiary
B. Geographic Range--India, Japan, U.S.A.
C. Deposit form--tabular (including those described as lacustrine deposits), roll-front of basal-type

IV. Volcanogenic basins

A. Geologic age--Tertiary, Quaternary
B. Geographic range--Italy, Mexico
C. Deposit form--tabular

V. Continental margin basins

A. Geologic age--Devonian, Permian, Cretaceous, Tertiary
B. Geographic range--Brazil, France, India, U.S.A.
C. Deposit form--roll-front, tabular (including those described as lacustrine and redistributed-fracture control)

The commonality of the various tectonic styles was their position on a stable crust, or at least marginal to the stable crust. Most of the basins were essentially closed except for a single escape to the sea, which prevented wholesale oxidation and promoted reducing conditions during and after sedimentation that was essential for uranium deposition. The adjacent elevated provenance terrane resulted mostly in high-energy fluvial systems that yielded variably transmissive sediments necessary to restrict groundwater flow and aid in concentrating the uranium into deposits.

The tectonic history of the host rock during and shortly after sedimentation as well as post-sedimentation have influenced the character of ores. Primary ores were precipitated in host rocks at or near their initial dips, and in the younger (Tertiary) host rocks the primary ores have been little changed. In older rocks (especially pre-Tertiary) in some regions, tectonic forces have redistributed the primary ores. Slight uplift and exposure of margins of basins allowed introduction of oxidizing ground water to redistribute tabular ores as tetravalent uranium minerals in roll-fronts and in faults (San Juan Basin, U.S.A.). In other areas, more severe tectonic forces folded and faulted the original host-rock beds into steeply dipping beds but with apparently no redistribution of ore minerals (San Rafael District, Argentina). In still other areas, severe tectonic forces and associated hydrologic activity redistributed ore into fractures and breccia zones (Lodeve, France). These various tectonic environments require special attention to guide exploration.

4. SEDIMENTARY ENVIRONMENTS

The tectonic setting influenced the sedimentary environments for the uranium host formations. The uranium ore deposits described in this volume are grouped in table 2 according to the dominant sedimentary environment.

The most common environment, both in geologic age and geographic distributions, is the continental (terrestrial) environment. The distinguishing character of environments that host sandstone-type uranium deposits, even those marginal to the sea, is the terrestrial nature of sedimentation. Wholely marine environments do not host typical epigenetic sandstone-type uranium deposits, but rather they host syngenetic uranium deposits in very fine-grained rocks. One notes even in the dominantly terrestrial environment where lacustrine conditions locally prevail, the uranium deposits have in part a syngenetic aspect.

5. CLIMATIC ENVIRONMENT

Climatic conditions were important at the time of host-rock sedimentation as well as in modern time. A wet sub-tropical climate was required for the growth of abundant trees in the headwaters of rivers. More arid and even desert conditions were apparently desirable in the midfan portions of the system. These intermittent and mixed climatic conditions afforded abundant plant material that was deposited in the potential uranium host rocks. In modern time, semi-arid to arid conditions have aided preservation of uranium deposits at and near the surface. In humid climates, deep weathering probably has destroyed deposits at the surface, and perhaps, enriched deeper deposits through supergene action. Exploration is more difficult under humid climate conditions.

6. ORIGIN, NATURE, AND FLOW OF ORE-BEARING SOLUTIONS

The papers of this volume almost unanimously point to meteoric ground water, either as part of the sedimentational and subsequent burial processes or as a later introduction from exposed basin margins, as the mineralizing solution. Variations in details of ground water are described to fit each districts' peculiarities of uranium deposit characteristics.

Paleohydrology at the time of primary mineralization was a controlling factor. A prerequisite to ore formation was hydrologic continuity between the source of uranium and the eventual host rock. A general hydrologic model has been proposed for the Frome Embayment, Australia, deposits [3]. Dispersed flow of uraniferous ground water from recharge areas was focused by transmissive channel sandstones sealed both above and below by much less permeable rocks. Precipitation of uranium was mainly upstream from tributary junctions and meander bends that afforded obstacles to fluid flow.

Table 2.--Uranium deposits in sandstone host rocks grouped according to dominant sedimentary environment

I. Continental (terrestrial) environment

A. Dominantly high-energy fluvial system

1. Geologic age--Permian, Triassic, Jurassic, Cretaceous, Tertiary
2. Geographic distribution--Argentina, Australia, Brazil, Canada, India, Niger, South Africa, U.S.A.
3. Deposit form--mostly tabular, few roll-front (including basal-type)

B. Dominantly low-energy lacustrine system

1. Geologic age--Tertiary
2. Geographic distribution--U.S.A.
3. Deposit form--tabular, partly syngenetic

C. Dominantly eolian system

1. Geologic age--Jurassic
2. Geographic distribution--U.S.A. (not discussed in this volume)
3. Deposit form--roll-front

D. Volcanogenic system

1. Geologic age--Tertiary, Quaternary
2. Geographic distribution--Italy, Mexico,
3. Deposit form--tabular

II. Marginal marine environment

A. Fluvial coastal plain and shore-zone system

1. Geologic age--Cretaceous, Tertiary
2. Geographic distribution--India, U.S.A.
3. Deposit form--roll-front

B. Lacustrine to briny lagoon system

1. Geologic age--Ordovician, Silurian, Permian
2. Geographic distribution--Eastern Europe, France
3. Deposit form--tabular

III. Marine

A. Shallow sea environment

1. Geologic age--Ordovician, Silurian
2. Geographic distribution--Europe
3. Deposit form--bedded syngenetic uraniferous black shale (not true sandstone-type)

B. Deep sea environment--no examples

Some uranium deposits characterized by uncommon uranium minerals occur in shallow fluvial host sandstones that lie on igneous and metamorphic basement rocks. These deposits, called "basal-type", seem to be limited to unconsolidated Tertiary fluvial sediments that overlie or are adjacent to major fault and fracture zones [4]. The source of the uranium and associated elements was apparently from the basement rocks, and the elements were carried in ground water solutions that rose through the fractures and infiltrated the host sediments. The geochemistry and the form of the deposits are most similar to roll-front deposits. The uranium minerals are in part exotic, though not limited to basal-type deposits, probably because of available phosphate.

Isotopic studies of sulfur in sulfides associated with uraninite (pitchblende) and coffinite replacements of organic plant matter at Zirovski vrh, Yugoslavia, indicate formation of uranium deposits in Permian sandstone during diagenesis [5]. Miocene orogenic activity remobilized sulfide and rock minerals but less so the primary uranium minerals.

At Lodeve, France, syngenetic concentrations of uranium in Permian organic lacustrine siltstone and minor fluvial sandstone were reconcentrated into fractures and bedding plane openings developed because of concurrent tectonic activity [6]. Later, mid-Jurassic invasion by meteoric water further reconcentrated some of the uranium into major fault zones and cataclastic breccia.

Hydrothermal or magmatic origin of typical sandstone-type deposits was commonly proposed early in research but has been discarded because of overwhelming negative evidence. The Latium, Italy deposits, however, are clearly of hydrothermal origin and are spatially part of a volcanic system [7]. Although the peneconcordant form of the deposits is similar to typical sandstone-type deposits, the geochemistry of the ore-forming solutions was decidedly different. These uranium deposits could be considered as a variety of young surficial deposits and as transitional between deposits of several types, namely sandstone-type, volcanogenic (mantle-dome), and surficial.

Depth of formation of primary uranium concentrations in most sandstone-type deposits seems to have been relatively shallow in most areas. Primary ore that formed in Jurassic time in the San Juan Basin, New Mexico, U.S.A., however, was redistributed in Tertiary time at considerable depth and at elevated temperatures commensurate with those of normal thermal gradient. Some tabular deposits in Carboniferous host rocks in Niger were similarly redistributed into roll-front deposits. Those associated with volcanic terranes were formed close to the surface at moderate temperature from solutions that originated from a deep high-temperature source and mixed with ground water.

The proper timing between the development of a potential source for the uranium and an eventual host rock was essential for ore formation. In areas where potential sources of uranium became available after ground water ceased flowing through a potential host rock, no uranium deposits could develop. In other places, sources perhaps were positioned incorrectly, for example, tuffaceous sediments lying below a potential host might not have been accessible to ground-water circulation.

7. MODELLING

In the past few years a number of attempts have been made to model mineral deposits, some in rather sophisticated ways to utilize computer techniques and artificial intelligence [8, 9,] to assess the favorability of an area to contain undiscovered uranium deposits. The relatively well-understood sandstone-type deposits have provided the best case examples for such modelling. In the so-called "Prospector" system [8], R. I. Rackley modelled the roll-front deposits in Wyoming and the San Juan Basin, New Mexico deposits [8]; S. S. Adams modelled the San Juan Basin deposits [8]; and J. K. Otton modelled the lacustrine deposits of the Date Creek Basin, Arizona, U.S.A. [9]. In addition to these computer-dependent models, Granger and others [10] built a complex conceptual genetic-geologic model of the tabular humate-related deposits in the Morrison Formation, San Juan Basin. To illustrate modelling, an example is given in this volume for roll-front deposits. The practical use of these various models has been limited to assessing favorability for undiscovered uranium resources by governmental groups [11]. Because these models have been available only a short time, actual application to physical exploration and success of such application will be in the future. Nevertheless, these various models provide a basis for future generations of modelling.

8. EXPLORATION

The most direct methods of exploration are radiometric surveys of the ground surface using either airborne or ground-borne instruments and by drilling, either coring or plugbit. Indications of a uranium deposit by drilling may be either direct in the case of actual intersection of mineralized rock or indirect by the intersection of altered rock or some other favorable geochemical or geologic feature. Other geophysical methods as well as geochemical surveys generally provide indirect indications of uranium mineralization.

Geophysical surveys, other than radiometric, generally apply standard oil-and-gas exploration techniques, but with appropriate modifications for mineral deposits. The U.S. Geological Survey has conducted research on using induced polarization and electromagmatic field methods [12]. Electromagnetic surveys appear to be useful in only indirectly locating favorable geologic structures, whereas induced polarization techniques may locate, particularly within 100-200 m depth, actual deposits because of associated sulfides and other chargeable minerals.

Prospection and exploration for uranium occurrence by hydrogeochemimcal surveys are dependent on rock terrane and modern environmental conditions [13]. Sedimentary terranes, sandstone in particular, are better suited to hydrogeochemical surveys than either igneous or metamorphic terranes, although uraniferous granite is a significant exception. Climate is a dominant factor in successful application of hydrogeochemical methods; semi-arid climate is best whereas tropical, temperate, artic, and arid (desert) climates are poor. Sampling design is second in importance only to careful sampling.

Helium and radon, which emanate from uranium deposits, can be useful as indirect methods of detecting buried uranium deposits [14]. Their usefulness is most dependent upon depth of deposit burial, permeability of overlying rock, and the relation of the ground-water table to the buried deposit. Gaseous emanation methods are excellent supplements in the exploration for shallow sandstone ores.

Because sandstone-type deposits are commonly distributed along linear sedimentary trends, a concept of "trendology" is commonly used to find additional ore in partially explored districts [15] The Uravan and Grants mineral belts are good examples in the United States. In frontier areas, where sedimentary trends have been established and by analogy to known mineralized areas, initial drilling patterns and spacing can be guided by "trendology."

The depths to which exploration for sandstone-type uranium deposits can be conducted are limited. The average grades and ore thicknesses are smaller than those for many vein-type ores with which sandstone-type ores must compete in the world market. Thus, exploration depths in the near future will be limited by mining economics to around 1000 m. The apparent restriction of sandstone ores to and near edges of sedimentary basins lessens the constraint of depth, especially for initial exploration in untested basins.

9. SUGGESTED RESEARCH

Several directions for research are evident from an analysis of the papers in this volume. The most important need is that of research on the paleohydrology of the ore-forming systems; even in the much-studied deposits in the United States our understanding of paleohydrology is quite poor, except perhaps for roll-front deposits. Dating of the ore and associated minerals is particularly needed in many regions. For example, the possible source of uranium from Cretaceous volcanics for deposits in Permian rocks in the Parana Basin, Brazil [16] needs to be investigated using lead-uranium dating of primary uranium minerals. Clay mineralogy, including isotopic dating, is another topic of study needed in many districts. Results of these various suggested research directions would enable us to develop better genetic models for exploration.

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